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Impact of Solar PV and Wind Penetration on Dynamic Performance of VSC-MT-HVDC Systems

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The rapid growth of renewable energy sources such as photovoltaic (PV) and wind energy is transforming modern power systems by introducing variable and distributed generation into transmission networks. Since these resources are often located far from load centers, flexible and efficient transmission technologies are required. Voltage-Source-Converter-based Multi-Terminal High-Voltage Direct-Current (VSC-MT-HVDC) systems provide a promising solution due to their fast dynamic response, independent active and reactive power control, improved power quality, and enhanced flexibility compared with conventional HVAC transmission. This paper investigates the impact of solar PV and wind penetration on the dynamic performance of a VSC-MT-HVDC system. A four-terminal, 1000 MW, 525 kV bipolar HVDC network with a 600 km transmission corridor was developed in MATLAB/Simulink by integrating renewable generation sources and decentralized DC voltage droop control. The proposed system was evaluated under variations in renewable penetration and representative fault conditions including DC pole-to-pole, DC pole-to-ground, and AC-side faults. The results demonstrate that the system maintains stable operation under renewable variability, with the post-fault DC voltage recovering to approximately 524.358 kV. The AC-side harmonic performance remained within acceptable limits, with a maximum total harmonic distortion (THD) of 1.126%. Furthermore, the VSC-MT-HVDC configuration achieved a transmission loss of approximately 5.6 MW, compared with 12.7 MW for an equivalent HVAC system over the same 600 km corridor, representing a reduction of around 55.9% in transmission losses. The findings confirm that properly coordinated droop control and protection strategies enable reliable integration of high renewable penetration while maintaining voltage stability, power quality, and transmission efficiency. These results highlight the suitability of VSC-MT-HVDC systems for future renewable-rich power networks.

Keywords: VSC-HVDC, Multi-Terminal HVDC, Renewable Energy Integration, Solar PV, Wind Power, Droop Control, Dynamic Stability, Fault Response, Power Quality.

Introduction:

The global transition towards sustainable energy has hastened the utilization of renewable energy sources such as solar photovoltaic (PV) and wind power. These technologies are clean, scalable, and increasingly cost-effective; however, they are associated with several operational challenges Solar and wind generation are variable and are often located at far distances from load centers, which increases the need for flexible and efficient transmission systems [1][2]. Conventional HVAC transmission has long been the predominant approach for bulk power transfer, but it becomes less suitable for long-distance renewable delivery due to reactive power losses, voltage constraints and limited controllability [3].

Voltage-source converter based High-voltage direct current (VSC-HVDC) transmission has therefore become a striking alternative. Compared with conventional HVAC transmission, VSC-HVDC offers fast dynamic response, independent regulation of active and reactive power, improved compatibility with weak AC systems and better performance for remote renewable integration [4][5]. These advantages are especially valuable in multi terminal HVDC systems where numerous converter stations can exchange power through a shared DC network [6][7].

The use of Modular Multi-level Converters (MMCs) has further enhanced the practical feasibility of modern HVDC systems. MMCs provide high efficiency, low harmonic distortion and scalable voltage operation making them extremely suitable for high-power renewable transmission applications [8][9]. However, integrating solar PV and wind generation into an MT-HVDC network introduces new dynamic challenges, including voltage fluctuations, power imbalance and fault sensitivity [10][11]. Therefore, considering the influence of renewable penetration on dynamic performance of VSC-MT-HVDC systems is essential for ensuring reliable and resilient future power networks.

The research inspects the effect of solar PV and wind penetration on the dynamic stability, power sharing quality, fault response and transmission efficiency of a VSC-MT-HVDC system. The analysis is based on simulation model developed in MATLAB/Simulink that mirrors the main characteristics of this thesis work, including a 4-terminal, 1000 MW, 525 kV, bipolar HVDC network over a 600 km transmission line with integrated solar PV and wind generation terminals.

Problem Statement:

Remote solar PV and wind injection adds variability and changes power flows in multi-terminal VSC-HVDC networks; a focused, scenario-based assessment of how combined renewable penetration affects DC voltage regulation, transient recovery, power sharing, THD, protection interaction, and long-distance efficiency is lacking.

Novelty:

Evaluates combined solar wind penetration in a 4-terminal VSC-MT-HVDC setup.

Shows interaction between decentralized droop control and graded protection under variable renewable injection.

Provides a direct HVDC vs HVAC loss comparison for a 600 km renewable transmission corridor.

Aims and Objectives:

Aim: Quantify how solar PV and wind penetration affect the dynamic performance of a VSC-MT-HVDC system and derive control/protection guidance.

Objectives:

Model a 4-terminal, 1000 MW, 525 kV VSC-MT-HVDC network with MMCs and renewable injection.

Implement decentralized DC droop control and graded protection.

Run scenarios varying solar/wind penetration and apply representative faults.

Measure DC voltage deviation/recovery, power sharing, THD, and corridor losses.

Compare HVDC and HVAC performance and recommend droop/protection tuning.

Literature Review:

The literature on HVDC transmission has evolved significantly over past decades. Early work established the technical basis for DC transmission as an efficient method for long distance power transfer and asynchronous interconnection [3]. With the emergence of VSC technology, HVDC systems became more flexible and controllable, which made them suitable for renewable-rich power grids [4][5].

Modern studies have shown that VSC-HVDC provides strong benefits over HVAC for long-distance transmission and offshore renewable integration [12][13]. In particular, VSC-HVDC allows independent control of active and reactive power, which recovers grid support and power quality. Its applicability is further reinforced when combined with modular multi-level converters (MMCs), which lessen switching harmonics and improve controllability at high voltage levels [8][9].

The growth of multi-terminal HVDC systems has attracted considerable attention because these networks can connect multiple generation and load points through a shared DC grid. MT-HVDC systems are especially pertinent for integrating geographically dispersed renewable sources such as offshore wind farms and remote solar plants [6][7]. The literature also suggests that decentralized control strategies, especially droop-based methods, are effective for maintaining DC voltage and power sharing without relying on continuous communication between networks [14][15].

Protection and fault handling are also key areas of research in HVDC systems. Because DC systems are more susceptible to faults than AC systems, protection coordination is critical for maintaining stability under abnormal conditions [16][17]. Recent work has highlighted the need for robust protection schemes in MMC-HVDC and multi-terminal grids, particularly when renewable sources are connected and generation profile is variable [18][19].

Effect of renewable penetration on power-system stability has also been studied extensively. Wind and solar integration can increase variability, create power imbalance, and effect dynamic response [20][21]. Nevertheless, literature shows that VSC-HVDC systems can manage these effects more effectively than HVAC systems, especially in long-distance transmission applications [22][23]. The current study contributes to this body of work by focusing especially on dynamic interaction between solar PV and wind generation within a VSC-MT-HVDC network.

Methodology:

This study uses simulation to investigate how solar PV and wind generation affect the performance of a VSC-MT-HVDC system. The research is based on a model made with MATLAB/Simulink, where a network with four terminals, a capacity of 1000 MW, and a voltage level of 525 kV is developed over a 600-kilometer transmission line. The main goal is to design the system and see how it works when we add solar panels and wind turbines and how this affects the system's ability to handle sudden changes, keep the voltage stable, share power, keep the power quality good and reduce transmission losses.

The proposed network is, like a grid where each terminal is connected through special stations and transmission lines. The part of the system that uses electricity is represented by simple sources, network impedances and load conditions while the part that uses direct current is used to see how solar panels and wind turbines affect the whole network. Solar panels and wind turbines are added to some terminals as power sources to make the simulation more realistic. The goal is to compare system performance under different operating conditions and determine whether stability is maintained as solar PV and wind penetration increases.

To analyze the effect of renewable variability, the study uses multiple operating scenarios. A base case is first established under nominal conditions. Then, additional cases are created by increasing the contribution of solar PV and wind generation at the terminals. In each case, the system is observed for changes in active power flow, DC voltage deviation, terminal power sharing, and transient recovery. This approach directly supports the title of the paper because it examines how renewable penetration influences the actual dynamic behavior of the VSC-MT-HVDC system rather than only validating the basic operation of the network. Figure 1 shows the PV module designed in MATLAB/Simulink.

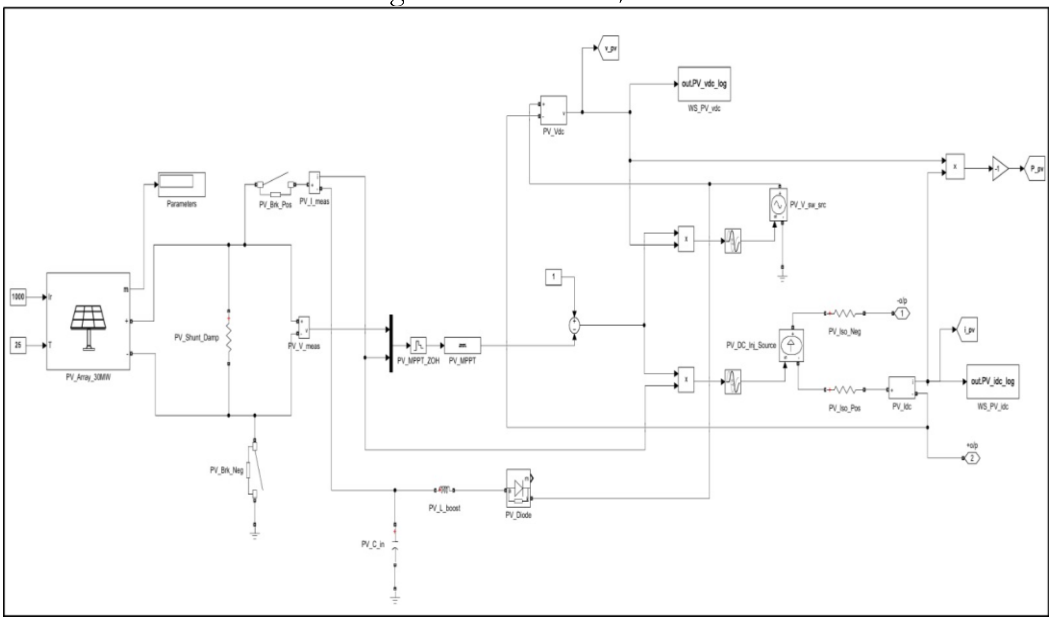

Figure 1. Connections and working of solar photovoltaic

Figure 2 shows wind generation in MATLAB/Simulink.

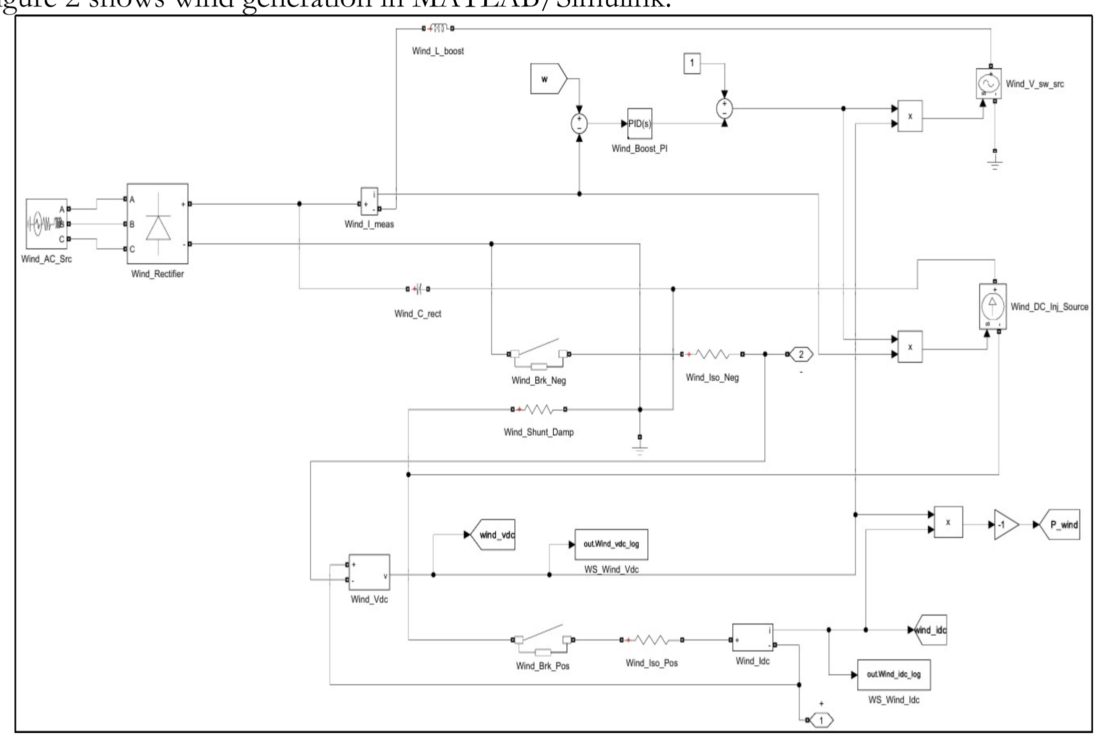

Figure 2. Connections and working of wind farm

The control strategy used in the simulation is a decentralized DC voltage droop control method. This method is selected because it allows each terminal to respond locally to changes in power balance without relying on continuous communication with a central controller. As renewable generation varies, each terminal must adjust its power exchange to maintain DC voltage stability. The droop control therefore becomes the key element in evaluating whether the system can maintain stable operation under variable renewable power injections. In addition, a graded protection scheme is integrated into the model to examine how the network behaves during disturbances. This scheme helps isolate faults at the terminal, corridor, and AC-system levels and allows the study to assess the system's resilience under severe conditions.

The performance of the system is evaluated using several indicators that are directly linked to the title of the paper. These include DC voltage deviation, transient stability, power-sharing balance between terminals, THD at the AC interfaces, and transmission losses. The study also compares the HVDC network with an equivalent HVAC network to determine whether the proposed system remains more efficient when renewable generation is transmitted over long distances. By comparing results across different renewable penetration levels, the methodology provides a clear basis for understanding the dynamic impact of solar PV and wind on VSC-MT-HVDC performance.

Results:

Renewable-driven dynamics: Introducing 30 MW of distributed solar PV and wind at selected terminals increased local transient activity and shifted steady-state power flows, but did not cause sustained instability under tested scenarios; all cases returned to stable operation after transients.

DC voltage regulation: After injected disturbances (DC pole-to-pole, DC pole-to-ground, and three-phase AC faults), the DC grid recovered to near-nominal voltage; post-fault stabilized DC voltage was measured at approximately 524.358 kV in the multi-terminal network. Figure 3 shows the voltage, current and active power injected by PV module in DC link.

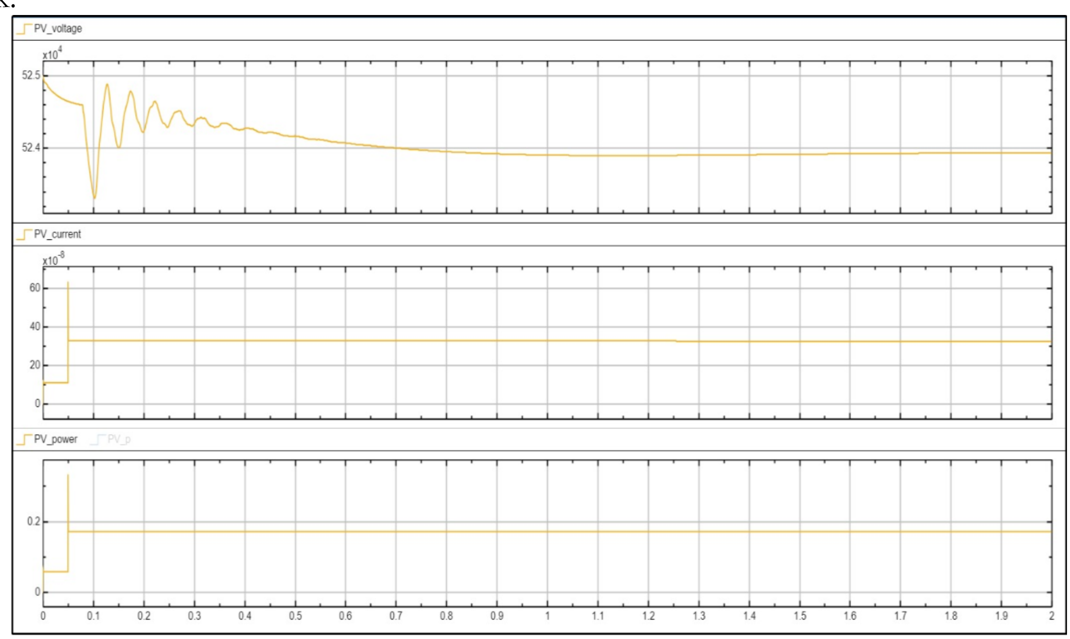

Figure 3. DC Voltage, Current and Power supplied by PV array

Power sharing and droop response: The decentralized DC voltage droop controller redistributed power among terminals proportionally and autonomously during renewable variability and fault conditions, preserving coordinated power-sharing without reliance on fast supervisory communication. Figure 4 shows the voltage, current and active power shared by wind module into DC link.

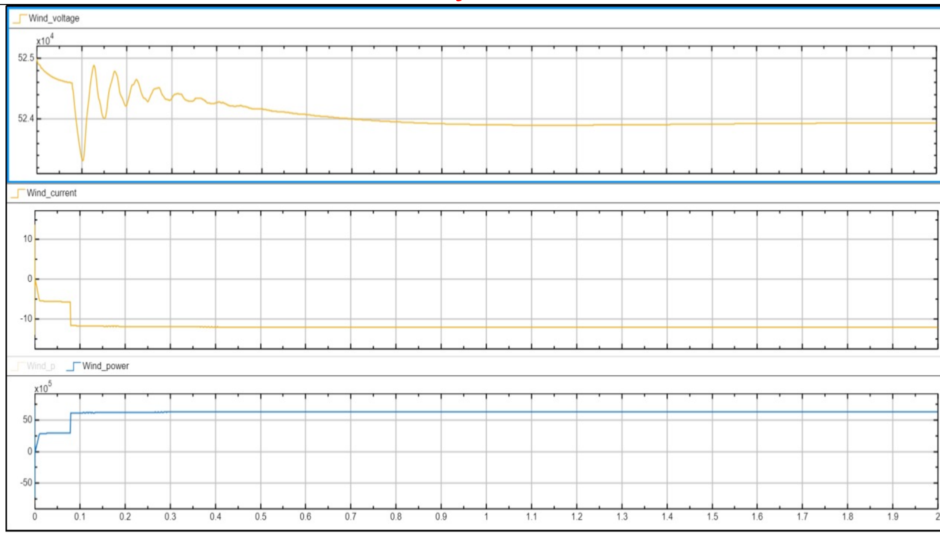

Figure 4. DC Voltage, Current and Power supplied by wind farm

Power quality: AC-side harmonic performance remained within acceptable limits for the modeled MMC converters; maximum voltage THD remained limited to 1.126%, below the 1.5% grid-code benchmark used in the study. Figure 5 shows the THD of the voltage at the receiving end.

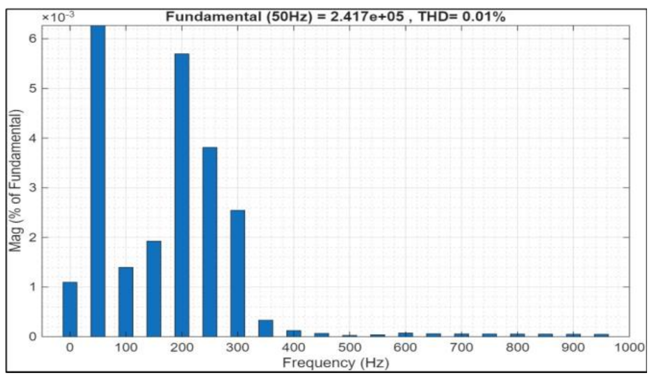

Figure 5. THD of receiving end Voltage

Fault Resilience and Restoration: The graded protection scheme (terminal-level, corridor-level, AC-system-level) enabled rapid detection, selective isolation, and autonomous restoration procedures that limited disturbance propagation and minimized service interruption.

Losses and Efficiency: For the 600 km corridor case at 350 MW transfer, the modeled HVDC multi-terminal configuration produced approximately 5.6 MW of transmission loss versus ~12.7 MW for an equivalent HVAC corridor—demonstrating substantial loss reduction for long-distance renewable transfer.

Sensitivity to penetration level: Increasing renewable contribution at terminals amplified transient magnitudes and recovery times modestly; however, appropriately tuned droop gains and converter control settings-maintained stability across the tested penetration range.

Practical Implications of the Proposed VSC-MT-HVDC Framework:

The proposed VSC-MT-HVDC framework provides significant practical benefits for future renewable-rich power systems. For utilities, the proposed approach enables efficient integration of geographically dispersed solar PV and wind resources while reducing transmission losses and improving overall system flexibility. The ability of VSC converters to independently control active and reactive power allows better adaptation to variable renewable generation.

For transmission system operators, the implementation of decentralized DC voltage droop control and graded protection strategies improves operational reliability by maintaining DC voltage stability, enabling coordinated power sharing, and reducing the impact of disturbances. These characteristics are particularly valuable for large-scale renewable transmission corridors where fast dynamic response and reliable fault management are required.

For future renewable-dominated power networks, VSC-MT-HVDC technology provides a scalable solution for connecting remote renewable generation areas with load centers. The demonstrated reduction in transmission losses, improved power quality, and stable operation under renewable variability indicate that the proposed framework can contribute to the development of flexible and sustainable electricity transmission infrastructure.

Conclusion:

This paper investigated the impact of solar PV and wind penetration on the dynamic performance of an MMC-based VSC-MT-HVDC system using MATLAB/Simulink simulations. The results demonstrate that renewable integration can be achieved without compromising system stability when decentralized DC voltage droop control and graded protection strategies are appropriately implemented. The proposed system maintained effective voltage regulation, power-sharing capability, and power quality under renewable variability and fault disturbances. The DC voltage recovered to approximately 524.358 kV after disturbances, while the maximum voltage THD remained limited to 1.126%, confirming satisfactory dynamic and harmonic performance. Furthermore, the VSC-MT-HVDC system achieved approximately 55.9% lower transmission losses compared with an equivalent HVAC system over a 600 km transmission corridor. These findings highlight the suitability of VSC-MT-HVDC technology as an efficient and reliable solution for future renewable-rich power networks. Future work will focus on experimental validation, adaptive control strategies, and large-scale HVDC network studies with higher renewable penetration levels.

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