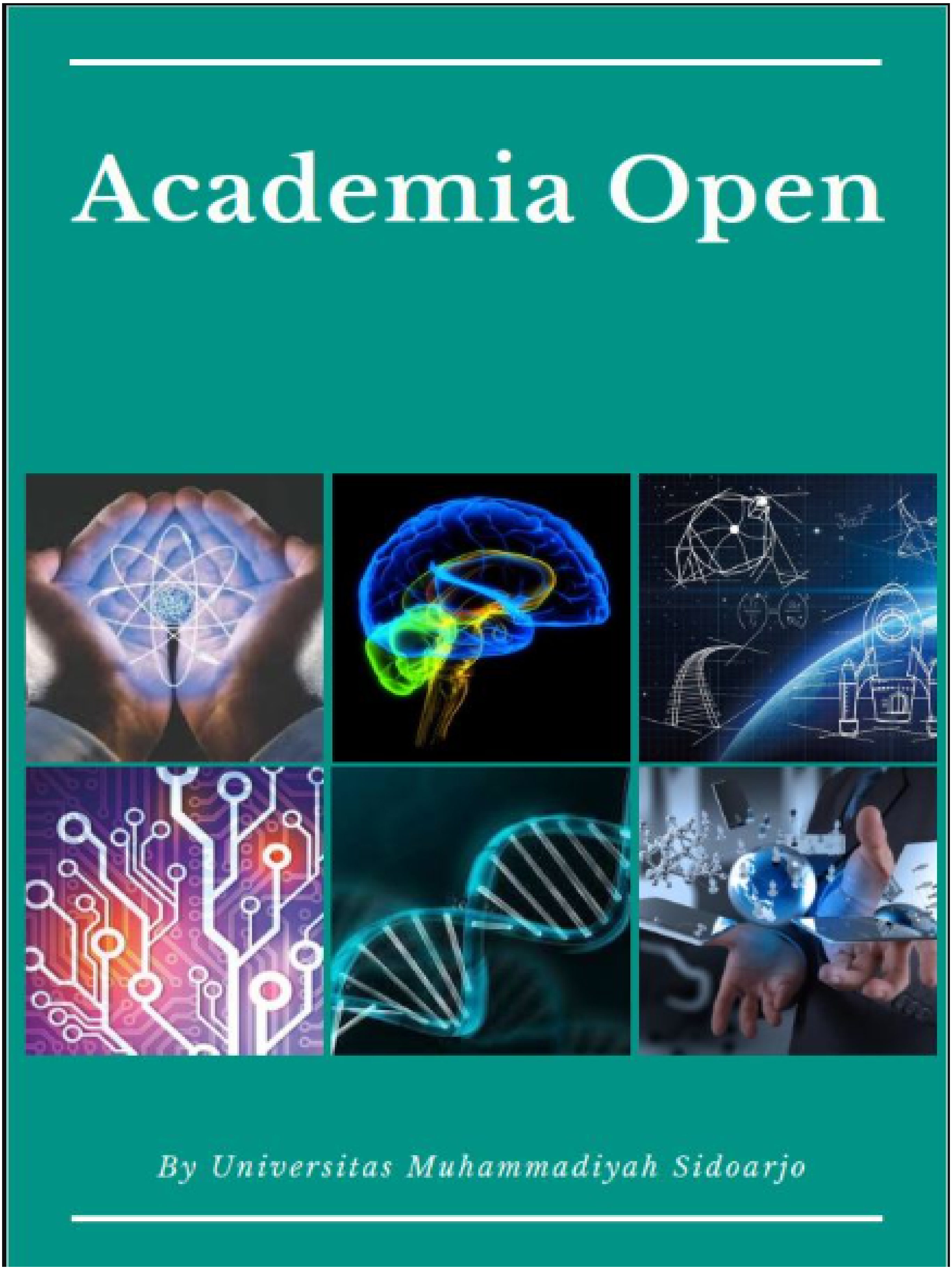
Academia Open

Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550



ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open

Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Table Of Contents

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Originality Statement

The author[s] declare that this article is their own work and to the best of their knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the published of any other published materials, except where due acknowledgement is made in the article. Any contribution made to the research by others, with whom author[s] have work, is explicitly acknowledged in the article.

Conflict of Interest Statement

The author[s] declare that this article was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright Statement

Academia Open

Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Academia Open
Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Article information

Check this article update (crossmark)

Check this article impact [*]

Save this article to Mendeley

[*] Time for indexing process is various, depends on indexing database platform

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Hierarchical AI Control and Protection for Renewable Integrated MTDC Grids: Pengendalian dan Perlindungan AI Hierarkis untuk Jaringan MTDC Terintegrasi Energi Terbarukan

Salah Faisal Abbood, Salah.aus970@gmail.com (*)
Electrical Engineering Department, Shahid Chamran University, Iraq

(*) Corresponding author

Abstract

General Background Renewable energy integration requires advanced transmission infrastructures capable of managing long-distance power transfer and fast system disturbances. **Specific Background** Multi-terminal VSC-HVDC grids offer operational flexibility but face challenges related to coordinated control and ultra-fast DC fault protection. **Knowledge Gap** Existing studies predominantly address control and protection separately, resulting in limited system-level coordination during dynamic and faulted conditions. **Aims** This study aims to develop and validate a unified hierarchical artificial intelligence-based framework that integrates control and protection for renewable-integrated MTDC systems. **Results** A three-layer architecture employing deep reinforcement learning for primary control, an AI-based secondary coordinator, and a hybrid AI-driven fault protection scheme was validated through EMT-based co-simulation of a modified CIGRE B4 MTDC benchmark. The framework achieved significant reductions in settling time, voltage deviation, fault detection latency, and post-fault recovery duration, alongside high fault classification accuracy. **Novelty** The proposed approach introduces a single, coordinated AI-driven architecture that simultaneously governs normal operation and emergency fault response within MTDC grids. **Implications** The results demonstrate the feasibility of deploying integrated AI-based control and protection to improve stability, resilience, and operational reliability in future renewable-dominated HVDC networks.

Keywords: Artificial Intelligence, VSC-HVDC, Multi-Terminal DC Grids, Fault Protection, Renewable Integration

Key Findings Highlights:

1. Integrated AI coordination significantly reduced dynamic settling time and voltage deviations under renewable variability
2. Intelligent fault protection achieved sub-millisecond detection with high classification accuracy
3. System resilience under converter outage conditions improved through adaptive secondary coordination

Published date: 2026-02-10

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open

Vol. 11 No. 1 (2026): June
DOI: 10.21070/acopen.11.2026.13550

Introduction

The large-scale deployment of renewable energy sources (RES), which is mainly made up of wind and solar photovoltaic (PV) energy, is at the core of the global shift to sustainable energy systems. These sources are frequently described as spatially dispersed and distant, i.e. offshore wind farms and large desert solar parks [1]. The effective and dependable bulk power delivery of these remote locations to larger load centers proves to be a big technical challenge [2]. Conventional alternating current (AC) grids have a low ability to transmit over a long distance because of the problem of reactive power losses, voltage fluctuation and synchronization. The High Voltage Direct Current (VSC-HVDC) technology utilizing Voltage Source Converter has become one of the most important enablers of the contemporary power systems providing clear benefits of integrating the RES [3]. These benefits are independent control of both active and reactive power, black-start, and capability to be connected to weak or passive AC networks [4]. Such a technological base makes it possible to advance beyond point-to-point HVDC connections to more complicated and flexible Multi-Terminal DC (MTDC) grids. The vision of MTDC grids has been to be linked grids capable of sharing the power generated by various geographically separated renewable generation centers and to redistribute and allocate power efficiently to other areas and hence increasing grid resilience and market flexibility [5].

The operation of a renewable-integrated MTDC grid presents complex challenges that span both control and protection domains. From a control perspective, the intermittent and stochastic behavior of RES, combined with the inertia-less characteristic of VSC stations, complicates the management of power flow, DC voltage stability, and dynamic power sharing among terminals. Traditional droop control schemes are often insufficient to address these issues [6].

Simultaneously, the MTDC system faces stringent protection challenges. DC fault can occur with extremely high rates of current side (di/dt) due to the low inductance of DC cables. Fault interruption is further complicated by the absence of natural current zero-crossings. Consequently, fault detection, classification and selective isolation must be executed very rapidly to prevent widespread converter blocking and potential catastrophic failure of the MTDC network [7].

Conventional solutions are often inadequate in this demanding environment. The widely used VSC control employs a linear Proportional-Integral (PI) controller, which is typically optimized for a specific operating point. However, its performance may degrade when operating across the wide and nonlinear range associated with variable renewable energy sources [8].

Traditional DC protection schemes, such as differential protection, can be limited by communication delays or they may not respond rapidly or selectively enough to support the large-scale meshed MTDC grids. A significant research gap exists in the prevailing siloed approach towards such problems. Although the issues of advanced control and intelligent protection schemes are commonly discussed separately, there is a gap in terms of a single, unified framework [9]. This research gap is an opportunity to capitalize on the flexibility and the ability to detect patterns of Artificial Intelligence (AI) and design a single hierarchical system that will ensure optimal operation and coordinate emergency fault correction [10].

The main aim of the research is to develop and test a single hierarchical AI-based control and protection system to increase the stability, efficiency, and resilience of the renewable-integrated MTDC systems. In order to reach this goal, the following specific contributions are used:

1. It is suggested to use a new three-level hierarchy of control (Primary, Secondary, Tertiary) with AI agents incorporated on the Primary and Secondary tiers in place of traditional control loops and to improve them.
2. A Deep Reinforcement Learning (DRL)-based Primary Controller is trained to be able to control local VSCs. This agent is informative of an ideal policy to substitute conventional inner current and outer power/voltage PI control, which allow a higher quality of dynamic response and flexibility.
3. A Secondary Coordinator based on AI is going to be developed to do optimal power sharing and DC voltage regulation. This module makes use of a centralized AI optimizer or a multi-agent system to dynamically operate system-wide setpoints, droop coefficients.
4. A Hybrid Advanced Fault Protection Scheme is provided. In this scheme, AI methods are used synergistically, i.e. Convolutional Neural Networks (CNNs) or Long Short-Term Memory (LSTM) networks to perform ultra-fast fault detection and classification, and a model-based algorithm to locate faults precisely.
5. An entire co-simulation validation framework is developed to validate the successful interplay of the AI-enhanced control hierarchy and intelligent protection scheme in a holistic and thoroughly considered situation of variability of the RES and DC faults under a wide range of operational and disturbance conditions.

The remainder of this paper is organized as follows. Section 2 presents a critical review of the available literature on the control of the category of MTDC, the application of AI in power electronics, and DC fault protection. Section 3 describes the architecture of the proposed hierarchical AI-driven control and protection scheme in detail. Section 4 explains the methodology, including the test system configuration, AI model development, and co-simulation framework. In Section 5 presents the simulation results along with a comprehensive discussion of system performance. Finally, Section 6 presents the conclusions and outlines directions for future research.

2. Literature Review

2.1 . Control of MTDC Grids

Multi-Terminal VSC-HVDC systems are traditionally hierarchically organized to be professionally controlled to guarantee effective and stable operation. This hierarchy is usually of three tiers [11]. At the Primary level, local droop control is used on each converter to offer decentralized power sharing and DC voltage stabilization just after a disturbance has been experienced. The Secondary level is then employed to remove steady-state DC voltage errors or power-sharing errors by the droop characteristic, usually by a centralized or distributed controller which broadcasts corrective setpoints [12]. Lastly, the Tertiary level carries out system wide optimization like economic dispatch to set the optimal system power flow setpoints to the complete MTDC grid as dictated by the market conditions and grid requirements. In order to improve the performance over the traditional linear controllers, some sophisticated methods such as Model Predictive Control (MPC) have been explored. MPC provides better management of system constraints and control of multi-variables but has commonly been hampered by excessive computational complexity particularly in large networks [13]. A little bit later, the use of Artificial Intelligence (AI) methods has been examined. Fuzzy logic controllers have been developed to cope with the non-linearities of converter systems and Artificial Neural Networks (ANNs) have been applied to identify systems and as non-linear compensators. Early research on the field of Reinforcement Learning (RL) has shown that it has the potential to achieve adaptive control in power electronic systems because it is model-free, and it can be used to optimize long-term performance [14].

2.2 . AI and Machine Learning in Power Electronics and HVDC

In the realm of AI implementation, Deep Reinforcement Learning (DRL) has received much interest in controlling power converters. The main benefit of DRL is that it is able to learn optimal control policies by interacting with a simulated environment, and does not need to have a clear and precise system model [15]. It has found application especially in non-linear, difficult-to-characterize systems such as VSC-HVDC terminals in a wide-range and uncertain environment, such as that dictated by intermittent renewable generation [16]. The agent is trained to optimize a specific reward form which may be a combination of several control goals such as reference tracking, oscillation damping, and constraint satisfaction. Parallel to it, supervised machine learning, mostly ANNs, is a popular technique used in auxiliary tasks. These involve dynamic system identification which trains a neural network model to act like the converters, and offline optimization of traditional controller parameters, to minimize reliance on expert knowledge and time-consuming manual performance optimization [17].

2.3 . Fault Protection in VSC-MTDC Systems

The high-speed dynamics of DC faults pose a challenge to the protection of the MTDC grids. Fault currents increase at a very large di/dt and do not necessarily have a natural zero-crossing, so special methods are required to use [18]. These techniques are by blocking the IGBTs of the converters, which is easy but causes a temporary stop in transfer of power, or by using fast mechanical AC Circuit Breakers (CBs) with synchronized coordinates. More selective solution is the development of dedicated DC Circuit Breakers (DCCBs) which is also expensive. To activate these breaking devices many protection algorithms are suggested. Traveling-wave-based techniques make use of high-frequency content of voltage or current signals to measure fault direction and fault location at high speed but may be susceptible to noise and high sampling rates may be necessary [19]. Existing derivative techniques also have high speeds but are likely to malfunction when switching large loads or other transients. Differentiated protection programs provide great selectivity, but are fundamentally reliant on high-speed effective communication between end of line terminals, as well as establishing a possible failure point [20]. To address such drawbacks, AI and Machine Learning (ML) protection schemes are currently actively studied. Support Vector Machines (SVMs) and Random Forests are the techniques that have been used to classify the types of faults based on the features gained out of measured signals. Still more recently, various deep learning methods have been exploited to automatically derive spatio-temporal detail in raw or pre-processed voltage and current data to detect and classify faults more quickly and reliably [21]. Table 1introduces summary of current methods, their applications, and limitations.

Domain	**Current Methods/Techniques**	**Primary Application**	**Key Problems and Limitations**
MTDC Control	Conventional Hierarchical Control (PI-based droop)	Primary voltage/power control & secondary correction.	Performance degrades under large-signal disturbances and non-linear operating regions; requires precise tuning.