SECURITY-CONSTRAINED AC/DC TRANSMISSION EXPANSION PLANNING USING METAHEURISTIC ALGORITHMS

BUI NGUYEN DUC HUY, DUONG THANH LONG*
Faculty of Electrical Engineering Technology, Industrial University of Ho Chi Minh City, Viet Nam
Corresponding author: duongthanhlong@iuh.edu.vn
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Abstract. Integrating security constraints is an essential requirement in transmission expansion planning (TEP) to guarantee system reliability. However, fulfilling this security criterion leads to high investment costs, which are primarily to accommodate rare contingency conditions and create significant economic waste. To mitigate this inefficiency, high-voltage direct current (HVDC) technology has been recognized as a highly economic replacement for conventional high-voltage alternating current (HVAC) systems, particularly for long-distance transmission lines. As a result, this study presents a security-constrained AC/DC TEP formulation to evaluate its economic advantages compared to the traditional HVAC transmission expansion approach. The proposed model is structured as a bi-level optimization problem: the master problem determines the optimal transmission investment proposals, while the subproblem evaluates operational security constraints. To obtain high-quality solutions, the bound limitation-evolution search modified artificial rabbits optimization (BL-ES-MARO) algorithm is applied to solve the considered problem on the well-known Garver 6-bus and IEEE 14-bus systems. Simulation results demonstrate two primary findings. First, the obtained AC/DC expansion plans yield substantial cost savings of up to 84.8 M$ and 289.84 M$ compared to conventional AC expansion plans on these systems, respectively. Second, the BL-ES-MARO algorithm shows superior performance in both optimality and robustness when compared to conventional differential evolution (DE), particle swarm optimization (PSO), and state-of-the-art glider snake optimizer (GSO).

Keywords. Transmission expansion planning, security-constrained, non-convex, high voltage direct current, metaheuristic.

1 INTRODUCTION

The transmission expansion planning (TEP) problem is considered one of the classical problems in power systems, aiming to determine an economic plan to meet future demand growth [1]. In addition, modern power systems require stringent system security requirements, such as satisfying the N-1 security criterion. However, this requirement presents techno-economic challenges to planners since it requires the construction of several additional transmission lines that may only be served in contingency conditions. In this context, modern high-voltage direct current (HVDC) technology has been recognized as a compelling solution to these techno-economic challenges. This technology effectively addresses several limitations of traditional high-voltage alternating current (HVAC) systems: i) reducing transmission power losses and the need for extra lines; ii) providing high efficiency over very long transmission distances, making it particularly suitable for offshore wind power integration; and iii) requiring fewer cables than HVAC technology of similar capacity [2].

Recognizing these advantages, several TEP studies have integrated HVDC technology. Papers [3, 4] investigate the significant benefits of HVDC technology in the TEP problem when photovoltaic (PV) and offshore wind powers are integrated. In addition, a multistage approach for the AC/DC grid TEP problem is proposed in [5] to address uncertainties in the power system. Furthermore, the total transfer capacity (TTC) index is included in [6] to evaluate the security limits of the AC/DC-based TEP problem. From a modeling aspect, a mixed-integer linear programming (MILP) formulation considering system power losses and security constraints is applied in [7] to solve the AC/DC TEP problem. Paper [8] presents the integration of energy storage (ES) devices into the AC/DC TEP problem under the presentation of renewable energy, utilizing a MILP formulation solved by the bender decomposition (BD) method. Furthermore, paper [9] introduces a multistage mixed-integer AC/DC TEP convex model that considers node voltages, reactive power, and network losses. While these investigations successfully address the AC/DC TEP problem, they

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also include a foundation limitation widely recognized within conventional TEP research. In particular, the mathematical approximations inherent in MILP and convex relaxation methodologies may fail to accurately reflect the AC power flow characteristics, thereby yielding impractical solutions for real-world deployment [10]. To overcome this limitation, the full AC non-convex formulation has drawn significant interest from the scientific community in addressing the AC/DC TEP problem. For instance, a static full AC non-convex approach is introduced in [11], and a mixed-integer nonlinear programming (MINLP) formulation for this problem is also presented in [12]. Furthermore, recent studies have also expanded this framework to other planning aspects. The co-planning of HVAC lines, HVDC lines, and Flexible AC Transmission System (FACTS) devices using a full AC non-convex model is investigated in [13]. Paper [14] incorporates energy storage systems (ESS) into the non-convex AC/DC TEP model, and [15] proposes a comprehensive planning framework that simultaneously coordinates generators alongside HVAC and HVDC transmission infrastructure.

As highlighted in the above review, relying on simplified models for AC/DC TEP (such as linearized [7, 8] or convex relaxation approaches [9]) may yield impractical solutions. Although these methods guarantee optimality within their simplified mathematical spaces, the resulting expansion plans frequently require adjustments for real-world implementation since the reactive power, voltage magnitudes, and exact power losses are ignored [9]. To overcome these limits, adopting a full non-convex AC formulation is presented in [11-15]. However, the highly non-linear and non-convex nature of the full AC model poses a significant computational burden, demanding high-performance optimization solvers. Furthermore, a major research gap can be observed regarding the N-1 security criterion from the literature review. This criterion is fundamental for guaranteeing uninterrupted power system operation, which is vital to support continuous economic growth and meet strict reliability requirements [16]. While the N-1 security criterion is addressed in the work [7], it has been frequently overlooked in recent full non-convex AC/DC TEP studies. As a result, this work proposes the following key contributions to cover the identified research gaps:

- The security-constrained AC/DC TEP problem is solved under a full AC non-convex formulation.
- The bound limitation-evolution search modified artificial rabbits optimization (BL-ES-MARO) algorithm [10] is applied to handle the non-linear and non-convex nature of the proposed full AC formulation.
- The performance of the BL-ES-MARO method is verified by comparing it with the conventional differential evolution (DE) [17], particle swarm optimization (PSO) [18], and state-of-the-art glider snake optimizer (GSO) [19] in the Garver 6-bus and IEEE 14-bus systems.

The rest of this paper is organized as follows: Section 2 introduces the mathematical formulation of the full AC non-convex security-constrained AC/DC TEP problem. The proposed method is introduced in Section 3. Section 4 shows and discusses the simulation results. Finally, a conclusion can be found in Section 5.

2 MATHEMATICAL FORMULATION

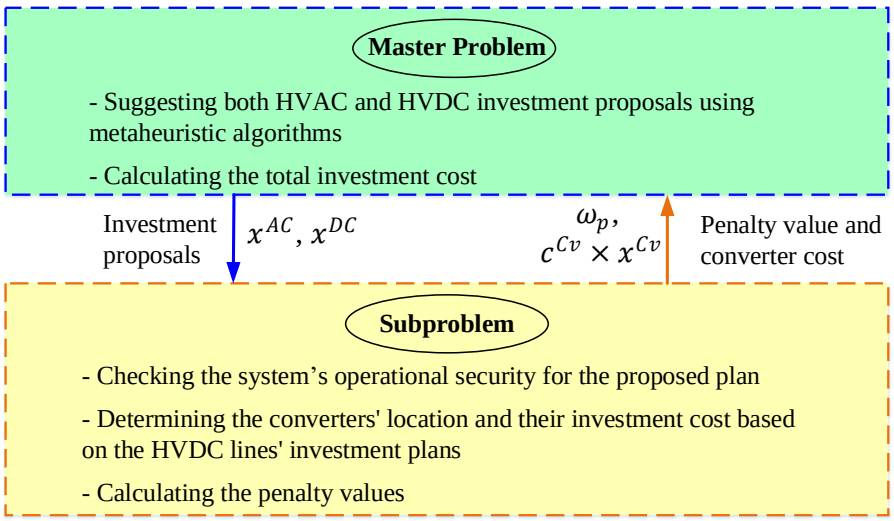


Figure 1. The proposed bi-level AC/DC TEP framework

In this paper, the AC/DC TEP problem is formulated as a bi-level optimization problem containing a master problem and a subproblem. The primary task of the master problem is to determine the investment proposals for both HVAC and HVDC transmission lines, while the subproblem evaluates the system's operational security utilizing an AC/DC optimal power flow (ACDC OPF) formulation [20]. The details of this proposed framework are illustrated in Figure 1.

2.1 Master problem

Objective function of the proposed AC/DC TEP problem including the investment cost of HVAC, HVDC extra transmission lines and converters. This objective function is presented in the following equation [11]:

$$\min C_{inv} = \sum_{ij \in \Omega_{AC}} c_{ij}^{AC} \times x_{ij}^{AC} + \sum_{mn \in \Omega_{DC}} c_{mn}^{DC} \times x_{mn}^{DC} + \sum_{m \in \Omega_{cv}} c_{m}^{cv} \times x_{m}^{cv} + \omega_p \quad (1)$$

Subject to:

$$0 \le x_{ij}^{AC} \le x_{ij}^{AC,max} \quad (2)$$

$$0 \le x_{mn}^{DC} \le x_{mn}^{DC,max} \quad (3)$$

$$0 \le x_{m}^{cv} \le 2 \times x_{mn}^{DC} \quad (4)$$

Where c_{ij}^{AC}, c_{mn}^{DC}, and c_{m}^{Cv} are the investment costs for the HVAC line, HVDC line, and converter at AC buses $i,\ j$ and DC buses $m,\ n$. Ω_{AC}, Ω_{DC}, and Ω_{cv} are set of candidate lines for the HVAC lines, HVDC lines, and converters. x_{ij}^{AC}, x_{mn}^{DC}, and x_{m}^{cv} are the number of invested HVAC lines, HVDC lines, and converters at AC buses $i,\ j$ and DC buses $m,\ n$. $x_{ij}^{AC,max}$ and $x_{mn}^{DC,max}$ are the allowed maximum circuits for the HVAC and HVDC lines at each right-of-way. ω_p is the penalty value, which is presented in the subproblem.

2.2 Subproblem

In this subproblem, an ACDC OPF formulation is deployed to assess the operational security of the investment plan generated by the master problem. To quantify this security, a load-shedding mechanism is introduced, which is mathematically represented by fictitious generators. These fictitious generators are dispatched only when the expanded transmission network fails to transfer required power from sources to load centers without violating thermal capacity limits. To strictly penalize this security violation, a significant penalty cost is added to the objective function. This penalty cost is driven by the value ω_p, which is calculated using the following equation [10]:

$$\omega_p = \sum_{s}^{cl+1} (\omega_1^s + \omega_2^s) \quad (5)$$

$$\omega_1^s = \sum_{i \in N_{PQ}} \rho_1 \times r_{P,i}^s \quad (6)$$

$$\omega_2^s = \rho_2 \times \tau^s \quad (7)$$

The penalty factor ω_p includes two components, as formulated in equations (5) and (6). In particular, equation (5) calculates the penalty associated with load shedding, whereas equation (6) determines the penalty incurred when the ACDC OPF calculation fails to converge. Here, s and cl denote the index of contingency scenarios and the set of contingency lines ($s = 1$ is the based case under normal operating condition), respectively. The variable $r_{P,i}^s$ represents the amount of active load-shedding at bus i under scenario s, and N_{PQ} is the set of AC load buses. The parameters ρ_1 and ρ_2 are penalty coefficients, typically set to 10^7 and 10^{15}, respectively. τ^s is a binary indicator that equals 1 if the ACDC OPF fails to converge, and 0 otherwise. The non-convergence of the ACDC OPF calculation occurs due to the violation of operational constraints, which are fully detailed in Section 2.3.

2.3 Operation constraints

2.3.1 AC network

- Active and reactive AC power injection [11]:

$$P_i(V,\theta)^{AC,s} = V_i^{AC,s} \times \sum_{ij \in N_{AC}} V_j^{AC,s} \times \left(G_{ij}^s \times \cos\theta_{ij}^s + B_{ij}^s \times \sin\theta_{ij}^s\right) \quad (8)$$

$$Q_i(V,\theta)^{AC,s} = V_i^{AC,s} \times \sum_{ij \in N_{AC}} V_j^{AC,s} \times \left(G_{ij}^s \times \sin\theta_{ij}^s - B_{ij}^s \times \cos\theta_{ij}^s\right) \quad (9)$$

Where, $V_i^{AC,s}$ and $V_j^{AC,s}$ are the AC voltage value at nodes i, j under scenario s. G_{ij}^s and B_{ij}^s are the series conductance and series susceptance. θ_{ij}^s and N_{AC} are the phase angle and set of AC buses.

- AC power balances [10]:

$$P_G^s - P(V,\theta)^{AC,s} - P_{cv}^{AC,s} - P_L + r_P^s = 0 \quad (10)$$

$$Q_G^s - Q(V,\theta)^{AC,s} - Q_{cv}^{AC,s} - Q_L = 0 \quad (11)$$

- Generation limits [10]:

$$P_G^{min} \le P_G^s \le P_G^{max} \quad (12)$$

$$Q_G^{min} \le Q_G^s \le Q_G^{max} \quad (13)$$

$$r_P^{min} \le r_P^s \le r_P^{max} \quad (14)$$

- AC voltage amplitude and transmission line thermal limits [10]:

$$V^{AC,min} \le V^{AC,s} \le V^{AC,max} \quad (15)$$

$$S^{from,s} \le S^{max} \quad (16)$$

$$S^{to,s} \le S^{max} \quad (17)$$

Where, P_G^s and Q_G^s are the active and reactive generation under scenario s, while P_L and Q_L are the active and reactive load demand. $P_{cv}^{AC,s}$ and $Q_{cv}^{AC,s}$ are the active and reactive power generated/absorbed by the converter on the AC side. $S^{from,s}$ and $S^{to,s}$ are the power flow in both terminals. The superscripts max and min denote the maximum and minimum limits of the corresponding variables, respectively.

2.3.2 DC network

- DC power flow [20]:

$$P_{mn}^{DC,s} = p_d \times V_m^{DC,s} \times \left(\frac{V_m^{DC,s} - V_n^{DC,s}}{r_d}\right) \quad (18)$$

$$P_{loss}^{DC} = p_d \times r_d \times \left(\frac{V_m^{DC,s} - V_n^{DC,s}}{r_d}\right)^2 \quad (19)$$

$$P_{mn}^{DC,s} + P_{nm}^{DC,s} = P_{loss}^{DC} \quad (20)$$

- DC power balance [20]:

$$\sum_{mn \in N_{DC}} P_{mn}^{DC,s} + P_{cv}^{DC,s} = 0 \quad (21)$$

- DC power flow and voltage limits [20]:

$$P_{mn}^{DC,min} \le P_{mn}^{DC,s} \le P_{mn}^{DC,max} \quad (22)$$

$$V_m^{DC,min} \le V_m^{DC,s} \le V_m^{DC,max} \quad (23)$$

Where, r_d and p_d are the resistor and number of poles (p_d is set to 2 according to paper [11]) in HVDC lines. $V_m^{DC,s}$ and $V_n^{DC,s}$ are DC voltage at buses m, n under scenario s. $P_{cv}^{DC,s}$ is the active power injection of the converter on the DC side. N_{DC} is set of DC buses.

2.3.3 Converters

- Power balance in converters [20]:

$$P_{cv}^{AC,s} + P_{cv}^{DC,s} = P_{cv,loss}^{DC,s} \quad (24)$$

$$P_{cv,loss}^{DC,s} = a_{cv} + b_{cv} \times I_{cv}^{AC,s} + c_{cv} \times \left(I_{cv}^{AC,s}\right)^2 \quad (25)$$

$$\left(P_{cv}^{AC,s}\right)^2 + \left(Q_{cv}^{AC,s}\right)^2 = \left(V_{cv}^{AC,s}\right)^2 \times \left(I_{cv}^{AC,s}\right)^2 \quad (26)$$

$$P_{cv}^{DC,s} = V_{cv}^{DC,s} \times I_{cv}^{DC,s} \quad (27)$$

- Power limits on the AC side [20]:

$$P_{cv}^{AC,min} \le P_{cv}^{AC,s} \le P_{cv}^{AC,max} \quad (28)$$

$$Q_{cv}^{AC,min} \le Q_{cv}^{AC,s} \le Q_{cv}^{AC,max} \quad (29)$$

$$\left(P_{cv}^{AC,s}\right)^2 + \left(Q_{cv}^{AC,s}\right)^2 \leq (S_{cv}^{max})^2 \quad (30)$$

- Power limits in the DC side [20]:

$$P_{cv}^{DC,min} \leq P_{cv}^{DC,s} \leq P_{cv}^{DC,max} \quad (31)$$

In this paper, the modern voltage source converter (VSC) is applied. Where, a_{cv}, b_{cv}, and c_{cv} are the no load losses of transformers, diode's switching losses, and conduction losses. Their values are fully reported in paper [20]. $V_{cv}^{AC,s}$ and $V_{cv}^{DC,s}$ are the voltage value on the AC and DC sides. Their values are similar to the values of $V^{AC,s}$ and $V^{DC,s}$ from Sections 2.3.1 and 2.3.2. $I_{cv}^{AC,s}$ and $I_{cv}^{DC,s}$ are the current magnitude of the converter on the AC and DC sides.

2.4 Security criterion evaluation

The primary role of the security criterion is to guarantee the uninterrupted operation of the power system. This aspect is of significant importance to the planning process, since it directly decides the reliability and robustness of the proposed expansion plan. In this study, the N-1 security criterion is employed, implying that the power system must remain fully operational following the unexpected failure of any single component. While contingencies can occur in various system elements (such as generators or transformers), this study specifically focuses on transmission line outages. The selection is justified by the fact that transmission lines connect long geographical distances and are extremely exposed to severe environmental threats, making them the common causes of N-1 contingencies. Therefore, planners must comprehensively anticipate and simulate all potential contingency scenarios throughout the planning phase to propose highly reliable investment strategies. The detailed workflow of this security-constrained planning process is presented in Figure 2.

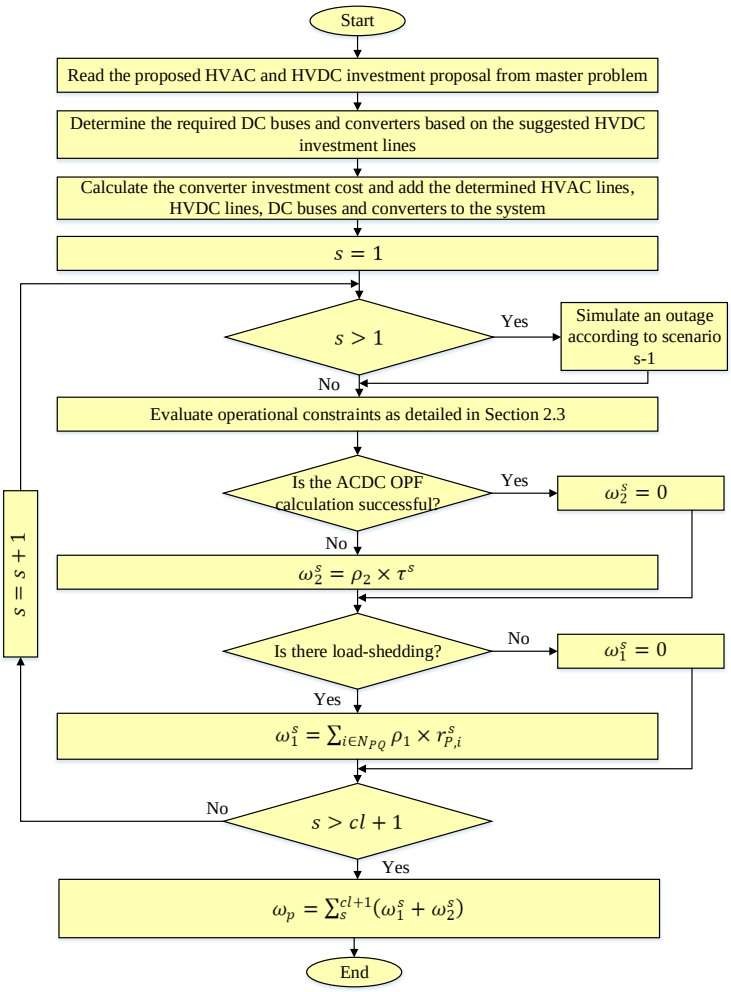


Figure 2. The workflow of security-constrained planning

3 PROPOSED METHOD

3.1 BL-ES-MARO algorithm

The BL-ES-MARO algorithm is an advanced variant of the modified artificial rabbits optimization (MARO) [21], enhanced by Bound Limitation (BL) and Evolution Search (ES) mechanisms. Different from conventional metaheuristics that primarily focus on exploration and exploitation balances using random search mechanisms, the BL strategy actively narrows the search space and accelerates convergence by eliminating unpromising, high-cost investment lines based on elite individuals. To mitigate the probability of local convergence, the ES strategy (implemented in the neighborhood search mechanism) is employed to relocate the search space around elite solutions, allowing the algorithm to avoid local optima. Details for the BL and ES strategies are available in paper [10].

3.2 AC/DC TEP problem implementation

The following steps present the implementation of the AC/DC TEP problem using the BL-ES-MARO algorithm:

Step 1: Read the system data and set the control parameters, as detailed in Table 1.

Step 2: Initialize the population using the following equation:

$$u_k^{ini} = lb + r \times (ub - lb) \tag{32}$$

Where, r is the distributed random number in range [0, 1]. lb and ub are the lower and upper bounds of the AC/DC TEP problem, which are defined in equations (33) and (34).

$$lb = \left[x_{ij}^{AC,min}\ \forall (ij) \in \Omega_{AC},\quad x_{mn}^{DC,min} \forall (mn) \in \Omega_{DC}\right] \tag{33}$$

$$ub = \left[x_{ij}^{AC,max}\ \forall (ij) \in \Omega_{AC},\quad x_{mn}^{DC,max} \forall (mn) \in \Omega_{DC}\right] \tag{34}$$

Step 3: Evaluate the proposed investment plans of the initial population, following the security evaluation process depicted in Figure 2, and calculate the objective function value for each plan.

Step 4: Apply the ES strategy [10] to generate new investment plans.

Step 5: Evaluate the new investment plans generated by the ES strategy and calculate their objective function values, as described in Step 3.

Step 6: Update the population using the following equation:

$$u_k = \begin{cases} u_k^{new}, if\ f(u_k^{new}) < f(u_k) \\ u_k, else \end{cases} \tag{35}$$

Step 7: Generate new investment plans utilizing the standard search characteristics of the MARO method, as detailed in [21].

Step 8: Evaluate the newly suggested investment proposals' security, calculate their objective function values, and update the population according to equation (35).

Step 9: Apply the BL strategy [10] to eliminate unpromising candidates and narrow the search space.

Step 10: Check the stop criterion: if the maximum number of iterations is reached, stop the program and print out the optimal solution; otherwise, return to Step 4.

Table 1. Control parameters for the considered methods

Algorithm	BL-ES-MARO	DE	PSO	GSO
Control parameters	$It^{max} = 150$ (Garver 6-bus system) $N_{Pop} = 30$ (Garver 6-bus system) $It^{max} = 300$ (IEEE 14-bus system) $N_{Pop} = 50$ (IEEE 14-bus system) $\tau = 0.1$ $\eta = 0.3$ $\sigma = 0.2 \times ub$ $N_{Pop}^{ES} = 0.1 \times N_{Pop}$ $It^{BL} = \frac{It^{max}}{20}$	$It^{max} = 150$ (Garver 6-bus system) $N_{Pop} = 30$ (Garver 6-bus system) $It^{max} = 300$ (IEEE 14-bus system) $N_{Pop} = 50$ (IEEE 14-bus system) $\beta = [0.2,0.8]$ $Cr = 0.7$	$It^{max} = 150$ (Garver 6-bus system) $N_{Pop} = 30$ (Garver 6-bus system) $It^{max} = 300$ (IEEE 14-bus system) $N_{Pop} = 50$ (IEEE 14-bus system) $U_{max} = 1$ $w_{max} = 0.9$ $w_{min} = 0.2$ $c_1 = 2.00$ $c_2 = 2.00$	$It^{max} = 150$ (Garver 6-bus system) $N_{Pop} = 30$ (Garver 6-bus system) $It^{max} = 300$ (IEEE 14-bus system) $N_{Pop} = 50$ (IEEE 14-bus system)

4 SIMULATION RESULT

In this section, the proposed security-constrained AC/DC TEP problem is evaluated using the Garver 6-bus and IEEE 14-bus systems. Detailed data for these systems can be found in [20]. The optimization model is implemented in the Julia programming language [22] utilizing the JuMP modeling package [23]. Furthermore, the AC/DC OPF calculations are performed using the PowerModels [24] and PowerModelsACDC [20] packages. The simulations run on the PC with an Intel Core i5 12^{th} , 3.1 GHz, and 16 GB of RAM. To accelerate the computational speed, Julia's parallel processing is applied with 8 processors. The optimization results for the proposed BL-ES-MARO algorithm have obtained over 30 independent runs, and its performance is compared to the DE, PSO, and GSO methods.

4.1 Garver 6-bus system

The Garver 6-bus system comprises 6 AC buses, 3 generators, and 6 existing AC transmission lines, providing a total load demand of 720 MW and 152 MVAr. Regarding the expansion candidates, the system has 15 AC rights-of-way, 6 potential DC buses, 6 DC converters, and 11 DC transmission corridors. A maximum of 5 new circuits can be installed on each candidate right-of-way [11]. To comprehensively evaluate the proposed approach, two separate planning scenarios are investigated: only AC transmission expansion (scenario A) and coordinated AC/DC transmission expansion (scenario B). The simulation results for both scenarios are summarized in Table 2. Observed from this table, the coordinated AC/DC transmission expansion plans are significantly more economical compared to the traditional AC expansion approach. Although integrating HVDC lines requires expensive converter installations, this strategy is still highly cost-effective for this system due to the significant reduction in the required number of new transmission lines. For instance, scenarios A1 and A2 demand the construction of 6 and 7 extra transmission lines, respectively, while scenarios B1 and B2 only require 3 and 4. As a result, the coordinated approaches in scenarios B1 and B2 yield significant cost savings of 72.3 M$ and 84.8 M$ compared to scenarios A1 and A2. Furthermore, the N-1 security criterion increases the overall investment costs compared to the base scenarios. The security-constrained plan in scenario A2 requires a total investment of 115 M$, which is 20 M$ higher compared to scenario A1. Similarly, scenario B2 requires a higher total cost compared to scenario B1 by 7.5 M$. This extra expense can be considered a “reliability cost” to secure the system under contingency conditions. From this perspective, the HVDC technology is more favored over traditional HVAC due to the converters’ flexibility. Therefore, the coordinated AC/DC framework (scenario B2) reduces the reliability cost by 12.5 M$ compared to the traditional approach (scenario A2).

Table 2. Simulation results for the AC/DC TEP problem on the Garver 6-bus system

	Scenario A		Scenario B	
	A1	A2	B1	B2
N-1 security criterion	×	✓	×	✓
HVAC additional lines	$l_{2-3}=1$ $l_{4-6}=2$ $l_{5-6}=3$	$l_{2-3}=2$ $l_{4-6}=2$ $l_{5-6}=3$	$l_{5-6}=1$	-
HVDC additional lines	-	-	$l_{2-6}=1$ $l_{4-6}=1$	$l_{2-6}=1$ $l_{3-6}=1$ $l_{4-6}=1$ $l_{5-6}=1$
Additional converters (DC bus to AC bus)	-	-	$2-2$ $4-4$ $6-6$	$2-2$ $3-3$ $4-4$ $5-5$ $6-6$
HVAC investment cost (M$)	95	115	5	-
HVDC investment cost (M$)	-	-	5.2	10.7
Converters’ investment cost (M$)	-	-	12.5	19.5
Total cost (M$)	95	115	22.7	30.2

Table 3 presents a performance comparison between the BL-ES-MARO algorithm and other methods on scenario B1. The achieved results show that the BL-ES-MARO algorithm successfully identifies the lowest investment cost of 22.7 M$, which can be verified in [11]. This optimal cost is lower than obtained by the

PSO and GSO methods by 5.4 M$ and 2.0 M$, respectively. Although both the BL-ES-MARO and DE methods can offer the same minimum cost, the DE algorithm includes significantly higher worst-cost, mean-cost, and standard deviation values. These statistical metrics highlight the high optimality and robustness of the proposed BL-ES-MARO algorithm in this scenario. Furthermore, as illustrated in Figure 3, the BL-ES-MARO algorithm requires a lower average number of iterations to converge (Ave. Iter) compared to DE and GSO, which is a direct benefit of the implemented bound limitation (BL) strategy. However, these high performances come with a longer computational time.

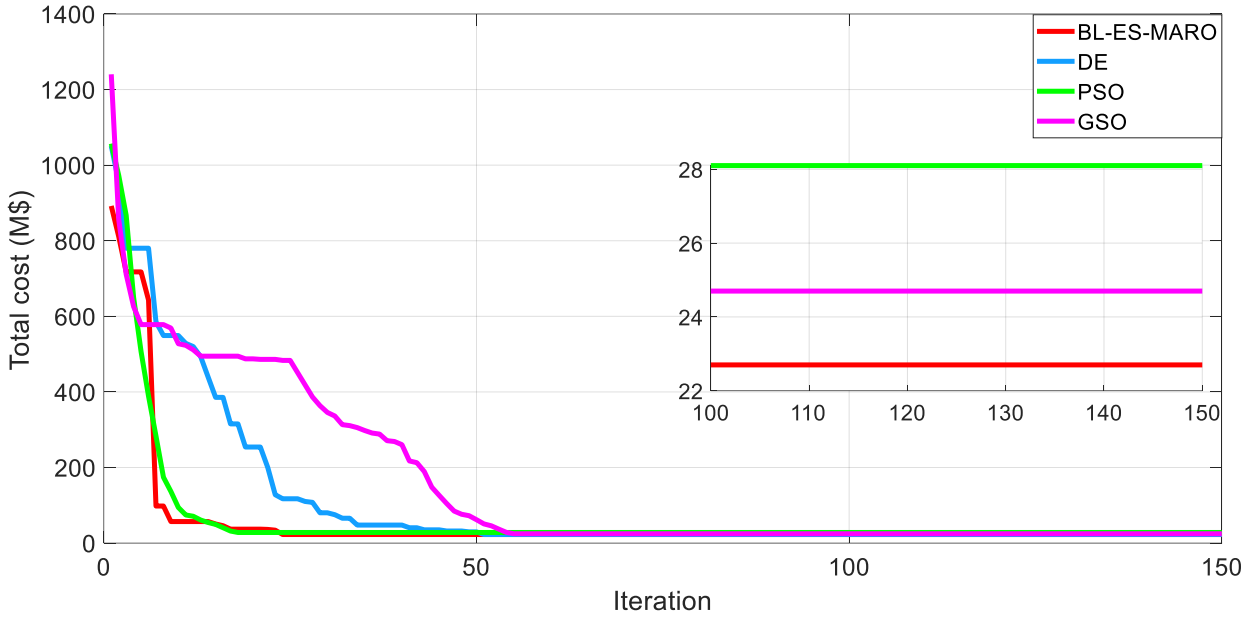


Figure 3. Convergency characteristics of the considered methods at scenario B2

Table 3. Performance comparison results for considered metaheuristic at scenario B1

	BL-ES-MARO	DE	PSO	GSO
Worst cost (M$)	25.1	25.9	381	323.1
Mean cost (M$)	22.8	24.1	126.7	131.1
Best cost (M$)	22.7	22.7	28.1	24.7
Standard deviation	0.4	1.3	91.8	76.8
Ave. Iter	51	63	16	108
Simulation time (min)	1.75	1.4	0.81	1.2

4.2 IEEE 14-bus system

The system includes 14 buses with a total load demand of 777 MW, 2 generators with a total capacity of 1197 MW, and 20 existing AC transmission lines. Regarding the AC grid expansion, the candidate set includes 20 AC rights-of-way. Furthermore, the DC expansion candidates have 14 potential DC buses, 14 DC converters, and 213 candidate DC transmission links. A maximum installed circuit for each right-of-way is 3. Detailed data for this test system can be found in [20]. Similar to the previous system, two scenarios are investigated: only AC transmission expansion (scenario C) and coordinated AC/DC transmission expansion (scenario D). The simulation results for these scenarios are summarized in Table 4. In this table, scenario D1 proposes an investment plan with a total cost of 12.8 M$ featuring two HVDC links ($l_{1-3} = 1$ and $l_{1-9} = 1$) and three converters (at nodes 1, 3, and 9). Under the N-1 security criterion (scenario D2), the cost rises by 6 M$ due to the additional HVDC infrastructure ($l_{1-3} = 1$, $l_{1-6} = 1$, and a converter at node 6). However, this plan is still 289.84 M$ smaller compared to the traditional AC expansion in scenario C2. This significant saving is caused by the reduction of extra transmission lines. Scenario C2 requires 15 additional lines, while D2 requires only 4. While traditional AC lines suffer from power losses and voltage degradation over long distances, HVDC transmission lines utilizing VSC technology effectively overcome these disadvantages by providing superior voltage profile regulation. As a result, the proposed AC/DC coordinated planning requires significantly fewer additional transmission components than traditional HVAC methods.

Table 4. Simulation results for the AC/DC TEP problem on the IEEE 14-bus system

	Scenario C		Scenario D	
	C1	C2	D1	D2
N-1 security criterion	×	✓	×	✓
HVAC additional lines	$l_{1-2}=3$ $l_{2-3}=1$ $l_{2-4}=3$ $l_{2-5}=1$ $l_{5-6}=2$ $l_{7-8}=1$ $l_{8-9}=1$ $l_{9-14}=1$	$l_{1-2}=3$ $l_{2-3}=2$ $l_{2-4}=3$ $l_{2-5}=1$ $l_{4-9}=2$ $l_{5-6}=1$ $l_{7-8}=2$ $l_{9-14}=1$	-	-
HVDC additional lines	-	-	$l_{1-3}=1$ $l_{1-9}=1$	$l_{1-3}=2$ $l_{1-6}=1$ $l_{1-10}=1$
Additional converters (DC bus to AC bus)	-	-	$1-1$ $3-3$ $9-9$	$1-1$ $3-3$ $6-6$ $10-10$
HVAC investment cost (M$)	259.02	308.64	-	-
HVDC investment cost (M$)	-	-	2.5	4.8
Converters' investment cost (M$)	-	-	10.3	14
Total cost (M$)	259.02	308.64	12.8	18.8

Table 5 summarizes the performance comparison of the considered methods for scenario D1. As observed from this table, the BL-ES-MARO algorithm successfully identifies the minimum cost of 12.8 M$, which is similar to the reported result from [11] and significantly lower than that suggested by the PSO and GSO methods. In addition, BL-ES-MARO continues to show robustness over the DE method that can be clearly observed by the standard deviation value (a reduction of 23.2). Figure 4 illustrates that PSO exhibits rapid convergence to local optima, significantly lowering its performance. On the other hand, the recently proposed state-of-the-art GSO method suffers considerably with this complex problem, underperforming even the conventional DE algorithm. This result demonstrates a key comment in TEP optimization: an algorithm's efficacy is determined not by its novelty but by its natural suitability to the problem's characteristics. For instance, the BL-ES-MARO method's specialized TEP-focused mechanism (BL strategy) provides high performance in the considered systems.

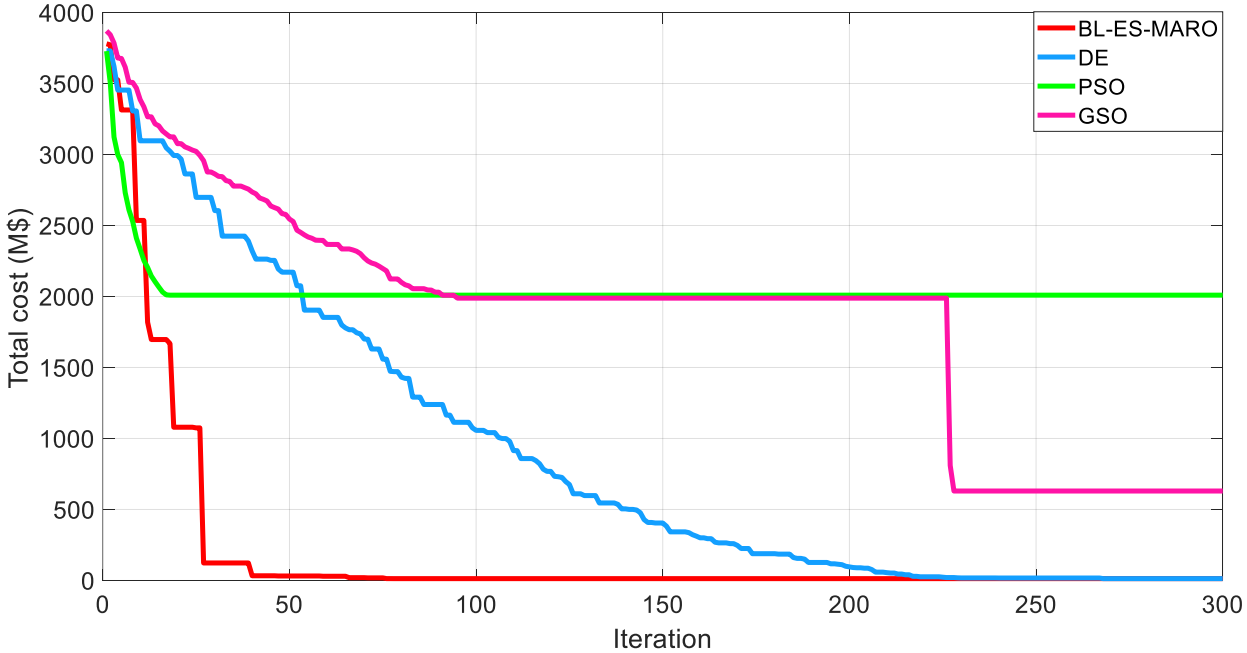


Figure 4. Considered methods' convergency curve at scenario D2

Table 5. Performance comparison results for considered metaheuristic at scenario D1

	BL-ES-MARO	DE	PSO	GSO
Worst cost (M$)	18.4	113	2553.3	1948
Mean cost (M$)	13.7	53.3	2178.7	958.8
Best cost (M$)	12.8	12.8	1718	629.8
Standard deviation	1.7	24.9	206.3	264.3
Ave. Iter	106	231.2	19	223
Simulation time (min)	17.7	15.2	14.5	16.8

5 CONCLUSION

This paper investigates the security-constrained AC/DC TEP problem using the Garver 6-bus and IEEE 14-bus test systems. The simulation results demonstrate that the coordinated AC/DC expansion requires significantly fewer new transmission lines compared to traditional AC transmission expansion, even under the N-1 security criterion. This advantage is primarily driven by the modern VSC in HVDC technology, which provides voltage profile regulation, thereby overcoming the voltage degradation suffered by distanced HVAC transmission. Therefore, the proposed AC/DC TEP approach yields significant investment savings of up to 84.8 M$ and 289.84 M$ for the Garver 6-bus and IEEE 14-bus systems, respectively. In the optimization aspect, the BL-ES-MARO method presents a higher performance in both optimality and robustness than DE, PSO, and GSO algorithms in the considered systems. This success is driven by its specific mechanisms (the BL and ES strategies), highlighting that an optimizer's efficiency in TEP heavily depends on its suitability rather than its novelty. Based on these findings, future studies can focus on the following approaches: i) developing hybrid or improved metaheuristic algorithms that are specifically designed for the mathematical properties of the TEP problem; ii) Although the proposed AC/DC framework offers investment savings, these cost evaluations are based on a static planning horizon and idealized market assumptions. Furthermore, HVDC components generally have shorter lifespans and higher maintenance requirements than traditional AC lines. As a result, addressing these limitations through a long-term dynamic expansion planning horizon that accounts for market uncertainties, equipment lifespans, and maintenance will be considered for future work.

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QUY HOẠCH MỞ RỘNG LƯỚI ĐIỆN TRUYỀN TẢI AC/DC CÓ XÉT ĐẾN CÁC RÀNG BUỘC AN NINH SỬ DỤNG CÁC THUẬT TOÁN METAHEURISTIC

BÙI NGUYỄN ĐỨC HUY, DƯƠNG THANH LONG*
Khoa Công nghệ điện, Trường Đại học Công nghiệp TP.HCM, Việt Nam
** Tác giả liên hệ: duongthanhlong@iuh.edu.vn*

Tóm tắt. Việc tích hợp các ràng buộc an ninh là một trong những yêu cầu thiết yếu trong quy hoạch mở rộng lưới điện truyền tải (TEP) nhằm đảm bảo độ tin cậy của hệ thống. Tuy nhiên, việc đáp ứng tiêu chí an ninh này có thể dẫn đến chi phí đầu tư cao, nhưng chủ yếu để ứng phó với các tình huống sự cố hiếm gặp, gây lãng phí kinh tế đáng kể. Để giảm thiểu sự kém hiệu quả này, công nghệ truyền tải điện một chiều cao áp (HVDC) được xem là giải pháp thay thế mang lại hiệu quả kinh tế cao so với hệ thống xoay chiều cao áp (HVAC) truyền thống, đặc biệt đối với các đường dây truyền tải đường dài. Do đó, nghiên cứu này trình bày mô hình quy hoạch mở rộng lưới điện AC/DC có xét đến ràng buộc an ninh nhằm đánh giá các lợi ích kinh tế so với phương pháp mở rộng lưới điện HVAC truyền thống. Mô hình đề xuất được thiết lập dưới dạng bài toán tối ưu hóa hai cấp: bài toán cấp trên xác định các phương án đầu tư lưới điện tối ưu, trong khi bài toán cấp dưới đánh giá các ràng buộc an ninh trong vận hành. Để đạt được các nghiệm chất lượng cao, thuật toán tối ưu hóa thỏ nhân tạo cải tiến kết hợp tìm kiếm tiến hóa và giới hạn biên (BL-ES-MARO) được áp dụng để giải bài toán trên các hệ thống chuẩn Garver 6 nút và IEEE 14 nút. Kết quả mô phỏng cho thấy hai phát hiện chính. Thứ nhất, các phương án mở rộng AC/DC thu được giúp tiết kiệm chi phí đáng kể, lần lượt lên tới 84,8 triệu USD và 289,84 triệu USD so với các phương án mở rộng AC truyền thống trên các hệ thống này. Thứ hai, thuật toán BL-ES-MARO thể hiện hiệu suất vượt trội cả về tính tối ưu lẫn độ bền vững khi so sánh với các thuật toán truyền thống như tiến hóa vi phân (DE), tối ưu hóa bầy đàn (PSO) và thuật toán tiên tiến tối ưu hóa rắn lượn (GSO).

Từ khóa. Quy hoạch mở rộng lưới điện truyền tải, ràng buộc an ninh, tối ưu hóa phi lồi, truyền tải điện một chiều cao áp, thuật toán metaheuristic.

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