Contingency Analysis of Embedded HVDC Lines Operating under AC Line Emulation Control Mode

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***Abstract*—The integration of embedded High-Voltage Direct Current (HVDC) links into AC-dominated grids offers new opportunities to improve transfer capability and reliability, but also raises operational challenges. This paper conducts a steady-state contingency analysis using a synthetic two-area equivalent model mapped to historical NYISO dispatch data to compare two HVDC control strategies: constant power dispatch and droop-based AC emulation. The results of the analysis show that while constant dispatch relieves AC stress, it can induce reverse flows and fails to adapt to varying dispatch conditions. AC emulation, on the contrary, dynamically adjusts transfers with phase angle differences, reducing angular stress, mitigating overloads, and improving resilience under N-1 and N-2 contingencies. However, the analysis also reveals that the HVDC AC emulation's droop tuning introduces trade-offs, as lowering the droop shifts stress onto the HVDC link itself, making the droop setting a complex optimization problem. These findings underscore both the benefits and limits of HVDC integration and provide insight for planning and operating reliable hybrid AC/DC systems.**

***Index Terms*—HVDC, AC Emulation, Contingency, Power Flow**

I. Introduction

A. Motivation

The goal of New York State of achieving 100% zero emission electricity by 2040, as outlined in the Climate Leadership and Community Protection Act (CLCPA), requires an expanded and efficient transmission infrastructure to support large-scale renewable integration. High-voltage direct current (HVDC) systems have emerged as a promising solution in this regard, due to their ability to transfer large amounts of power over long distances with lower losses and enhanced controllability compared to traditional AC systems [1]. Initiatives, such as the Clean Path NY project (recently terminated) and the Champlain Hudson Power Express (CHPE), proposed embedding HVDC lines within the AC transmission grid or interconnecting asynchronous regions to increase the delivery of renewable energy into densely populated load centers such as New York City [2], [3].

As these HVDC projects are integrated into the grid, understanding their impact on system reliability becomes critical. Although HVDC systems can improve power flow control and support clean energy targets under normal conditions, their behavior during contingencies, such as transmission line outages, must be well understood, particularly when they operate in parallel with AC lines. Because embedded HVDC lines can alter power flow paths, voltage angles, and other responses, there is a need to assess how these interactions play out under stressed conditions.

Contingency analysis allows one to evaluate system performance and identify potential vulnerabilities introduced by AC/DC hybrid interactions. For proposed infrastructure, such as Clean Path NY, where HVDC links are expected to operate in parallel with existing AC corridors, this type of analysis is particularly important to ensure grid stability, inform on the use of different HVDC operational control strategies, and guide future planning decisions. By investigating how HVDC links influence the system response to outages and other disruptions, planners can better anticipate operational challenges and reinforce the reliability of the evolving transmission network.

B. Previous and Related Works

HVDC lines have shown benefits in terms of increased transmission capacity and efficiency, particularly over long distances, while also contributing to a reduction in loading stress and losses on nearby transmission paths [4]. Several studies have discussed the advantages of integrating HVDC systems into existing transmission networks to improve power flow controllability, reduce congestion, and facilitate the integration of renewable energy [5], [6] .

Previous research in this area has focused mainly on constant power dispatch in HVDC lines [7]. However, recent work introduced advanced control strategies such as angle droop control, also known as AC line emulation, to mimic the behavior of conventional AC lines and improve grid stability [8], [9]. If more HVDC are embedded within AC grids that operate within a sychronous control area, the interactions between AC and DC systems under contingency will require additional attention. Advanced methods like AC line emulation control have the potential of enhancing the operational flexibility of embedded HVDC systems; however, careful analysis is required to address operational scenarios that may result in undesired power flow reversal and where AC line outages lead to AC transmission path degradation.

Despite recent advances, there remains a need to analyze the performance of such HVDC control strategies during N-1 and N-2 contingencies. Few studies have systematically assessed how embedded HVDC systems with droop control interact with surrounding AC lines [10]. In particular, limited

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attention has been paid to the analysis of trade-offs between HVDC support and AC network resilience.

This paper aims to bridge that gap by exploring how embedded HVDC links, operating under different control modes, influence system performance during transmission contingencies and by evaluating their role in enhancing grid reliability in real-world configurations like those considered in New York State.

C. Paper Contributions

The contributions of this paper are as follows.

- To compare power flow under two different HVDC control modes: standard dispatch and AC emulation with voltage angle droop control, using a synthetic two-area equivalent model mapped to historical NYISO data.
- To study the behavior of the hybrid AC/DC system in power reversal scenarios in different operating modes of HVDC
- To evaluate system performance in AC transmission path degradation (line outages) and highlight the critical importance of properly setting HVDC droop control to effectively manage overload risks.
- To analyze key questions such as: What advantages do embedded HVDC lines offer to power system operations? What considerations must grid operators account for during the planning and operation of embedded HVDC infrastructure?

II. Grid Modeling

The present study employs a synthetic two-area equivalent power system model with an embedded HVDC link operating in parallel with existing AC transmission corridors. This model is used to evaluate the performance of the HVDC in two operating modes: standard constant power dispatch and AC emulation control. To assess system resilience, the framework is further extended to include AC path degradation through N-1 and N-2 contingency scenarios, allowing a comparative analysis of how each HVDC control strategy manages transmission outages and supports overall grid reliability.

A. Grid Model With Data Integration

This study adapts the well-known "Two-Area" power system model [11] by extending with an embedded HVDC link as shown in Figure 1 where the model is integrated with dispatch scenarios to analyze the behavior of embedded HVDC systems [12]. The model has four identical AC tie-lines a-d (X=0.011pu, 276 MVA) and a HVDC line (R=0.052 Ω, 250 MVA). This allows to use the model to robustly assess the impacts of embedded HVDCs under different dispatch scenarios.

B. Standard Dispatch and AC Emulation Dispatch Modes

To investigate the operational characteristics of embedded HVDC systems, this study compares two distinct operational control strategies: the standard constant power dispatch mode and the AC line emulation mode based on angle-droop control. These modes govern how the HVDC link interacts with the surrounding AC grid and respond differently under varying load, generation, and contingency conditions.

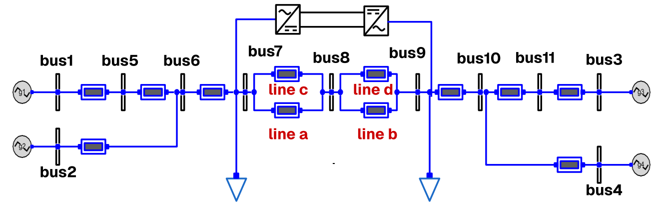

Fig. 1: Embedded HVDC link with two area model

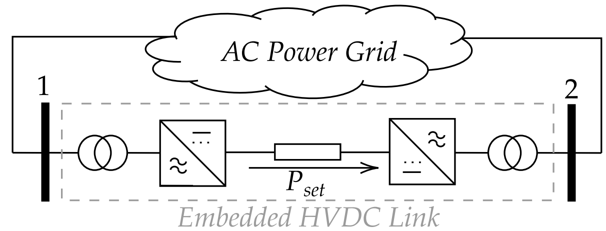

Fig. 2: Standard (Fixed P_{set}) HVDC dispatch

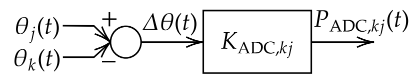

Fig. 3: AC line emulation controller

In the standard dispatch mode, the HVDC system operates at a fixed power set point as shown in Fig. 2, maintained by the converter controls. The rectifier regulates the DC current, while the inverter manages the DC voltage to deliver the scheduled power transfer. Meanwhile, the AC emulation mode enhances control flexibility and responsiveness by dynamically adjusting power transfer in response to the voltage angle difference between the HVDC link's AC terminals. This approach is implemented using a droop control law, which relates the power transfer to the difference in the phase angles of the connected AC buses [8]–[10]. Specifically, the active power injected by the HVDC link is governed by:

$$P_{ADC,kj}(t) = K_{ADC,kj} \cdot (\theta_j(t) - \theta_k(t)) \quad (1)$$

where $K_{ADC,kj}$ is the droop gain in MW/degree, and $\theta_j(t)$ and $\theta_k(t)$ represent the voltage phase angles on the respective terminal buses. This approach, as shown in Fig. 3, allows the HVDC link to mimic the behavior of a traditional AC transmission line, effectively acting as a 'virtual' AC line that participates in load sharing and support of angular stability.

III. Study Cases And Results

A. Study Cases

To evaluate the impact of embedded HVDC under different dispatch and contingency conditions, the following cases are defined:

A. Baseline system with only the AC corridor active, serving as the reference. No HVDC embedded.

B. AC corridor plus a parallel HVDC line operating in standard dispatch, where the HVDC maintains a fixed power dispatch setpoint.

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C. AC corridor plus HVDC under AC emulation, where droop control allows the HVDC to adjust the power transfers based on the phase angle differences.

B. *Power Flow Under Multiple HVDC Modes*

Using the cases defined in the previous Section, the sequel compares the performance of the system in terms of power transfer through the AC lines (buses 7–9) and the difference in voltage angle. The corresponding power system models are all configured with the total power transfer between areas remaining nearly identical (Fig. 4), which is expected since the overall transfer of the link line should remain consistent regardless of the control mode (to comply with market clearance).

In case A, the full burden of power transfer is placed on the AC lines, resulting in higher loading, as shown in Fig. 4, and a greater voltage angle difference between buses 7 and 9, as shown in Fig. 5, where the blue trace (Case A) shows peak angle differences exceeding 20 degrees during high-load periods. This is due to the lack of an alternative power path, leading to increased thermal and angular stress on the tie lines compared to the other two cases. In contrast, Case B introduces a parallel HVDC link operating at a fixed power set point. The HVDC power was chosen as half of the maximum AC connection capacity (210 MW), effectively offloading part of the load from the AC path (visible as the red and green traces for the AC and HVDC power, respectively, in Case B) as shown in Fig. 4. In addition, Fig. 5 shows that Case B (red) reduces AC flow through fixed HVDC support, which significantly reduces the angle difference. Case C further improves performance by adding an angle droop control to the HVDC link. The droop gain is initially calculated using 1, with the voltage angle difference during extreme transfer conditions as a reference. This allows the HVDC system to respond to load fluctuations as reflected in the angular difference between the receiving and sending AC buses, by adjusting its power transfer. The HVDC (yellow star) contribution is therefore no longer constant in Case C, providing flow balancing by reducing stress on the AC line (purple star) as shown in Fig. 4. This case achieves the best performance, and the voltage angle differences are effectively maintained as shown in Fig. 5. The droop-based adapts the power dispatch, which in turn helps in system condition, resulting in less variability in power flow and angle difference. Lower voltage angle differences are important for maintaining steady state stability, especially under stressed conditions, as they offer a larger margin before reaching practical stability thresholds $<< 90^{\circ}$.

C. *Power Reversal Scenario*

Examining the AC corridor across different HVDC modes reveals a crucial finding: when the HVDC link is assigned an intentionally high setpoint (~ 260 MW), exceeding the actual transfer requirement of the system for certain intervals, reverse power flow in the AC line is observed in Case B (Fixed HVDC Power Dispatch), as shown in Fig. 6 (red line). This occurs when the fixed power set point (P_{set}) exceeds

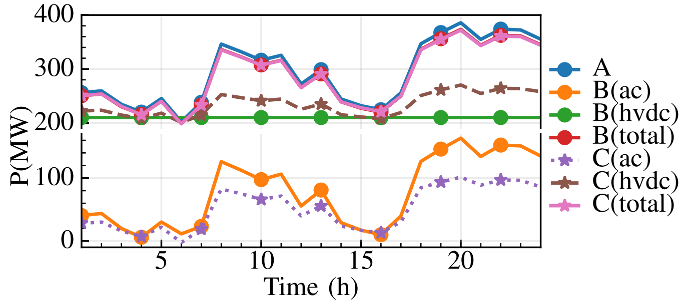

Fig. 4: Power flow through the tie lines for different modes

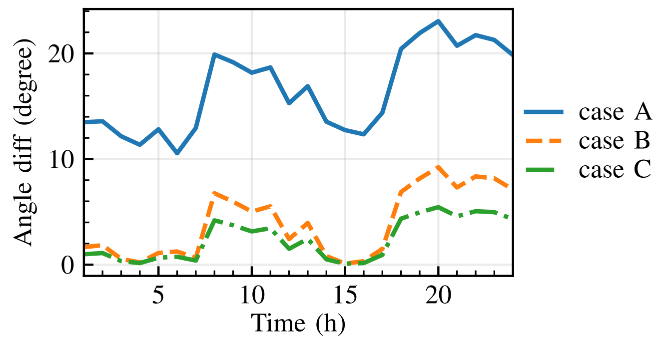

Fig. 5: Angle difference response under different modes

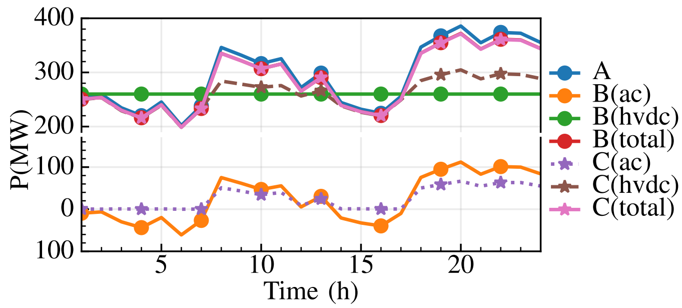

Fig. 6: Tie-line power flow under reversal scenario

the demand, causing the HVDC link to provide power, thus reversing the power flow of the AC corridor. This behavior not only reduces operational efficiency, but can also impose undesirable stress on the network.

Under such conditions, and in contrast to Case B, Case C (AC Emulation mode) can effectively mitigate this issue. As shown in Fig. 6 this control mode adapts the HVDC power transfer (yellow star) in response to the phase angle difference between the terminal buses, and the HVDC system ensures that the AC corridor flow (purple star) is consistent with the system requirements. In addition, this adaptive mechanism reduces unnecessary strain on the AC transmission path, as can be observed in Figs. 4-5.

D. *AC Transmission Path Degradation*

In this part of the analysis, the behavior of the hybrid AC/DC system is evaluated when subjected to contingency scenarios that involve outages $N-1$ and $N-2$ line outages. The objective is to understand the ability of the HVDC line to compensate for AC path degradation and the importance of proper controller settings, i.e. the droop for AC emulation mode.

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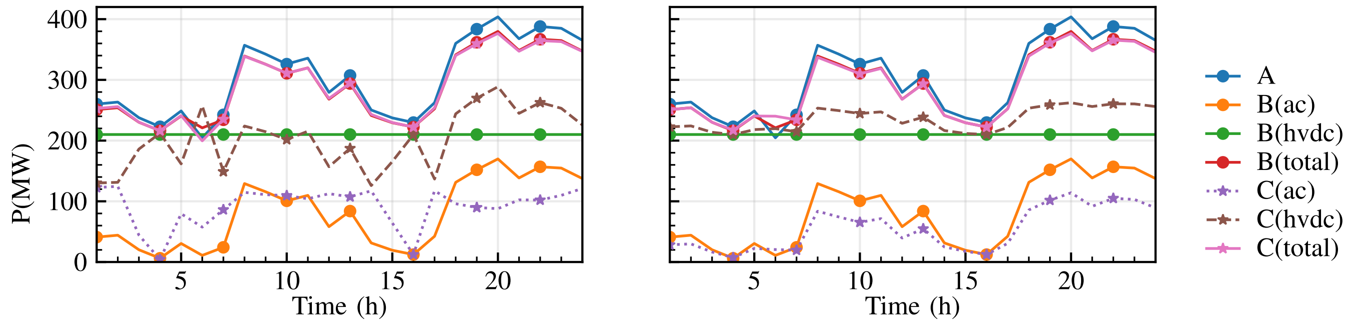
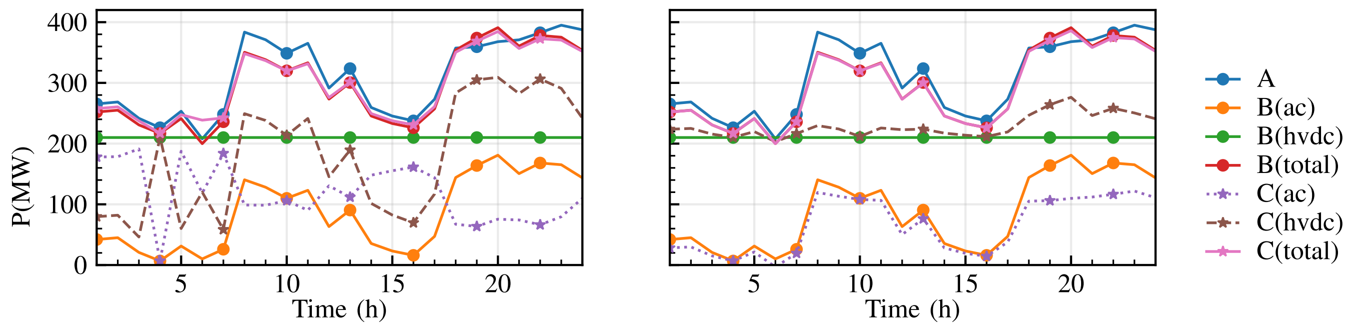


(a) with baseline droop (b) with tuned droop (0.75* baseline droop)

Fig. 7: Tie-line power flow under N-1 contingencies (post-contingency scenario)



(a) with baseline droop (b) with tuned droop (0.5* baseline droop)

Fig. 8: Tie-line power flow under N-2 contingencies (post-contingency scenario)

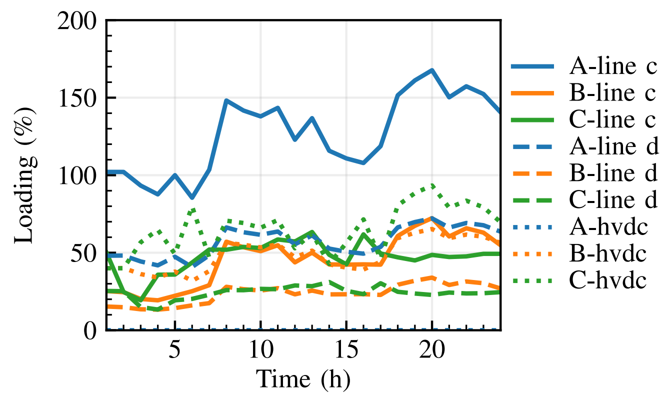


Fig. 9: Tie line loading percentage for N-1 contingencies

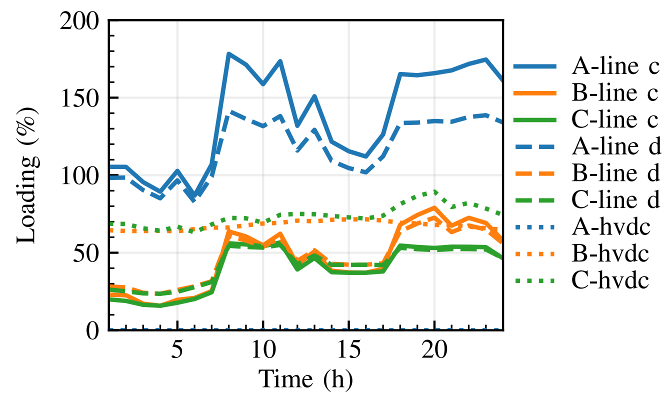


Fig. 10: Tie line loading percentage for N-2 contingencies

1) Effect of Droop Settings on System Performance: One of the crucial controller parameters in AC emulation is the droop value, which governs the power-angle sensitivity of the embedded HVDC. Two configurations are compared: baseline droop gain in MW/degree, $K_1 = 16.76$ (which is set considering the voltage angle difference over maximum power transfer for extreme case) and reduced droop ($K_2 = 0.75 \cdot K_1$ in $N{-}1$; $K_2 = 0.5 \cdot K_1$ in $N{-}2$).

As shown in Figs. 7 and 8, reducing the droop value results in a smooth power sharing between the AC and DC paths. Under both $N{-}1$ and $N{-}2$ conditions, the lower droop also reduces fluctuations in AC tie-line flows between Bus 7 and Bus 9. This reinforces the need for adaptive droop tuning, especially in response to line contingencies.

2) Contingency Scenarios: The $N{-}1$ scenario considers the removal of a single AC line (line a - bottom right to Bus 7 - in Fig. 1). This removal increases the burden on parallel paths, i.e. line c, which becomes critical for maintaining power transfer between two areas.

The results in Fig.9 show that, after the N-1 contingency is applied, without an HVDC link (Case A), line c becomes significantly overloaded, breaching thermal limits. This increases the risk of cascading failures. When the HVDC link is present in standard mode (Case B) or AC emulation mode (Case C), the stress on line c is considerably mitigated, maintaining loading within acceptable limits throughout the operational horizon.

In the $N{-}2$ case, both line a and line b (see Fig. 1) are removed, mimicking a more severe AC network degradation scenario. This imposes extreme stress on the remaining AC lines, i.e., lines c and d, which are now essential to maintain power flow across the network.

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The results in Fig. 10 show that Case A (no HVDC) leads to simultaneous overloading of both lines beyond 100% of their rated capacity. The introduction of the HVDC link again alleviates this stress. In both Case B and Case C, the loading in the remaining lines is reduced to safe operating ranges, although the HVDC line itself operates close to 100% during peak hours.

AC emulation provides limited incremental benefit under low-to-medium loading when the corridor is not constrained and angle separation remains small, whereas its advantages become apparent under high-load or stressed conditions (e.g., N-1/N-2 outages) where adaptive power sharing can mitigate AC overload risk and reduce flow volatility.

3) Trade-Offs and Operational Limits: From the prior analysis, it is evident that embedded HVDC links have the potential to enhance system resilience. Nevertheless, this comes with inherent limitations and necessitates careful consideration of specific trade-offs. As illustrated in Figs. 9 and 10, the HVDC link approaches its rated capacity in both scenarios. This indicates that reducing the droop parameter, although effective in relieving stress on AC lines, simultaneously increases the loading on the HVDC system. Consequently, the HVDC link itself may require redundancy to maintain reliability for credible contingencies. Therefore, determining the appropriate droop setting is not just a tuning exercise, but is intrinsically a complex optimization problem, requiring a balance between reducing AC corridor stress and avoiding excessive HVDC loading.

This highlights the need for routine engineering processes, including droop gain tuning, headroom allocation at converter stations, and reliability studies that account for N-1 conditions to avoid HVDC overload. Once HVDC assets are built, appropriate market mechanisms must be established to incentivize operators to maintain headroom. In the absence of such mechanisms, HVDC owners may choose to maximize transfers at the expense of contingency readiness. In addition, compensation mechanisms for HVDC services must strike a balance between fixed transfers and system-supportive operation. Borrowing approaches from ancillary service markets may be useful, but care must be taken to avoid incentives that favor only static operation.

E. Overloading Considerations

As discussed in Section IIID, reducing droop can relieve AC corridor loading variability, but this simultaneously increases the loading burden on the HVDC link, which approaches rated capacity under severe contingencies. This AC relief vs. HVDC stress trade-off reinforces that droop selection is an operational optimization problem, balancing corridor relief against converter headroom and redundancy; rather than a purely local controller-tuning task.

IV. Conclusions

This study demonstrates that embedded HVDC links can improve the operational resilience of the hybrid AC / DC system, but their effectiveness depends on the chosen control strategy. The comparative analysis shows that while constant dispatch can relieve AC stress (as long as the dispatch setpoints are properly set), AC emulation allows dynamically to adjust transfers providing other additional benefits that improve steady-state stability and avoid potential reverse flows in AC transmission paths. Under contingency conditions, HVDC support proved essential in mitigating overloads; however, droop tuning introduces trade-offs between relieving AC corridors and stressing HVDC capacity, making droop setting itself an optimization challenge. These findings highlight the need for new coordinated planning, sufficient redundancy of AC or DC lines, and potentially a market mechanism to fully harness the reliability benefits of embedding HVDC links in existing AC networks.

These findings raise practical issues requiring further analysis. Key questions include how to quantify whether AC emulation reduces effective HVDC utilization in normal operation when contingency headroom must be preserved, and how AC emulation can support a security-oriented framework that relieves AC corridor stress and mitigates undesirable flow patterns rather than maximizing throughput. This demands a routine process to compute and deploy the AC emulation gains K_{ADC}, adding operational planning complexity that system operators must address. It also requires methods to benchmark AC emulation against alternatives such as adaptive P_{ref} scheduling and/or gain scheduling, to determine where each is preferable in terms of robustness, headroom management, and flow controllability. Moving forward, future research should extend this work to include dynamic models and simulations that capture transient phenomena and system stability under disturbances [10].

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