Indonesian Journal of Electrical Engineering and Computer Science
Vol. 40, No. 1, October 2025, pp. 1~9
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v40.i1.pp1-9

Enhancing small-signal stability in high-voltage DC systems: supplementary controls for damping inter-area oscillations

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Article Info

Article history:

Received Jan 5, 2025
Revised Apr 24, 2025
Accepted Jul 3, 2025

Keywords:

HVAC
LD-HVDC
RES
Small-signal distrurbances
Two-area four-machine system (Kundur Model)

ABSTRACT

High voltage direct current (HVDC) transmission systems have emerged as a leading technology for efficient and cost-effective long-distance power transmission, offering significant advantages over traditional high voltage alternating current (HVAC) systems. These benefits include seamless integration of asynchronous grids and renewable energy sources (RES), enhancing the reliability of power supply. However, the dynamic behavior of HVDC systems and their ability to maintain stability under small disturbances introduce challenges to overall system stability.To address these challenges, this study focuses on improving small-signal stability in HVDC systems by exploring supplementary control strategies for damping interarea power oscillations.The proposed strategy was tested using the kundur two-area four-machine (K-TAFM) system modeled in power systems computer-aided design (PSCAD), incorporating case study under a three-phase-to-ground fault scenario.The active power imbalance and inter-area oscillations observed during fault conditions highlight the critical need for advanced stability enhancement techniques to effectively mitigate small-signal disturbances. This approach significantly improved the small-signal stability of the HVDC system, underscoring its potential to enhance the reliability and resilience of modern power grids.

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1. INTRODUCTION

High voltage direct current (HVDC) transmission serves as the “Electrical Superhighway” of modern power systems, offering significant advantages over traditional high voltage alternating current (HVAC) transmission systems. HVDC technology efficiently transmits large amounts of electrical power over long distances via overhead lines and submarine cables, overcoming geographical challenges with ease, compared to HVAC, HVDC provides superior voltage regulation, lower transmission costs, and reduced power losses, making it particularly advantageous for long-distance power transfer. Additionally, HVDC systems play a crucial role in integrating diverse power grids and facilitating the seamless incorporation of renewable energy sources (RES) into the energy mix. The architecture of HVDC systems include power converters, advanced controllers, and voltage regulation components designed to ensure reliable and stable power transmission. This study highlights the critical importance of addressing small-signal stability challenges in HVDC transmission systems. Through the implementation of supplementary control strategies, specifically the power oscillation damping (POD) controller integrated into an line commutated converter (LCC)-HVDC system, the research effectively mitigates stability issues arising from active power imbalances and inter-area oscillations under fault conditions. Using the kundur two-area four-machine (K-TAFM) system modeled in power systems computer-aided design (PSCAD), the proposed approach significantly enhances system stability, particularly during three-phase-to-ground fault scenarios.

However, the dynamic characteristics of the power system and the impact of small-signal disturbances pose challenges to maintaining HVDC system stability [1]. Enhancing small-signal stability through the implementation of supplementary control strategies is vital for achieving optimal and reliable HVDC operation. The small-signal stability of an HVDC transmission system refers to its ability to maintain stable operation in the presence of minor power system disturbances. This requires developing a small-signal stability model for the entire system, incorporating variations in current injection into transmission lines. Such models are essential for evaluating control strategies under both small and large disturbances. Small-signal stability models are typically linear state-space representations that capture the dynamic behavior of the system, aiding in the design and refinement of control strategies. Significant research has been conducted in this area, particularly in designing converters based on small-signal stability analysis. For instance, the authors utilize linear state-space models to represent HVDC systems and FACTS devices [2], [3]. The nonlinearity of HVDC systems arises primarily from the firing actions of converter switches, which introduce frequency variations on both AC and DC sides. These models also incorporate subsystems such as converters, which handle time-variant frequency conversion, AC voltage and current regulation, and parameters of phase-locked loop (PLL)-based switching angle control. This detailed modeling approach simplifies system formulation while accurately capturing the dynamic characteristics of converters. By doing so, these models surpass traditional quasi-state models, offering a more precise representation of HVDC system dynamics [4].

A VSC-HVDC system with modular multilevel converters (MMC) connected to an AC network and operating in external grid connection mode has been studied to analyze its small-signal stability characteristics, focusing on the effects of control strategies on reactive power compensation and voltage stability. The study explored control methods such as reactive power control, AC voltage control, remote bus voltage control, and AC voltage droop control, considering the influence of the short circuit ratio (SCR). The SCR significantly impacts system performance depending on the converter control strategies employed. For instance, AC voltage control with low SCR improves stability but can weaken the least-damped mode. Increased AC line length and low active power flow enhance the converter’s active power control and zero-energy sum control [5]-[8]. Additionally, the impact of power flow direction on system stability was analyzed using the impedance method, where the load impedance to current source impedance ratio (modeled as Norton equivalent parallel impedance) was used. Stable operation was observed when power flowed from the power-controlled converter to the DC voltage converter; instability occurred in the reverse direction.

The role of supplementary control systems in improving the small-signal stability of multi-infeed HVDC transmission systems was systematically reviewed in [9]. This study analyzed the linearized integrated models of LCC-HVDC and VSC-HVDC networks connected to AC systems. Control parameters highly sensitive to small-signal stability, particularly under the least-damped mode, were identified. Key factors include the PLL proportional gains at both stations, the AC voltage controller parameters in the VSC outer loop, and PLL settings for the LCC station. The findings suggest that maintaining lower PLL gains at both stations and in the VSC station’s AC voltage controller improves stability by efficiently damping oscillations. For enhancing power transfer capabilities, series capacitors are often employed in HVDC systems. However, they introduce sub-synchronous resonance, adversely affecting reliable transmission by impacting the turbo generator torque. Additionally, DC link control signals can lead to sub-synchronous oscillations. To address these challenges, [10] proposed a time-domain-based multimodal damping controller integrated with a power system stabilizer (PSS). The controller effectively damped torsional and inertial mode oscillations using test signal injection and phase correction methods. Torque phase differences were used to optimize the firing angle for compensation, ensuring improved stability and damping performance. An optimized control approach for improving the small-signal stability of VSC-based HVDC systems is presented in [11]. This method involves the development of a damping controller with finely tuned control signals to mitigate small-signal oscillations on the AC side. The proposed damping control integrates AC internal and external loop control of VSCs with DC PLL control. By evaluating the controller’s state-space model, the study identified the adverse effects of control gain parameters and the active damper gain of outer loop PI controllers on system stability. These parameters were optimized to enhance small-signal stability and reduce high-frequency oscillations. Seshu *et al.* [12], two supplementary control methods-modulation-based active power injection control (P-WAF) and reactive power injection control (Q-WAF) are proposed for small-signal stability enhancement. These methods utilize frequency signals for electromagnetic damping under both small and large disturbances. The effectiveness of these control strategies was demonstrated using the Nordic 32A test system, highlighting their capability not only to improve transient stability but also to damp interarea oscillations. A DC frequency controller based on extension theory was introduced in [13].

This controller adapts to various signal magnitudes and speeds of frequency change, employing flexible calculation methods for efficient modulation of DC power. It maintains active and reactive power balance in the HVDC system and was validated using a time-domain model of a four-machine two-area system, achieving superior performance outcomes.

Voltage stability analysis is further refined in [14], which introduce the voltage stability correlation ratio (VSCR) to study systems with multi-infeed HVDC configurations. The analysis demonstrated that HVDC converters significantly influence voltage stability, with stronger correlation ratios observed on the inverter side compared to the rectifier side. Additionally, [15] systematically analyzed supplementary damping controls for managing interarea oscillations in multi-terminal HVDC MTDC systems. The study highlighted improved damping of interarea oscillations when MTDC systems were implemented, particularly in scenarios involving AC and DC faults. Previous research has underscored the challenges posed by small-signal stability in HVDC systems, including sub-synchronous oscillations resulting from insufficient synchronization and damping effects. These issues hinder fast fault recognition and response, underscoring the need for effective damping controllers to ensure secure system operation. POD controllers, particularly when combined with supplementary control loops, significantly enhance the stability and reliability of power systems.

This paper builds on earlier studies [16], [17] by addressing the limitations of HVDC control systems through detailed small-signal stability analysis and the development of an efficient supplementary controller. Specifically, a POD controller integrated into an LCC-HVDC system was designed to mitigate small-signal disturbances and enhance overall system stability. Using the K-TAFM system as a case study, this research evaluated the small-signal stability of HVDC systems under three scenarios. The results demonstrate that the integration of the POD controller with LCC-HVDC significantly improves stability and reliability, providing a robust solution for high-voltage DC transmission systems. This research builds on extensive prior work focused on HVDC system stability and control. Earlier studies have explored various control methods, including state-space modeling and advanced converter design, to enhance small-signal stability. The current study advances this knowledge by integrating a POD controller tailored for LCC-HVDC systems and conducting detailed stability analysis using the K-TAFM system. By addressing the limitations identified in prior research, such as sub-synchronous oscillations and the need for more effective damping mechanisms, this study provides a robust solution for maintaining stable power transmission in interconnected grids.

2. METHODOLOGY

The primary contribution of this study is the analysis of small-signal stability in HVDC transmission systems, with a focus on the role of supplementary control systems. HVDC technology is highly effective for long-distance power transmission and offers precise control over transmitted power, significantly influencing synchronization and damping to mitigate disturbances on the AC network side [18], [19]. While PSS and automatic voltage regulators (AVR) are commonly employed on the AC side to suppress oscillations, the integration of supplementary controllers on the DC side provides a more robust approach to enhancing overall system stability. These supplementary controllers are particularly effective in damping power system oscillations, including local sub-synchronous oscillations and low-frequency inter area oscillations, which arise during small-signal disturbances. The design of supplementary controllers for HVDC systems is essential to enhance the overall performance of both AC and DC networks. The stability analysis was performed for K-TAFM system without monopolar LCC-based HVDC transmission link.

2.1. Fundamental theory and background

The K-TAFM system is commonly used as a benchmark model to analyze the dynamics and stability of power systems, particularly with regard to interarea oscillations. This system consists of two interconnected areas, each containing a synchronous generator. Figure 1 illustrates a simplified two-area network, where each area features incoherent machines with generator inertias denoted as H_A and H_B. The rotor angles δ_A and δ_B correspond to the oscillations of Area-1 and Area-2, respectively, each operating at different frequencies and amplitudes [20].

The initial focus is on analyzing the inertia swings of the synchronous machines to calculate the necessary damping coefficients required to effectively suppress power system oscillations. This ensures that the system maintains sufficient torque for stable frequency control and reliable operation across the interconnected areas. These coefficients help regulate the rate at which the oscillations decay, preventing sustained or growing disturbances that could compromise system reliability. By carefully calculating and tuning these damping parameters, the power system ensures sufficient torque is maintained for stable frequency control, enabling the coordinated and reliable operation of interconnected regions. This approach not only improves the overall resilience of the power network but also enhances the efficiency of power delivery across the system.

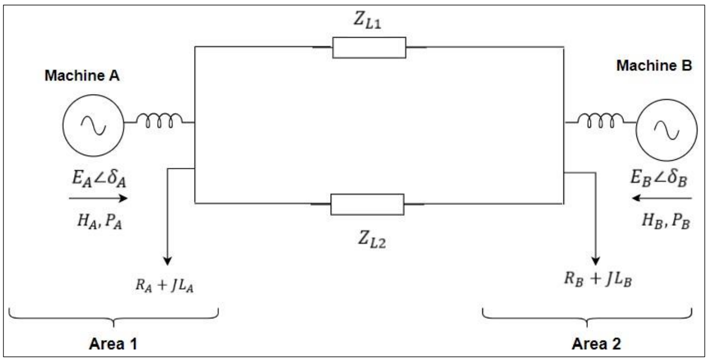

Figure 1. Basic two area machine system

2.2. K-TAFM system model

The K-TAFM system is used in this study to evaluate power system stability. Developed in PSCAD, the K-TAFM model offers a simplified yet effective representation of interconnected power systems, making it ideal for analyzing inter-area oscillations and stability issues. The system consists of two areas, each containing two coupled units rated at 900 MVA and 20 kV, connected by a weak tie. The standard K-TAFM configuration includes two areas linked by two parallel transmission lines. Each area consists of four buses, which include two generator buses and two load buses. This symmetrical setup is designed to support the analysis of dynamic performance in two areas with well-defined electrical and mechanical characteristics. In the first area, the synchronous generators are denoted as G1 and G2, while in the second area, they are represented as G3 and G4, as shown in Figure 2. Each area is equipped with a constant impedance load corresponding to its respective demand. The parallel transmission lines facilitate power exchange between the two areas and influence inter-area oscillations [21], [22]. To ensure the system's stability and reliability, the network is equipped with various control and protection systems. The excitation system for all four synchronous generators incorporates AVR, which control the generators' terminal voltage. Additionally, PSS are implemented with each generator to dampen electro mechanical oscillations and enhance overall system stability. The parameters of the generators, based on the rated MVA and kV, are provided in Table 1.

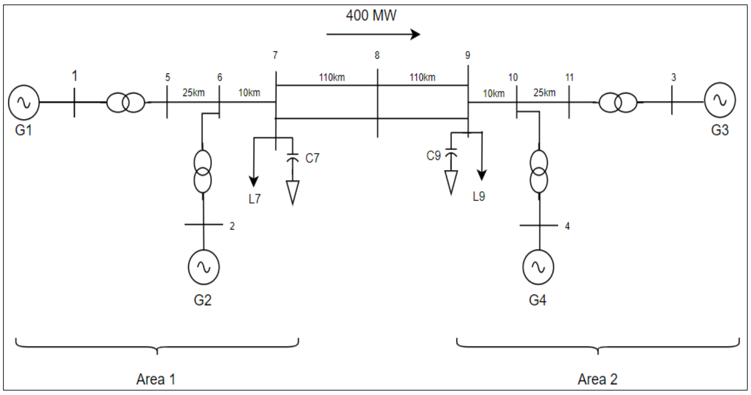

Figure 2. Kundur two-area four-machine system

Table 1. Generator parameters (per unit)

Parameters	Values
X_d	1.75
$X_{d''}$	0.22
X_q	1.68
X_l	0.25
$X_{d'}$	0.33
$X_{q'}$	0.56
R_a	0.0027
H_{A1}	5.9 (for G1 and G2)
H_{A2}	6.0 (for G3 and G4)
K_D	0.0

In the K-TAFM system, each step-up transformer has an impedance of 0 + j 0.15 Ω based on a 900 MVA and 20/230 kV base, with an off-nominal ratio of 1.0. The nominal voltage of the transmission system is 230 kV. The line parameters are given as: r = 0.0001 pu/km; x_L = 0.001 pu/km; b_c = 0.00175 pu/km. The HVDC system operates across two distinct areas with the following power generation values for the various generators as shown in Table 2.

Table 2. power generated by the generators

Generators	P (MW)	Q (MVAr)	Et (per unit, angle)
G_1	700	184	1.03 ∠ 20.3°
G_2	700	233	1.01 ∠ 10.7°
G_3	720	175	1.03 ∠ -6.6°
G_4	700	200	1.01 ∠ -16.0°

All generators (G1, G2, G3, and G4) are controlled under manual excitation, and the eigenvalues of the system are computed to assess its small-signal performance. These eigenvalues are used to determine the system frequency, damping ratio, and oscillatory modes. The eigenvalues, along with frequency and damping ratio, are calculated when all four generators are equipped with a thyristor excitation system and PSS, as specified in Table 3 and Figure 3.

Table 3. Eigen value

Parameters	Values
K_A	200
T_R	0.01
T_W	10
K_{STAB}	20
T_1	0.05
T_2	0.502
T_3	3
T_4	5.4

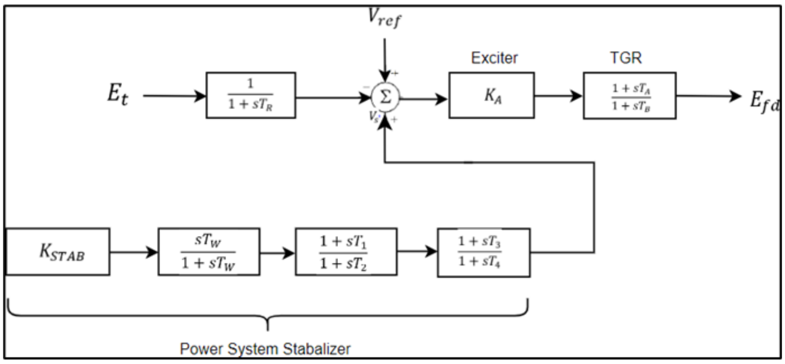

Figure 3. Thyristor excitation system with PSS

2.3. LCC BASED HVDC MODEL

The research focuses on a 200 MW LCC-based HVDC system. The system operates at a voltage rating of 56 kV and a current of 3.6 kA. It employs 12-pulse converters for both the rectifier and inverter stages. The DC line has a resistance of 1.1 Ω and an inductance of 100 mH. Key parameters of the DC line include a resistance of 1.1 Ω and an inductance of 100 mH, while the commutating reactance (XC)for each converter is 0.57 Ω. To enhance system stability, a 50 mH smoothing reactor is incorporated at both terminals. In the system layout, the AC line connecting bus 7 and bus 9 is substituted with the LCC HVDC line, as illustrated in Figure 4 [23]-[25].

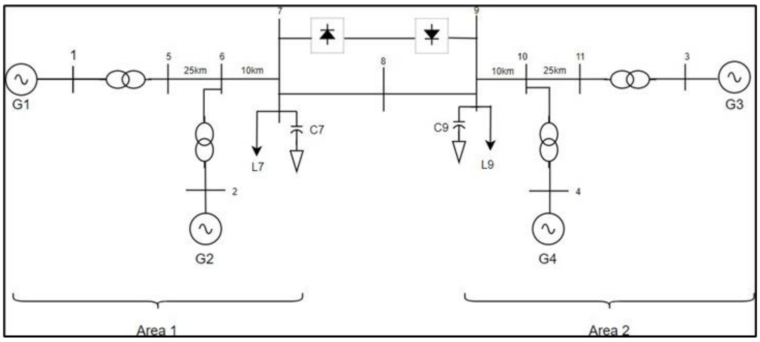

Figure 4. K-TAFM with LCC based HVDC Line

3. RESULTS AND DISCUSSION

This research evaluates the small-signal stability of the LCC-based HVDC transmission system to enhance system stability by mitigating targeted inter-area oscillations. The study aims to enhance overall system stability by effectively mitigating targeted inter-area oscillations, a critical challenge in interconnected power networks. These oscillations, if not properly damped, can lead to system instability and reduced operational reliability. To address this, detailed simulations are carried out using the PSCAD software, which provides an accurate and high-fidelity environment for modeling and analyzing complex power system dynamics. The simulations are conducted based on a carefully designed case study that captures real-world operating conditions and disturbance scenarios, ensuring the results are both practical and applicable. Through this approach, the research provides valuable insights into the behavior of LCC-based HVDC systems and offers strategies to improve their contribution to inter-area stability and robust system performance.

This case study analyzes the base K-TAFM system without incorporating any additional models. The objective is to examine the inherent functional characteristics of the original system under standard operating conditions. Figure 4 illustrates the simulation model of the K-TAFM system. This base case evaluation provides valuable insights into potential areas for stability enhancement and offered a baseline for assessing system performance following modifications. To test system stability, a three-phase-to-ground fault is applied on transmission line 4 between bus 7 and bus 8 at 1.5 seconds into the simulation. The system successfully cleares the fault within 100 milliseconds, demonstrating stable operation under pre-fault conditions. During the fault period, the power output of the four synchronous generators, as shown in Figure 5, is analyzed. It is observed that the power generation from generators 1 and 3 droppes to zero due to their proximity to the fault location. Meanwhile, generators 2 and 4 experience a reduction in active power output. This analysis confirmes the system’s12 ability to maintain stability post-fault clearance.

Following the clearance of the fault, the reduction in active power output from generators 2 and 4 results in a compensatory increase in the active power of generators 1 and 3, which reaches 850 MW to restore balance and address inter-area oscillations. This active power imbalance impacts the Two-Area system, inducing inter-area oscillations as shown in Figure 6. These oscillations initially peak at 540 MW, accounting for 35% of thesteady-state power at the onset of the fault. Over time, the oscillations gradually diminish, albeit at a slow rate as the simulation progress.

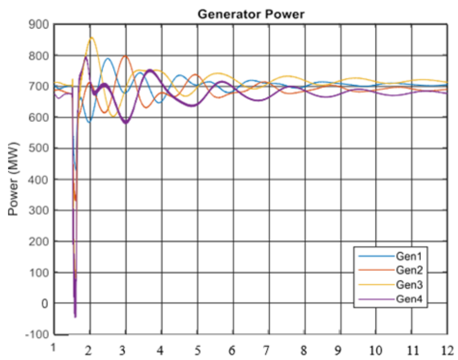

Figure 5. Active power generation of four generators under 3 phase to ground fault

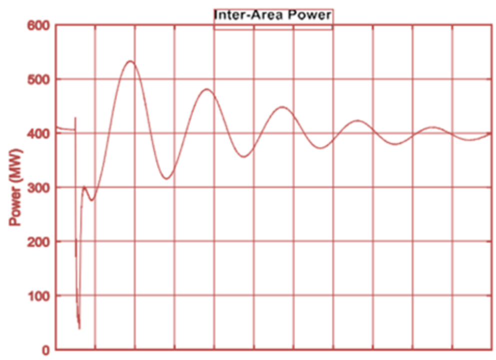

Figure 6. Interarea power transfer between two area

The results of the case study highlight the need for enhanced damping mechanisms to effectively suppress inter-area power oscillations. The findings emphasize the significant impact of fault conditions on active power generation. The observed active power imbalance and inter-area oscillations during the fault condition underscore the necessity for advanced stability improvement techniques to mitigate such small-signal disturbances.

4. POTENTIAL FUTURE RESEARCH

Future research in this area could be oriented towards exploring several promising directions to further enhance the stability and reliability of HVDC transmission systems. One key avenue is the development of adaptive control strategies that can respond dynamically to changing grid conditions and unexpected fault scenarios, enabling more resilient and flexible system performance. Another important area of investigation is the impact of integrating RES, such as wind and solar power, on the small-signal stability of HVDC systems, given their intermittent and variable nature. Additionally, extending the scope of study to MTDC systems would provide deeper insights into stability challenges and control requirements across larger, more complex interconnected networks. This would help address the growing demand for efficient cross-regional power exchange. Furthermore, the application of machine learning and artificial intelligence techniques offers significant potential for real-time stability prediction and control optimization, allowing for faster and more accurate decision-making in maintaining system balance and preventing instability. Together, these research directions would pave the way for more robust and future-ready HVDC systems in modern power grids.

5. CONCLUSION

This study demonstrates the importance of addressing small-signal stability challenges in HVDC transmission systems to enhance the reliability and resilience of modern power grids. Through the implementation of supplementary control strategies aimed at damping inter-area power oscillations, the proposed approach effectively mitigated stability issues arising from active power imbalances and inter-area oscillations under fault conditions. The results, obtained using the K-TAFM system modeled in PSCAD, show that the proposed control strategy significantly improves system stability, particularly during a three-phase-to-ground fault scenario. These findings emphasize the critical role of advanced stability enhancement techniques in ensuring the robust operation of HVDC systems, particularly in the context of integrating RES and asynchronous grids. Overall, the study highlights the potential of the proposed methods to strengthen the reliability of long-distance power transmission networks. This study underscores the importance of advanced stability enhancement techniques in ensuring the robust and reliable operation of HVDC transmission systems. By demonstrating the effectiveness of supplementary control strategies, the research provides a practical framework for mitigating small-signal disturbances and enhancing grid resilience. These findings have significant implications for the future development of stable, long-distance power transmission networks, particularly in the context of integrating diverse and RES.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Siddharthsingh K. Chauhan	✓	✓	✓	✓		✓		✓	✓	✓	✓		✓	
Vineeta S. Chauhan		✓				✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

When papers talk about using people or animals, authors should make it clear that the research followed all national rules and institutional policies, and it was approved by the authors' institutional review board or a similar committee. The Helsinki Declaration's tenets must guide all investigations involving human subjects. Authors must also identify the committee or review board approving the experiments and provide a statement indicating approval of the research. Incorporate the following (or a similar) statement: The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee; or: The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [Vineeta S. Chauhan].

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