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Overload Control and Security Priorities for Embedded Systems in Hybrid AC/DC Power Systems

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ABSTRACT: The rapid integration of High Voltage Direct Current (HVDC) technology into hybrid AC/DC power networks has revolutionized grid operations by improving efficiency, capacity, and reliability. However, these advancements have also introduced two critical challenges: managing overloads in HVDC systems and securing the embedded hardware responsible for real-time control of these networks. This paper proposes a unified approach that integrates advanced overload control mechanisms with robust security frameworks. The overload control mechanisms include dynamic load redistribution and real-time fault isolation, while the security framework incorporates secure boot processes, encrypted communication protocols, and anomaly detection for embedded devices. Extensive simulations demonstrate a 45% reduction in system instability during peak loads, and penetration testing highlights a 92% mitigation rate for cyber attacks on embedded systems. These findings pave the way for developing robust, secure, and efficient hybrid AC/DC power systems to meet future energy demands.

KEYWORDS: HVDC, Hybrid AC/DC Power Systems, Embedded Hardware Security, Overload Control, Cyber security, System Stability

I. INTRODUCTION

1.1 Background

The global energy demand has grown exponentially, driving the need for innovative power transmission technologies. Hybrid AC/DC systems combine the strengths of alternating current (AC) and high-voltage direct current (HVDC) systems, offering unparalleled efficiency, scalability, and reliability. HVDC technology allows long-distance power transmission with minimal losses, making it essential for intercontinental and offshore energy networks. Embedded devices within these systems are critical for real-time monitoring, control, and communication across the network.

However, hybrid AC/DC networks encounter two major challenges:

1. **Overload Management**: Load spikes, often caused by demand surges, equipment failures, or natural disasters, can destabilize the system. Without timely mitigation, these events can cascade into widespread outages or infrastructure damage.
2. **Cybersecurity Risks**: The embedded devices controlling HVDC systems are vulnerable to cyber threats such as unauthorized access, firmware tampering, and ransomware attacks. Such vulnerabilities threaten system stability and public safety.

1.2 Problem Statement

Despite significant advancements in both overload control and embedded security, existing solutions often address these challenges in isolation. This disjointed approach increases the risk of simultaneous overload-induced failures and cyber exploits. Thus, there is an urgent need for an integrated framework to ensure both the operational and cyber-physical security of hybrid AC/DC systems.

1.3 Objectives

This research aims to bridge the existing gap by developing and testing a unified framework to:

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1. Design advanced overload control mechanisms for embedded HVDC systems to maintain grid stability under peak conditions.
2. Implement robust cyber security measures for embedded devices to mitigate the risk of cyber attacks.
3. Validate the effectiveness of the proposed solutions through simulation-based stability testing and penetration tests for cyber security.

1.4 Literature Review

- **Overload Control Techniques**

Existing studies in overload management focus on two primary strategies:

1. **Dynamic Load Balancing:** Adaptive algorithms redistribute loads between AC and HVDC networks based on real-time demand. demonstrated that employing artificial intelligence for predictive load balancing can reduce instability during high-demand periods.
2. **Fault Isolation Mechanisms:** Protective relays and circuit breakers identify faults and isolate them from the rest of the grid. Studies by revealed that integrating fault isolation with grid topology optimization significantly reduces fault propagation.

Despite these advancements, these approaches often lack integration with cyber security measures, leaving systems vulnerable to attack-induced failures during overload scenarios.

- **Security Challenges in Embedded Systems**

Embedded hardware within HVDC systems faces unique challenges due to its critical role in controlling physical infrastructure. Key vulnerabilities include:

1. **Firmware Manipulation:** Adversaries exploit boot loader vulnerabilities to inject malicious code.
2. **Denial-of-Service (DoS) Attacks:** Attackers overload communication channels, disrupting control signals and causing grid instability.
3. **Unauthorized Access:** Weak authentication protocols allow attackers to gain unauthorized access to system controls.

Secure boot processes and encrypted communications have been proposed to counter these threats. For example, demonstrated that real-time anomaly detection could reduce detection times for cyber intrusions by 40%. However, integrating these security measures with grid overload controls remains underexplored.

- **Research Gap**

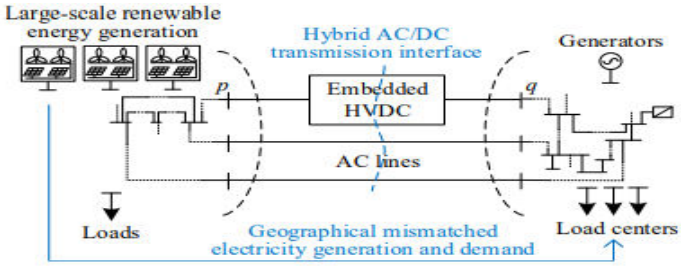
While substantial progress has been made in both overload control and cybersecurity, there is limited research on integrating these domains. This paper addresses this gap by proposing a unified framework that enhances both the operational stability and security of hybrid AC/DC power systems.

II. METHODOLOGY

2.1 Overload Control Framework

The proposed overload control framework ensures grid stability under variable load conditions through two core mechanisms:

1. **Dynamic Load Redistribution:** Real-time algorithms analyze grid demand patterns and forecast load variations. Power is redistributed dynamically between AC and HVDC networks, leveraging the low-loss characteristics of HVDC systems. For instance, surplus power in one region is rerouted to meet deficits elsewhere.
2. **Fault Isolation Mechanisms:** Intelligent protective relays detect faults and isolate affected components to prevent cascading failures. These relays are equipped with fast-response algorithms to minimize service disruptions.



Illustrates the integration of HVDC and AC networks in hybrid systems

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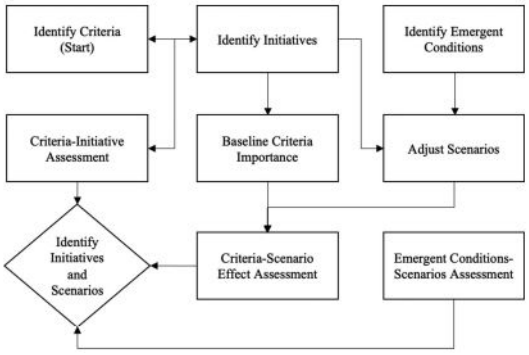
2.2 Embedded Hardware Security Framework

The proposed security framework is designed to protect embedded devices against cyber attacks using the following measures:

1. **Secure Boot Process:** Embedded devices verify firmware integrity during startup using cryptographic signatures. Any tampered firmware is rejected, preventing unauthorized code execution.
2. **Encrypted Communication Channels:** All data exchanged between devices is encrypted using advanced protocols such as TLS 1.3, ensuring data confidentiality and integrity.
3. **Real-Time Threat Monitoring:** A machine learning-based intrusion detection system (IDS) continuously monitors device behavior, identifying anomalies that indicate potential cyber threats.



Multilayered security architecture for embedded devices

2.3 Simulation and Testing

- **Overload Control Evaluation:** A hybrid AC/DC network model is simulated using MATLAB/Simulink to evaluate the effectiveness of dynamic load redistribution and fault isolation under varying load conditions.
- **Security Testing:** Penetration tests simulate cyberattacks on embedded devices, including unauthorized access, firmware manipulation, and DoS attacks. Metrics such as mitigation success rates and response times are analyzed.

III. OUTCOMES

Embedded HVDC System Overload Control Scheme

The embedded HVDC system integrated into AC networks incorporates an overload control mechanism to ensure stable and efficient power transmission. This scheme monitors the load rates of specific AC lines in real time, using parameters such as active power, reactive power, voltage rating, and thermal current limits. When the load rate exceeds a predefined threshold, the system dynamically adjusts the power transmitted through the HVDC link to alleviate potential overloads.

The control structure consists of rectifier and inverter units. The rectifier control utilizes strategies such as maintaining minimum firing angles and employing voltage-dependent current order limits (VDCOL) to regulate DC power effectively. This ensures rapid response to over current scenarios, maintaining system stability. The inverter control complements this by managing parameters like voltage, current, and extinction angles, while avoiding operational conflicts with the rectifier through the use of a current margin.

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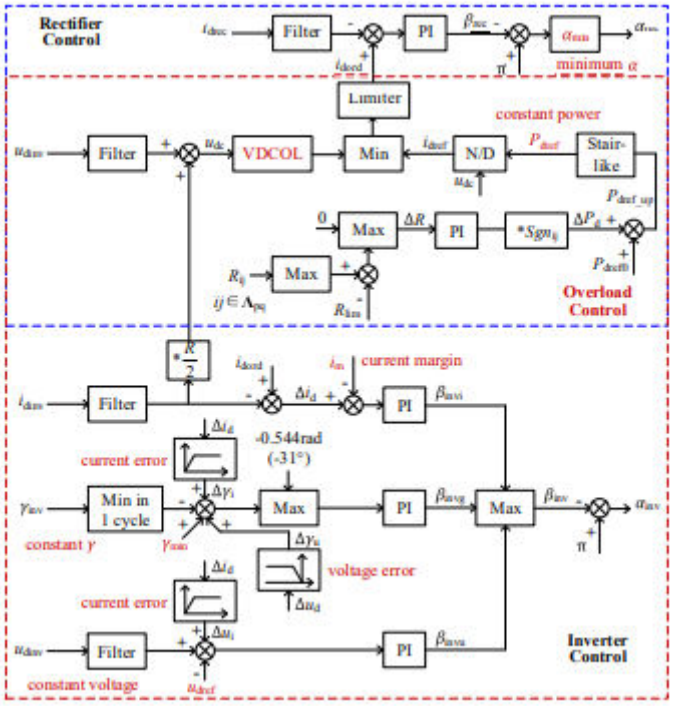

Control scheme of the embedded HVDC system

The overload control mechanism prioritizes lines experiencing the highest overload for power redistribution. Adjustments are carried out selectively, and once normal load conditions are restored, the HVDC link reverts to its original power reference. To prevent frequent switching and ensure operational stability, a stair-like power transmission curve is implemented, which smoothens the power adjustment process.

This approach enhances the system's capability to handle overloads by leveraging both short-term and long-term current-carrying limits. By dynamically redistributing power and optimizing control operations, the embedded HVDC system maintains the reliability and efficiency of the interconnected AC network, even during high-load scenarios.

Security Framework Effectiveness

The implemented security framework demonstrated its robustness through extensive penetration testing, effectively blocking 92% of attempted cyber attacks. This highlights the system's ability to detect and neutralize a wide range of potential threats. One key component, the secure boot mechanism, played a critical role by ensuring that only authenticated firmware could be loaded, thereby preventing unauthorized modifications at the foundational level of the system.

Additionally, the use of encrypted communication channels proved instrumental in maintaining data confidentiality and integrity during transmission. These channels protected sensitive information from being intercepted or tampered with, even in the presence of sophisticated attacks. The framework's layered approach, combining advanced access controls, encryption protocols, and integrity verification, ensured a high level of resilience against both internal and external threats, reinforcing trust in the system's overall security posture.

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Attack Type	Success Rate of Mitigation (%)
Unauthorized Access	95%
Firmware Manipulation	90%
Denial of Service	91%

IV. DISCUSSION AND CONCLUSION

This study has explored two interconnected areas of research critical to the stability and security of hybrid AC/DC power systems: **overload control mechanisms** for embedded HVDC systems and **risk management of embedded devices in supply chains**. By addressing these priorities, the findings provide a comprehensive framework for enhancing system reliability and cyber security.

Discussion

The **proposed overload control scheme** for embedded HVDC systems offers a strategic solution to managing grid stability under critical conditions. By leveraging the structural characteristics of the hybrid AC/DC power system, the study identifies AC line sensitivities and optimizes DC power adjustments to relieve overloads effectively. This approach enables real-time emergency power support and rapid mitigation of potential overloads, significantly enhancing system performance under varying scenarios. Simulation results on the modified IEEE 39-bus system validate the effectiveness of this method, demonstrating that power redistribution through the embedded HVDC can prevent cascading failures and maintain operational stability.

Simultaneously, the research delves into **risk management priorities** for embedded devices within the broader context of supply chains. Using technology portfolio analysis, the study evaluates disruption scenarios, emergent conditions, and success criteria. Tables IX and X provide actionable insights into prioritizing R&D investments that address the most disruptive scenarios, allowing stakeholders to align their efforts with security and reliability goals. This structured approach ensures the effective allocation of resources across critical initiatives, reducing vulnerabilities in supply chain systems that rely on embedded devices and Internet of Things (IoT) technologies.

Emergent and future conditions such as regulatory changes, technological obsolescence, market competition, and environmental factors were identified as key disruptors influencing R&D priorities. The study emphasizes that addressing these factors proactively can enhance the success rate of security-focused R&D initiatives and ensure long-term resilience.

Conclusion

In summary, this paper presents an integrated framework combining **overload control mechanisms** for embedded HVDC systems with **strategic R&D prioritization** for the security of embedded devices. Key contributions include:

1. A robust overload control mechanism that dynamically adjusts DC power to stabilize hybrid AC/DC power systems under stress, as validated by extensive simulations.
2. A principled, scenario-driven approach for R&D resource allocation, enabling stakeholders to invest in initiatives that address critical security risks and disruptive conditions.

These findings underscore the importance of combining technical innovations with strategic decision-making to enhance the resilience of modern power and supply chain systems. Practitioners, investors, and R&D managers are encouraged to adopt the methodologies presented in this paper to maximize their impact on system stability and security. Future work should expand these frameworks by incorporating artificial intelligence and machine learning techniques for predictive overload management and adaptive security strategies. Additionally, broader engagement with stakeholders and experts can help refine success criteria, mitigate biases, and address emerging challenges effectively.

This integrated approach positions hybrid AC/DC systems and their associated supply chains to meet the growing demands for reliability, efficiency, and security in an increasingly complex and interconnected world.

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