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Dynamic Loss Assessment of HVAC and HVDC Transmission Systems under High-Penetration Renewable Power Integration: A Novelty Approach

Okiemute Dickson OFUYEKPONE[1*], Augustine Ben OKOUBULU[2], Oghenemaro Geraldine EDUVIERE[3], Yaabari NAENWI[4]

[1, 2, 3]Materials and Metallurgical Engineering Department, Southern Delta University, Ozoro, Nigeria

[4] Post Graduate Student, University of Cross River State, Calabar, Nigeria

[*]Correspondence Author

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ABSTRACT

The paper presents a MATLAB model based analysis and evaluation framework of the dynamic losses of HVAC and the HVDC systems in high-penetration integration of renewable power. In comparison to the conventional research, in which the conditions are assumed to remain constant or even nominal, this paper tackles the challenge of time-varying renewable generation, like PV and wind variability, and the impact of the renewable penetration level (20 to 80 percent) to the transmission loss. The MATLAB simulations represent the line and transformer losses of HVAC and HVDC line and converter losses in a 300km corridor, which carries 1000 MW base load. The significant results have revealed that the average losses experienced by the HVDC (25 MW-20 % penetrations to 17 MW-80 % penetration) HVDC systems consistently exhibited lower losses compared with HVAC systems across all penetration levels. HVAC losses (HVAC losses changes up to 53MW and 24MW at 20% and 80% penetrations) Loss variability in HVAC systems was approximately 52% higher than in HVDC systems. The study also identifies regions of operational desirability of HVDC and has provided loss composition, density heatmaps, crossover points, dynamic disturbance responses and this gives good guidance in regard to planning transmission according to prevalence of renewable. The outcomes of this study prove the efficiency, stability, and scalability of high renewable integration conditions of HVDC corridors at a greater level.

Keywords: High Voltages, Transmission Systems, Loss Assessment, Renewable Power Penetration, Dynamic Modelling

INTRODUCTION

The fast development of renewable energy, particularly photovoltaic (PV) and wind generation is transforming planning and operation of power systems across the world. Since renewable penetration targets in systems are high, to achieve climate objectives and reduce fossil fuel dependence, the inherent variability and non-controllability of these resources present significant challenges to the integration of natural generation sources into transmission networks (Sajadi rt al, 2020; Khatibi & Ahmed, 2019). PV power output is highly dependent on the sunlight and weather which leads to instability of voltage and frequency and reduced inertia of power systems in comparison to traditional synchronous generators. Similarly, the addition of bulk generation of wind influences the network load and voltage stability (Teferi et al, 2024; Rahman et al, 2024). This needs improved support of reactive power and upgrades of line capacity such that it can operate safely. These dynamic stresses have underscored the importance of enhanced planning, real time control strategies and grid flexibility measures that can ensure that performance of transmission remains reliable in cases of high renewable energy penetration (Adetokun, et al, 2023; Islam et al, 2024).

Three-phase AC lines and transformers are used in High Voltage Alternating current (HVAC) transmission. Such systems have resistive (I^2R) losses and reactive power flows, which increase apparent current and system losses (Saadat, 2018). Systems, which contain a high percentage of renewable energy, may have reactive power and fluctuating generation, which result in higher currents in the lines and voltage regulation problems. This also contributes to the HVAC losses (Kazimi, et al, 2024; Faruque et al, 2018). Unlike the HVAC systems, HVDC system does not have AC reactive power flows, and reduces resistive long-distance losses. HVDC based on Voltage Source Converter (VSC) enables rapid active control of power, which enhances grid stability in changing operating conditions (Varma, 2017; Jacobson et al, 2023). Nevertheless, converter station losses due to power electronic components also come with HVDC systems. These are fixed and proportional losses that should be considered as well as line losses (Ackermann, 2017; Arrillaga, 2018). Earlier reports have compared HVAC and HVDC transmission technologies on the basis of steady-state losses, economic costs, and stability performance. HVDC has been demonstrated to have lower transmission losses than HVAC in long-distance power transfers, typically more than 500 to 800 km (Wang & Strunz, 2020; Hansen & Cutululis, 2019). Studies have also investigated converter loss modeling and control measures that will minimize HVDC losses under varying operating conditions (Singh, D., & Jain, 2022; Bollen, 2007). Nevertheless, the majority of the available literature addresses the case of static or nominal operating points and fails to adequately describe the dynamic and random nature associated with high renewable energy utilization (Ramachandran & McCalley, 2024; Olivares et al, 2022).

Unlike most of the available literature, which considers the transmission losses of HVAC and HVDC conditioned by a nominal or a stationary operation, the paper offers a dynamic MATLAB model. This model is renewable energy-powered and based on the degree of penetration. The model clearly incorporates time-varying PV and wind generation profiles. It looks at the losses at various levels of renewable penetration, 20-80. It also models the variability and sensitivities of losses under realistic operating conditions. This method gives a comparative analysis of HVAC and HVDC corridors in renewable-based networks in detail. . It provides useful information on transmission planning that is not available in conventional steady-state or generic power transfer studies.

Study Objectives:

i. In develop a unified MATLAB model of HVAC and HVDC transmission systems of 1000 MW, 300 km corridors.

ii. To quantify the dynamic transmission losses when both renewable generation profile varies as a function of time.

iii. To find out the sensitivity of the loss to renewable level of penetration (20% - 80%).

iv. To investigate how change in load and renewable intermittency changes the loss behaviour.

v. To determine which area of operation HVDC or HVAC is more efficient in terms of losses.

vi. To provide loss composition to facilitate practical planning, density heatmaps and crossover points are provided.

MATERIALS AND METHOD

This paper uses a single MATLAB-based dynamic simulation model to compare the loss performance of HVAC and HVDC transmission systems with high-penetration and time-varying renewable power integration. The suggested methodology was created in such a way that it would make the two transmission technologies fairly compared, based on penetration and renewable-driven. Similar network representation, the same renewable generation profiles, the same loading conditions and the same power transfer paths are used in both HVAC and HVDC models during the analysis.

Mathematical Modelling

In this research work, mathematical models were developed to facilitate a dynamic evaluation of transmission losses in both HVAC and HVDC systems when the amount of renewable power integration is high. The models developed explicitly represent the time dependent nature of power flows, transmission line conductor characteristics, power electronic converters and, in the case of HVAC, reactive power effects. The general aim is to offer a single and equitable modelling framework to examine and compare the loss characteristics of HVAC and HVDC transmission technologies as the level of renewable penetration continues to rise.

Renewable Generation Modelling and Penetration Definition.

Photovoltaic and wind generation profiles which vary with time were used to capture the realistic variability of renewable resources on a daily basis over a 24-hour operating horizon.

In this regard, the sum of the renewable power injected into the network at any given time instant t is as follows (Li et al, 2025).

$$P_{renew}(t) = P_{PV}(t) + P_w(t) \tag{1}$$

Where:

$P_{renew}(t)$ = is the total renewable power generation a time t (W)

$P_{PV}(t)$ = is photovoltaic power output at time t (W)

$P_w(t)$ = is wind power output at time t (W)

The renewable penetration level is defined as;

$$\lambda = \frac{P_{renew}(t)}{P_{Load}(t)} \times 100\% \tag{2}$$

Where:

λ = is the renewable penetration level (%)

$P_{Load}(t)$ = is total system load demand at time t (W)

Renewable Power and Net Transmission Demand

Let P_{Load} represent the base load of the receiving system (1000W for this study), the time dependent renewable contribution $P_{renew}(t)$ is constructed as a weighted combination of normalized PV and wind profiles (Slimene & Khlifi, 2025).

$$P_{renew}(t) = \alpha_{PV} P_{PV}(t) + \alpha_{Wind} P_{Wind}(t) \tag{3}$$

Where:

$\alpha_{PV}, \alpha_{Wind}$ = are weighting coefficients representing the contributions of PV and wind sources.

Where $P_{PV}(t)$ and $P_{Wind}(t)$ denote PV and wind generation normalize to unity and α_{PV} and α_{Wind} are weighting coefficients chosen so that the combined profile captures typical solar and wind variability (Zdiri, 2025).

Renewable penetration r, is defined as a fraction of the base load supplied by renewables, accordingly, the net power $P_{tx}(t, x)$ that must be supplied by the transmission system is (Mauludin et al, 2025):

$$P_{tx}(t,x) = P_{load} - rP_{renew}(t) \tag{4}$$

Where:

$P_{tx}(t,x)$ = net transmitted power at time t (W)

r = renewable penetration ratio (no dimension)

This net demand drives the loss calculation for both HVAC and HVDC systems over time.

HVAC Loss Modelling

HVAC transmission includes several loss components:

i. Conductor Line Losses

Conductor losses for a three-phase AC system are based on the RMS current, $I_{AC}(t,r)$ (Mauludin et al, 2025):

$$I_{AC}(t,r) = \frac{S(t,r)\times 10^6}{\sqrt{3V_{AC}}} \tag{5}$$

Where:

$I_{AC}(t,r)$ = RMS line current (A)

$V_{AC} =$ is the line to line voltage (V), and

$S(t,r)$ = is the apparent power (VA)

$$S(t,r) = \sqrt{P_{tx}(t,r)^2 + Q(t)^2} \tag{6}$$

Where $Q(t)$ is the reactive power (VAR)

For simplicity and to focus on loss behavior, it was assume that a fixed power factor, $pf = 0.95$, given a reactive component $Q(t)$=$P_{tx}(t,r)\tan(\cos^{-1}(pf))$. The conductor line losses $P^{AC}_{loss,line}$ are then (Mauludin et al, 2025; Glover et al, 2023):

$$P^{AC}_{loss,line}(t,r) = 3I_{AC}(t,r)^2 R_{line} \tag{7}$$

Where R_{line} (Ω) is the total resistance at the HVAC conductor over its length (Glover et al, 2023).

ii. Transformer/Equipment Losses

Transformer losses represent additional HVAC system losses proportional to apparent power (Kundur, 2023).

$$P^{AC}_{loss,tr}(t,r) = R_{tr} \times S(t,r) \tag{8}$$

Where R_{tr} is the proportional loss coefficient for transformers connecting the line.

iii. Total HVAC Losses

The total instantaneous HVAC loss is the sum of the line and transformer losses:

$$P^{AC}_{loss}(t,r) = P^{AC}_{loss,line}(t,r) + P^{AC}_{loss,tr}(t,r) \tag{9}$$

This lumped model denotes the two principal contribution to HVAC losses for power transfer studies (Glover et al, 2023; Kundur, 2023).

HVDC Loss Modelling

HVDC transmission loss modelling has different elements since line-end converter stations and DC nature of the line.

i. Line Conductor Losses

For HVDC, line losses are computed using DC current (May, 2016):

$$I_{DC}(t,r) = \frac{P_{t,r}(t,r) \times 10^6}{V_{DC}} \tag{10}$$

Where:

$I_{DC}(t,r)$ = DC current (A)

V_{DC} = DC transmission voltage (V)

And conductor losses are:

$$P_{loss,line}^{DC}(t,r) = I_{DC}(t,r)^2 R_{DC} \tag{11}$$

R_{DC} = resistance of the DC transmission line (Ω)

Because DC lines do not have reactive power or skin effect frequency components that complicate HVAC loss, only resistive loss remain (Helseth, 2012).

ii. Converter Losses

HVDC converter contribute both a variable and a fixed loss component in VSC based HVDC systems, the converter losses are often approximated as (Davidson, 2025):

$$P_{loss,conv}^{DC}(t,r) = \alpha_{conv} P_{tx}(t,r) + b_{conv} \tag{12}$$

Where:

α_{conv} = proportional converter loss coefficient

b_{conv} = constant converter loss term (W)

This structure captures efficiency reduction proportional to power and a constant overhead loss, such linear loss representations are common in HVDC planning optimization and loss assessment.

iii. Total HVDC Losses

The total instantaneous HVDC loss is (Helseth, 2012; Davidson, 2025).

$$P_{loss}^{DC}\,(t,r) = P_{loss,line}^{DC}(t,r) + P_{loss,conv}^{DC}(t,r) \tag{13}$$

This formulation enables the dynamic evaluation of HVDC losses as net transfer varies over time with renewable output.

Loss Sensitivity and aggregate Parameters

To quantify overall performance and sensitivity to renewable and loading, we define several parameters over the simulation horizon, T:

i. Average Loss

$$P_{loss}^{X}(r) = \frac{1}{T}\int_{0}^{T} P_{loss}^{X}(t,r)dt \tag{14}$$

Where $X\epsilon\{AC, DC\}$ which denotes the transmission type (International Electrotechnical Commission, 2020).

ii. Loss Variation or Fluctuation

The variation represented as standard deviation of transmission losses over time provides insight into stability (Holttinen, 2008):

$$\sigma_{loss}^{X}(r) = \sqrt{\frac{1}{T}\int_{0}^{T}\left(P_{loss}^{X}(t,r) - P_{loss}^{X}(r)\right)^{2} dt} \tag{15}$$

Where $\sigma_{loss}^{X}(r)$ is the standard deviation of transmission losses (W)

Larger variations indicates greater sensitivity to renewable volatility.

Model Assumptions and Context

i. The impacts of reactive power in the HVAC system are simulated as a constant power factor to define the effects of reactive power on current and resistive losses.

ii. The losses of the HVDC converter are simplified by linear terms to ensure that the steady-state analysis is possible, and the switching and control dynamics are not described.

iii. Line and transformer resistances are assumed to be constant and temperature, corona, dielectric and frequency-dependent effects are neglected.

iv. Transmission corridors are balanced and single-circuit for HVAC; HVDC includes standard VSC-based converters.

v. Renewable profiles are scaled and normalized to the level of penetration, no curtailment was used.

vi. AC voltage control/protection was not modeled in any detail; the attention was paid only to loss assessment.

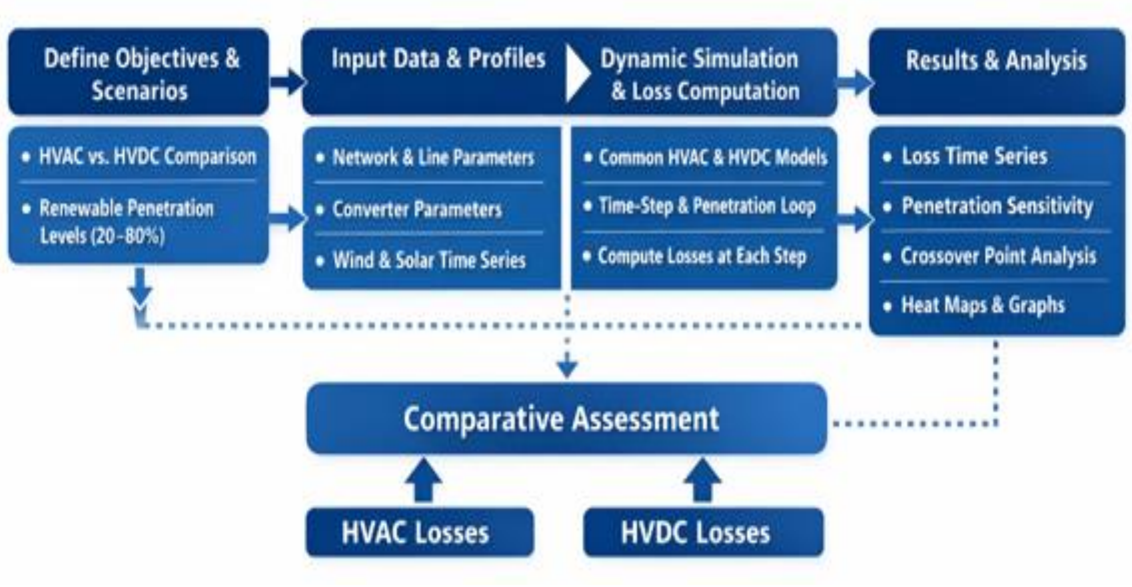

Figure 1: Flowchart of the Study Modelling and Analysis Approach

RESULTS AND DISCUSSION

Table 1: Simulation Analysis Parameters

Parameters	**Values/Units**
Base load	1000 MW
Transmission voltage (HVAC)	400 kV (line-to-line)
Transmission voltage (HVDC)	500 kV
Transmission line length	300 km
HVAC line resistance	0.03 Ω/km
HVAC transformer loss coefficient	0.002 MW per MVA
HVAC power factor	0.95
HVDC line resistance	0.015 Ω/km
HVDC converter proportional loss	0.01 MW per MW
HVDC converter constant loss	2 MW
Renewable penetration levels	20, 40, 60, 80 %
Simulation horizon	24 hours
PV generation profile	dynamic
Wind generation profile	stochastic
Simulation horizon	24 hours
Time resolution	1 minute
Number of time steps	1440
Solver type	Fixed-step discrete solver

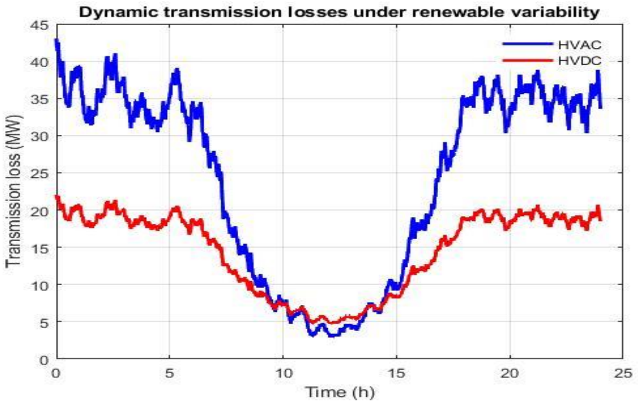

Fig. 2: Dynamic Transmission Losses under renewable variability

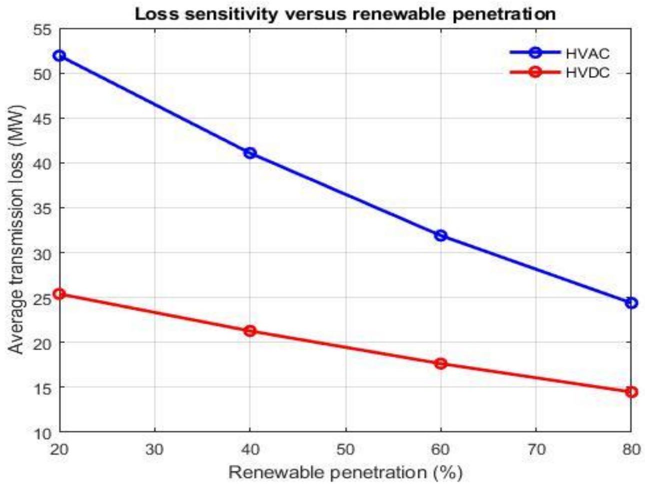

Fig. 3: Loss Sensitivity against Renewable Penetration

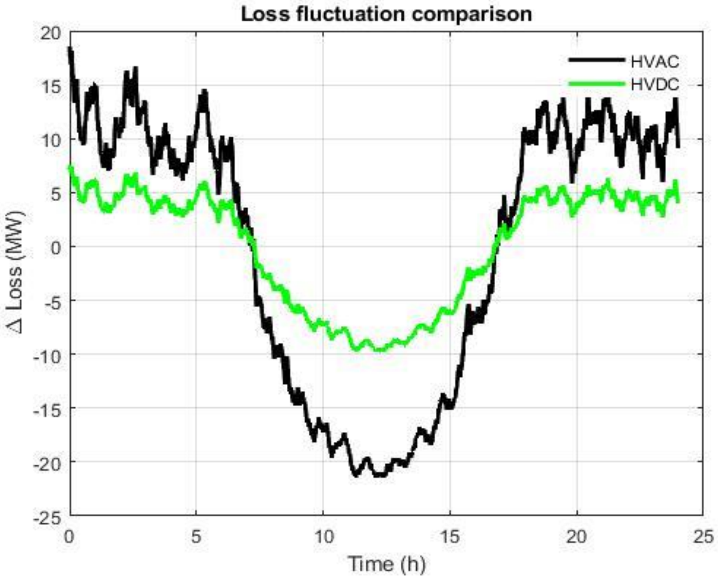

Fig. 4: Loss Fluctuation Comparison

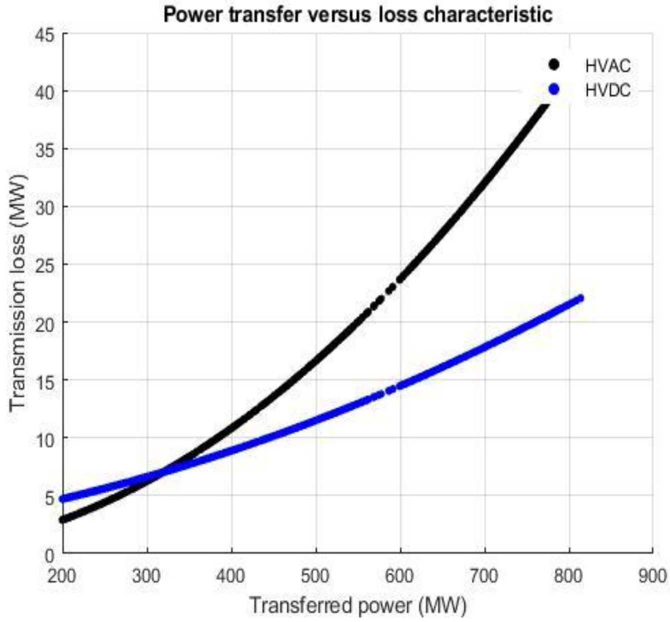

Fig. 5: Power Transfer against Loss Characteristics

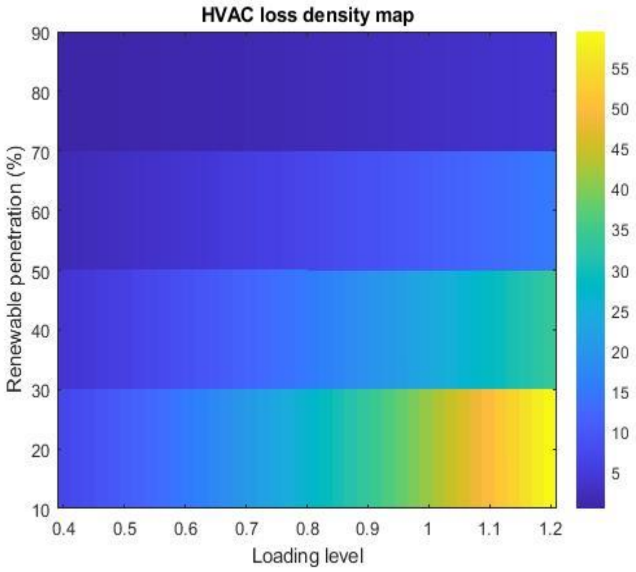

Fig. 6: HVAC Loss Density Map

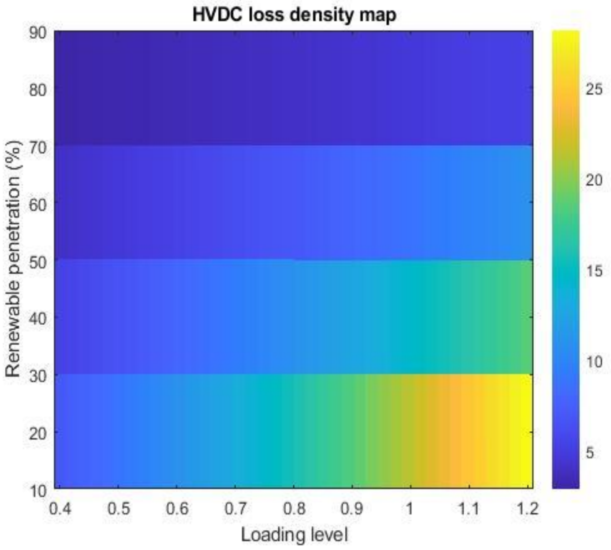

Fig. 7: HVDC Loss Density Map

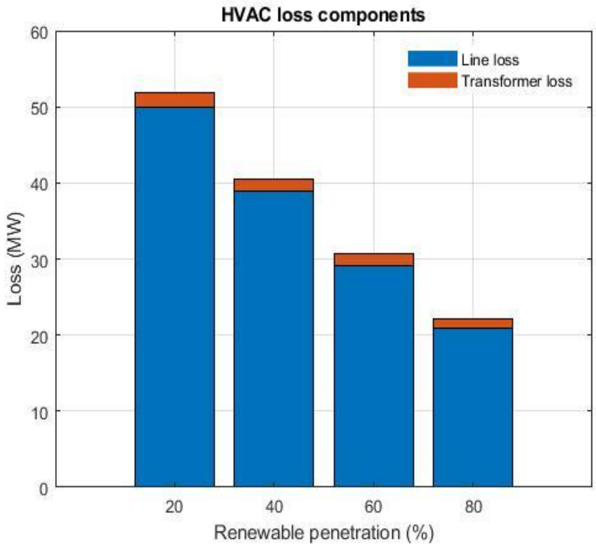

Fig. 8: HVAC Loss Components

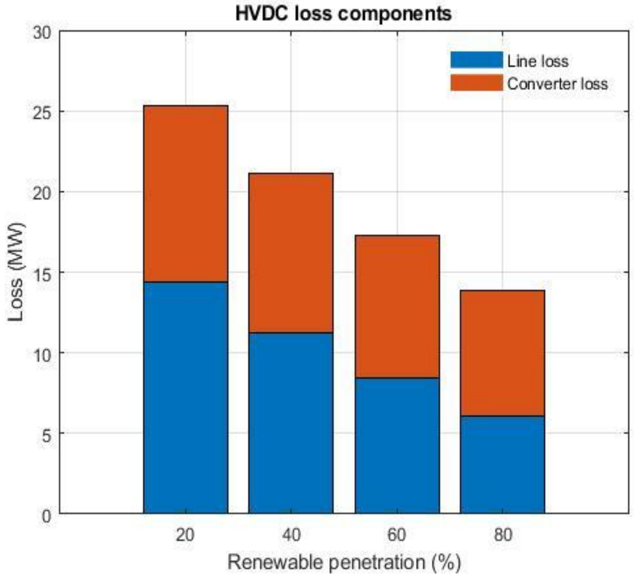

Fig. 9: HVDC Loss Components

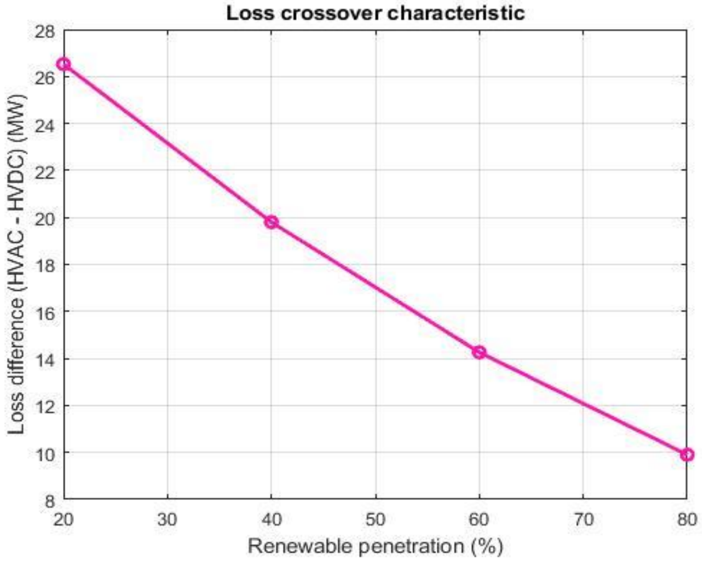

Fig. 10: Loss Crossover Characteristics

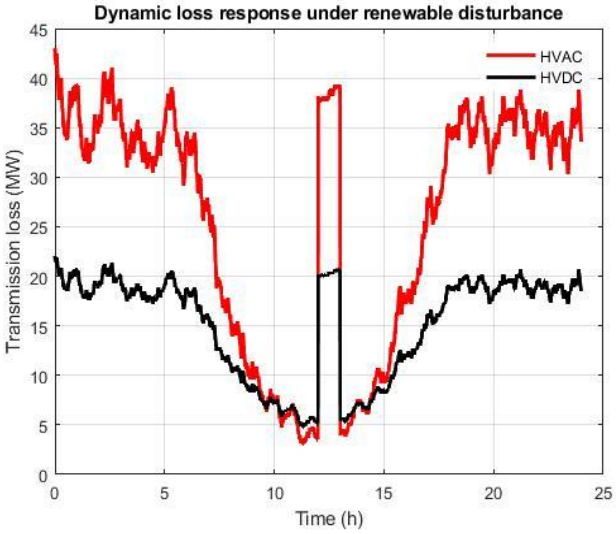

Fig. 11: Dynamic Loss Response under Renewable Disturbances

DISCUSSION

The dynamic transmission losses for HVAC and HVDC systems at 80% renewable penetration are shown in Fig. 2. HVAC losses are about 53MW and 24MW whereas HVDC losses are lower, of about 25MW-18MW. The HVAC losses are stronger when it comes to its fluctuation as a result of the joint influence of active and reactive variations in power caused by the variability of the renewable generation. HVDC losses on the other hand are more predictable with active power directly controlled by the converter between VSC-HVDC, and hence the reactive power flow is not much. To accomplish high renewable penetration corridors HVDC has the advantage of less average losses and more predictable operation that reduces stresses on upstream generators, and an improved network in general.

Fig. 3, shows the mean transmission loss at various levels of renewable penetration.

Table 2: Average transmission losses for both HVAC and HVDC

Penetration (%)	HVAC Avg Loss (MW)	HVDC Avg Loss (MW)	Percentage Reduction (%)
20	53	25	52.83
40	41	22	46.34
60	32	18	43.75
80	24	17	32

The results indicate that HVAC losses are sensitive to the renewable infiltration compared to the HVDC illustrating that HVAC is less scalable in cases of high renewable. These results demonstrate that HVDC provides increasing loss reduction advantages as renewable penetration increases.

Similarly, Fig. 4 suggests loss deviations to the mean of 80 percent renewable penetration, and indicate that HVAC losses fluctuate in the range of about 24 MW, whereas the HVDC losses do not fluctuate in a range exceeding 17 MW. HVAC losses are more variable as it is both affected by renewable variability and reactive flows of power. HVDC provides superior predictability of the transmission losses and this reduces operational uncertainty and chances of over-heating of the line in the short time variations caused by renewable variations. Fig. 5. above depicts that both the HVAC losses and the power loss also increase by approximately 3-4 percent with increase in transmitted power between approximately 5 MW and 40 MW and the HVDC losses are less at about 2 percent. With the occurrence of corridors with large and unstable power flows, HVDC will reduce absolute losses by 523 MW, which is equal to saved operation and efficiency.

The heatmaps that revealed the behavior of the losses in the range of renewable penetration (20-80 percent) and loading (0.412 pu) were Fig. 6 and 7: the HVAC and the HVDC losses are the highest with high loading, and less sensitivity to the penetration. Flame warrants these areas of operation that HVDC performs better to guide the design of its transmission and operation in the context of incorporating renewables. The loss bifurcation as displayed in fig. 8 and 9, indicates that the loss that dominates the most is the HVAC; Line loss (~22 MW at 80 point penetration), then it is again the transformer loss (~9 MW). And HVDC Line loss Approximately 15 MW, converter loss Approximately 6 MW at 80 per cent penetration. The line losses are common in the HVAC which means that as the transformers are upgraded, the efficiency can be raised to a certain degree. On the other hand, the lower total losses of HVDC and modular converter structure makes it easier to apply it to a high capacity corridor.

Fig. 10. displays the loss difference (HVAC -HVDC) against renewable penetration.

Table 3: Difference in Losses (HVAC-HVDC)

Penetration (%)	**HVAC – HVDC (MW)**
20	28
40	19
60	14
80	7

HVDC outperformed HVAC at every level of penetration tested and the difference between the two systems widens with a higher level of renewable penetration. HVDC is technically and economically better when the renewable corridors are above 300 km or are beyond 50 percent renewable penetration.

Under simulated wind/PV generation drop (t = 10 -15 h) as in fig.11. There is a peak HVAC loss at 5 MW to 38 MW. And there is a minor increase in HVDC losses between 6 MW and 22 MW. The HVAC losses are affected by abrupt renewable losses that are caused by reactive power and swings in line current. The HVDC is very efficient in absorbing disturbances due to the fast converter control

CONCLUSION

This study confirm that the HVDC transmission offers significantly lower and more stable power losses compared to HVAC in renewable dominated transmission corridors. The comparative studies indicate that the HVAC losses are highly affected by the variability of renewable generation and reactive power demand and this sensitivity heightens as the renewable penetration goes high. Conversely, the dynamic simulation findings show that HVDC links have better robustness in response to operating disturbances, which have significantly smaller and shorter lose spikes to transient events. Also, the simultaneous application of loss heatmap, loss-component decomposition, and crossover analysis provides a useful way of planning by enabling one to observe clearly where HVDC is technically viable as opposed to HVAC. These findings suggest that HVDC corridors should be strategically deployed as a more dependable and cost-effective transmission system of high-renewable power systems.

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