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Performance Optimization of Hybrid AC-DC Power Systems with HVDC, SSSC, and STATCOM: Advanced Control and Optimization Strategies

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Abstract: - This study focuses on the AC-DC load flow challenge in hybrid power systems, incorporating Flexible AC Transmission System (FACTS) devices such as the Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM). To improve system performance, an innovative Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm is developed for the optimal placement and operation of these devices. The methodology involves detailed mathematical modeling of AC-DC links, FACTS devices, and the formulation of an optimization problem targeting reduced power losses, improved voltage stability, and system reliability. Simulation results on IEEE test systems show the efficiency and reliability of the suggested method, showing significant improvements in voltage profiles, loss minimization, and overall system stability. The superior performance of HCB-GPSO compared to existing optimization techniques underscores its potential for addressing complex operational challenges in modern power systems.

Keywords: AC-DC Load flow, FACTS devices, SSSC, STATCOM, Optimization, HCB-GPSO.

I. INTRODUCTION

The growing complexity of modern power systems is largely influenced by the integration of renewable energy sources (RES), growing demand, and stringent reliability requirements, has necessitated advanced techniques for system analysis and optimization. Hybrid AC-DC power systems, combining alternating (AC) and direct current (DC) transmission technologies, have emerged as a viable solution for addressing these challenges. These systems offer improved transmission efficiency, enhanced power quality, and greater flexibility in incorporating diverse energy resources, including solar, wind, and traditional fossil fuels. However, the seamless operation of hybrid networks requires effective management of power flow, voltage stability, and loss minimization, particularly under varying load and generation conditions.

The AC-DC load flow problem lies at the heart of hybrid power system operation. It involves the simultaneous analysis of AC and DC networks, considering the interdependencies between them. The introduction of high-voltage direct current (HVDC) systems further complicates this analysis due to the nonlinear characteristics of AC-DC converters. The traditional Newton-Raphson and Gauss-Seidel methods often struggle to handle these complexities efficiently, especially in large-scale networks with high penetration of RES. To overcome these challenges, power electronic devices like the Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) have been integrated into power systems. These Flexible AC Transmission System (FACTS) devices provide dynamic control over power flows and voltage levels, enhancing system stability and reliability.

Despite their advantages, the optimal deployment and operation of SSSC and STATCOM remain a significant challenge. Determining their placement and settings in a hybrid AC-DC network requires solving a multi-objective optimization problem that considers diverse criteria such as loss reduction, voltage regulation, and cost minimization. Conventional optimization techniques, such as genetic algorithms (GA), particle swarm optimization (PSO), and differential evolution (DE), often struggle with issues related to convergence speed, solution accuracy, and overall robustness when applied to such intricate problems.

The summarized critical literature review and its key contributions

References	Key Contributions	Remarks
Hybrid AC-DC System Integration and Power Flow Modeling		
Dahane and Sharma [1], Kaur and Sharma [2], Ahmed et al. [5], Eajal et al.	- Analyzed coordinated control strategies for hybrid AC-DC grids. - Explored power flow methodologies for modular multi-terminal hybrid systems.	Practical implementation is hindered by oversimplified assumptions. Scalability to real-world networks is still a challenge.

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[6], Ding and Zhang [7], Hu et al. [8]	- Developed adaptive power flow algorithms for dynamic hybrid networks.	
FACTS Devices for Power Flow Control and Stability Enhancement		
Sharma et al. [3], Haroon et al. [4], Nasir and Bakar [9], Zhao and Liu [10], Kumar and Agarwal [11], Bhuiyan and Rahman [12]	- Reviewed STATCOM and SSSC applications in hybrid power systems. - Investigated multi-device coordination strategies for voltage regulation and power stability. - Explored optimization approaches for FACTS placement in renewable-heavy grids.	Most studies focus on individual FACTS devices rather than their coordinated operation. Need for AI-based multi-device coordination strategies.
Optimization Algorithms for Hybrid System Control		
Ali et al. [15], Pathak and Hota [14], Bhattacharya and Khatun [17], Kumar et al. [18], Mondal and Rahman [19]	- Introduced hybrid optimization models combining PSO, GSA, and CSA. - Demonstrated improved convergence rates for hybrid AC-DC optimization. - Addressed challenges in renewable energy management through advanced algorithms.	Hybrid optimization models improve efficiency but face scalability challenges in real-time implementation. Need for lightweight algorithmic adaptations.
Renewable Energy Integration and Grid Stability		
Vignesh and Varadharajan [20], Akhtar and Zaman [21], Saha and Mondal [22], Usman and Khatab [16], Mondal and Rahman [19]	- Examined FACTS-based solutions for stabilizing renewable-heavy grids. - Developed optimization models to mitigate power fluctuations caused by variable RES generation. - Investigated control strategies for managing high RES penetration.	Current research often neglects grid inertia effects due to high RES penetration. Future work should incorporate comprehensive modeling and control strategies.
Hybrid Optimization for Power Flow Challenges		
Ali et al. [15], Ranjan and Singh [23], Patil and Karajgi [24], Saha and Mondal [22], Wang and Wei [25]	- Investigated the combination of evolutionary algorithms (PSO, CSA, GSA) for improved convergence and accuracy. - Explored the impact of deregulation on FACTS placement optimization. - Proposed integrated hybrid models for enhancing large-scale system stability.	Hybrid optimization frameworks excel in theoretical studies but require real-world validations under dynamic conditions. Need for experimental validation in diverse operational scenarios.

In this context, the Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm is proposed as an innovative solution. HCB-GPSO combines the strengths of Cuckoo Search (CS), Modified BAT Algorithm (MBAT), The Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm integrates the Gravitational Search Algorithm (GSA) and Particle Swarm Optimization (PSO) to enhance optimization performance. By utilizing the exploratory ability of Cuckoo Search (CS), the exploitation efficiency of the Modified BAT Algorithm (MBAT), the global search capability of GSA, and the convergence stability of PSO, HCB-GPSO offers a robust framework for addressing the AC-DC load flow problem in systems incorporating SSSC and STATCOM.

This paper presents a comprehensive approach to modeling and optimizing hybrid AC-DC power systems. The mathematical models for AC-DC links, SSSC, and STATCOM are developed, incorporating their operational characteristics into the load flow analysis. The optimization problem is formulated with the primary objectives include reducing transmission losses, optimizing voltage profiles, and enhancing overall system stability. The HCB-GPSO algorithm is utilized to identify the optimal placement and parameter settings of FACTS devices, ensuring the efficient and reliable performance of the power system.

Simulation studies are conducted on standard IEEE test systems to validate the proposed approach. The results demonstrate significant improvements in voltage stability, loss minimization, and system performance, highlighting the effectiveness of HCB-GPSO over conventional optimization techniques. This work provides a valuable contribution to the field of power system optimization, offering practical insights into the deployment of advanced optimization algorithms and FACTS devices in modern hybrid networks.

This paper is structured as follows: Section 2 covers the modeling of power flow problems, including the mathematical representation of AC-DC links, SSSC, and STATCOM. Section 3 defines the optimization problem, detailing objectives, equality, and inequality constraints. Section 4 introduces the HCB-GPSO algorithm along with its implementation methodology. Section 5 presents the simulation results and their analysis. Lastly, Section 6 concludes the paper by summarizing key findings and suggesting future research directions.

II. MODELING OF POWER FLOW PROBLEM FORMULATION

This section presents the mathematical and analytical framework for tackling power flow challenges in hybrid AC-DC systems. It highlights the integration of HVDC links and Flexible AC Transmission System (FACTS) devices into conventional AC networks, emphasizing their contributions to improving system stability, efficiency, and reliability.

A. Mathematical modeling of AC-DC link

The AC-DC power flow model is vital for integrating renewable energy sources and improving the transmission efficiency of hybrid systems. This model must account for the interactions between AC and DC components, including rectifier and inverter operations. The arrangement of various components in an HVDC link is illustrated in Fig.1. The voltages of the AC network at the sending and receiving end buses are denoted as ‘V_s’ and ‘V_r’ respectively. These buses typically connect active and reactive loads, similar to those in conventional AC systems. The sequence begins with a transformer at the sending end bus, which adjusts voltage levels as required by the rectifier. Following voltage transformation, the rectifier converts AC voltage into a DC voltage denoted as ‘V_{dr}’, with the associated DC current represented as ‘I_d’. At the receiving end, the inverter converts the incoming DC voltage ‘V_{di}’ back into AC, and another transformer modifies this voltage to meet the requirements of the receiving end AC bus. This bus then connects to the rest of the AC network. Complete AC-DC load flow modeling is given in Yadaraju and Kumar (2024) [26].

In the context of Line Commutated Converter (LCC)-based HVDC systems, reactive power consumption is an inherent characteristic. The rectifier draws reactive power in the forward direction from the sending end (‘S’), while the inverter draws reactive power in the reverse direction at the receiving end (‘R’). In a sequential modeling approach, the effects of the rectifier and inverter are represented as equivalent power injections at their respective buses, thereby simplifying their impact on the overall network.

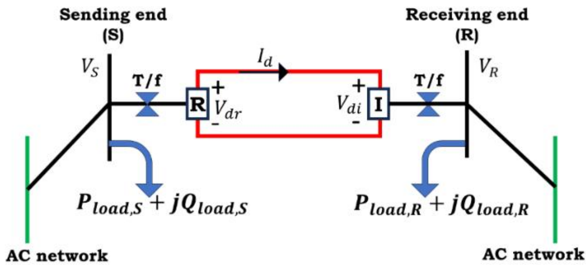


Fig.1 HVDC link configurations within an existing AC network

Figure 2 illustrates the power injection model of the HVDC link. In this representation, ‘P_{dr}’ and ‘Q_{dr}’ denote the active and reactive power injections from the rectifier at the sending end bus (‘S’), while ‘P_{di}’ and ‘Q_{di}’ correspond to the inverter's injections at the receiving end bus (‘R’). These power injections are then incorporated into the Newton-Raphson AC power flow algorithm to determine the net power values. By modeling the DC link’s influence as equivalent power injections at the respective buses, this approach simplifies its integration into the overall power flow analysis.

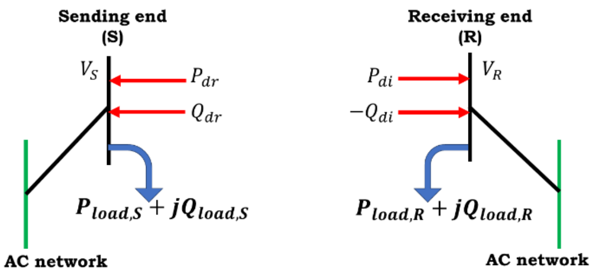


Fig.2 HVDC Link Equivalent Power Injection Model

Sending end (Rectifier Unit)

The sending end is where the AC network feeds power into the rectifier to convert it into DC for transmission. Key components and equations are:

Active Power (P_{dr}): This represents the DC power delivered by the rectifier, as calculated by:

$$P_{dr} = V_{dr} \times I_d = V_{dr} \times \left(\frac{V_{dr} - V_{di}}{R_{dc}}\right) \tag{1}$$

Here, V_{dr} is the rectifier's output voltage, I_d is the DC current, and R_{dc} is the resistance of the DC transmission line.

Reactive Power (Q_{dr}): The rectifier requires reactive power for its operation, which is determined by the active power (P_{dr}) and the power factor angle (ϕ_r), calculated as:

$$Q_{dr} = P_{dr} \times \tan(\phi_r) \tag{2}$$

The rectifier requires reactive power for its operation, which is primarily supplied by different sources. One major source is the AC grid, which provides reactive power through the sending-end bus to support the rectifier's functioning. Additionally, capacitor banks and Static VAR Compensators (SVCs) are often installed near rectifiers to enhance voltage stability and ensure a steady supply of reactive power. Another important source is synchronous condensers, which dynamically compensate for reactive power variations and help maintain stable voltage levels in the system.

Receiving End (Inverter Unit)

The receiving end is where the DC power is converted back into AC by the inverter to supply the AC network or loads.

Active Power (P_{di}): This is the DC power delivered to the inverter and converted to AC. It is calculated by:

$$P_{di} = V_{di} \times I_d \tag{3}$$

Here, V_{di} is the inverter's input DC voltage, and Id is the DC current.

Reactive Power (Qdi): The inverter absorbs or delivers reactive power, depending on its operating conditions. This is calculated using:

$$Q_{di} = P_{di} \times \tan(\phi_i) \tag{4}$$

where ϕi is the inverter's power factor angle.

At the inverter end, reactive power is essential for converting DC power back into AC and integrating it into the receiving-end grid. One of the main sources is the receiving-end AC grid, which can either supply or absorb reactive power depending on the system's operational conditions. Additionally, shunt capacitors and STATCOMs play a crucial role in voltage regulation and dynamic reactive power compensation. Phase-shifting transformers also contribute by controlling reactive power flow and improving power transfer efficiency in hybrid AC-DC networks.

B. Mathematical modeling of Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a FACTS device designed to regulate power flow and enhance voltage stability in power systems. It achieves this by injecting a controllable AC voltage in series with the transmission line, thereby compensating for voltage drops. This alters the receiving end voltage, with compensation typically ranging from 20% to 80% of the line reactance. The SSSC is integrated into the transmission network through a coupling transformer, while its voltage source converter generates a voltage that is 90° out of phase with the line current. The connection of SSSC in a transmission line with impedance (ZLine) along with-it coupling transformer is shown in Fig.3.

The SSSC operates in two modes:

- Inductive Mode: Injected voltage causes current to lag, increasing line reactance and reducing active power flow.
- Capacitive Mode: Injected voltage causes current to lead, decreasing line reactance and increasing active power flow.

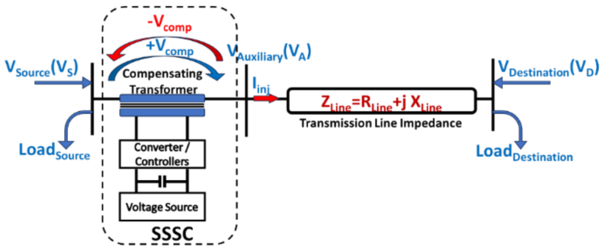


Fig.3 SSSC connected in a transmission line

The SSSC is represented by injecting both active and reactive power at its connection points within the network. The resulting power injection model of the SSSC is illustrated in Fig. 4 [9-11].

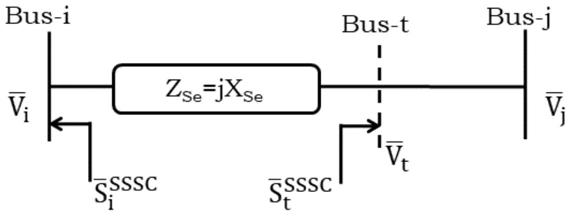


Fig.4 Final power injection model of SSSC

The active and reactive powers injected at bus-i can be expressed as

$$P_i^{SSSC} = V_i V_{se} B_{se} \sin(\delta_i - \theta_{se}) \;\;\&\;\; Q_i^{SSSC} = -V_i V_{se} B_{se} \cos(\delta_i - \theta_{se}) \tag{5}$$

Similarly, the active and reactive powers injected at bus-t can be expressed as

$$P_t^{SSSC} = V_t V_{se} B_{se} \sin(\delta_t - \theta_{se}) \;\;\&\;\; Q_t^{SSSC} = -V_t V_{se} B_{se} \cos(\delta_t - \theta_{se}) \tag{6}$$

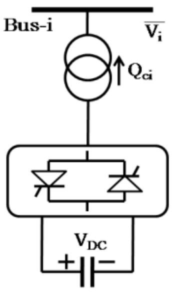
C. Mathematical modeling of Static Synchronous Compensator (STATCOM)

A STATCOM is a device connected to the power system to help control voltage and provide reactive power compensation. It is commonly used to improve voltage stability in systems where there is a sudden change in power consumption.

STATCOM is used to control the voltage at a bus (a point in the power system) that needs support for reactive power. When there is a sudden change in load, the voltage may drop. The connection of STATCOM with a voltage source of "VDC" at bus-i is shown in Fig.5. The STATCOM helps in such situations by either:

Injecting reactive power to raise voltage levels (capacitive mode).

Absorbing reactive power to lower voltage levels (inductive mode).



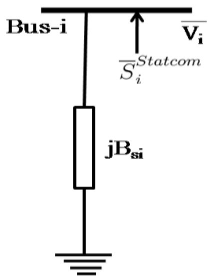


Fig.5 STATCOM connected at bus-i Fig.6 Final power injection model of STATCOM

The STATCOM is modeled by injecting active and reactive power at its connection buses. The final power injection model of SSSC is shown in Fig.6 [9-11].

The active and reactive powers injected at bus-i can be expressed as

$$P_i^{STATCOM} = V_i V_{si} B_{si} \sin(\delta_i - \theta_{si}) \;\;\&\;\; Q_i^{STATCOM} = -V_i V_{si} B_{si} \cos(\delta_i - \theta_{si}) \tag{7}$$

D. Power flow incorporation procedure

The process for integrating devices like SSSC and **STATCOM** into power flow analysis can be summarized as follows:

Power mismatches: Add the injected power terms to the power mismatch equations

$$\Delta P_i^{new} = \Delta P_i^0 + P_i^{device}; \Delta Q_i^{new} = \Delta Q_i^0 + Q_i^{device} \tag{8}$$

Jacobian matrix: Adjust the partial derivatives in the Jacobian to include the device's impact

$$\frac{\partial P_p^{new}}{\partial \delta_p} = \frac{\partial P_p^0}{\partial \delta_p} + \frac{\partial P_p^{SSSC}}{\partial \delta_p}; \frac{\partial P_p^{new}}{\partial \delta_q} = \frac{\partial P_p^0}{\partial \delta_q} + \frac{\partial P_p^{SSSC}}{\partial \delta_q} \tag{9}$$

E. Optimal location of SSSC and STATCOM

To optimize the placement of SSSC and STATCOM for improving system stability and performance, a severity-based index approach is used. These indices help identify the most critical locations under contingency conditions.

For SSSC

The severity index for transmission line overloading under contingency is calculated as: $\text{Severity Index}_k =$

$$\sum_{i=1}^{N_{OL}} \left(\frac{S_{flow,i}}{S_{flow,i}^{max}}\right)^2 \;\; ; \;\; k \,\forall\, N_{Contingencies} \tag{10}$$

Here, NOL is the total number of overloaded transmission lines under kth contingency.

Fuzzy Logic Line Loading Indicator (FLLI) assigns weights to line loading severities:

Low Severity: Min(SI)×0.25
Moderate Severity: 0.5×Max(SI)
High Severity: 0.75×Max(SI)
Critical Severity: Max(SI)×1.00

$$\text{FLLI Formula: } \mathrm{FLLI_k} = \mathrm{W_{SI}} \times \sum_{i=1}^{N_{OL}} \left(\frac{S_{flow,i}}{S_{flow,i}^{max}}\right)^2 \quad ; \quad k \forall N_{Contingencies} \tag{11}$$

To determine the optimal placement of an SSSC, calculate the Fuzzy Logic Line Loading Indicator (FLLI) for all contingencies and identify the transmission line contributing the least to the highest FLLI for installation, as this minimizes system severity. Lines connected to tap-changing transformers or to buses with shunt capacitors or generators are excluded from consideration to ensure effective and practical placement.

For STATCOM

The severity index for bus voltage violations under contingency is calculated as:

$$\text{Severity Index}_k = \sum_{i=1}^{N_{VB}} \left(\frac{V_i - V_i^{nom}}{V_i^{nom}}\right)^2 \quad ; \quad k \forall N_{Contingencies} \tag{12}$$

Here, NVB is the total number of voltage violated buses under kth contingency.

The FVVI assigns weights to voltage violation severities:

Low Severity: Min(SI)×0.25
Moderate Severity: 0.5×Max(SI)
High Severity: 0.75×Max(SI)
Critical Severity: Max(SI)×1.00

$$\text{FVVI Formula: } \mathrm{FVVI_k} = \mathrm{W_{SI}} \times \sum_{i=1}^{N_{VB}} \left(\frac{V_i - V_i^{nom}}{V_i^{nom}}\right)^2 \quad ; \quad k \forall N_{Contingencies} \tag{13}$$

To determine the optimal placement of a STATCOM, calculate the Fuzzy Logic Voltage Violation Indicator (FVVI) for all contingencies and identify the bus contributing the least to the highest FVVI for installation, as this helps mitigate voltage violations. Buses connected to lines with tap-changing transformers or those already connected to shunt compensators are excluded to ensure effective and practical placement.

F. General Steps for Both Devices:

- Define Contingencies: Identify system contingencies (e.g., overloaded lines or voltage violations).
- Calculate Severity Indices: Use SI formulas for lines (SSSC) or buses (STATCOM).
- Apply Fuzzy Logic: Assign weights and calculate FLLI (for SSSC) or FVVI (for STATCOM).
- Select Optimal Location: Identify the line or bus that minimizes the maximum system severity.
- Exclude Ineligible Locations: Apply constraints such as transformer and shunt connections.

This approach ensures the effective placement of FACTS devices to enhance system reliability and stability.

III. OPTIMIZATION PROBLEM FORMULATION

The Optimal Power Flow (OPF) problem is a fundamental optimization task in power systems, aiming to optimize specific objectives while maintaining operational constraints. It can be expressed in a general mathematical form:

$$\text{Minimize } F(x,u) \quad \text{Subjected to } g(x,u)=0 \; ; \; h(x,u)\leq 0 \tag{14}$$

State variables (**x**) consist of dependent variables, including active power generation at the slack bus ($\mathbf{P_{g,slack}}$), voltage magnitudes at load buses ($\mathbf{V_L}$), reactive power outputs of generators ($\mathbf{Q_g}$), and apparent power flows in transmission lines ($\mathbf{S_{line}}$). Control variables (**u**) represent independent variables such as active power outputs of generators ($\mathbf{P_g}$), generator voltage levels ($\mathbf{V_g}$), transformer tap settings (**T**), and reactive power outputs of VAR sources ($\mathbf{Q_{VAR}}$).

*A. **Equality** constraints*

These constraints are generally expressed through power flow equations, which are efficiently solved using the Newton-Raphson load flow method:

$$P_i - P_{d,i} = \sum_{j=1}^{N} |V_i||V_j|Y_{ij}\cos(\theta_{ij} + \delta_j - \delta_i) \tag{15}$$

$$Q_i - Q_{d,i} = -\sum_{j=1}^{N} |V_i||V_j|Y_{ij}\sin(\theta_{ij} + \delta_j - \delta_i) \tag{16}$$

where:

- Pi and Qi are the active and reactive power generations at bus i,
- Pd,i and Qd,i are the active and reactive power demands at bus i,

- N is the total number of buses in the system,
- Yij is the admittance magnitude between buses i and j,
- θij is the admittance angle between buses i and j,
- Vi and Vj are the voltage magnitudes at buses i and j,
- δi and δj are the voltage phase angles at buses i and j.

These equations model the active and reactive power flow between interconnected buses in a power system.

B. ***In-****equality* ***constraints***

The constraints for various system components are defined as follows:

- Voltage limits at generator buses: $V_{G_i}^{min} \leq V_{G_i} \leq V_{G_i}^{max}$
- Limits on active power generation: $P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max}$
- Tap setting limits for transformers: $T_i^{min} \leq T_i \leq T_i^{max}$
- Limits on reactive power generation by capacitors: $Q_{sh_i}^{min} \leq Q_{sh_i} \leq Q_{sh_i}^{max}$
- Limits on transmission line power flows: $S_{l_i} \leq S_{l_i}^{max}$
- Limits on reactive power generation: $Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max}$
- Limits on voltage magnitudes at load buses: $V_i^{min} \leq V_i \leq V_i^{max}$

To generalize the problem presented in Equation (14), penalty factors are introduced, leading to the following formulation:

$$\min(f(x) + \sum \lambda_i g_i(x)) \tag{17}$$

where λi denotes the penalty coefficients, which are assigned large positive values. The limit values for the variables are defined as xmin≤xi≤xmax

Here, xi represents the variable being constrained, and it must lie within its specified minimum (x_{min}) and maximum (x_{max}) bounds.

IV. OBJECTIVES CONSIDERED

Performance parameters are critical in evaluating the effectiveness of AC-DC power systems, especially when integrating HVDC links and supplementary controllers.

A. *Total power losses*

Total power loss is one of the most important parameters to be considered for analyzing the performance of the power system. This helps to plan the system operation to increase efficiency and to supply continuous power to load centers. This directly influences operational costs, investment decisions, and overall energy savings. Generator scheduling in a power system can be optimized to enhance voltage stability and reliability while minimizing flue gas emissions and tariffs. Active power losses in the system can be determined using line parameters, including resistance and the voltages at the sending and receiving end buses.

In order to calculate total power losses, initially active (Pi) and reactive (Qi) power at bus 'i' can be calculated using voltages (Vi, Vj), phase angles (θi, θj) and connecting line conductance (Gij), susceptance (Bij) is

$$P_i = V_i \sum_{j=1}^{N} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) ;\ Q_i = V_i \sum_{j=1}^{N} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \tag{18}$$

The active power losses in a transmission line connecting buses 'i' and 'j' can be calculated as

$$P_{ij} = G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}\right) \tag{19}$$

The total system losses can be evaluated by adding the line losses (Eqn.19) of all transmission lines, and expressed as

$$Obj_{TPL} = \sum_{j>i}^{nl} P_{ij} \tag{20}$$

This can be calculated using load flow solution procedure by following the below steps

- Calculate admittance matrix (Ybus)
- Solving power flow equations
- Calculating individual line losses
- Calculating total power losses in system.

B. *Voltage deviation*

It is one of the most challenging performance parameters to decide the voltage stability of the power system. It is calculated by taking the difference between the actual voltage at a bus and the nominal voltage or desired voltage level. It directly impacts the system reliability and there by the efficiency of the system. This factor mainly depends on the load performance/characteristics to avoid problem of over voltage, under voltage, voltage fluctuations, voltage flickering, etc. The power quality of a system is decided by this performance parameter. Initially, the specified/nominal voltage is given (Vnominal) and the actual voltage (Vactual) value at buses is obtained after solving load flow problem. The voltage deviation at bus 'i' can be expressed as

$$\Delta V_i = \left| V_{actual,i} - V_{nominal} \right| \tag{21}$$

This can also be expressed in percentage as

$$\%\ \text{Voltage deviation} = \frac{\Delta V_i}{V_{nominal}} \times 100 \tag{22}$$

Total system voltage deviation can be calculated by adding all individual bus voltage deviations can be expressed as

$$Obj_{vdev} = \sum_{i}^{NB} \Delta V_i \tag{23}$$

C. Transmission efficiency

This parameter is helps to improves effectiveness of the power transmission network to deliver maximum power to the load centers from generation stations. The critical conditions, changes in the power flow through the transmission lines, changes in the load impacts the transmission efficiency. HVDC links directly impacts the transmission voltage and improves the power factor. This also helps to analyze and fix the need of system maintenance operational schedules.

After solving load flow problem, the power generation at slack bus is updated. Using this, the power generation at all PV buses is added to obtain total active power generation (Pgen). It was given in the system data, the total load in terms of active (Pload) and reactive (Qload) loads. The transmission efficiency can be expressed as

$$Obj_{efficiency} = \frac{P_{Load}}{P_{Generation}} \times 100 \tag{24}$$

D. Corona loss

This loss is due to the ionization of surrounding air of the conductor when the intensity of the applied electric field is greater than the critical voltage. The formation of corona in HVDC systems is having similar characteristics as that of in AC systems. However, the calculations is different due to the nature of electrical field and steady state operating DC voltages. Mostly, the voltage level, conductor dimensions, conductors spacing, environmental conditions, surface conditions, etc plays crucial role while estimating the corona in DC systems.

The commonly used mathematical expression to calculated corona loss (Pc-kW/km/phase) in DC link having radius (r- 1.5 centimeters) with conductor spacing (D-5 meters) operating at sending end rectifier voltage of (Vdr-kV) using modified Peek's formula is

$$Obj_{Corona\ loss} = P_c = 2 \times 10^{-5} \times V_{dr}^2 \times \left(\frac{D}{r}\right)^2 \times e^{-\frac{V_0}{V_{dr}}} \tag{25}$$

Where, 'V0' is critical disruptive voltage for DC (kV). This voltage can be calculated using an expression by considering the continuous nature of DC voltage in terms of surface irregularity factor (m with 0.85) and disruptive critical voltage gradient (gdc is 21.2 kV/cm under standard operating conditions) is

$$V_0 = m \times g_{dc} \times r \times \ln\left(\frac{D}{r}\right) \approx 157.4\ \text{kV} \tag{26}$$

It is necessary to decrease the effect of corona in HVDC systems by increasing conductor size, conductor spacing, improving surface, etc. The only parameter which effects corona loss is operating voltage of rectifier (Vdr). By managing and maintaining this voltage, the reliability, efficiency and operation can be enhanced for long distance transmission systems.

V. PROPOSED HYBRID CUCKOO-BAT-GRAVITATIONAL PSO (HCB-GPSO)

A new hybrid optimization algorithm, integrating elements [15, 24, 48] from the Cuckoo Search Algorithm (CSA), Modified BAT Algorithm (MBAT), Gravitational Search Algorithm (GSA), and Uniform Distribution Two-Stage Particle Swarm Optimization (UDTPSO). The algorithm name is Hybrid Cuckoo-BAT-Gravitational PSO (HCB-GPSO). This algorithm combines the strengths of Cuckoo Search (CSA), Modified BAT (MBAT), Gravitational Search Algorithm (GSA), and Particle Swarm Optimization (PSO) to enhance optimization efficiency. Each of these algorithms contributes a unique mechanism that improves different aspects of the search process—exploration, exploitation, convergence, and diversity.

A. Cuckoo Search Algorithm (CSA)

Purpose: Enhance exploration and prevent premature convergence.

Exploration Capability: CSA uses Levy flights, which allows for random but long jumps in the search space, ensuring that the algorithm explores distant regions early in the optimization process. This mechanism reduces the chance of getting stuck in local optima.

Efficient Search Mechanism: By simulating the parasitic behavior of cuckoos laying eggs in other birds' nests, CSA replaces poorly performing solutions (nests) with better-performing ones, ensuring that bad solutions are removed early.

Balancing Exploration: The probability of abandoning a nest (pa) ensures that there is enough exploration without overdoing it.

Necessary: In problems with complex landscapes, where the global optimum is far from the starting points, CSA ensures that the algorithm doesn’t miss critical areas of the search space and avoids local optima traps.

B. Modified BAT Algorithm (MBAT)

Purpose: Improve local search exploitation and fine-tune solutions near the optimum.

Exploitation through Echolocation: The BAT algorithm simulates bats adjusting their pulse rate and loudness to fine-tune their search near potential prey. This mechanism helps to precisely navigate toward the best solutions, making it ideal for local search once the algorithm identifies promising regions.

Balancing Exploration and Exploitation: MBAT adjusts the pulse rate and loudness dynamically during iterations, which allows for a smooth transition from wide exploration to focused exploitation. This is essential as it ensures that the algorithm performs a global search in the beginning but concentrates on the best areas later.

Velocity Update: BAT’s velocity update mechanism ensures that particles have diverse movements, enabling them to search for both global and local optima effectively.

Necessary: After exploring the search space, MBAT's fine-tuning capability ensures that the algorithm zeroes in on the best solution efficiently by balancing global and local search. This is especially useful when refining candidate solutions close to the optimum.

C. Gravitational Search Algorithm (GSA)

Purpose: Improve diversity and adaptive search based on agents' performance.

Mass-Based Interaction: In GSA, agents are treated as masses that interact with each other based on gravitational forces. Heavier masses (better solutions) attract lighter ones, allowing efficient search toward promising solutions. This mass-based attraction ensures that better solutions are given more weight in guiding the search process.

Adaptive Search Power: The gravitational constant G(t) decreases over time, allowing for a more aggressive exploration at the beginning and more focused exploitation later. The heavier agents represent good solutions that “pull” others towards them.

Maintaining Diversity: GSA introduces stochastic elements (forces from randomly selected agents) that allow for a broader exploration in the search space, maintaining population diversity, which is crucial in avoiding premature convergence.

Necessary: The dynamic adaptation of search intensity based on fitness levels (masses) ensures that the algorithm is robust in both exploration (early stages) and exploitation (later stages). GSA complements the search process by adding adaptive learning based on solution quality.

D. Particle Swarm Optimization (PSO)

Purpose: Efficient information sharing among particles for both exploration and exploitation.

Collective Learning: PSO allows particles (solutions) to share information through global and personal best values. The swarm learns from both its own experience (personal best) and the experience of the best-performing particle (global best), creating a balance between exploring new areas and exploiting known good solutions.

Velocity and Position Updates: PSO’s update rules ensure that particles move through the search space with both random and deterministic components, adjusting their velocities based on their past velocities and the experience of the swarm. This enables a smooth transition between global exploration and local exploitation.

Simplicity and Speed: PSO’s simple mechanics ensure fast convergence, and its efficiency in searching for optima makes it ideal for many real-world optimization problems. The inertia weight, along with acceleration coefficients, allows fine-tuning of exploration versus exploitation.

Necessary: PSO’s capability to quickly find promising regions in the search space and refine solutions is critical to the algorithm’s speed. It contributes to efficient optimization by leveraging the swarm’s collective intelligence.

E. Need of Hybridization

By combining these four algorithms, the hybrid HCB-GPSO approach leverages the following strengths:

CSA: Provides a strong exploratory mechanism, ensuring the algorithm doesn't get trapped in local minima early in the search.

MBAT: Improves local search capabilities, especially in fine-tuning the solution once good regions are identified.

GSA: Maintains diversity in the population and adds adaptive behavior that allows better solutions to guide the search process.

PSO: Ensures quick convergence by using shared information among particles to balance exploration and exploitation.

F. Working of proposed HCB-GPSO

Early Exploration (CSA + GSA): In the beginning, CSA and GSA focus on exploring large areas of the search space, identifying promising regions without getting stuck in local optima.

Transition to Exploitation (MBAT + PSO): As the iterations progress, MBAT and PSO take over, refining the search around the best solutions found, improving the algorithm's efficiency in converging to the global optimum.

Summary of each algorithm's role:

CSA: Expands the search space and prevents premature convergence by introducing Lvy flights and nest abandonment.

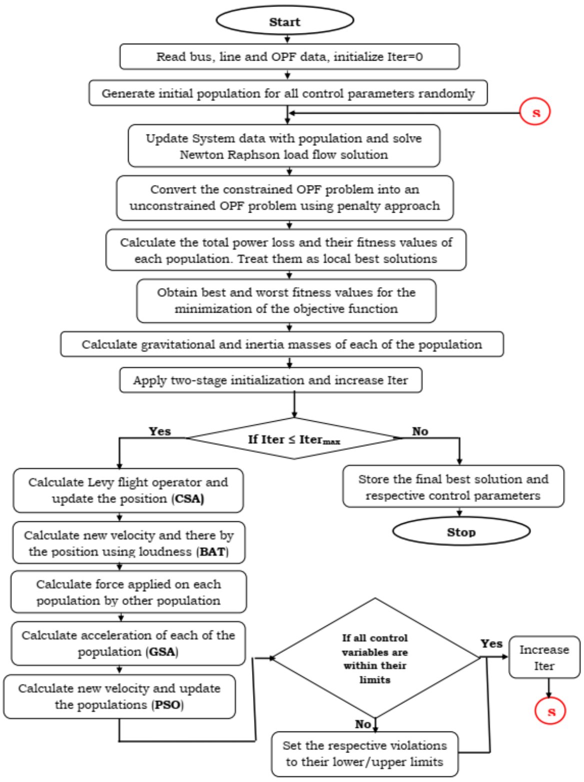
MBAT: Fine-tunes solutions with adaptive echolocation mechanisms.

GSA: Adds gravity-based interaction, allowing better solutions to guide the search while maintaining diversity.

PSO: Provides a collaborative learning mechanism to ensure quick and efficient convergence toward the global best solution.

This HCB-GPSO hybridization ensures that the algorithm can handle complex, multi-modal, and non-linear optimization problems effectively, combining the best of exploration, exploitation, and adaptive learning.

G. Flowchart of the HCB-GPSO



Flowchart of the proposed HCB-GPSO algorithm

VI. IMPLEMENTATION METHODOLOGY

To optimize the performance parameters (such as total power loss, voltage deviation, transmission efficiency, and corona loss) in AC-DC power systems subjected to constraints, a complete implementation methodology must integrate the strengths of hybrid algorithms. The proposed methodology combines multiple optimization techniques to leverage their advantages in solving complex optimization problems efficiently.

Step 1: Define the Optimization Problem

The first step involves defining the objective function and the associated constraints. For this AC-DC load flow problem in the presence of FACTS devices is solved, the primary performance parameters evaluated to optimize are:

Total Power Loss (TPL): Minimize the total power losses across the transmission system.

Voltage Deviation (Vdev): Minimize the deviation in voltage to maintain stability.

Transmission Efficiency: Maximize the efficiency of power transfer.

Corona Loss: Minimize losses due to corona discharge.

Step 2: Hybrid Algorithm Selection

The Hybrid Cuckoo-BAT Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm is selected to solve this problem.

Step 3: Initialize Population

Each algorithm starts with an initial population (control variables for optimization). For HCB-GPSO, we initialize the population as follows:

Particle positions and velocities (PSO) are initialized randomly.

Cuckoo nests (CSA) are selected randomly within the search space.

Gravitational agents (GSA) and BAT agents (BA) are initialized based on random positions and fitness evaluations.

The initial population size N is set, and each control variable is generated between the minimum and maximum limits.

Step 4: Fitness Evaluation

The fitness of each agent or particle is evaluated using the objective function. Each solution (particle/nest/agent) is evaluated based on the combined objective function defined in Step 1.

Step 5: Cuckoo Search (Exploration Step)

The Cuckoo Search Algorithm (CSA) is used to explore new regions in the search space. A new solution is generated for each cuckoo using Levy flights.

Step 6: BAT Algorithm (Local Search Step)

The BAT Algorithm (BA) refines the solution locally by adjusting the loudness and pulse rate.

Step 7: Gravitational Search Algorithm (Exploitation Step)

The Gravitational Search Algorithm (GSA) focuses on exploiting the most promising areas of the search space.

Step 8: Particle Swarm Optimization (Global Best Update)

In this step, PSO updates the velocity and position of each particle based on its local best and global best positions.

Step 9: Check Constraints

After updating the positions for all agents, check whether the new solutions satisfy all the constraints:

Voltage limits

Power flow limits

Thermal constraints

If a solution violates any constraint, apply a penalty to the fitness function to discourage the selection of this solution.

Step 10: Stopping Criteria

The algorithm iterates through the above steps until one of the following stopping criteria is met:

The maximum number of iterations is reached.

The change in the global best solution is smaller than a predefined tolerance.

Step 11: Output Optimal Solution

Once the stopping criteria are met, the global best solution represents the optimal set of control variables that minimize total power loss, voltage deviation, and corona loss, while maximizing transmission efficiency.

VII. Results and Analysis

This section evaluates the optimization framework applied to the IEEE-14 bus system using the Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm. The performance is assessed under various configurations: without HVDC, with HVDC, with SSSC, and with STATCOM. Key performance metrics, including total power loss, voltage deviation, transmission efficiency, and corona loss, are analyzed and compared.

Case 1: Optimal Location Identification for FACTS Devices

To determine the optimal placement of SSSC and STATCOM, the Fuzzy Logic Line Loading Indicator (FLLI) and Voltage Violation Indicator (FVVI) values were calculated. The results, shown in Table.1, indicate that Line-7 (connecting buses 4 and 5) is the most suitable location for installing SSSC, while Bus-5 is optimal for STATCOM placement based on their contributions to minimizing system severity under contingency conditions.

Table.1 FLLI and FVVI Values for IEEE-14 Bus System

Location No	Contingency			FLLI value	FVVI value
	Line no	From bus	To bus		
1	7	4	5	290.38	7.384
2	8	4	7	227.11	9.728
3	9	4	9	312.27	8.839
4	15	7	9	293.23	9.334
5	16	9	10	301.28	9.102
6	17	9	14	287.58	8.495
7	18	10	11	295.39	9.002
8	19	12	13	288.57	8.467
9	20	13	14	290.54	7.574

These optimal placements are used in subsequent simulations to analyze the impact of these FACTS devices on system performance.

After this, the optimal location for HVDC link is obtained by placing HVDC link in all possible device installation location once at a time and total power losses are evaluated. The results are tabulated in Table.2. From this table, it is identified that the line-19 connected between buses 12 and 13 is having highest power losses. By installing HVDV link in this line and by varying converter control parameters, it is possible to decrease the power losses in this line. Further analysis is performed by installing HVDC link in this line.

Table.2 TPL values in different possible locations of IEEE-14 bus system

Location No	HVDC link installed line			TPL (kW)
	No	From bus	To bus	
1	7	4	5	12.6331
2	8	4	7	13.1800
3	9	4	9	12.8231
4	15	7	9	10.2209
5	16	9	10	10.1136
6	17	9	14	13.1554
7	18	10	11	13.1296
8	19	12	13	13.3027
9	20	13	14	13.1861

In order to study the impact of installing SSSC in line-7 (4-5) and STATCOM at bus-5 along with HVDC link in line-19 (12-13).

Case 2: Performance Comparison Across Other Algorithms

This section analyzes the results obtained from the Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) algorithm. The results of the optimization analysis for this bus system using multiple algorithms reveal significant insights into the performance of various methods, with a particular focus on the Hybrid Cuckoo-BAT-Gravitational Particle Swarm Optimization (HCB-GPSO) are given in Table.3.

In terms of total power loss, the HCB-GPSO algorithm consistently outperformed all other methods by achieving the lowest loss value of 2.0761 MW. This reflects its robust capability to navigate the solution space effectively, combining the exploration strengths of the Cuckoo Search Algorithm (CSA) and the fine-tuning capabilities of Particle Swarm Optimization (PSO). In contrast, CSA recorded the highest power loss at 5.9912 MW, indicating its limitations in refining solutions toward a global optimum. The BAT algorithm and Gravitational Search Algorithm (GSA) performed moderately well, with total power losses of 2.191 MW and 2.9815 MW, respectively. These results highlight the superior optimization capacity of HCB-GPSO in reducing system losses, a critical factor for improving overall system efficiency.

Voltage deviation, a critical measure of system stability, further demonstrated the advantages of hybrid optimization. While the PSO algorithm achieved the lowest deviation at 0.7318 p.u., HCB-GPSO closely followed at 1.153 p.u., underscoring its effectiveness in maintaining voltage stability across the network. CSA and BAT showed higher deviations, reflecting their relatively weaker ability to ensure stable voltage levels under varying conditions. The comparative results emphasize HCB-GPSO's ability to balance trade-offs across multiple metrics without compromising on voltage performance.

Transmission efficiency results further validated the efficacy of the HCB-GPSO algorithm. With the highest efficiency recorded at 99.2048%, it surpassed all other methods, marginally outperforming BAT at 99.1611% and PSO at 98.8798%. These findings indicate HCB-GPSO's proficiency in optimizing energy delivery while minimizing losses. CSA, which had the lowest efficiency of 97.7391%, was limited by its inability to converge effectively to an optimal solution. Despite the small differences, the results consistently underscore the enhanced performance of HCB-GPSO in critical operational metrics.

Corona loss, while a relatively minor contributor to overall efficiency, also demonstrated competitive performance across algorithms. HCB-GPSO maintained a value of 2.541 kW, comparable to other methods but slightly higher than some due to its prioritization of minimizing power loss and maximizing transmission efficiency. This balance between different objectives highlights the algorithm's ability to manage trade-offs effectively, ensuring robust overall system performance.

Also, the computational time required by each algorithm provides insight into their operational efficiency. While CSA achieved the shortest computation time at 16.6668 seconds, this came at the expense of accuracy, as evidenced by its higher total power loss and lower transmission efficiency. In comparison, HCB-GPSO took slightly longer at 19.2356 seconds but delivered optimal results across all major metrics, justifying the additional computational effort. The results emphasize that the slightly increased computation time of HCB-GPSO is a reasonable trade-off for achieving superior overall performance.

The results consistently demonstrate the advantages of adopting HCB-GPSO for power system optimization. Its hybrid nature allows it to effectively combine the strengths of multiple algorithms, addressing the inherent limitations of individual approaches. By achieving superior outcomes in minimizing power loss, maintaining voltage stability, and maximizing transmission efficiency, HCB-GPSO proves to be a robust and scalable solution

Table.3 Consolidated Optimization Results for IEEE-14 Bus System (Without HVDC)

Metric	CSA	BAT	GSA	PSO	HCB-GPSO
Total Power Loss (MW)	5.9912	2.1911	2.9815	2.9343	2.0761
Voltage Deviation (p.u.)	0.7451	1.2812	0.8866	0.7318	1.1531
Transmission Efficiency (%)	97.7391	99.1611	98.8619	98.8798	99.2048
Corona Loss (kW)	2.1848	2.6172	2.4721	2.4165	2.5411
Computing Time (s)	16.6668	20.0926	18.237	17.877	19.2356

***Case 3: Performance* Comparison Across Other Devices**

The optimization results highlighting the impact of using HVDC, SSSC, and STATCOM devices on various operational objectives, including power loss minimization, voltage deviation reduction, transmission efficiency improvement, and corona loss mitigation are tabulated in Table.4. Across all setups, advanced controllers demonstrate significant potential to enhance system performance, though they introduce trade-offs depending on the chosen optimization objective.

HVDC link improves power flow management and reduces transmission losses, but its implementation is associated with higher voltage deviations. This suggests that while HVDC offers control benefits, it requires effective reactive power management to maintain voltage stability. STATCOM, on the other hand, excels in voltage regulation and transmission efficiency, achieving the lowest voltage deviations across all scenarios. However, its deployment can lead to higher power losses and requires careful integration to balance energy efficiency with its benefits in voltage stability. SSSC provides a balanced solution, offering improved voltage regulation and reduced power losses compared to HVDC, though it does not outperform STATCOM in overall stability. These findings underline the importance of selecting controllers based on system priorities, whether minimizing losses, improving stability, or enhancing transmission efficiency.

Further, results for minimizing corona loss reveal that SSSC is the most effective device in reducing discharge-related losses. It achieves this through precise reactive power control and voltage regulation. STATCOM also performs well, providing a notable reduction in corona loss while maintaining strong voltage regulation. HVDC offers a balanced improvement, mitigating corona losses and maintaining moderate voltage stability and efficiency.

In terms of computational performance, STATCOM configurations require the most processing time due to their complex control algorithms, while HVDC and SSSC maintain a lower computational overhead. The trade-offs between efficiency, stability, and computational demands highlight the necessity of tailored deployment strategies for these technologies.

Table.4 Comprehensive Optimization Results with Devices for IEEE-14 bus system

Objective	Parameter	Without HVDC	With HVDC	With SSSC	With STATCOM
Power Loss Minimization	Real Power Loss (MW)	2.0761	2.1968	2.4199	1.9482
	Voltage Deviation (p.u)	1.1531	1.3649	1.6011	0.5587
	Transmission Efficiency (%)	99.2048	99.1589	92.0333	99.2534
	Corona Loss (kW)	2.5411	2.6292	1.0238	2.3082
	Computing Time (sec)	19.2356	20.2584	31.0223	44.5971
Voltage Deviation Reduction	Real Power Loss (MW)	7.1357	12.8841	4.9373	11.3605
	Voltage Deviation (p.u)	0.1261	0.1057	0.0932	0.0765
	Transmission Efficiency (%)	97.3188	95.2612	98.1294	95.7981
	Corona Loss (kW)	1.8187	1.9214	1.9158	1.9136
	Computing Time (sec)	31.9135	31.3185	36.8969	33.7791
Transmission Efficiency Optimization	Real Power Loss (MW)	6.0144	2.9371	2.0854	43.1709
	Voltage Deviation (p.u)	0.4517	0.7892	0.4198	4.3089
	Transmission Efficiency (%)	97.7305	98.8788	99.2012	99.7131
	Corona Loss (kW)	2.0185	2.4171	2.2275	0.384
	Computing Time (sec)	35.7542	37.6561	34.3889	41.4402
Corona Loss Reduction	Real Power Loss (MW)	29.2701	18.8124	22.6915	24.4105
	Voltage Deviation (p.u)	0.3948	1.2086	6.5619	2.8778
	Transmission Efficiency (%)	89.4217	93.2284	73.6441	91.3869
	Corona Loss (kW)	1.5086	1.1861	0.0517	0.9369
	Computing Time (sec)	36.0544	40.6625	49.6996	46.1562

Table 5 compares different optimization techniques for the IEEE-30 bus system without HVDC, focusing on power loss, voltage deviation, transmission efficiency, corona loss, and computing time. PSO achieved the lowest power loss and highest transmission efficiency, while HCB-GPSO showed the best voltage stability and lowest corona loss. CSA was the fastest in computation, whereas GSA required the longest time. The optimization results for this system are tabulated in Table.6 demonstrate the significant impact of implementing advanced power electronic devices—HVDC, SSSC, and STATCOM—on various performance objectives. Each device showcases unique strengths, with STATCOM consistently emerging as the most effective solution across multiple scenarios. When minimizing power losses, STATCOM achieves the lowest real power loss of 9.9681 MW and the highest transmission efficiency at 96.6022%, underscoring its ability to optimize power flow through robust reactive power support and voltage regulation. HVDC and SSSC also contribute to improved efficiency, achieving power losses of 12.2251 MW and 11.8101 MW, respectively, while maintaining transmission efficiencies of 95.8647% and 95.9994%. While all configurations reduce losses compared to the base case without HVDC (13.2508 MW), STATCOM clearly outperforms others due to its superior control capabilities.

Voltage deviation is another critical parameter where STATCOM excels. Under the voltage deviation minimization objective, STATCOM achieves the lowest deviation of 0.7114 p.u., a significant improvement over HVDC (1.0414 p.u.) and SSSC (0.9876 p.u.). This result highlights STATCOM's ability to maintain a stable voltage profile, which is essential for system reliability and stability. SSSC also performs well, showing balanced improvements in voltage stability and transmission efficiency. While HVDC demonstrates notable gains in transmission efficiency and voltage regulation, its performance under this objective is comparatively moderate, achieving a deviation of 1.0414 p.u. and transmission efficiency of 95.167%. These results affirm that STATCOM provides superior voltage regulation, making it the preferred technology for voltage-sensitive applications.

When optimizing for transmission efficiency, STATCOM again stands out, achieving the highest efficiency at 96.4971% while reducing power losses to 10.2875 MW. This efficiency gain is attributed to STATCOM's advanced control strategies, which effectively manage reactive power and minimize energy losses. SSSC achieves moderate success, reducing power losses to 11.2924 MW while maintaining efficiency at 96.1681%. HVDC shows a marginal improvement over the base case, achieving 95.8641% efficiency with power losses of 12.2269 MW. The ability of STATCOM to maintain high efficiency while reducing losses reinforces its critical role in enhancing system performance under this objective.

In minimizing corona loss, STATCOM achieves the best results, reducing corona loss to 0.5077 kW, a marked improvement over HVDC (1.5737 kW) and SSSC (1.1618 kW). However, this achievement comes at the cost of increased voltage deviation, with STATCOM recording a deviation of 3.3819 p.u., the highest among the configurations. HVDC, on the other hand, balances corona loss reduction with better voltage stability, achieving a deviation of 0.9232 p.u. while maintaining moderate corona loss levels. SSSC offers an intermediate solution, achieving balanced performance across corona loss reduction and voltage stability. These results highlight the inherent trade-offs when optimizing specific objectives and underscore the need for careful selection of technologies based on system priorities.

Across all objectives, computing time varies among configurations, with STATCOM generally requiring the longest computation due to its complex control algorithms. Despite this, its superior performance in reducing losses and enhancing stability justifies the additional computational effort. HVDC and SSSC configurations show relatively shorter computation times, offering more resource-efficient solutions, albeit with slightly reduced performance.

Table.5 Consolidated Optimization Results for IEEE-30 Bus System (Without HVDC)

Metric	CSA	BAT	GSA	PSO	HCB-GPSO
Total Power Loss (MW)	11.7087	15.4287	15.2137	10.2875	15.0086
Voltage Deviation (p.u.)	1.7267	1.4644	1.2567	1.2042	1.0768
Transmission Efficiency (%)	96.0324	94.8369	94.9052	96.4971	94.9705
Corona Loss (kW)	2.0265	2.6065	3.4269	1.5471	1.4881
Computing Time (s)	12.9853	15.6774	26.9641	28.0731	26.276

Table.6 Comprehensive Optimization Results **with Devices for IEEE-30 bus system**

Objective	Parameter	Without HVDC	With HVDC	With SSSC	With STATCOM
Power Loss Minimization	Real Power Loss (MW)	13.2508	12.2251	11.8101	9.9681
	Voltage Deviation (p.u)	1.1727	1.1153	0.9366	0.8253
	Transmission Efficiency (%)	95.5332	95.8647	95.9994	96.6022
	Corona Loss (kW)	2.9205	1.5045	1.8506	1.7024
	Computing Time (sec)	31.8601	35.9043	35.2896	37.4648
Voltage Deviation Reduction	Real Power Loss (MW)	15.0086	14.3922	12.8774	11.2923
	Voltage Deviation (p.u)	1.0768	1.0414	0.9876	0.7114
	Transmission Efficiency (%)	94.9705	95.167	95.6536	96.1681
	Corona Loss (kW)	1.4881	2.8721	1.8401	1.8074
	Computing Time (sec)	26.276	26.884	24.822	26.9431
Transmission Efficiency Optimization	Real Power Loss (MW)	12.2296	12.2269	11.2924	10.2875
	Voltage Deviation (p.u)	1.7796	1.2008	0.7114	1.2042
	Transmission Efficiency (%)	95.8632	95.8641	96.1681	96.4971
	Corona Loss (kW)	2.0179	1.9251	1.8074	1.5471
	Computing Time (sec)	34.9899	41.4584	36.9435	38.073
Corona Loss Reduction	Real Power Loss (MW)	10.7031	14.8279	15.2823	21.1495
	Voltage Deviation (p.u)	0.7594	0.9232	1.3954	3.3819
	Transmission Efficiency (%)	96.3608	95.028	94.8834	93.0389
	Corona Loss (kW)	1.6174	1.5737	1.1618	0.5077
	Computing Time (sec)	40.4745	36.1039	36.7347	44.9883

VIII. Conclusion

This research has extensively analyzed the optimization of hybrid AC-DC power systems by incorporating advanced power electronic controllers such as HVDC, SSSC, and STATCOM to enhance efficiency and stability. By formulating mathematical models and validating them on IEEE-14 and IEEE-30 bus systems, the study demonstrated the importance of precise optimization techniques in improving system performance. The results revealed that STATCOM significantly reduces power losses and enhances transmission efficiency, while HVDC plays a key role in voltage stabilization. Addressing challenges such as minimizing power losses, improving voltage stability, and optimizing transmission efficiency, the study underscores the need for hybrid control strategies that integrate traditional power flow models with modern power electronics. These findings contribute to the development of more resilient and efficient power networks, especially with the increasing integration of renewable energy sources. Future research should explore large-scale power networks, real-time dynamic conditions, and artificial intelligence-based optimization methods to further enhance system performance and adaptability. Expanding this approach will ensure the continued advancement of intelligent and sustainable power systems capable of meeting future energy demands.

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