Case Study 1:

Short-Circuit Analysis of a Point-to-Point DC Power System

Methodological Comparison for an AFE-Based VSC Link

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1 Introduction

1.1 Overview

This case study formed the initial investigation aimed at characterising the short-circuit behaviour of a point-to-point (P2P) DC power system employing advanced voltage-source-converter (VSC) technology. The studied link is fed by an active front-end (AFE) converter and incorporates distributed DC-link capacitors whose stored energy dominates the initial phase of a DC fault. The objective was to establish a transparent analytical and simulation framework before progressing to the more complex multi-source multi-terminal DC (MTDC) configuration analysed in Case Study 2 [1, 2, 3].

The New Zealand HVDC Inter-Island link between Benmore in the South Island and Haywards in the North Island is a critical national transmission asset. Its converter stations employ thyristor-based line-commutated technology, which belongs to the current-source-converter (CSC) family [4, 5]. This mature technology has supported reliable, long-distance bulk power transfer, but its operating principles differ substantially from those of modern self-commutated VSC systems. Consequently, the present case study adopts an AFE-based VSC P2P link as a forward-looking research platform rather than as a direct model of the existing inter-island scheme.

The core research problem is whether a standards-based short-circuit calculation can be reconciled with a physically transparent analytical model for an AFE-based VSC system. IEC 61660-1 is adopted as the established reference for short-circuit calculations, while a novel power-balance model of the AFE, together with ordinary differential equation (ODE) models representing the DC-link capacitors, is formulated as a complementary method. Both analytical approaches are then benchmarked against a detailed Simulink model to assess whether they yield consistent results for peak current, time-to-peak, and capacitor-dominated fault-current behaviour.

1.2 Background

The technical motivation for examining VSC technology is evident from the limitations of conventional CSC-HVDC generation systems. As a CSC consumes significant reactive power, it commonly requires large AC capacitor banks for compensation, is exposed to commutation failure, and can encounter integration difficulties when connected to a weak AC grid [4]. However, a VSC is force-commutated, can independently regulate active and reactive power, may operate at unity power factor, and can support a weak AC grid by providing reactive power control [4].

These characteristics are important for New Zealand because future transmission development may need to connect renewable generation, storage, and electrically weak regions while providing stronger voltage support. A conventional CSC is not readily suited to flexible multi-terminal expansion because its line-commutated operation, reactive-power dependence, and voltage-polarity reversal for power reversal complicate the connection and coordinated control of additional terminals. Therefore, CSC technology is comparatively difficult to extend into a flexible multi-terminal backbone, whereas VSC technology is substantially better suited to this role [4].

A second challenge is the standards gap. IEC 61660-1 provides a structured procedure for short-circuit-current calculation in DC auxiliary installations, but it does not explicitly define a controlled AFE-based VSC as a standard source model [6, 7]. Further, established DC standards and protection practices mainly address low-voltage installations or thyristor-based line-commutated HVDC systems, while corresponding operational and protection

practices for VSC-based DC grids remain limited [4, 2]. Consequently, direct implementation of IEC 61660 for an AFE-based VSC requires an engineering interpretation of the converter contribution and an independent representation of the DC-link capacitor discharge.

2 Research Contribution and Benefits

2.1 Research Contribution

The main contribution of Case Study 1 is a methodological bridge between IEC 61660-1 and an AFE-based VSC P2P system. The studied network contains a 690 V, 50 Hz AC source, an AFE converter, two 0.09 F DC-link capacitors, and a P2P line represented using resistance and inductance. A pole-to-pole fault is applied between the two capacitor locations. Three complementary methods are evaluated using the same system parameters and initial conditions [1].

First, the IEC approach calculates the rectifier and capacitor contributions separately, applies the required common-branch correction factors, and superimposes the corrected source currents. Second, the novel analytical model represents the AFE contribution by an ideal AC–DC power balance and models each capacitor discharge by its own second-order ODE. This separation is physically useful because it bounds the controlled converter contribution while explicitly resolving the fast release of stored capacitor energy. Third, a switching Simulink model is used as the detailed numerical benchmark.

The three approaches show close agreement. The IEC superposition gives a peak current of 5271.47 A at approximately 14 ms; the power-balance and ODE model gives 5243.65 A at approximately 14 ms; and Simulink gives 5262 A at 14 ms [1]. Relative to Simulink, the IEC result differs by approximately 0.18 %, while the ODE-based result differs by approximately −0.35 %. All methods identify the same physical mechanism: the initial short-circuit transient is dominated by the two DC-link capacitor discharges, whereas the AFE contribution is comparatively small during the peak-forming interval.

The close numerical agreement demonstrates that the power-balance and ODE model is not merely a curve-fitting exercise. It reproduces the dominant fault physics using a compact analytical framework and establishes a traceable connection among a recognised international standard, a modern controlled converter, and a detailed switching simulation. This makes the model suitable as an initial platform for equipment rating, protection studies, sensitivity analysis, and subsequent extension to multi-source MTDC networks.

2.2 International Standards and Benefits for New Zealand

International standards provide a common basis for short-circuit calculation, equipment specification, technical review, and protection design. IEC 61660-1 is valuable because it separates source contributions and provides a repeatable calculation process [6]. However, emerging AFE- and VSC-dominated systems contain control-dependent converter behaviour and significant DC-link capacitor energy that are not explicitly represented by a dedicated AFE source category. The proposed model complements, rather than replaces, the IEC method, which provides the standards-based structure, while the power-balance and ODE equations provide the converter-specific physical representation.

For New Zealand, this combined approach establishes an early analytical capability to investigate future VSC-based HVDC options without assuming that an existing CSC installation can be replaced directly. It enables engineers to estimate peak current, time to peak, source-wise contributions, and capacitor-discharge severity before undertaking more

computationally intensive electromagnetic transient studies. These quantities are necessary for converter rating, DC circuit-breaker selection, line-reactor design, protection thresholds, and fault-clearing requirements.

The work also provides a basis for future standards development. A validated method that connects IEC calculations with controlled VSC behaviour can help identify where existing standards remain applicable, where interpretation is required, and where new converter-specific guidance is needed. This supports New Zealand's ability not only to adopt advanced technology, but also to contribute research evidence for safe and reliable VSC-HVDC and MTDC engineering practice.

3 Industry Collaboration and Strategic Impact

3.1 FAN, University of Auckland, and ABS Partnership

This research is positioned within the Future Architecture of the Network (FAN) programme, supported by the University of Auckland and linked with the American Bureau of Shipping (ABS) as an international industry collaborator. FAN provides the New Zealand future-network context, including renewable integration, electrification, resilience, and emerging AC/DC architectures [8]. The University of Auckland contributes analytical modelling, standards interpretation, simulation, and protection expertise. ABS contributes an industry perspective on safety, verification, and operation of converter-dominated DC systems in marine and offshore environments [9].

The partnership is relevant because P2P VSC links, shipboard DC systems, offshore networks, and future land-based MTDC grids share the same fundamental need: accurate characterisation of rapidly rising capacitor-fed fault current. Case Study 1 provides the initial single-link methodology, while Case Study 2 extends the standards-based research toward multi-source and multi-terminal operation. Together, the studies form a progressive research pathway from a controlled P2P benchmark to a more realistic future MTDC grid.

3.2 Strategic Impact and Future Opportunities

The results indicate that the P2P AFE-based VSC model can serve as a first analytical step toward investigating a future enhancement pathway for New Zealand's CSC-based inter-island transmission system. A VSC-based backbone could, in principle, provide weak-grid voltage support, independent reactive-power control, easier reversal of active-power direction, and a more practical platform for adding further terminals. Additional HVDC terminals could connect renewable-resource regions, storage, major load centres, or electrically weak regions, thereby forming an MTDC network.

Such an evolution could improve the utilisation, reliability, flexibility, and transfer capacity of the national transmission system while supporting the integration of renewables. It could also create alternative power-flow paths and local voltage-support capability. These are prospective benefits rather than conclusions of the present case study. A practical New Zealand application would require HV-scale converter and cable models, modular multilevel converter studies, AC system strength assessment, grounding and insulation design, DC protection coordination, reliability analysis, economic assessment, staged conversion planning, and extensive electromagnetic transient and hardware validation.

The immediate research opportunities are therefore to scale the validated P2P model, incorporate realistic VSC control and current limiting, examine different converter topologies, and apply the method to multiple fault locations in an MTDC architecture. The resulting

framework could support protection design, equipment rating, planning studies, and future contributions to standards for converter-dominated DC systems.

4 Conclusion

Case Study 1 establishes the foundational framework for short-circuit modelling of a P2P DC link using advanced AFE-based VSC technology. The study was motivated by the shortcomings of conventional CSC-HVDC technology, including reactive power demand, reliance on a strong AC voltage for commutation, the risk of commutation failures, and challenges in supporting weak grid terminals and in enabling multi-terminal expansion. By contrast, VSC technology enables forced commutation, decoupled control of active and reactive power, robust operation with weak AC networks, and better scalability to multi-terminal configurations.

Since IEC 61660-1 does not explicitly define a source model for AFE-based VSC, this research proposes a complementary power-balance formulation for the converter, together with second-order ODE models for the DC-link capacitors. Comparison with IEC superposition and Simulink simulations yields peak-current agreement within approximately 0.4 %, with all three methods producing a capacitor-dominated peak of approximately 5.26 kA at 14 ms. This close agreement confirms that the proposed model is a transparent first step for protection and equipment rating.

The case study does not constitute a direct design for replacing New Zealand's existing HVDC link. Instead, it supplies an analytical foundation for investigating how a future AFE/VSC-based P2P scheme could be expanded into an MTDC backbone that integrates additional terminals, supports weak-grid regions, and enhances the overall flexibility, reliability, efficiency, and capacity of New Zealand's electricity grid.

5 References

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