Comparative Analysis and Optimization of HVAC and Multi-Terminal HVDC Integration 400kV Super Grid (Case Study of Iraq)

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Abstract. The Iraqi 400-kV super grid faces significant operational challenges, including high transmission losses, overloaded transmission lines, voltage instability, and limited long-distance power transfer capability. The main objectives of this study are to minimize transmission losses, reduce transmission line overloading, maintain acceptable voltage profiles, and improve the overall performance of the Iraqi transmission network through the integration of Multi-Terminal High-Voltage Direct Current (MT-HVDC) technology. These objectives were achieved by modeling the Iraqi transmission network using real operational data for 2024 and analyzing it in PSS®E Version 33 under normal, 10%, and 20% loading conditions. A Genetic Algorithm (GA) was employed to identify the optimal MT-HVDC converter station locations and transmission corridors. The most important results indicate that the optimization process identified RU-MILPP, BGS4, and KESK4 as the optimal MT-HVDC terminal locations within the Iraqi 400-kV network. The proposed hybrid AC/DC configuration reduced total transmission losses by 22.5 MW and 13.75 MVar under normal operating conditions. Under a 20% load increase, the number of overloaded transmission lines decreased from 16 to 3 while maintaining all bus voltage magnitudes within the acceptable range of 0.95–1.05 p.u. Furthermore, the bipolar MT-HVDC configuration demonstrated superior loadability and long-distance power transfer capability compared with conventional HVAC transmission systems. **The significance of the obtained results** lies in improving transmission efficiency, enhancing voltage stability, alleviating network congestion, increasing operational flexibility, and providing a practical foundation for future renewable energy integration and regional power system interconnections.
***Keywords*:** HVDC, HVAC, Iraqi national grid, power losses, voltage stability, loadability, optimization, genetic algorithm, renewable energy integration.

DOI: https://doi.org/10.52254/1857-0070.2026.3-71.08
UDC: 621.311

Analiză comparativă și optimizarea integrării HVAC și MT-HVDC într-o super rețea de 400 kV (studiu de caz: Irak)

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Abstract. Rețeaua națională irakiană de 400 kV se confruntă cu provocări operaționale semnificative, inclusiv pierderi ridicate de energie în transmisie, supraîncărcarea liniilor de transport, instabilitatea tensiunii și o capacitate limitată de transfer al energiei pe distanțe lungi. Obiectivele principale ale acestui studiu sunt minimizarea pierderilor de transmisie, reducerea supraîncărcării liniilor de transport, menținerea profilurilor de tensiune în limite acceptabile și îmbunătățirea performanței generale a rețelei de transport din Irak prin integrarea tehnologiei Multi-Terminal High-Voltage Direct Current (MT-HVDC). Aceste obiective au fost atinse prin modelarea rețelei de transport irakiene utilizând date operaționale reale aferente anului 2024 și prin analiza acesteia în PSS®E Versiunea 33, atât în condiții normale de funcționare, cât și pentru creșteri ale nivelului de încărcare de 10% și 20%. Un Algoritm Genetic (GA) a fost utilizat pentru identificarea locațiilor optime ale stațiilor convertizoare MT-HVDC și ale coridoarelor de transmisie. Cele mai importante rezultate indică faptul că procesul de optimizare a identificat RU-MILPP, BGS4 și KESK4 drept locații optime pentru terminalele MT-HVDC din rețeaua irakiană de 400 kV. Configurația hibridă AC/DC propusă a redus pierderile totale de transmisie cu 22.5 MW și 13.75 MVar în condiții normale de funcționare. În condițiile unei creșteri a nivelului de încărcare cu 20%, numărul liniilor

supraîncărcate a scăzut de la 16 la 3, menținând, în același timp, toate valorile tensiunii în intervalul acceptabil de 0.95–1.05 p.u. În plus, configurația bipolară MT-HVDC a demonstrat o capacitate superioară de încărcare și de transfer al energiei pe distanțe lungi comparativ cu sistemele convenționale HVAC. Semnificația rezultatelor obținute constă în îmbunătățirea eficienței transmisiei energiei, creșterea stabilității tensiunii, reducerea congestiei rețelei, sporirea flexibilității operaționale și furnizarea unei baze practice pentru integrarea viitoare a surselor regenerabile de energie și pentru interconectarea regională a sistemelor electrice.
***Cuvinte-cheie*:** HVDC, HVAC, rețeaua națională irakiană, pierderi de putere, stabilitate a tensiunii, sarcină, optimizare, algoritm genetic, integrarea energiei regenerabile.

Сравнительный анализ и оптимизация интеграции систем переменного тока высокого напряжения и многотерминальных систем постоянного тока высокого напряжения в сверхмощную энергосеть напряжением 400 КВ (на примере Ирака)

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Аннотация. Энергосистема Ирака напряжением 400 кВ сталкивается с рядом существенных эксплуатационных проблем, включая высокие потери при передаче электроэнергии, перегруженные линии электропередачи, нестабильность напряжения и ограниченные возможности передачи мощности на большие расстояния. Основными целями данного исследования являются минимизация потерь при передаче электроэнергии, снижение перегрузки линий электропередачи, поддержание допустимых уровней напряжения и повышение общей эффективности иракской сети электропередачи за счёт интеграции технологии многотерминальной высоковольтной передачи постоянного тока (MT-HVDC). Эти цели были достигнуты путём моделирования иракской энергосистемы с использованием реальных эксплуатационных данных за 2024 год и её анализа в программном комплексе PSS®E Version 33 при нормальном режиме работы, а также при увеличении нагрузки на 10% и 20%. Для определения оптимальных мест размещения преобразовательных станций MT-HVDC и маршрутов передачи энергии был использован генетический алгоритм (GA). Наиболее важные результаты показывают, что процесс оптимизации определил RU-MILPP, BGS4 и KESK4 как оптимальные места размещения терминалов MT-HVDC в сети Ирака напряжением 400 кВ. Предложенная гибридная конфигурация AC/DC позволила снизить суммарные потери передачи на 22.5 МВт и 13.75 МВАр при нормальных условиях эксплуатации. При увеличении нагрузки на 20% количество перегруженных линий электропередачи сократилось с 16 до 3 при сохранении всех значений напряжения в допустимом диапазоне 0.95–1.05 о.е. Кроме того, биполярная конфигурация MT-HVDC продемонстрировала более высокую пропускную способность и эффективность передачи электроэнергии на большие расстояния по сравнению с традиционными системами HVAC. Значимость полученных результатов заключается в повышении эффективности передачи электроэнергии, улучшении устойчивости напряжения, снижении перегрузок сети, повышении эксплуатационной гибкости и создании практической основы для будущей интеграции возобновляемых источников энергии и регионального межсистемного объединения энергосистем.
***Ключевые слова*:** HVDC, HVAC, Иракская национальная энергосеть, потери мощности, стабильность напряжения, нагрузочная способность, оптимизация, генетический алгоритм, интеграция возобновляемых источников энергии.

INTRODUCTION

The Iraqi power system faces urgent challenges related to electricity generation, transmission, and distribution, requiring substantial modernization efforts. Decades of conflict, limited infrastructure investment, rapid population growth, and increasing industrial demand have resulted in an aging national grid characterized by frequent outages, high transmission losses, and insufficient capacity to meet peak electricity demand. These challenges are particularly critical within the transmission network, where long-distance power transfer across Iraq's vast and geographically diverse territory further exacerbates system instability and operational inefficiencies [1].

Historically, Iraq has relied on high-voltage alternating current (HVAC) transmission for bulk power delivery. While HVAC remains a widely adopted solution for medium-distance transmission, it presents inherent technical limitations when applied to long transmission corridors, including high reactive power demand, reduced voltage stability, and increased power losses [2]. As Iraq seeks to expand its transmission capacity, integrate renewable energy resources, and strengthen interconnections with neighboring countries, these limitations have become increasingly pronounced [3].

In response to similar challenges worldwide, high-voltage direct current (HVDC) technology has emerged as a competitive and technically mature alternative for long-distance and high-capacity power transmission. Compared with HVAC systems, HVDC offers several advantages, including lower transmission losses, improved voltage regulation, enhanced power flow controllability, and the capability to interconnect asynchronous power systems. These characteristics make HVDC a promising solution for supporting the transition toward a more reliable, flexible, and resilient electrical grid in Iraq [4].

A. Related Work

Numerous studies have investigated the application of high-voltage direct current (HVDC) systems for improving power transmission efficiency and grid stability. **Lemdani and Benbouheni (2021) [5]** investigated the optimal placement of FACTS devices using an evolutionary optimization method to improve voltage stability in electrical power systems. Their results demonstrated that the optimal allocation of FACTS devices can enhance voltage profiles, improve system stability, and increase network performance under different operating conditions**. Veera Bhadra Chary, Katuri, and Mercy Rosalina (2023) [6]** evaluated HVDC integration in IEEE 57-bus networks and confirmed significant reductions in active power losses under varying loading conditions. Similarly, **Psaras, Tzelepis, and Burt (2023) [7]** demonstrated that genetic-algorithm-based optimization provides effective solutions for complex transmission networks without requiring extensive infrastructure reinforcement.

Further developments were reported by **-Ortega and Gómez-Expósito (2024)** and **Li (2024)** [8], who demonstrated the effectiveness of HVDC systems in maintaining acceptable voltage profiles and improving overall network performance under different loading conditions. In addition**, Merzah A.N. et al. (2025)** [9] Merzah et al. investigated the comparative performance of MT-HVDC and UPFC technologies for reducing short-circuit current levels and transmission losses in the Iraqi super high-voltage grid. The results indicated that both technologies enhanced system performance, while MT-HVDC provided superior improvements in loss reduction and network operating conditions.

Nikou et al. (2025) [10] compared HVAC and VSC-HVDC transmission systems for long-distance power transfer and reported that HVDC systems achieve lower overall operational costs despite higher initial investment costs. Furthermore, Davidson**, C. Davidson (2025)** [11] confirmed the positive impact of HVDC integration on transmission efficiency and voltage stability in modern power systems. In other hand, **Chindam et al. (2026)** [12] proposed a UPFC-based approach to enhance power quality and regulate power flow in grid-connected systems. Their results demonstrated noticeable improvements in voltage regulation and system performance under varying operating conditions. More recently, **Abo-Khalil, Hassan, and Sayed (2026)** [13] studied the integration of HVDC systems with renewable energy transmission networks and demonstrated that HVDC becomes more economical than HVAC for transmission distances exceeding 150–200 km.

However, limited studies have investigated the practical integration of multi-terminal high-voltage direct current (MT-HVDC) systems into the Iraqi 400 kV grid using real operational data under varying loading conditions. Furthermore, the optimal placement of HVDC stations using genetic algorithms within the Iraqi transmission network has not been sufficiently addressed in previous studies.

B. Motivation

The Iraqi 400-kV transmission network faces increasing operational challenges due to growing electricity demand, transmission congestion, and the need for reliable long-distance power transfer. Conventional HVAC systems exhibit technical limitations when transferring large amounts of power over extended distances, particularly under heavily loaded operating conditions. MT-HVDC technology offers improved controllability, higher transmission capability, and enhanced operational flexibility. Therefore, investigating its application within the Iraqi national grid is essential for improving network performance and supporting future system expansion.

C. Research Gap and Contributions

Most existing studies on HVAC/HVDC integration are primarily based on IEEE benchmark systems and simplified network models, which do not adequately represent the operational complexity of large-scale national transmission networks. Furthermore, limited research has addressed the application of Multi-Terminal HVDC (MT-HVDC) technology to real transmission systems using actual operational data and optimization-based planning approaches.

To address this gap, this study develops a GA-based optimization framework for the integration of MT-HVDC technology into the Iraqi 400-kV super grid using real network data and a detailed PSS/E simulation model. The proposed approach identifies the optimal locations of MT-HVDC converter stations and transmission corridors while minimizing transmission losses, reducing line overloading, and maintaining acceptable voltage profiles.

The main contributions and findings of this work can be summarized as follows:

1. Development of an optimization methodology for MT-HVDC integration in the Iraqi 400-kV transmission network using Genetic Algorithm and PSS/E simulation tools.
2. Identification of the optimal MT-HVDC topology connecting RU-MILPP, BGS4, and KESK4 substations, providing a practical framework for future AC/DC hybrid network expansion.
3. Reduction of total transmission losses by 22.5 MW and 13.75 MVar under normal operating conditions.
4. Mitigation of transmission congestion by reducing the number of overloaded transmission lines from 16 to 3 under a 20% loading increase.
5. Maintenance of all bus voltage magnitudes within the acceptable operating range of 0.95–1.05 p.u., thereby improving voltage stability and system reliability.
6. Demonstration that the bipolar MT-HVDC configuration provides significantly higher loadability and superior long-distance power transfer capability compared with conventional HVAC transmission systems, making it a promising solution for future renewable energy integration and regional interconnection projects.

Methodology for Power Flow Modelling

The integration of multi-terminal high-voltage direct current (MT-HVDC) technology into the Iraqi 400 kV super grid is evaluated through a rigorous steady-state and optimization framework. To eliminate procedural operational details and maintain scholarly rigor, the methodology is structured around mathematical load flow formulation and heuristic parameter optimization.

A. Mathematical Formulation of the Load Flow Framework

The steady-state behavior of the hybrid HVAC/MT-HVDC Iraqi power system is modeled using non-linear power flow equations. The conventional alternating current (AC) network nodes are governed by the standard active and reactive power balance equations:

$$Pi = Vi\sum_{(j=1)}^{N} Vi(Gij\cos\theta ij + Bij\sin\theta ij) \qquad (1)$$

$$Qi = Vi\sum_{(j=1)}^{N} Vi(Gijsin\theta ij + Bijcos\theta ij) \qquad (2)$$

Where Vi and θij represent the voltage magnitude at bus i and the voltage angle difference between buses i and j, respectively. Gij and Bij denote the real and imaginary parts of the bus admittance matrix (Y_bus).

To solve these high-dimensional non-linear equations under stressed conditions, the Newton–Raphson numerical method was executed within the Siemens PSS/E (version 33) environment.

The grid performance was systematically evaluated across three distinct operational loading trajectories: normal base load, a 10% step increase, and a 20% stressed loading condition.

This multi-scenario approach ensures the validation of the MT-HVDC links under critical grid contingency and peak demand profiles.Fig. (1) illustrates a VSC-HVDC system and its equivalent circuit. [11].[12].

B. Active and Reactive Power Losses

The VSC-HVDC total power equation is:[14]

$$P_{VR1} + P_{VR2} + P_{DC} = 0 \qquad (6)$$

$$\Delta P_{HVDC} = \Delta P_{VR2} - \Delta P_{VR2} = 0 \qquad (7)$$

For a three-phase AC system, the active power loss will be:

$$P_{Losses}DC = 3 * I^2 * R * \mathrm{D} \qquad (8)$$

where the conductor's resistance is (R), Ω/km, D is route distance in km and the line current (I) is per phase.

For a two-pole DC system, the active power loss will be:

$$P_{Losses}DC = 3 * I^2 * R_{DC} * \mathrm{D} \qquad (9)$$

where the DC line's resistance is RDC, Ω/km, and the line current (I) is per pole.

These equations are used to describe the power balance and quantify transmission losses in the VSC-HVDC and AC systems. Equations (6) and (7) ensure power equilibrium and define the total HVDC losses, while (8) and (9) provide a basis for comparing active power losses in AC and DC transmission lines under overloaded operating conditions.

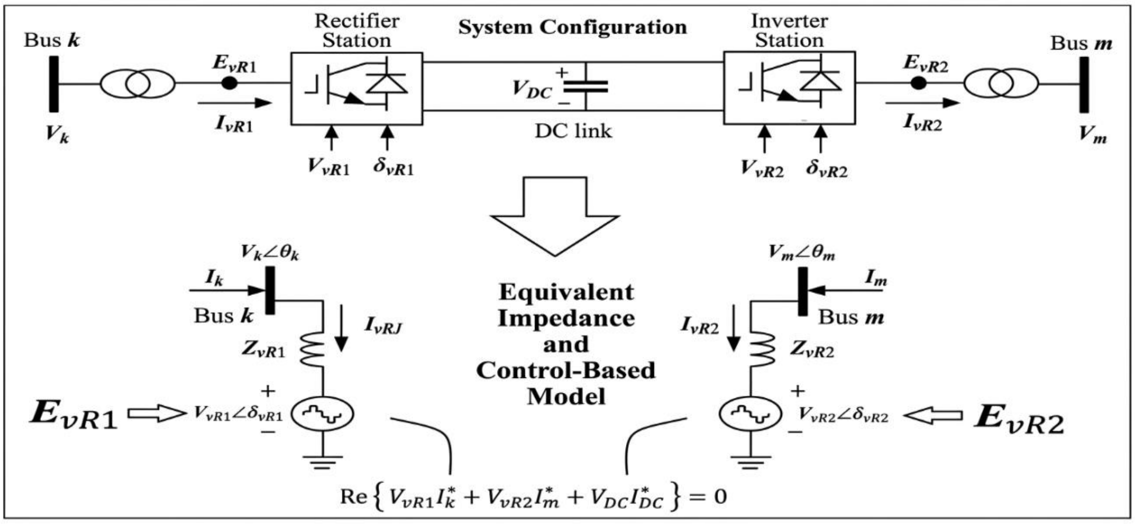

Fig. 1. HVDC equivalent circuit model [20].

Transmission Line Loadability

To further investigate the impact of MT-HVDC integration on transmission performance, the loadability characteristics of HVAC and HVDC transmission systems are compared. This assessment provides insight into the relative power transfer capability of each technology and their effectiveness in supporting increased network loading while maintaining secure operation.

The following factors will be taken into account in the following section:[15][16]

A. HVAC Line Loadability

1. The Thermal Limit

The conductor type and length for AC lines are the primary determinants of the thermal limit. The conductor's thermal capacitances rise as a result of external influences like the field and corona effects. The power's corresponding thermal limit (Pth) is [16][17]:

$$P_{th} = \sqrt{3} * I * \mathrm{V} \quad (10)$$

The line's maximum power capacity is as follows, and the (I) thermal current limit varies from 2038 to 2952 A based on the weather and geographic region, as well as the V line voltage (400kV):

$$P_{\max} = P_{th} COS\theta_r \quad (11)$$

where $\cos\theta_r$ is the power factor (PF) at the receiving end of the line.

2. Limit of Voltage Drop

The limiting factor for intermediate AC line lengths (approximately 80–320 km) is the maximum allowable voltage drop (ΔVmax).

The voltage drop along a transmission line can be expressed as [16]

$$\Delta V = |V_r| - |V_s| \quad (12)$$

where $|V_r|$ and $|V_s|$ are the voltages at the sending and receiving ends of the line, respectively. Due to the line's reactive properties, the voltage drop tends to decrease as the line length increases. The loadability of AC lines under varying power factor conditions is illustrated in Fig. (2). As shown, the AC line loadability is highly sensitive to the power factor, increasing as the power factor improves. [17][18]

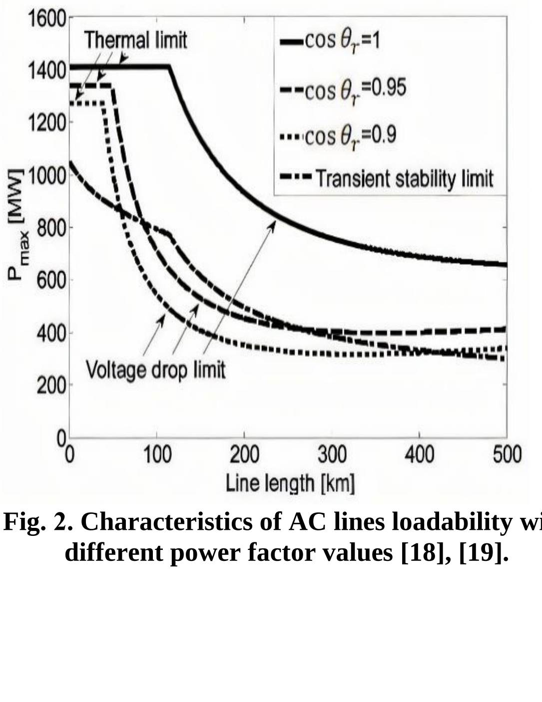

Fig. 2. Characteristics of AC lines loadability with different power factor values [18], [19].

B. HVDC Line Loadability

Compared to AC lines, HVDC lines have a lower voltage drop and are less loadable with respect to length. [20]

1. Thermal Limit

The corresponding thermal power limit for DC line (P_{dcth}) is equal to:

$$P_{dcth} = N * I_{DC} * V_{DC} \qquad (13)$$

where N is the number of DC lines (it is equal to 1 for monopolar and 2 for bipolar).

Idc, the power is 1200 MW for monopolar and 2400 MW for bipolar, with a thermal limit of 2400 A. [21]

2. Limit of Voltage Drop

The DC line's voltage drop is computed using [2]

$$\Delta E = E_1 - E_2 = 2 * R * I_{DC} \qquad (14)$$

where *R* is the DC line resistance and E_1 and E_2 are the voltage drops through the line. The DC line's power loss percentage, or $\Delta P_{Line}\,\%$, is calculated by:

$$\Delta E\% = 2 * R * (I_{DC} / V_{DC}) * 100 = \Delta P_{Line}\,\% \qquad (15)$$

There is an additional 0.7% to 1% power loss from the two converter stations.

Therefore, the voltage drop (Δ E%) is less than the proportion of total power losses ($\Delta PT\%$).

This guarantees that the voltage drop between the two AC terminals can be managed by the converter terminals. [21,22]

The primary factor limiting HVDC's loadability is power loss.

While loadability lines of the bipolar type (two monopolar) can be operated at their thermal limit over the whole range of line lengths, loadability lines of the monopole type in Fig. (3) have a power loss limit that starts at 250 km due to the influence of power loss.

In contrast to monopolar, bipolar loadability will be impacted by power losses starting at L500 km. [5][6]

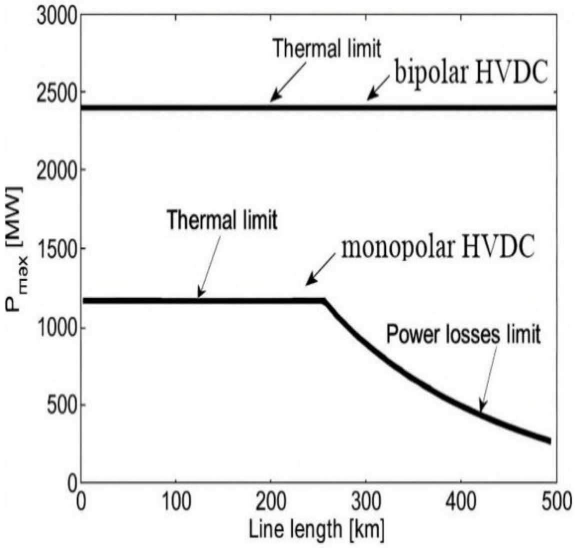

Fig. 3. Loadability characteristics of bipolar and unipolar (HVDC) lines [17], [19].

Optimization Objectives and Constraints

In this study, the Genetic Algorithm (GA) is employed to optimize the placement and operation of HVDC links in the AC power system. The GA aims to achieve multiple objectives simultaneously, including maximizing system loadability, improving voltage profiles, minimizing total power system losses, controlling power flow through overloaded transmission lines, and reducing overall generation costs. The objective function and constraints considered in the optimization process include:[21][22]

- Optimal HVDC location
- Minimization of total system losses
- Avoidance of line overloads (kept below 100%)
- Maintaining bus voltage magnitudes within acceptable limits.

IV. HVDC Placement

The optimal location for HVDC links is determined by analyzing variations in the power system and HVDC network parameters to identify the most effective transmission line for HVDC installation [23].

A. Minimization of Total System Losses

The GA selects HVDC route variables that minimize both AC network losses and interaction losses across transmission lines. The total active and reactive power losses can be calculated using the following equations:[24]

$$P_1 = \sum_{i=1}^{N1} G_{ij} [V_i^2 + V_j^2 - 2V_i V_j cos(\delta_i - \delta_j)] \qquad (16)$$

$$Q_1 = \sum_{i=1}^{N1} B_{ij} [V_i^2 + V_j^2 - 2V_i V_j \sin(\delta_i - \delta_j)] \qquad (17)$$

B. Overloaded Lines

The active and reactive power in each line is computed to identify overloaded lines and reduce excessive power flows:[25]

$$P_{Gi} - P_{Di} = V_i \sum_{i=1}^{Nb} V_j \left(G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right) \quad (18)$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{i=1}^{Nb} V_j \left(G_{ij} \sin(\delta_i - \delta_j) + B_{ij} \cos(\delta_i - \delta_j) \right) \quad (19)$$

C. The voltage deviation (VD)

The voltage deviation should be as small as feasible to provide good voltage regulation, and it may be shown as follows:[26]

$$V_D = \sum_{i=1}^{N_{pq}} \left| V_i - 1 \right|^2 \quad (20)$$

Where: Nb is the number of buses

$N1$ is the number of transmission lines.

Npq The quantity of load buses

$P1$ Active power losses

$Q1$ Reactive power loss

(PDi) The demand, or active load, on the bus (i)

QDi The demand, or reactive load, on bus (i)

PGi The active power generation at bus (i)

QGi The reactive power generation on the bus's (i); Vi The voltage magnitude at bus (i)

δi The phase angle of the voltage at bus (i)

D. Genetic Algorithm-Based Optimization

The MATLAB implementation of the GA encodes the HVDC location and sizing parameters as chromosomes. The algorithm iteratively optimizes these variables through standard GA operations: initialization, evaluation via a fitness function (Newton-Raphson power flow), selection, crossover, mutation, and termination. [27],[28]. The fitness function was formulated to minimize the total active power losses and transmission line overload index, subject to voltage magnitude limits (0.95–1.05 p.u.) and transmission line thermal constraints.

In Fig. (4) provides a summary of the optimization technique.

The objective function can be expressed as $F = min\ (sum\ Ploss\ +\ sum\ OL)$ [29], where $(Ploss)$ represents the total active power losses in the transmission system, and (OL) represents the transmission line overload index.

The main stages of the GA optimization procedure are illustrated in Fig. 4.

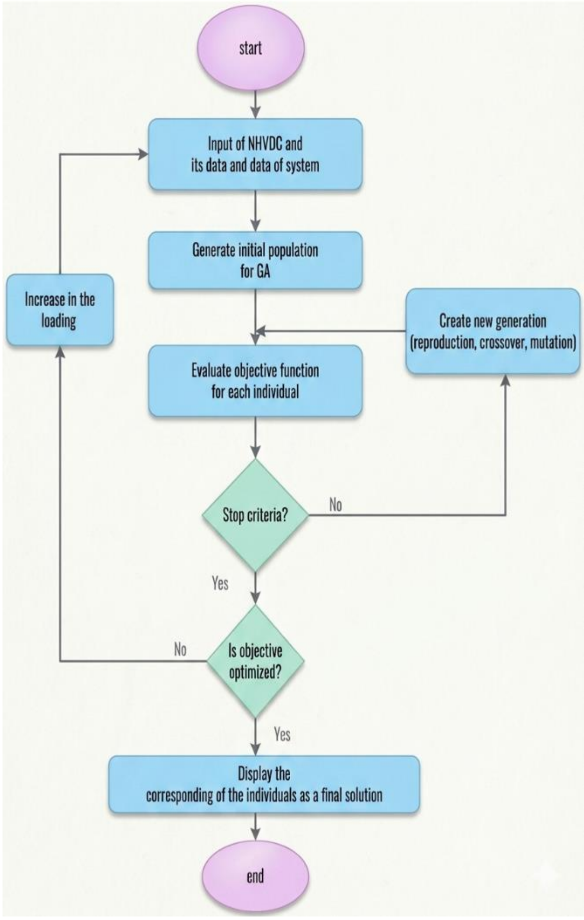

Fig. 4. Flow Diagram for HVDC Implementation Using GA.

The algorithm starts by initializing a population of candidate HVDC locations and ratings, followed by power flow analysis and fitness evaluation. Successive generations are produced through selection, crossover, and mutation operations until the stopping criterion is satisfied and the optimal solution is obtained.[30]

Table 1. Genetic Algorithm Parameters Used in the Optimization Process.

Parameter	Value
Population Size	80
Crossover Probability	0.85
Mutation Probability	0.02
Maximum Generations	100
Power Flow Method	Newton–Raphson

V. RESULTS AND DISCUSSION

A. Iraqi System of Super High Voltage (400kV)

The Iraqi (400 kV) super high voltage grid (ISHVG) is made up of 96 transmission lines, 115 400/132 kV transformers, 27 generating units, and

53 buses. The North, Middle, Euphrates, and South regions are the four operational sub-systems that make up the Iraqi electrical power system from the perspective of operational control. Bus and line statistics, as well as other ISHVG practical system data, are tabulated from [31]

All simulations were performed in PSS/E using a 100 MVA base and 50 Hz system frequency. The MT-HVDC link was modeled as a VSC-based system rated at 1000 MW with a ±500 kV DC voltage and 98% converter efficiency. Voltage limits were set to 0.95–1.05 p.u., and an ambient temperature of 25°C was assumed. Standard 400 kV overhead line parameters and steady-state operating conditions were considered to ensure reproducibility

B. Impact of MT-HVDC Integration on Total Power Generation and Grid Efficiency

A combined assessment of Figs. (5) and (6) highlights the impact of MT-HVDC integration on the performance of the ISHVG network.

The results show that MT-HVDC reduces the total active power generation requirement under all loading conditions. Although the generation demand increases as the loading level rises from the normal case to 10% and 20%, the MT-HVDC configuration consistently requires less active power generation than the conventional HVAC network due to reduced transmission losses and improved power flow controllability.

A similar behavior is observed for reactive power generation, where MT-HVDC decreases the overall reactive power requirement across all loading scenarios. The reactive power support provided by the VSC stations improves voltage regulation and reduces the burden on conventional generators.

Overall, MT-HVDC integration enhances network efficiency by lowering both active and reactive power generation requirements, leading to improved transmission performance and more effective utilization of network resources under increased loading conditions.

One of the major challenges facing the Iraqi Super High Voltage Grid (ISHVG) is the overloading of transmission lines, particularly during peak summer demand periods.

Under such conditions, several transmission corridors operate close to or beyond their thermal limits, which may lead to line outages, reduced system reliability, and an imbalance between generated and consumed power.

The obtained results as shown in Fig. (**7**) indicate that transmission line congestion increases significantly with the loading level in both network configurations.

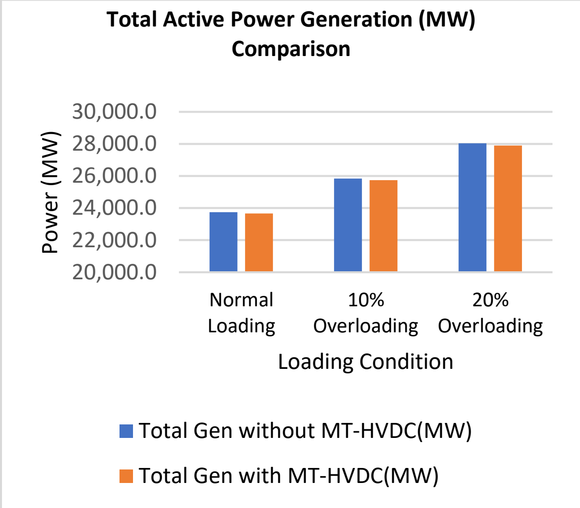

Fig. 5. Total Active Power Generation (MW) Comparison.

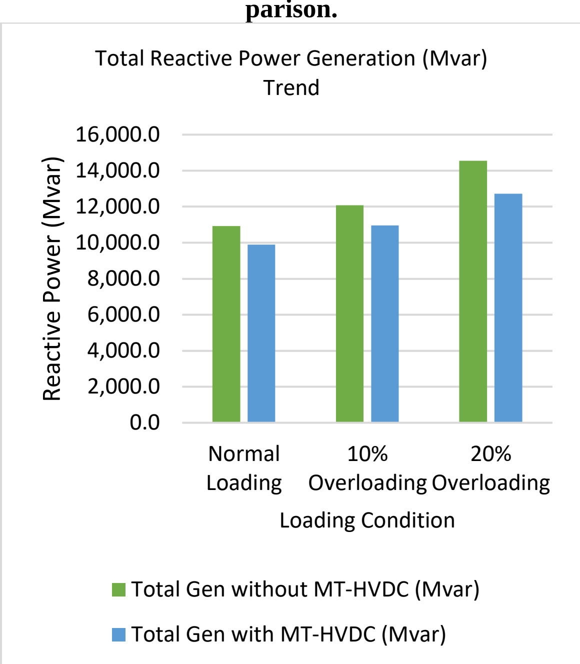

Fig. 6. Total Reactive Power Generation (Mvar) Trend.

C. Effect of MT-HVDC Integration on Transmission Line Loading

In the conventional HVAC network, the number of overloaded lines rises from 2 under normal loading conditions to 10 and 16 under 10% and 20% overloading conditions, respectively. The integration of MT-HVDC significantly reduces the number of overloaded transmission lines, limiting them to 1, 3, and 4 under normal, 10%, and 20% loading conditions, respectively. This improvement is attributed to the enhanced controllability of power flow provided by the MT-HVDC system, which enables a more balanced utilization of transmission corridors and alleviates the loading of critical lines. These findings clearly demonstrate the effectiveness of MT-HVDC technology in mitigating one of the most critical operational issues in the Iraqi power network. By relieving transmission congestion and redistributing power flows more efficiently, the proposed MT-HVDC configuration enhances network security, improves operational flexibility, and increases the capability of the system to accommodate higher loading levels without excessive stress on transmission assets.

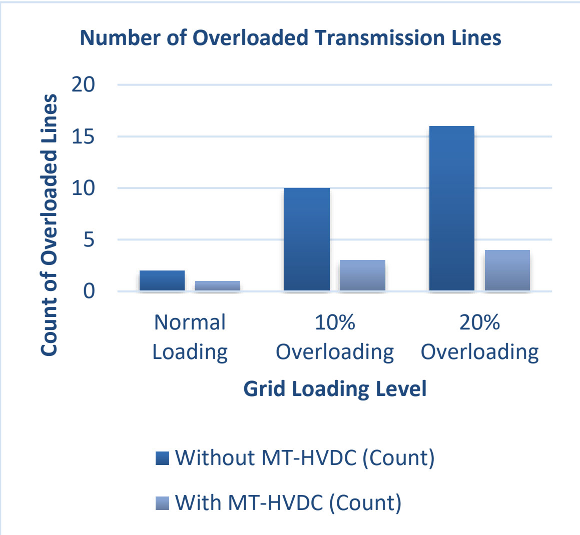

Fig. 7. Number of Overloaded Transmission Lines.

D. Impact of MT-HVDC Integration on Active and Reactive Power Losses

The total active and reactive power losses under different loading conditions are presented in Figs. (8) and (9). As the loading level increases from the normal operating condition to 10% and 20%, both active and reactive power losses increase due to the higher power transfer demand and increased network loading. Nevertheless, the integration of MT-HVDC consistently results in lower losses compared with the conventional HVAC configuration. The reduction becomes more pronounced at higher loading levels, indicating the capability of MT-HVDC to improve power flow distribution and alleviate network congestion. By providing additional controllability and flexible power routing, the MT-HVDC system mitigates excessive current flow in heavily loaded transmission corridors, thereby reducing both active and reactive power losses. These results demonstrate that MT-HVDC enhances transmission efficiency and supports secure operation of the ISHVG network under increased loading conditions.

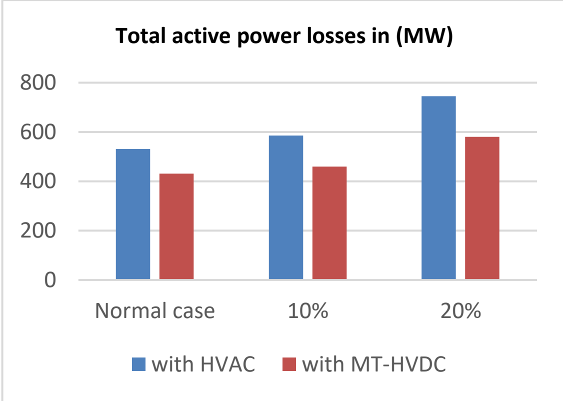

Fig. 8. Comparison of active power losses with and without MT-HVDC.

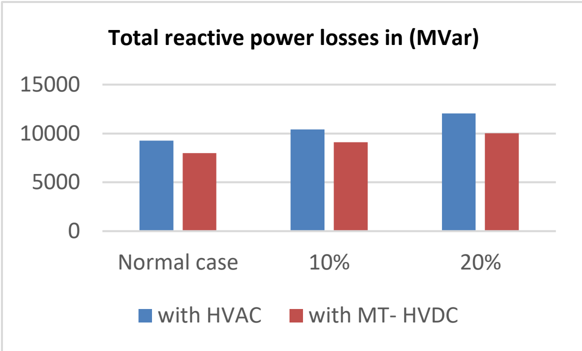

Fig. 9. Comparison of reactive power losses with and without MT-HVDC.

In other hands, the percentage reduction analysis of active and reactive power losses can be evaluated by

$$Loss\,Red. = (Losswo - Lossw / losswo) * 100\% \quad (21)$$

where, $Loss_{wo}$ and $Loss_{w}$ are the total losses without and with adding MT- HVDC

Table 3 illustrates the impact of adding the MT-HVDC system on loss reduction in terms of both active power (MW) and reactive power (Mvar).

Can show in the term 20% case, the reduction in active power losses increases to 22.2%, whereas the reduction in reactive power losses decreases to 11.77%, suggesting that the effect of MT-HVDC on MW losses is more stable than on Mvar losses as system conditions change.

Overall, the table demonstrates that integrating MT-HVDC leads to a considerable reduction in system losses across all studied cases, with a more consistent improvement observed in active power loss reduction compared to reactive power losses

After integrating MT-HVDC, as illustrated in Fig. 10, the loading profile becomes more balanced, and the highly stressed regions are significantly reduced.

Table 2. Losses reduction after adding MT-HVDC.

CASE	Reduction in losses %	
	MW	Mvar
Normal	22.5%	13.75%
10%	21.5%	12.70%
20%	22.2%	11.77%

The MT-HVDC configuration improves power flow controllability, redistributes transmission loading more effectively, and alleviates congestion in critical corridors, resulting in enhanced operational reliability and improved network stability under heavily loaded conditions

D. Analysis of Voltage Magnitude

Due to the transfer of a portion of the transmitted power through DC lines—which do not require reactive power support—the voltage drop along transmission lines is significantly reduced after integrating the MT-HVDC system compared to the conventional HVAC-only case.

As a result, the voltage magnitude at system buses is noticeably improved. Fig. (**10**), (**11**), and (**12**) illustrate the voltage magnitude profiles of all load buses in the ISHVG network before and after MT-HVDC integration under different loading conditions.

The results clearly show that the inclusion of MT-HVDC enhances voltage regulation and maintains bus voltages closer to their nominal values, particularly under increased load levels.

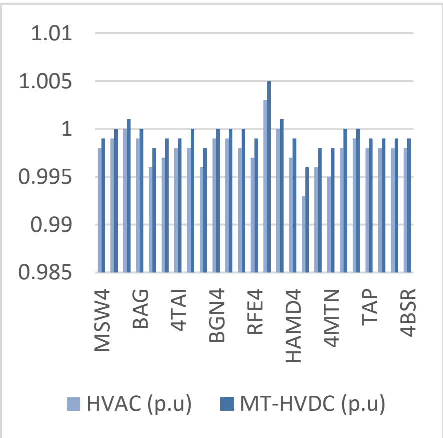

Fig. 10. ISHVG voltage profile under normal operating conditions.

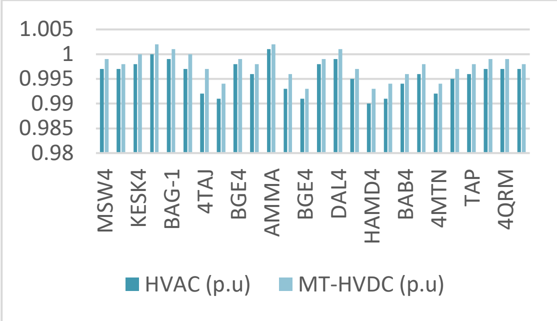

Fig. 11. ISHVG voltage profile under 10% operating conditions.

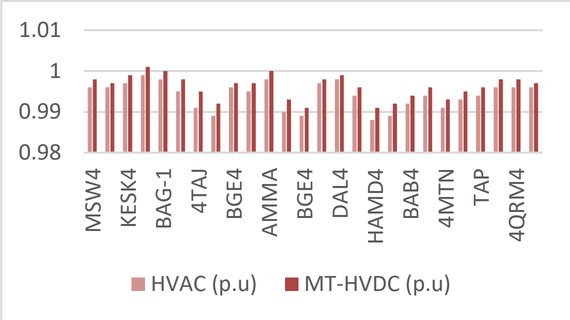

Fig. 12. ISHVG voltage profile under 20% operating conditions.

E. MT-HVDC's Ideal Position in ISHVG 400kv.

One of the plans is to build a VSC-based MT-HVDC to transport 1000 MW of additional power from the southern region at a rated DC voltage of ±500 kV. The parameters of the three terminals of the HVDC system-based VSC are provided in Table **7**. In other hand Fig. (**13**) shows a general geographical view of the optimal routes for the proposed MT-HVDC network for the Iraqi grid.

Tables 3. The parameters of three terminals of HVDC system based VSC.

Parameter	DC Line 1	DC Line 2	DC Line 3
Rectifier Bus Code	27401	16419	27401
Inverter Bus Code	16419	11402	11402
Rectifier Bus Name	RU-MILPP	BGS4	RU-MILPP
Inverter Bus Name	BGS4	KESK4	KESK4
Base Voltage (kV)	500	500	500
Transformer Ratio	0.9256	0.9256	0.9256
Rdc (Ω)	10.802	20.051	9.051
DC Power (MW)	1000	500	500

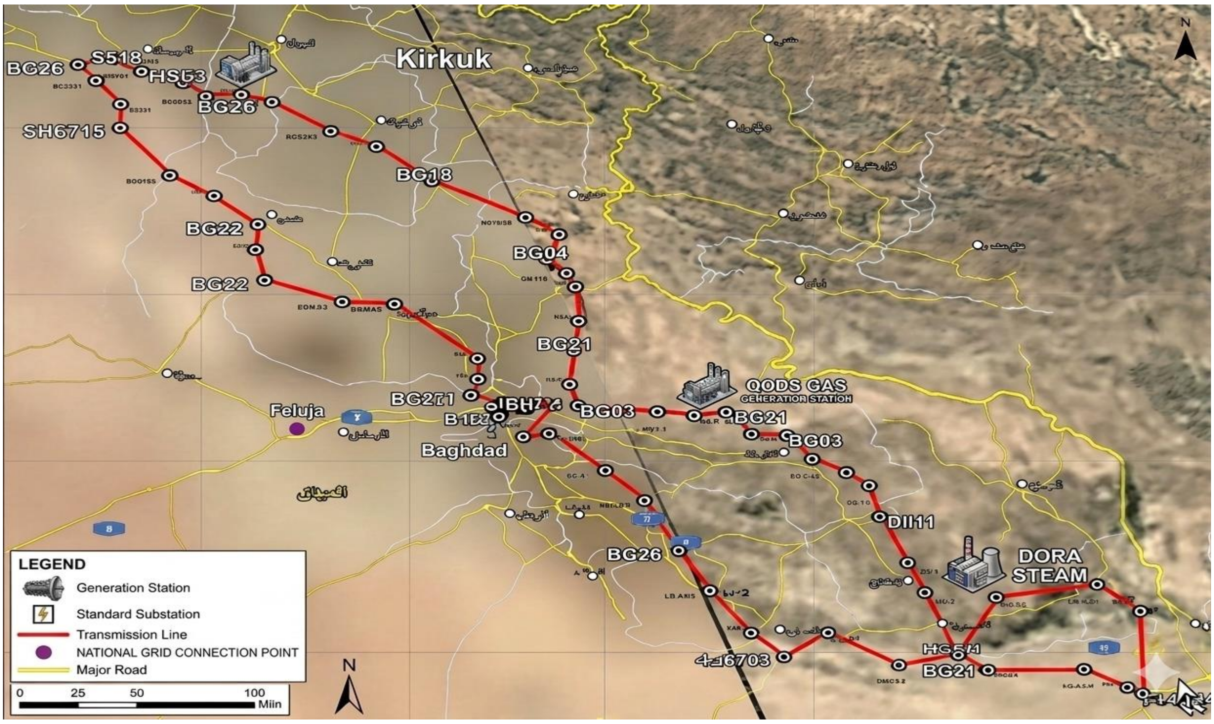

Fig. 13. The best paths of a MT-HVDC proposed for the Iraqi grid [18].

F. AC System and DC System Line Loadability

Assume that both AC and DC transmission lines are constructed using a conventional 500-km Aluminum Conductor Steel Reinforced (ACSR) line. Equations (19) and (20) are used to evaluate the loadability of AC transmission lines at power factors of 1.0 and 0.95. Table 8 presents the loadability characteristics of the AC transmission line under different line lengths and power factor conditions.

Table 4. AC transmission line loadability under different power factors.

PF	L(km)	I_{max}	I_{max}/I_{th}	P_{max}(MW)	P_{max}/P_0	ΔPL%
1	100	2038	1	1412	2.28	1.86
	200	1348	0.66	934	1.51	2.46
	300	1093	0.54	757	1.22	3
	400	994	0.49	689	1.11	3.36
	500	948	0.47	657	1.06	4.33
0.95	100	1085	0.53	714	1.15	1.04
	200	690	0.34	454	0.73	1.33
	300	613	0.304	403	0.65	1.77
	400	608	0.29	400	0.65	2.34
	500	627	0.31	413	0.67	3.01

The loadability of transmission lines is strongly affected by both line length and power factor. As the power factor decreases, the AC line loadability also decreases significantly over long transmission distances.

According to Table 8, the loadability ratio (Pmax/P0) for a 400-km AC line decreases from 1.11 at PF = 1 to 0.65 at PF = 0.95.

For the DC system, Equations (22) – (24) are used to evaluate the loadability characteristics of DC transmission lines. Table 9 presents the DC line loadability for bipolar and monopolar configurations under different transmission distances. Where can show the bipolar DC transmission maintains higher loadability and lower power loss variation over long transmission distances compared with monopolar operation.

In the monopolar configuration, the transferable power capability decreases significantly as the line length increases, whereas the bipolar configuration maintains stable transmission performance with lower loadability degradation.

Table 5. DC transmission line loadability for bipolar and monopolar configurations.

Configuration	**L(km)**	**Imax**	**I_{max}/I_{DCth}**	**P_{max}(MW)**	**ΔPL%**
For Bipolar	100	2400	1	2400	0.815
	200	2400	1	2400	1.63
	300	2400	1	2400	2.44
	400	2400	1	2400	3.24
	500	2400	1	2400	4.05
For Monopolar	100	2400	1	1200	1.65
	200	2400	1	1200	3.24
	300	2046	0.85	1023	4.15
	400	1535	0.64	767.5	4.155
	500	1228	0.51	614	4.15

V. CONCLUSION

The obtained results demonstrate that the integration of MT-HVDC technology can effectively address several critical operational challenges in the Iraqi 400-kV transmission network. The optimized hybrid AC/DC configuration significantly reduced transmission losses, mitigated line overloading, and maintained acceptable voltage levels under both normal and stressed operating conditions. The reduction in overloaded transmission lines from 16 to 3 under a 20% load increase highlights the capability of the proposed configuration to relieve network congestion and improve system reliability. The optimization process identified RU-MILPP, BGS4, and KESK4 as the most suitable locations for MT-HVDC terminals, providing an efficient transmission topology for large-scale power transfer across the Iraqi grid. Given the large-scale nature of the Iraqi 400-kV network, which consists of numerous buses and high-voltage transmission lines, determining the optimal MT-HVDC integration locations using conventional trial-and-error or random selection approaches would be computationally inefficient and impractical. Therefore, the Genetic Algorithm proved to be an effective optimization tool for rapidly identifying optimal converter station locations and transmission corridors while satisfying the technical constraints of the network. From a practical perspective, the proposed framework offers a realistic planning tool based on actual Iraqi grid data and demonstrates the technical feasibility of deploying MT-HVDC technology within the national transmission system. The enhanced transmission capability and operational flexibility achieved by the proposed configuration can support future renewable energy integration, strengthen energy security, and facilitate potential interconnections with neighboring power systems.

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