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Original Article

Transmission Congestion Management by Rescheduling of Generation using an Enhanced Spider-Tailed Horned Viper Optimization Algorithm

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Abstract - *Transmission congestion in present-day heavily-loaded and deregulated power systems acts as a major bottleneck to economic power exchange and severely jeopardizes system reliability. Congestion management is part of maintaining market efficiency and system security. This paper describes an optimization technique for relieving transmission congestion through the optimal rescheduling or redispatch of active power generation. The problem is a nonlinear, constrained optimization aimed at minimizing the total cost of generation redispatch with strict adherence to the constraints of the system. Given the inherent high-dimensionality and complex constraints in power system optimization problems, a newly introduced efficient metaheuristic algorithm known as the Spider-Tailed Horned Viper Algorithm (STHVA) is used to discover the solution space for the global or near-global optimum. The basic version of the algorithm is enhanced as Levy Flight-based Spider-Tailed Horned Viper Algorithm (LESTHVA). The robust concert of the proposed method is tested on the IEEE 30-Bus test system and demonstrates its ability to quickly and efficiently relieve any line overload with minimal penalties in operational costs, thus setting up a practical framework for real-time system operation and resource utilization.*

Keywords - *Transmission Congestion Management, Generation Rescheduling, Spider-Tailed Horned Viper Optimization Algorithm, Power System Optimization, Deregulated Power System, Operational Cost Minimization.*

1. Introduction

Grid congestion happens when the electrical load on particular transmission lines exceeds their physical or operational limits, i.e., their thermal, voltage, or stability limits. This phenomenon has been identified as a major challenge to handle modern interconnected electric grids. A combination of growing energy needs, green energy development, and the move to competitive energy markets has created these grid congestions. As a result, congestion reduces the efficiency of electricity markets, increases operational costs, and may threaten system security if not managed properly [1, 2]. When transmission capacity becomes a limiting factor, generators cannot be dispatched purely based on their economic merit order. This results in suboptimal system operation and separation of Locational Marginal Prices (LMPs) across different network nodes [3]. Transmission Congestion Management (TCM) aims to alleviate line overloads while maintaining system reliability and minimizing operational cost. In general, congestion management strategies are categorized into 2: preventive and corrective approaches. Preventive methods involve actions taken before congestion occurs, such as network reconfiguration, optimal generation scheduling, or transmission switching. In contrast, corrective methods are implemented after congestion is detected and include generator rescheduling, demand curtailment, and redispatch actions in real time [4, 5].

Among these techniques, generation rescheduling is considered as one of the most practical and cost-effective approaches since congestion can be relieved through small adjustments in generator outputs without affecting system reliability [6, 7]. In generator rescheduling-based congestion management, the objective is to minimize the total generation cost while satisfying transmission line loading limits and system operating constraints. The problem is typically formulated as an augmented Optimal Power Flow (OPF) or Economic Dispatch (ED) model, where penalty terms for transmission line flow violations are incorporated into the generation cost function [8, 9].

Generator production cost is commonly represented using quadratic fuel cost functions [10], and the penalty factors ensure that transmission line overloads are minimized or eliminated during optimization [11]. However, the congestion management problem formulated through OPF is highly nonlinear, non-convex, and constrained, mainly because of the presence of power flow equations, generator operating limits, and transmission capacity constraints.

Traditional mathematical programming techniques often face difficulties in solving such complex problems efficiently, particularly when multiple constraints and nonlinearities are involved. Therefore, metaheuristic optimization algorithms have gained increasing attention due to their ability to handle complex search spaces and nonlinear optimization problems effectively [12]. Over the past decade, several nature-inspired metaheuristic algorithms such as Particle Swarm Optimization (PSO) [13], Genetic Algorithm (GA) [14], Grey Wolf Optimizer (GWO) [15], Ant Lion Optimizer (ALO) [16], and Teaching-Learning-Based Optimization (TLBO) [17] have been widely applied to congestion management through generator rescheduling. These algorithms demonstrate strong global search capability and flexibility in solving OPF-based optimization problems.

Nevertheless, many of these approaches suffer from several limitations, including premature convergence, slow convergence speed, and insufficient capability to escape local optima in highly complex OPF search spaces [18]. In addition, the inclusion of incremental and decremental generation cost coefficients along with penalty terms for transmission line violations increases the computational complexity of the optimization problem [19, 20].

Despite significant progress in metaheuristic-based congestion management approaches, several important research gaps remain unfilled. First, many existing algorithms struggle to maintain an effective balance between exploration (global search) and exploitation (local refinement), which may lead to premature convergence during generator rescheduling optimization [21, 22]. Second, most algorithms demonstrate limited adaptability when dealing with highly nonlinear OPF landscapes involving congestion penalties and complex power flow constraints. Third, stochastic search enhancement techniques such as Levy flights, which can improve exploration capability through long-range random movements, have not been sufficiently integrated into congestion management optimization frameworks. Finally, hybrid bio-inspired optimization frameworks specifically designed for transmission congestion management remain limited in the literature. These limitations highlight the need for developing an improved hybrid optimization algorithm capable of enhancing exploration capability while maintaining strong local exploitation for efficient congestion alleviation.

Recently, a new nature-inspired metaheuristic known as the Spider-Tailed Horned Viper Optimization (STHVO) algorithm has been proposed [23]. This algorithm is inspired by the hunting behaviour of Pseudocerastes urarachnoides, a species of horned viper that uses its spider-like tail as a lure to attract prey before executing a precise attack.

The algorithm mimics this predatory strategy to achieve efficient search and optimization performance. Motivated by the above research gaps, this study proposes an enhanced Levy Flight-based Spider-Tailed Horned Viper Algorithm (LESTHVA) for transmission congestion management using generator rescheduling. The combination of Levy flight mechanisms with the STHVO algorithm increases the global search capability by introducing long-range stochastic jumps that help the algorithm escape local optima and explore the search space more effectively. The major contributions of this work are summarized as follows: A novel Levy Flight-based Spider-Tailed Horned Viper Algorithm (LESTHVA) is proposed for transmission congestion management. The integration of Levy flight with the hunting mechanism of STHVO enhances the balance between global exploration and local exploitation.

The proposed algorithm effectively minimizes congestion cost while reducing line-flow violations through optimal generator rescheduling. The optimization formulation incorporates incremental and decremental generator cost coefficients together with penalty factors for line-flow violations to represent practical congestion management scenarios. The rest of this paper is organized as follows. Section 2 presents the mathematical formulation of the congestion management problem and the adaptation of the STHVO algorithm. Section 3 describes the basic and enhanced versions of the algorithm. Section 4 presents simulation results and comparative analysis. Finally, Section 5 concludes the paper.

2. Problem Formulation

2.1. Objective Function

The total congestion management cost F is calculated as the aggregation of incremental generation cost, decremental generation cost, and the congestion penalty cost associated with line flow.

$$min\, F = \sum_{i=1}^{N_G} \left(C_i^{inc} + C_i^{dec} \right) + \lambda \sum_{l=1}^{N_L} P_{OL,l} \tag{1}$$

where

C_i^{inc}→ incremental (up-rescheduling) cost of generator i
C_i^{dec}→ decremental (down-rescheduling) cost of generator i
λ→ penalty weight for line-flow violation, taken as 100000.
P_{OL}→ penalty function for line l

2.1.1. Incremental and Decremental Cost Terms

The rescheduling of the generator is denoted as:

$$\Delta P_{Gi} = P_{Gi} - P_{Gi}^0 \quad (2)$$

where P_{Gi}^0 is the pre-congestion (base-case) generation and P_{Gi} is the rescheduled generation output.

The incremental cost (when generation increases, i.e. $\Delta P_{Gi} > 0$) is modeled as:

$$C_i^{inc} = a_i^{inc}\,\Delta P_{Gi}^{inc} \quad (3)$$

and the decremental cost (when generation decreases, i.e. $\Delta P_{Gi} < 0$) is modeled as:

$$C_i^{dec} = b_i^{dec}\,\Delta P_{Gi}^{dec} \quad (4)$$

a_i^{inc} is the incremental (upward) cost coefficient.

b_i^{dec} is the decremental (downward) cost coefficient.

These can be obtained from generator offer/bid curves or from quadratic cost expansion near the base case.

2.1.2. Congestion Penalty Term

The line-flow violation penalty is expressed as:

$$P_{OL} = \begin{cases} 0, & |S_l| \le S_l^{max} \\ (|S_l| - S_l^{max})^2, & |S_l| > S_l^{max} \end{cases} \quad (5)$$

2.2. Subject to

Power balance constraint

$$\sum_{i=1}^{N_G} \Delta P_{Gi} = 0 \quad (6)$$

Generator limits

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}, \quad \forall\, i \quad (7)$$

Transmission line limits

$$|S_l| \le S_l^{max}, \ \forall\, l \quad (8)$$

3. Spider-Tailed Horned Viper Optimization (STHVO)

3.1. Basic Spider-Tailed Horned Viper Optimization Inspiration

The Spider-Tailed Horned Viper, found in Western Iran, relies on a spider-like tail for deceiving and attracting insectivorous birds. Its ambushing strategy comprised of (i) relocating to appropriate sites for ambush, as well as (ii) attracting and attacking prey)-directly translates into the algorithm's two stages:

Exploration phase → modelling the process of migration towards luring sites.

Exploitation phase → modelling tail movement and local attack near the ambush.

3.1.1. Population Initialization

If Every viper resembles to a candidate solution in the m-dimensional decision space.

The starting position of the i^{th} viper in the d^{th} dimension can be calculated as:

$$x_{i,d} = lb_d + r \times (ub_d - lb_d) \quad (9)$$

where
lb_d, ub_d= lower and upper bounds of variable d;

$r \in (0,1)$ = uniform random number.

All positions form the population matrix:

$$X = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,m} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N,1} & x_{N,2} & \cdots & x_{N,m} \end{bmatrix}_{N\times m} \quad (10)$$

and their corresponding fitness (objective) values:

$$F = \begin{bmatrix} F(X_1) \\ F(X_2) \\ \vdots \\ F(X_N) \end{bmatrix}_{N\times 1} \quad (11)$$

Phase 1 - Exploration: Moving to Ambush Locations

Each viper will identify a set of peer nodes that perform better (potential ambush points):

$$CA_i = \{ X_k \mid F_k \le F_i \} \quad (12)$$

From this list, a site SA_i is selected at random as:

$$x_{i,j}^{P1} = x_{i,j} + \sin\left(\frac{\pi}{2} r\right) \cdot \left(SA_{i,j} - I \cdot x_{i,j}\right) \tag{13}$$

where $I \in \{1,2\}$ is a random integer.

If the new location yields a better fitness:

$$X_i = \begin{cases} X_i^{P1}, & F_i^{P1} < F_i \\ X_i, & \text{otherwise} \end{cases} \tag{14}$$

The new exploratory position is then calculated as this phase resembles the world of global exploration because it allows vipers to explore other locations to set up ambushes.

Phase 2 - Exploitation: Caudal Luring and Attack

In a favourable ambush situation, the viper executes small amplitude local oscillations of its tail in order to attract prey - modelled as local search:

$$x_{i,j}^{P2} = x_{i,j} + \left(1 - 2\sin\left(\frac{\pi}{2} r\right)\right) \times \frac{(ub_j - lb_j)}{t} \tag{15}$$

where
t= current iteration number.

If this new local movement improves fitness:

$$X_i = \begin{cases} X_i^{P2}, & F_i^{P2} < F_i \\ X_i, & \text{otherwise} \end{cases} \tag{16}$$

This process of fine-tuning increases exploitation around promising regions, akin to the viper's fast, localized strike.

3.1.2. Complete Algorithmic Flow

Initialize number of vipers N, maximum iterations t_{max}, and variable bounds.

Generate initial positions using Eq. (9) and evaluate $F(X_i)$ for all vipers.

Repeat for each iteration $t = 1,2,\dots,t_{max}$:
For each viper i:
Form CA_i (Eq. 12) and select ambush SA_i.
Compute new exploratory position via Eq. (13).
Apply update rule (Eq. 14).
Perform local luring/attack update via Eq. (15).
Apply update rule (Eq. 16).
Evaluate all new solutions.
Update the global best X_{best}.
Stop when $t = t_{max}$ or convergence criteria met.
Return X_{best} as the optimal solution.

3.1.3. Motivation for the Hybrid Algorithm

The Spider-Tailed Horned Viper Algorithm (STHVA) by itself shows good exploitation capacity with the lure and strike process but can be prone to getting stuck at local optima much like any metaheuristic. Levy Flights brings:

Long range
Heavy-tailed Step
Improved escaping capability from local minima
More diversification of the population

3.2. Hybrid Levy Flight and Spider-Tailed Horned Viper Algorithm (STHVA)

The hybridization method that works very effectively and efficiently for metaheuristics, such as the STHVA, is the incorporation of a unique randomly walked phenomenon or the Levy Flight. The Levy Flight-Enhanced Spider-Tailed Horned Viper Algorithm (LESTHVA) modifies the inherently global exploration property of the Levy flight with the hunting-inspired exploitation process of the well-known Spider-Tailed Horned Viper Optimization Algorithm (STHVOA). The proposed methodology can be utilized for the improvement of the speed of convergence, the prevention of stagnation, and the improvement of the accuracy of solutions for the problems related to optimal power flow, congestion management, and the economical dispatch.

3.2.1. Levy Flight Mechanism

Levy flights have a probability distribution wit infinity of variance, which helps Levy flights make large movements occasionally among small steps.

The step size is computed as.

$$LF_{step} = \alpha \times \frac{u}{|v|^{\frac{1}{\beta}}} \tag{17}$$

where,

$u \sim N(0, \sigma_u^2)$, $v \sim N(0, \sigma_v^2)$
β= Levy distribution parameter (typically 1.5)
α= scaling factor

The candidate solution update is:

$$x_{i,j}^{P1} = x_{i,j} + LF_{step} \cdot \left(SA_{i,j} - I \cdot x_{i,j}\right) \tag{18}$$

This allows large random walks that break stagnation.

3.3. Algorithmic Steps (Pseudo-Code)

Hybrid Levy Flight–Spider-Tailed Horned Viper Algorithm

Initialize population X_i, bounds, and parameters
Evaluate fitness of all snakes
Identify the best prey X_{best}
For iteration t = 1 to MaxIter:
Compute diversity measure
For each snake i:
(a) Levy-Based Exploration

- If random < P_{LF}:
- Perform Levy update

(b) Prey Attraction Phase (STHVA)
- Adjust movement toward prey

(c) Ambush & Strike (Exploitation)
- Update via ambush and strike equations
- Enforce boundary limits
- Update global best solution
- Return optimized best solution

4. Results and Analysis
4.1. Modified 30 Bus System
The extension of the standard IEEE 30-Bus System [24] by first serializing the generator buses is a major re-indexing method used mainly for improving the computer efficiency of Power Flow Solution techniques using the Newton Raphson method. This test system involves a 30 bus system, with six buses chosen as the Gen Buses (Bus 1 as the Slack, and Buses 2, 5, 8, 11, and 13 as PV Buses), and the remaining twenty-four buses chosen as the Load (PQ) Buses. In the revised system, the first six numbers (1 through 6) will be used for the six Gen Buses, starting from Bus 1 (retaining the Slack Bus designation), and followed by the remaining five PV Buses.

Next, the twenty-four original Load Buses in the system can be systematically re-indexed starting from Bus 7 through Bus 30. Generation values and load values presented in Table 1 will be taken equally valid initial values of the market clearance prices, P_G^C and P_D^C. In the power system, congestion can be caused by several factors.

Table 1. Generator data of IEEE 30 bus system

Bus No	P_g^{min} (MW)	P_g^{max} (MW)	Q_g^{min} (MVAr)	Q_g^{max} (MVAr)	P_g^c (MW)	Price Bids ($/MWh)	
						a_i	b_i
1	0	360.2	-30	100	138.59	22	18
2	20	140	-30	100	57.56	21	19
3	15	100	-30	100	24.58	42	38
4	10	100	-30	100	35.90	43	37
5	10	100	-30	100	17.93	43	35
6	12	100	-30	100	16.91	41	39

Six case studies are used for illustration:

Case 1: The outage of line 1-2 leads to congestion in lines 1-3 & 7-8

Case 2: Line 2-9 is derated from 65 MW to 32 MW which causes overloading to line 2-9.

Case 3: 20% increase in load leads to line overload in line 1-2.

Case 4: Bilateral transaction of 100 MW of power between GENCO 2 and DISCO 8.

Case 5: Derating of lines 5-6 and 6-12

Case 6: Derating of line 2-3

4.1.1. Case 1: Outage of Line 1-2
Line connecting buses 1 & 2 has a tripped line. It leads to congested flow in the line connecting buses 1 & 3, 7 & 8. In order to clear the congested line, the power generation varies based on the STHVA & LESTHVA algorithm. The line currents after clearing the congested line, rating, & the congested flow are provided in Table 2.

Table 2. Line flows-comparison in case 1

Line number	Line rating	Before TCM	After TCM	
			STHVA	LESTHVA
1-2	Outaged	Outaged	Outaged	Outaged
1-3	**130**	**147.7194**	**129.7498**	**129.9011**
2-4	65	26.3867	19.977	20.0029
7-8	**130**	**140.1272**	**123.1161**	**123.2589**
2-5	130	44.8462	47.0443	47.0973
2-9	65	17.4039	17.895	17.9017
8-9	90	82.9115	74.607	74.6789
3-10	70	32.0137	29.3826	29.4377
4-12	130	50.5129	48.0403	48.092
9-4	32	2.4755	1.0789	1.1541
9-11	65	12.8079	12.8524	12.9276
9-12	32	11.5729	11.666	11.6854
11-12	65	26.7296	26.778	26.708
11-12	65	36.6051	36.8538	36.8251

8-13	0	30.984	30.3596	30.4072
13-14	65	31.7734	31.461	31.4464
12-14	32	8.8794	8.836	8.8364
13-15	32	21.5703	21.3873	21.3891
1-7	130	10.3206	10.1293	10.133
14-15	16	2.3694	2.3357	2.336
16-17	16	6.213	6.0394	6.0428
15-18	16	7.3761	7.2635	7.2661
18-19	16	3.9714	3.8683	3.8707
19-20	32	6.1515	6.268	6.2654
12-20	32	8.5977	8.7158	8.7131
15-21	32	4.5744	4.7694	4.7656
10-21	32	18.8937	18.9219	18.9186
12-22	32	9.0252	9.0439	9.0417
21-22	32	2.1445	2.1203	2.123
17-24	16	7.6676	7.5861	7.5857
22-24	16	6.7777	6.8276	6.822
23-24	16	4.034	3.972	3.9717
24-25	16	0.8908	0.8481	0.844
25-26	16	4.2709	4.2708	4.2708
25-27	16	4.6881	4.7144	4.7184
28-27	16	18.5494	18.5979	18.6046
27-29	65	6.4308	6.4305	6.4305
27-30	16	7.3085	7.3081	7.3081
29-30	16	3.7584	3.7583	3.7583
4-28	32	4.2977	4.2095	4.2237
9-28	32	13.3032	13.4413	13.4347

The loss of the line 1-2 creates a large redistribution of power, which causes the lines between buses 2 & 3 and 7 & 8 to be overloaded. As is evident by the extent of the line between buses 2 & 3 overloaded pre-rescheduling flow value of 147.7194 MW, which exceeds its rating of 130 MW.

In an attempt to relieve this overload, the optimizer has utilized the services of the two optimization techniques, STHVA, & the improved LESTHVA algorithm.

Both techniques were successful in relieving the line 2-3 below the limit, & thereby resulted in the value being decreased to 129.7498 MW by the former technique. The LESTHVA algorithm provided a further improvement to this value of 129.9011MW. The former algorithm resulted in a slightly improved optimization, evident by the slightly lower or more balanced value after the completion of both rescheduling. The congestion relief by the algorithms, in line 7-8 is also more or less same as in the case of line 2-3 as shown in Table 2.

Tabel 3. Benefits of TCM in case 1

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	482.6089	477.9321
Loss	6.2494	13.2559	13.2836
Voltage deviation	0.5292	0.5248	0.5249

The trade-off between overall optimality and network performance is quite evident from the comparison metrics as given in Table 3, where the best performer in terms of overall cost is the LESTHVA (477.93 vs 482.61), and hence it has been identified as the optimum when the main focus is to minimize the generation price. While STHVA has performed marginally better in terms of overall system loss (13.2559 vs 13.2836) and the overall voltage profile (0.5248 vs 0.5249). Figure 1 depicts how both STHVA and LESTHVA have brought the congested values of the flow carried by lines 2-3 and 7-8 within the admissible line flow limit of 130 MW. Although the congested values are significantly greater by about 148 MW for line 2-3 and 140 MW for line 7-8, both STHVA and LESTHVA have been able to bring the values below the limit. On lines 2-3, both STHVA and LESTHVA have brought the value below the limit of 130 MW from 147.7194 MW (Table 2). On lines 7-8, both STHVA and LESTHVA have been able to bring the congested value further down to about 123 MW, leaving a comfortable margin within the limit.

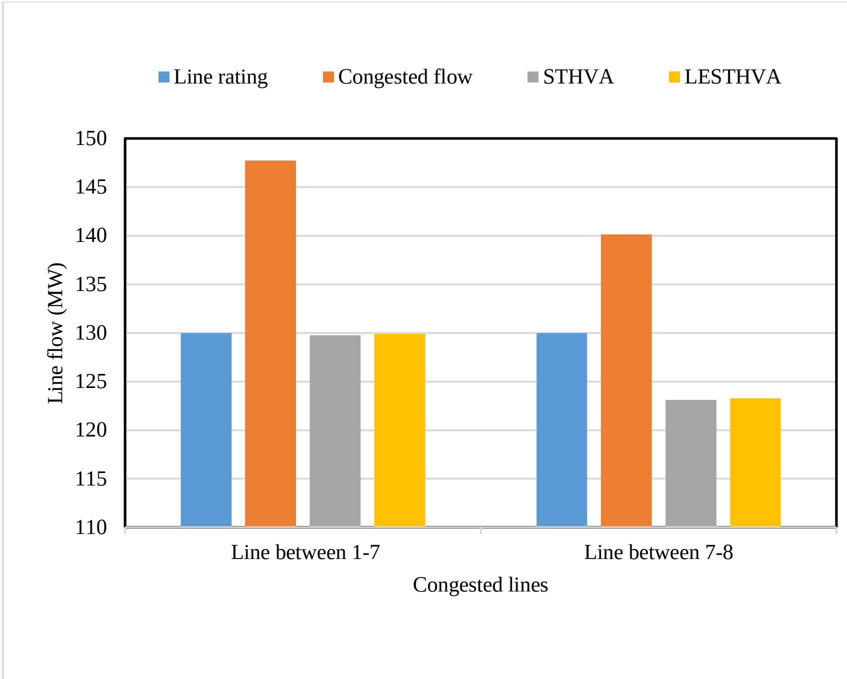

Fig. 1 Power flow in congested lines-comparison in case 1

The modified generation rescheduled in Figure 2 clearly manifests that both STHVA and the improved LESTHVA are able to modify the generator outputs with respect to the base market clearing values Pgc, whereas LESTHVA shows more stable and well-balanced rescheduling for the generators. In the highly loaded generators (Pg1 and Pg2), the LESTHVA makes the outputs slightly closer to the base values, expressing better maintenance of the base economic dispatch between the generators despite overload relief.

In the mid-size generators (Pg5 and Pg8), LESTHVA depicts better with improved consistency. In the smaller generators (Pg11 and Pg13), the rescheduling was found to be nearly the same, endorsing the convergence in the less significant region. The improved LESTHVA improves system stability, showing smaller deviations from the base values compared to STHVA.

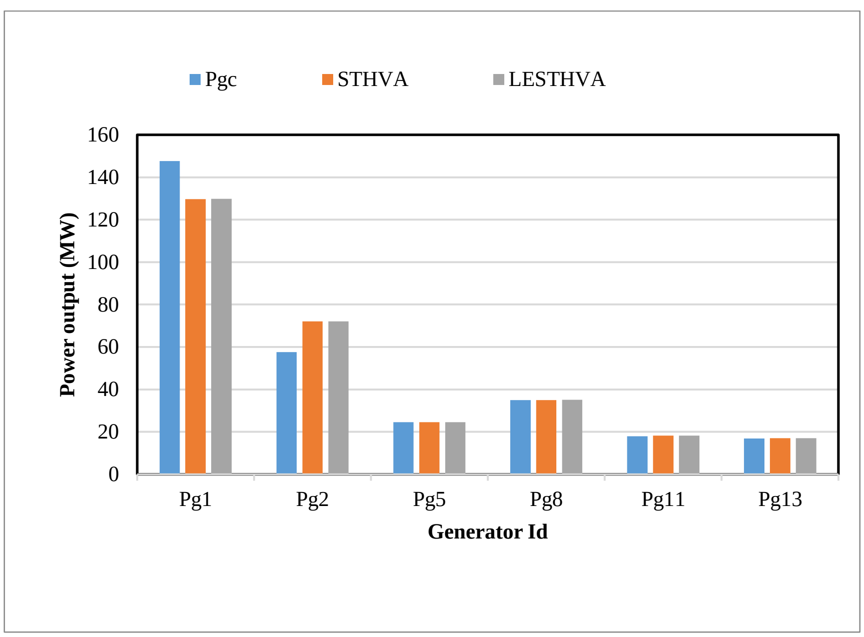

Fig. 2 Rescheduled generation in case 1

4.1.2. Case 2: Derating of Line 2-9

This reduction of the flow range of the 2-9 corridor from a value of 65 MW to that of 32 MW increases the pre-reschedule flow value on the same corridor to 38.16 MW, although with the help of the STHVA and LESTHVA algorithms, the situation on the congested element is rectified, thus reducing the flow of the 2-9 corridor to about 31.98 MW and 31.95 MW for the former and latter algorithms, which is just within the specified limit of 32 MW. The performance on the congested element indicates that the algorithms are efficient for hard constraint enforcement, and that LESTHVA gives a marginally better residual.

Table 4. Line flows-comparison in case 2

Line number	Line rating	Before TCM	After TCM	
			STHVA	LESTHVA
1-2	130	91.8849	91.6708	95.0408
1-3	130	47.7962	43.7509	44.5085
2-4	65	29.7147	24.9825	24.9272
7-8	130	44.2629	40.3886	41.1114
2-5	130	58.8703	55.9267	55.9619
2-9	**32**	**38.1597**	**31.9805**	**31.9505**
8-9	90	37.506	31.1194	31.2141
3-10	70	16.8551	19.4323	19.6478
4-12	130	35.7612	38.6285	38.7186
9-4	32	3.0677	11.1289	15.9145
9-11	65	14.3857	8.9564	13.6599
9-12	32	12.4093	11.1772	12.2347
11-12	65	26.1453	32.6568	26.8277
11-12	65	37.6149	40.5907	37.9303
8-13	30	28.0377	26.1112	26.6733
13-14	65	30.7588	30.6938	31.2450
12-14	32	8.6462	8.5008	8.6266
13 - 15	32	20.592	19.9939	20.5108
1 - 7	130	9.3584	8.6932	9.2806
14 - 15	16	2.1994	2.1035	2.1862
16 - 17	16	5.3895	4.9074	5.3289
15 - 18	16	6.8018	6.3605	6.7537
18 - 19	16	3.4668	3.1169	3.4271
19 - 20	32	6.778	7.2974	6.8335
12 - 20	32	9.2302	9.754	9.2860
15 - 21	32	5.6936	6.6194	5.7969
10 - 21	32	19.0085	19.3126	19.0213
12 - 22	32	9.1014	9.3036	9.1099
21 - 22	32	2.0495	1.8583	2.0394
17 - 24	16	7.2338	7.0498	7.2000
22 - 24	16	6.9814	7.5332	7.0042
23 - 24	16	3.7447	3.6515	3.7265
24 - 25	16	0.7207	0.7713	0.7242
25 - 26	16	4.2704	4.2704	4.2704
25 - 27	16	4.9162	4.7211	4.9340
28 - 27	16	18.9295	18.6321	18.9555
27 - 29	65	6.4297	6.4296	6.4295
27 - 30	16	7.3071	7.3069	7.3069
29 - 30	16	3.7581	3.7581	3.7580
4 - 28	32	4.1523	5.2418	6.1978
9 - 28	32	13.928	12.8083	12.3259

System-wide impacts reveal their differing styles: STHVA tends to apply more conservative, localized adjustments that keep many neighbouring line flows lower-for instance, on 9-4 and 9-11-reducing the risk of creating new hotspots. On the other hand, LESTHVA redistributes the power flow more globally-notably higher flows on lines such as 9-4 and 4-28-which can result in a smoother global cost optimum but shifts load onto other corridors (Table 4). This is to say that very often, LESTHVA attains slightly better overall balancing and optimality but at the price of larger, yet controlled, secondary flow changes.

Table 5. Benefits of TCM in case 2

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	1119.8	1085.2
Loss	7.4292	6.7581	6.9400
Voltage deviation	0.5125	0.5069	0.5099

Table 5 reveals that the application of both STHVA and LESTHVA brings significant improvements to the system performance post-congestion management. The value of the cost of congestion is reduced to 1119.8 and 1085.2, with the latter being of lower value, which is the prime objective of the problem for LESTHVA. The lowest value of loss of 6.7581 and voltage difference of 0.5069, which are the best technical performance, are achieved by the former, whereas the latter provides better performance marginally less than the former.

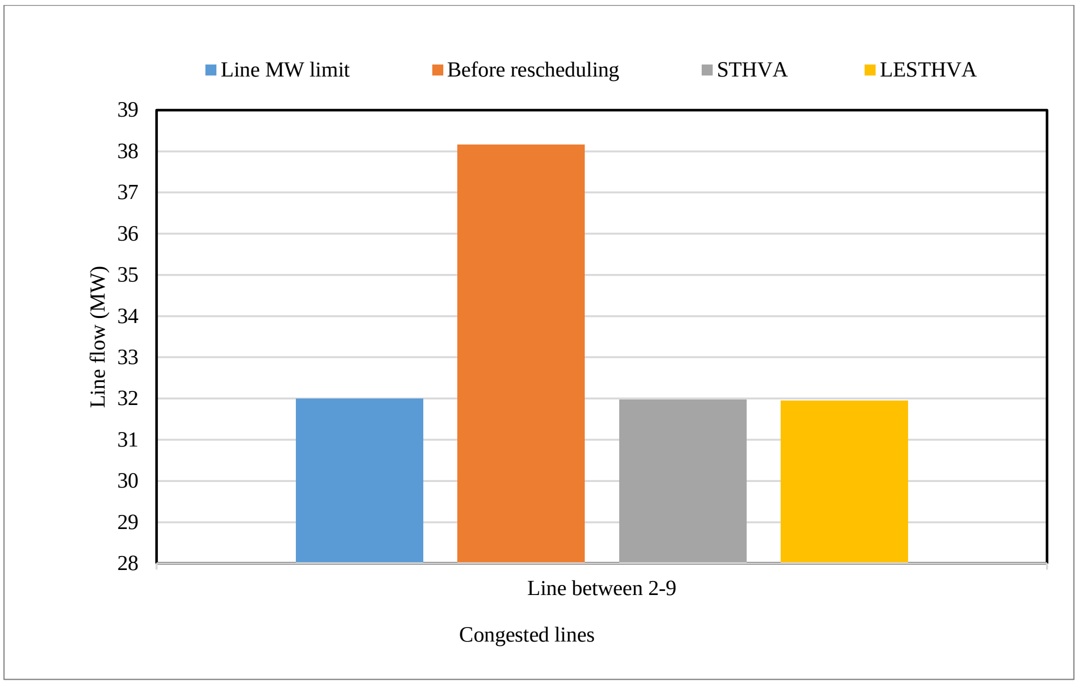

Fig. 3 Power flow in congested lines-comparison in case 2

It is clear from Figure 3 that the MW limit of 32 MW on the line connecting buses 2-9 is violated even before the rescheduling when it goes to nearly 38.2 MW. Both STHVA and LESTHVA work as perfect congestion reducers as they reduce the post-rescheduling value of this line to within the limit.

STHVA does this to nearly 32 MW, which is the exact limit of this line, while LESTHVA does it to an even lower value than STHVA, thus offering an additional margin of safety.

Figure 4 depicts the rescheduling of generators using STHVA, LESTHVA, and the original pattern of generation. Both algorithms decrease the output of heavily stressed generators such as Pg1 and Pg2, thus relieving congestion in the network. At the same time, the spin markets in less stressed regions, especially Pg8 and Pg11, are expected to generate more in order to balance loads without breaching network constraints.

LESTHVA indicates a slightly higher generation in spin markets Pg1 and Pg8 than in STHVA, thus depicting a slightly different pattern of redistribution, although they depict the same pattern of relocating generation from stressed areas.

Both algorithms demonstrate coordinated rescheduling of generation, with LESTHVA slightly more aggressive in relocating some of the generators.

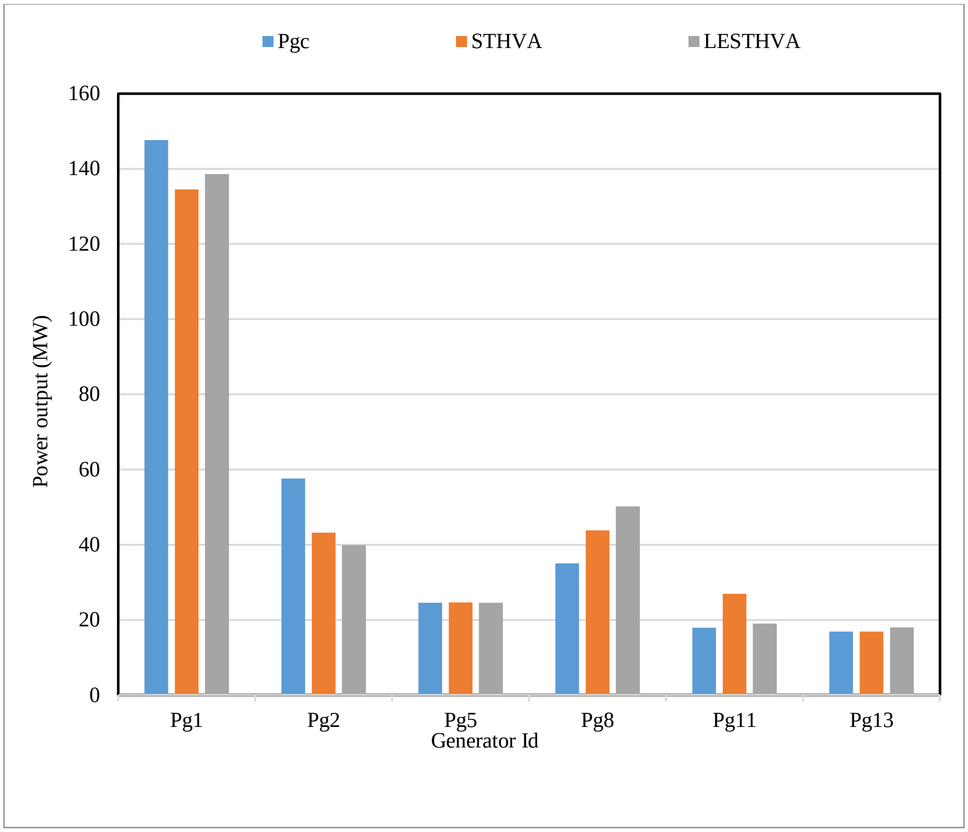

Fig. 4 Rescheduled generation in case 1

4.1.3. Case 3: 20 % Increased Load

The line-flow results from Table 6 clearly show that both STHVA and LESTHVA effectively relieve overloads on the critical lines while keeping all the network operation secured. In fact, for the congested line 1-2, the post-TCM flows achieved by both algorithms fall well below the rating; LESTHVA often provides a slightly larger reduction, reflecting a stronger congestion-relief capability.

Table 6. Line flows-comparison in case 3

Line number	Line rating	Before TCM	After TCM	
			STHVA	LESTHVA
1 - 2	**130**	**137.1241**	**108.4276**	**83.2037**
1 - 3	130	66.1808	57.4394	56.3501
2 - 4	65	38.3861	36.5183	42.8410
7 - 8	130	61.3304	52.9283	51.8641
2 - 5	130	75.8523	63.5906	77.3847
2 - 9	65	50.1000	46.0973	53.4741
8 - 9	90	52.0917	42.7270	47.4391
3 - 10	70	22.1942	15.2037	20.7566
4 - 12	130	43.3722	35.7200	41.8333
9 - 4	32	9.7616	6.0521	9.6982
9 - 11	65	20.1134	20.3530	20.2708
9 - 12	32	15.9221	16.0563	16.0030
11 - 12	65	28.5470	28.4812	28.5317
11 - 12	65	44.6905	44.8773	44.8051
8 - 13	30	37.1015	36.3137	36.8031
13 - 14	65	35.0527	35.0713	35.0394
12 - 14	32	10.3898	10.3469	10.3665
13 - 15	32	24.7108	24.5325	24.6136

1 - 7	130	11.1422	10.9794	11.0505
14 - 15	16	2.6107	2.5821	2.5954
16 - 17	16	6.3260	6.2004	6.2555
15 - 18	16	8.1338	8.0355	8.0773
18 - 19	16	4.0976	4.0164	4.0511
19 - 20	32	8.1707	8.2827	8.2354
12 - 20	32	11.1626	11.2760	11.2281
15 - 21	32	6.9333	7.1461	7.0544
10 - 21	32	22.8228	22.8355	22.8356
12 - 22	32	10.9166	10.9250	10.9250
21 - 22	32	2.5044	2.4935	2.4938
17 - 24	16	8.5505	8.4732	8.5112
22 - 24	16	8.2710	8.2932	8.2932
23 - 24	16	4.3398	4.3008	4.3210
24 - 25	16	1.0765	1.1215	1.0909
25 - 26	16	5.1495	5.1494	5.1495
25 - 27	16	6.1951	6.2622	6.2205
28 - 27	16	23.4180	23.5123	23.4556
27 - 29	65	7.7770	7.7767	7.7769
27 - 30	16	8.8430	8.8427	8.8429
29 - 30	16	4.5265	4.5265	4.5265
4 - 28	32	5.0679	5.5901	5.0755
9 - 28	32	17.6703	17.0666	17.7003

The lines with moderate values, like 2-4, 8-9, and 4-12, also observe notable relief, sometimes with slightly higher flows from LESTHVA than STHVA depending upon the strategy followed by the method. On non-critical lines, both algorithms maintain the power flows almost constant, proving that the correction activities do not contribute to any unnecessary stress on the system. On the whole, while there is stability on most of the congested lines with STHVA, there is more relief with LESTHVA on the principal congested routes, and thus there is efficient and secure congestion relief.

Table 7. Benefits of TCM in case 3

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	672.0805	1271.2
Loss	13.2865	10.0688	10.9469
Voltage deviation	1.2421	0.7260	0.7288

It is evident from Table 7 that both STHVA and LESTHVA lead to better system operational conditions post-congestion management.

The system losses and voltage deviation reduce substantially using both techniques, with STHVA giving the smallest system loss of 10.0688 and smallest voltage deviation of 0.7260, thus optimizing system performance.

Though both techniques result in better system performance post-LESTHVA, the reduction in congestion cost using STHVA (672.08) is substantially less compared to LESTHVA (1271.2), thus proving that STHVA performs congestion relief more efficiently.

This case study thus reveals that while both techniques improve system performance, STHVA performs better regarding efficiency. The congestion level in the overloaded line between buses 1&2 is in excess of the limit of approximately 130 MW prior to rescheduling, standing close to 138 MW, which is sufficient to confirm congestion as seen from Figure 5.

Both STHVA and LESTHVA are successful in reducing this below in the limit post-optimization.

STHVA is able to reduce it to approximately 108 MW, providing an excellent security margin in addition to removing congestion. LESTHVA is even more effective in removing congestion as it reduces it to nearly 83 MW, which provides an extensively larger security margin than STHVA.

LESTHVA is more effective than STHVA in removing congestion as it reduces the flow aggressively. Both methods are successful in removing congestion, but LESTHVA performs much better than STHVA in this process.

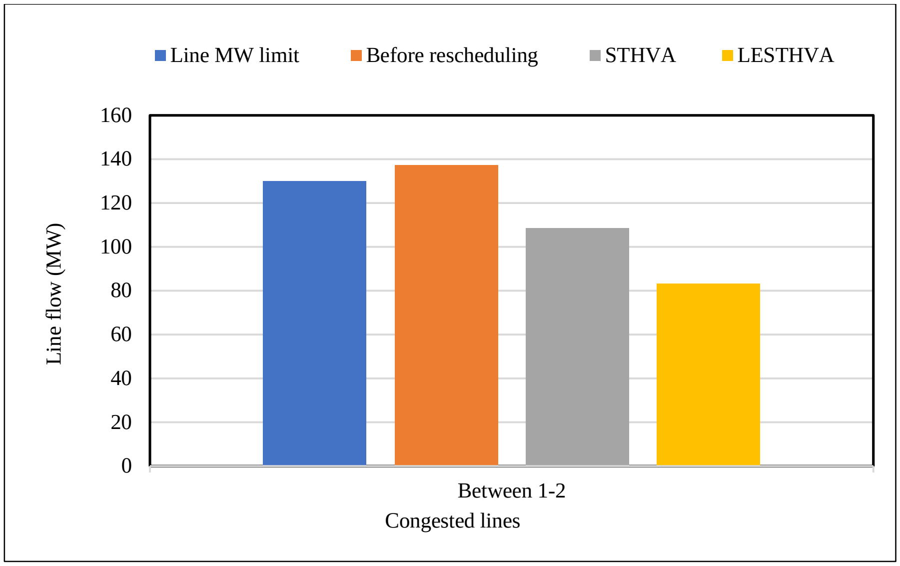

Fig. 5 Power flow in congested lines-comparison in case 3

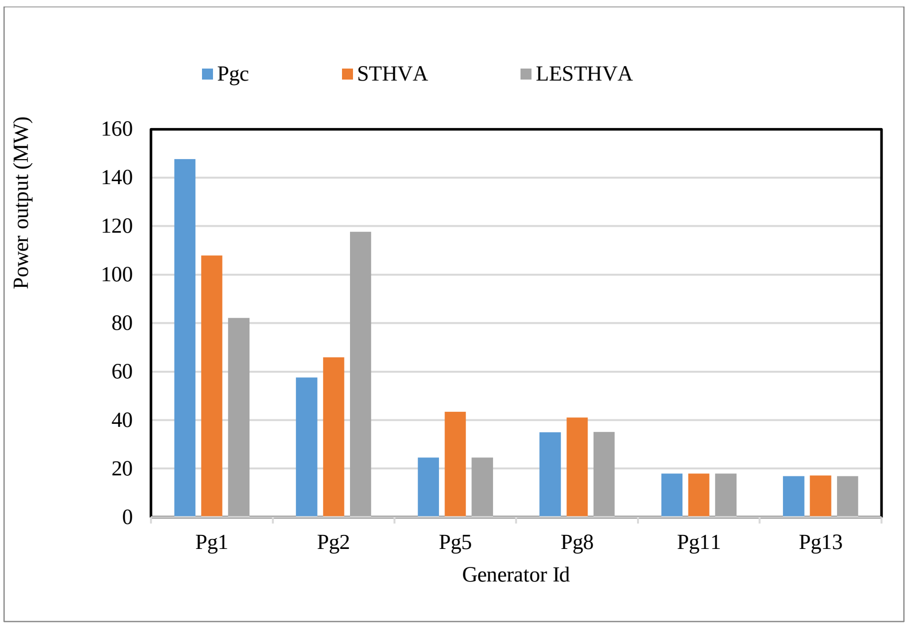

Fig. 6 Rescheduled generation in case 3

The adjustment of the two algorithms from the original dispatch Pgc shows the clear tendency of distinction. Both the schemes take off the excessively high output of Pg1 which definitely helps for congestion alleviation but does it in a different way. STHVA applies moderation in generations by distributing its burden with quite sharing of Pg2, Pg5, and Pg8 to have the whole graceful decline while keeping the system costs in check. In contrast, LESTHVA did an aggressive rescheduling further by reducing Pg1 and hand-in-hand boosting Pg2, reflecting thereby that the correctively strong action is done towards relieving the overloaded corridors (Figure 6). In smaller units, Pg11 and Pg13, both methods make only marginal adjustments reflecting thereby their limited influence on congestion. Overall STHVA is in favour of balanced redistribution, while LESTHVA keeps its strategy of more assertive rescheduling to enhance congestion relief.

4.1.4. Case 4: Bilateral Transaction of 100 MW between GENCO 2 and DISCO 8

The incorporation of a 100 MW bilateral transfer from GENCO-2 to DISCO-8 forces corridors 2-4 and 2-9 into overload, and both STHVA and LESTHVA perform generation re-dispatch successfully. STHVA tends to exert more robust and localized effects on the congested elements, causing a sharp reduction in the post-transfer flows on 2-4 and 2-9 corridors closer to their capacity limits as shown in Table 8.

Table 8. Line flows-comparison in case 4

Line number	Line rating	Before TCM	After TCM	
			STHVA	LESTHVA
1 - 2	130	71.0825	129.6403	101.6471
1 - 3	130	73.1846	83.7915	78.7323
2 - 4	**65**	**67.6873**	**62.5791**	**64.9989**
7 - 8	130	68.1712	78.313	73.476
2 - 5	130	71.8692	70.0779	70.9522
2 - 9	**65**	**66.5725**	**62.6773**	**64.5311**
8 - 9	90	3.5387	6.9432	4.951
3 - 10	70	9.3046	10.0498	9.6677
4 - 12	130	23.0876	24.7311	23.9653
9 - 4	32	10.4947	10.3707	10.4152
9 - 11	65	15.6131	15.3544	15.4757
9 - 12	32	12.9464	12.8296	12.8825
11 - 12	65	27.2593	27.324	27.2853
11 - 12	65	38.848	38.728	38.7749
8 - 13	30	25.7009	25.9276	25.8007
13 - 14	65	33.6624	33.7192	33.7036
12 - 14	32	8.455	8.482	8.4705
13 - 15	32	19.8085	19.9205	19.8728
1 - 7	130	8.6048	8.6999	8.6595
14 - 15	16	2.0678	2.0825	2.0763
16 - 17	16	4.8175	4.8738	4.8497
15 - 18	16	6.3399	6.4027	6.3761
18 - 19	16	3.0868	3.1318	3.1126
19 - 20	32	7.3039	7.2249	7.2584
12 - 20	32	9.7648	9.6856	9.7191
15 - 21	32	6.6841	6.5322	6.5967
10 - 21	32	19.1484	19.1349	19.1402
12 - 22	32	9.193	9.184	9.1875
21 - 22	32	1.9322	1.9422	1.9383
17 - 24	16	6.897	6.9384	6.9207
22 - 24	16	7.2143	7.1903	7.1998
23 - 24	16	3.5689	3.578	3.5741
24 - 25	16	0.8254	0.7918	0.806
25 - 26	16	4.2711	4.2711	4.2711
25 - 27	16	5.099	5.0621	5.0783
28 - 27	16	19.2085	19.1567	19.1796
27 - 29	65	6.4314	6.4315	6.4314
27 - 30	16	7.3092	7.3092	7.3092
29 - 30	16	3.7586	3.7586	3.7586
4 - 28	32	5.0485	5.0338	5.0364
9 - 28	32	13.5944	13.5422	13.5693

However, its aggressive approach also makes the STHVA more effective when fast, immediate relief for a particular bottleneck is the main operational aim. LESTHVA, on the other hand, removes congestion through a more general, continuous process of redistribution of injections and withdrawals, which keeps all neighbouring line flows relatively close to their pre-contingency values. This more general process will typically provide better performance on the overall objective (less generation cost or losses), but with a tendency for less extreme secondary movements, although at the cost of greater residuals on the initially congested lines. Thus, if local, immediate relief with minimal impact on the congested element is a higher operational priority, then use STHVA; otherwise, LESTHVA is preferable. Based on operational preferences, use punchy and local relief of STHVA for immediate operational targets, while use LESTHVA for combined operational, optimal, and stable restoration of the whole power system.

Table 9. Benefits of TCM in case 4

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	2334.3	2271.8
Loss	12.2935	14.5170	13.2834
Voltage deviation	0.5376	0.5380	0.5378

The analysis of the results reveals that both STHVA and LESTHVA are effective in relieving congestion, as evidenced by the decrease in the congestion cost from the pre-TCM state (Table 9). The LESTHVA approach yields the minimum congestion cost (2271.8), slightly outperforming STHVA in terms of cost effects. However, the improved solution with STHVA is at the expense of increased system losses for the former and more manageable system losses for the latter. The voltage deviation values are virtually the same for both approaches, and these algorithms are effective in maintaining the voltage value during the rescheduling process. Therefore, LESTHVA has slightly better overall performance in terms of the congestion cost and system performance with negligible difference in voltages.

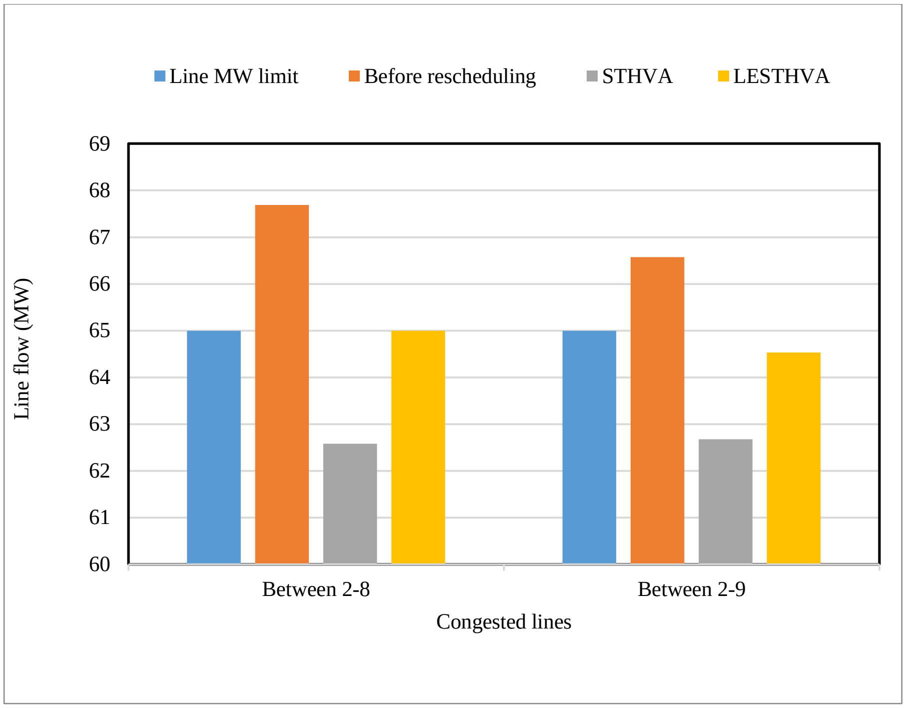

Fig. 7 Power flow in congested lines-comparison in case 4

Figure 7 shows the congestion level of lines 2-8 and 2-9, which are both overloaded with respect to their MW limits before the implementation of the optimization techniques.

After optimization techniques, STHVA effectively reduces the level of power flow of both lines well below the limit, thus providing relief from congestion.

Also, congestion relief through the reduction of both flows to values that are at or below the limit for LESTHVA ensures that the generating system avoids overload, and STHVA performs better than the other two techniques, as it provides higher security margins against overload.

Figure 8 illustrates that the output of STHVA and LESTHVA is rescheduled in comparison with original generation dispatching. Both algorithms reduce Pg1, as it causes congestion, although the degree of reduction is varied, in that STHVA reduces it slightly, while LESTHVA reduces it more drastically.

STHVA then compensates this by increasing Pg2 output to an equal level, whereas LESTHVA lets Pg2 output increase drastically, so that it becomes a dominant source in fulfilling system demand after rescheduling.

Then, as far as the smaller units of Pg5, Pg8, Pg11, and Pg13, despite being less involved in congestion mitigation, in that they make trivial modifications, are concerned, in that of both algorithms, minimal modifications are made.

Hence, while STHVA seeks balanced rescheduling among different units, LESTHVA seeks a corrective approach from Pg1 to Pg2, which results in more obvious rescheduling.

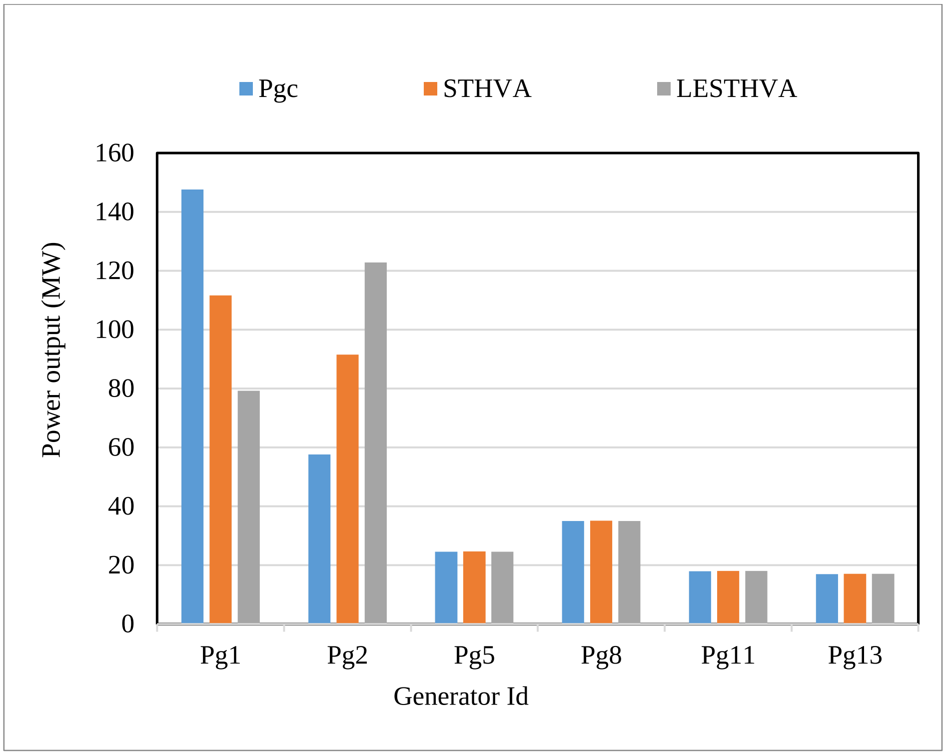

Fig. 8 Rescheduled generation in case 4

4.2. Modified IEEE 57 System

The modified IEEE 57-bus system used in this study is based on the standard configuration [24], retaining the original 80 transmission lines, 7 generators, and 42 load buses. In order to simplify the implementation of the algorithms in this paper and to ensure higher computational efficiency, some renumbering has been made to the buses such that all the generator buses come before the load buses. The reordering in the structure does not alter the electrical parameters, topology, or operating characteristics of the network and therefore does not affect the validity of the comparative studies presented in this work.

Table 10. Generator data of IEEE 57 bus system

Bus No	P_g^{min} (MW)	P_g^{max} (MW)	Q_g^{min} (MVAR)	Q_g^{max} (MVAR)	P_g^c (MW)	Price Bids ($/MWhr)	
						a_i	b_i
1	0	575.88	−140	200	146.39	44	41
2	0	100	−40	50	87.55	43	39
3	0	140	−40	60	41.97	42	38
4	0	100	−30	25	89.67	43	37
5	0	550	−140	200	461.21	42	39
6	0	100	−30	9	100.00	44	40
7	0	410	−150	155	344.95	44	41

4.2.1. Case 5: Derating of lines 5-6 and 6-12

To further stress the network, capacity limitations for transmission lines 5-6, rating = 175 MW, and line 6-12, rating = 35 MW, were reduced from their nominal ratings of 200 MW and 50 MW, respectively. This resulted in immediate overloading of the transmission lines, and the results of this can be found in Table 11.

Table 11. Benefits of TCM in case 5

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	6055.47	5809.43
Loss	69.64	25.342	24.657
Voltage deviation	1.5421	0.9260	0.8288

The results establish the effectiveness of the developed algorithms in reducing congestion. Although, initially, the system was operating under stressed conditions with considerable losses and voltage deviations, with the aid of STHVA, congestion costs were reduced to 6055.47 $/h, and losses were minimized to 25.342 MW.

It has also been observed that LESTHVA outperformed both the benchmark data and STHVA with lower congestion costs, such as 5809.43 $/h, reduced losses of 24.657 MW, and an improved voltage profile at 0.8288 deviation, thereby proving itself as the best solution for optimization.

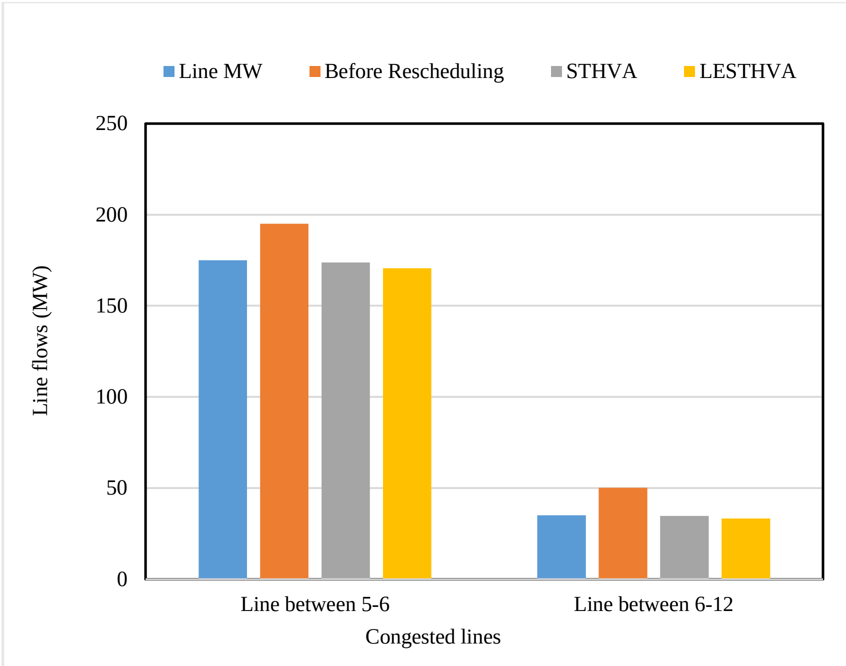

Fig. 9 Power flow in congested lines-comparison in case 5

Figure 9 presents a comparison of line power flow for congested branches 5-6 and 6-12. Even though these algorithms help in resolving congestion, it is observed that LESTHVA is found to be more efficient because of its ability to decrease line loading; for branch 5-6, the flow is reduced to 170 MW, compared to 173 MW, while for branch 6-12, this value is reduced to 33 MW, as opposed to 35 MW.

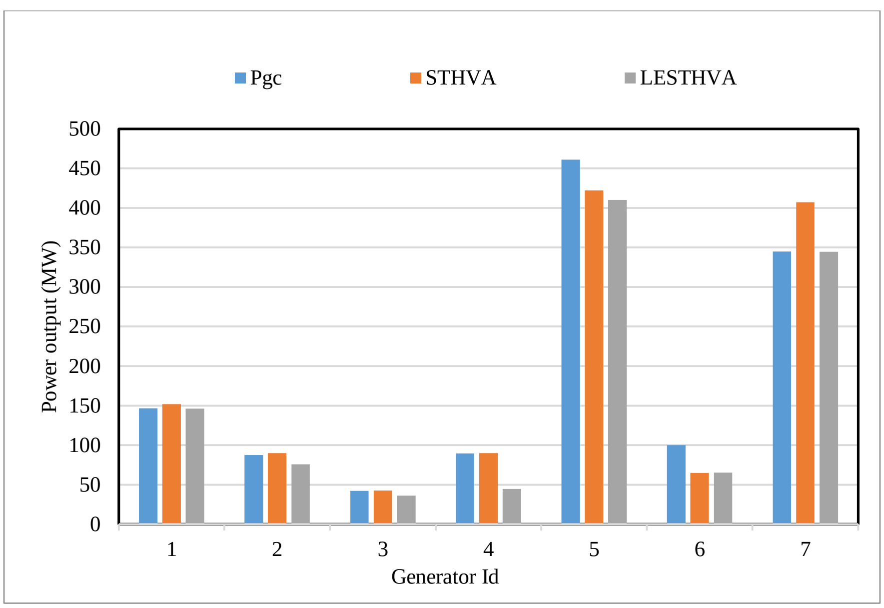

Fig. 10 Rescheduled generation in case 5

With regard to generation rescheduling, it is indicated in Figure 10 that a better balance is attained relative to real power output with respect to base case, STHVA, and LESTHVA. G5 and G7 generators remain key areas of relief, and as such, a more balanced and economic outcome is assured, given that there is a minimum change in minor generators with LESTHVA, compared to STHVA.

4.2.2. Case 6: Derating of line 2-3

Capacity limitations for transmission lines 2-3, rating = 35 MW, was reduced from its nominal rating of 50 MW, respectively. This resulted in immediate overloading of the transmission lines, and the results of this can be found in Table 12.

Table 12. Benefits of TCM in case 6

Description	Before TCM	STHVA	LESTHVA
Congestion cost	-	2314.34	2243.45
Loss	78.23	26.432	25.532
Voltage deviation	1.5572	0.9760	0.8988

Table 12 shows the validation of the proposed TCM strategies by the data. It is observed that the system is under huge stress initially with very high congestion losses, 78.23 MW, and a large voltage deviation of 1.5572. The STHVA algorithm successfully diminishes the congestion costs to 2314.34 $/h and losses to 26.432 MW; however, the LESTHVA method is far better. In fact, LESTHVA gives the best result for all the aforementioned cases, which considerably reduces the congestion cost to 2243.45 $/h, shrinks the loss to the least value of 25.532 MW in this study, and improves the voltage profile with a voltage deviation of 0.8988 only.

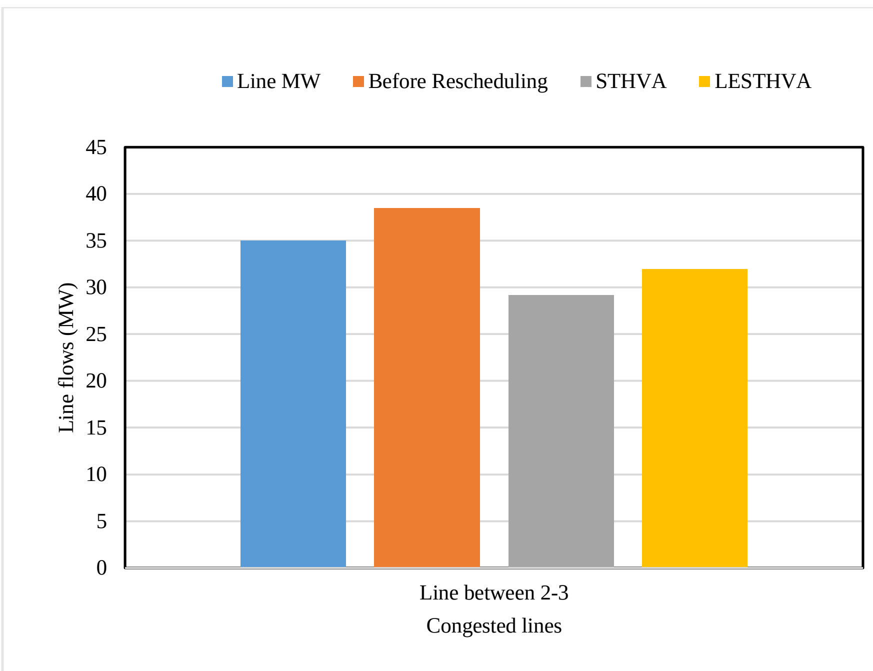

Fig. 11 Power flow in congested lines-comparison in case 6

Figure 11 depicts the power flow transitions on line 2-3 throughout the rescheduling process. Initially, the line suffers from severe overloading, significantly exceeding its operational threshold. While the STHVA algorithm successfully curtails the flow to 29 MW, the LESTHVA algorithm provides a more optimized adjustment, stabilizing the flow at approximately 32 MW.

By maintaining the flow closer to the 35 MW limit without exceeding it, LESTHVA demonstrates a more controlled and sophisticated approach to congestion relief, ensuring both system security and efficiency. The actual generator outputs corresponding to various operating scenarios are depicted in Figure 12 above. From the results, it is observed that generator output rescheduling is effectively performed to remove line congestion, and at the same time, satisfy all other operating constraints. Accordingly, generators 5 and 7 dominate the congestion relief process and show the highest degree of output adjustment, followed by other generators exhibiting smaller output fluctuations. Therefore, the rescheduling process ensures a reliable and cost effective transition towards a stable state.

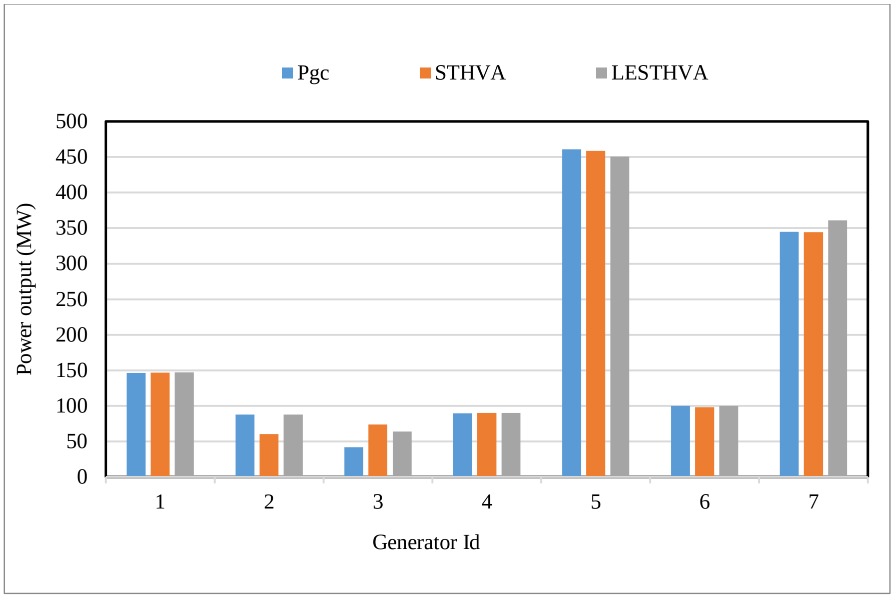

Fig. 12 Rescheduled generation in case 6

5. Conclusions and Future Work

Levy Flight Enhanced Spider Tailed Horned Viper Algorithm (LESTHVA) with optimal generation rescheduling for handling transmission congestion effectively in a power system was introduced in the proposed study. Indeed, by combining the adaptive Levy flight exploration process with the predatory exploitation process from the conventional STHVA algorithm, the new technique has managed to overcome the previous versions with respect to the search diversity, convergence rate, and strength. The new technique has been tested on the changed IEEE-30 bus system and IEEE-57 bus system with the six different real-world transmission congestion modes, including line outage, line reduction, 20% uniform load, as well as bilateral transactions and derating of lines.

Simulation outcomes have managed to prove the substantial better performance of ESTHVA compared with other tested approaches regarding the minimization of congestion costs, loss reduction, and improvement of the voltage level. Moreover, the capacity of ESTHVA to arrive at appropriate rescheduling strategies even within critical situations verifies the appropriateness of the proposed method to be applied by the respective utilities through real-time and/or near real-time congestion management. In combination, the simulation outcomes have managed to verify the high potential of the proposed method acting as a valid means during the secure and economic operation of the deregulated power utilities.

The proposed ESTHVA can be extended further by integrating stochastic and uncertainty-based models, which can be used to represent variable renewable resources and stochastic load. Its popularity may be increased by extending it for multi-objective congestion management, where all the parameters like cost and voltage stability can be considered at the same time. The future research works can be based on the combination of ESTHVA and machine learning algorithms, which can increase the precision and convergence speed. The real-time performance can be verified based on the implementation of the algorithm in the SCADA/EMS system.

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