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Optimizing deregulated power systems: Facts devices for congestion alleviation and cost reduction

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Abstract
The shift towards deregulation in modern power systems has sparked intense competition within energy markets, leading to a surge in system congestion. This surge not only jeopardizes the reliability and security of the system but also escalates energy costs. To tackle this challenge, an effective approach involves adjusting generator schedules, albeit at a higher expense. However, the emergence of sophisticated power electronic devices, such as Flexible AC Transmission System (FACTS) devices, presents a promising avenue to mitigate the necessity for generator rescheduling. These FACTS devices play a pivotal role in optimizing the overall power distribution by curbing power losses. This study delves into leveraging FACTS devices to cut down on generation costs by tackling congestion in deregulated power systems. Specifically, we strategically integrate Static Var Compensators (SVC) and Thyristor-Controlled Series Compensators (TCSC) to alleviate overloading. To pinpoint the optimal locations and fine-tune parameters for these FACTS devices, we propose employing the JAYA Optimization algorithm. This approach is geared towards enhancing the efficacy of these devices in managing system congestion.

Keywords: Flexible AC Transmission systems, deregulated power system, congestion, generation cost, JAYA algorithm

Introduction

The modern societal landscape, characterized by its technological advancement and dense population, has created an insatiable demand for power. To meet this demand, there has been a significant shift towards the deregulation of power systems, granting private entities the authority to supply power to contracted consumers through existing transmission lines. However, this increased demand often strains these transmission lines, leading to inefficiencies and heightened power losses, ultimately jeopardizing the reliability of the entire system [1]. In response to the challenges posed by geographical and economic limitations in expanding transmission infrastructure, the concept of Flexible AC Transmission Systems (FACTS) has emerged as a viable solution. FACTS technology serves a dual purpose by relieving system overloads and reducing power losses without placing additional strain on generators. Although the initial investment is considerable, strategically deploying FACTS devices in optimized locations proves essential for maximizing cost-effectiveness [2]. The function of FACTS devices encompasses various aspects such as altering line reactance, controlling voltage levels, supplying both active and reactive power, and adjusting voltage angles at different bus locations [3]. Their application is particularly advantageous in congested systems, where they enhance voltage stability and ensure uninterrupted power supply [4, 5]. The integration of FACTS devices into the system requires meticulous planning to ensure both safety and cost-effectiveness [6]. Determining the optimal locations for FACTS devices involves employing a variety of methodologies, including sensitivity factor-based approaches and bio-inspired algorithms. Sensitivity factor-based techniques utilize parameters like DC Power Transfer Distribution Factor (DCPTDF) [7], line outage sensitivity [8], total system loss sensitivity indices [9], and locational marginal price differences [10] to precisely position the devices. On the other hand, bio-inspired algorithms such as genetic algorithms and simulated annealing offer real-time solutions, even in dynamic conditions, thereby enhancing the accuracy of FACTS device placement [11]. Various types of FACTS devices, including Thyristor-Controlled Series Compensator (TCSC), Static Synchronous Compensator (STATCOM) [12], Static VAR Compensator

(SVC) [13], Unified Power Flow Controller (UPFC) [14], and Interline Power Flow Controller (IPFC) [15], are strategically utilized to alleviate congestion and minimize voltage profile deterioration and power losses. Algorithms like Particle Swarm Optimization [16], Artificial Bees Colony [17], and Whale Optimization Algorithm [18] aid in identifying optimal locations for these devices, thereby improving system efficiency. While adjusting active power generation schedules can mitigate congestion, it may lead to economic repercussions. Combining FACTS devices with generator rescheduling offers a balanced approach to enhancing cost-effectiveness and operational performance. Optimal Power Flow (OPF) serves as a valuable tool for evaluating the economic and technical benefits of such interventions.
This paper investigates the economic advantages of strategically deploying FACTS devices, specifically SVC and TCSC, in the IEEE 30 Bus power system. Using JAYA Optimization Algorithm, it validates the effectiveness of FACTS devices in enhancing profitability, mitigating congestion, reducing power loss, and minimizing generation costs. By simulating deregulation through N-1 contingency analysis, the research demonstrates that the applied JAYA algorithm effectively optimizes the size and parameter setting of SVC and TCSC devices, thereby reducing active and reactive losses in power system and decreasing the overall cost of generation.

Modelling of FACTS Devices
The mathematical representation of active power and reactive power flow between bus *m* and bus *n* is as follows.

$$P_{m,n} = V_m^2 g_{m,n} - V_m V_n \left(g_{m,n} cos\theta_{m,n} + b_{m,n} sin\theta_{m,n}\right) \quad (1)$$

$$Q_{m,n} = -V_m^2 \left(b_{m,n} + b_{sh}\right) - V_m V_n \left(g_{m,n} sin\theta_{m,n} - b_{m,n} cos\theta_{m,n}\right) \quad (2)$$

Where, $P_{m,n}$ and $Q_{m,n}$ represents the active power and reactive power flow between buses *m* and *n*, V_m and V_n denotes voltages and θ_m and θ_n are corresponding voltage angle at bus *m* and bus *n*. $g_{m,n}$ and $b_{m,n}$ represents conductance and susceptance of line between bus *m* and bus *n*.

Modelling of SVC
The SVC, a crucial component of FACTS, aids in maintaining stable voltage levels along transmission lines and improving the overall efficiency of power systems. Its swift adjustment of reactive power helps bolster the reliability of the grid, delivering advantages to both operators and utility companies [19]. Fig. 1 depicts the diagram of a Static Var Compensator (SVC), showcasing a setup comprising a thyristor-controlled reactor alongside a constant capacitor. The equation representing the current flowing through the SVC can be expressed as:

$$I_{SVC} = jB_{SVC} V_{ref} \quad (3)$$

Here, I_{SVC} represents the current flowing through the SVC, B_{SVC} denotes the susceptance of the SVC and V_{ref} denotes reference voltage at bus (node *m*). The reactive power limitations of SVC can be given by.

$$Q_{max} = B_L \times V_{ref}^2 \quad (4)$$

$$Q_{min} = B_C \times V_{ref}^2 \quad (5)$$

Here, B_C & B_L refers to the capacitive susceptance and inductive susceptance of SVC.

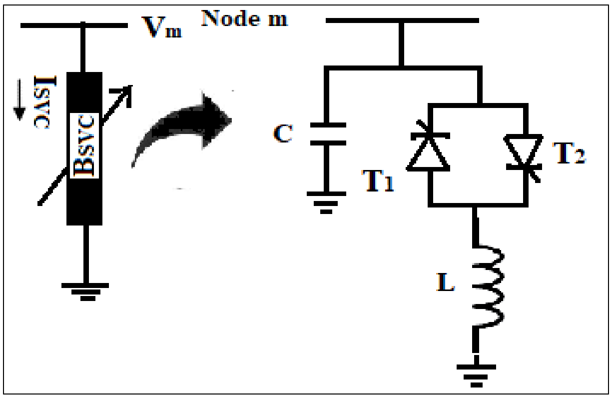

Fig 1: Schematic of SVC

TCSC Modelling
The TCSC configuration combines a static capacitor with a parallel Thyristor Controlled Reactor (TCR) connected alongside the capacitor to provide a continuously adjustable capacitive reactance in series. The main idea behind the TCSC strategy is to generate a capacitor that can be dynamically adjusted by partially counteracting the compensating capacitance with the TCR. TCSC dynamically alters the reactance of transmission lines to optimize power flow. Refer to Figure 2 for the schematic representation of TCSC.

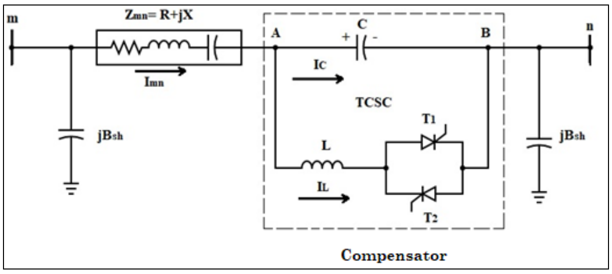

Fig 2: Schematic of TCSC

The active $P_{l(m,n)}$ power loss and reactive power loss $Q_{l(m,n)}$ in the line between bus *m* and bus *n* can be expressed as:

$$P_{l(m,n)} = g'_{m,n}\{((V_m - V_n)^2 + V_m V_n (\theta_m - \theta_n)^2\} \quad (6)$$

$$Q_{l(m,n)} = \left(b'_{m,n} + b_{sh}\right)\{((V_m - V_n)^2 + V_m V_n (\theta_m - \theta_n)^2\} \quad (7)$$

Let Y_{mn} be the line admittance between bus *m* and bus *n* without placing TCSC, this can be mathematically represented as.

$$Y_{mn} = G_{mn} + jB_{mn} \tag{8}$$

When TCSC is implemented in the circuit the change in admittance can be given as.

$$\Delta Y_{mn} = y'_{mn} - y_{mn} \tag{9}$$

$$\Delta Y_{mn} = \{(g'_{mn} + b'_{mn}) - (g_{mn} + b_{mn})\} \tag{10}$$

In equation (10)

$$\left.\begin{aligned} g_{mn} &= \frac{R_{mn}}{\sqrt{R_{mn}^2 + X_{mn}^2}} \\ b_{mn} &= \frac{-X_{ij}}{\sqrt{R_{mn}^2 + X_{mn}^2}} \end{aligned}\right\} \tag{11}$$

and

$$\left.\begin{aligned} g'_{mn} &= \frac{R_{mn}}{\sqrt{R_{mn}^2 + (X_{mn} + X_{tcsc})^2}} \\ b'_{mn} &= \frac{-(X_{mn} + X_{tcsc})}{\sqrt{R_{mn}^2 + (X_{mn} + X_{tcsc})^2}} \end{aligned}\right\} \tag{12}$$

By adjusting X_{tcsc} parameter the overall conductivity of the line changes, which are then integrated into the load flow analysis to calculate the line flows.

JAYA Algorithm

'JAYA' originates from the ancient language Sanskrit, where it signifies 'victory'. This algorithm stands out as non-probabilistic, eliminating the need for specific parameters unique to algorithms like GA, PSO, HS, ABC, etc., aside from setting the population size and number of iterations. It emulates a process akin to agents striving to achieve a goal. These agents progress towards the target by adopting the optimal solution path while steering clear of worst solutions. Within the predefined solution space, agents solely adhere to the best positions and continually update other positions with superior solutions. In the realm of the JAYA algorithm, solutions can be likened to particles existing at specific positions within the space. The functionality of the JAYA algorithm can be understood with the help of flowchart given in Fig. 3.

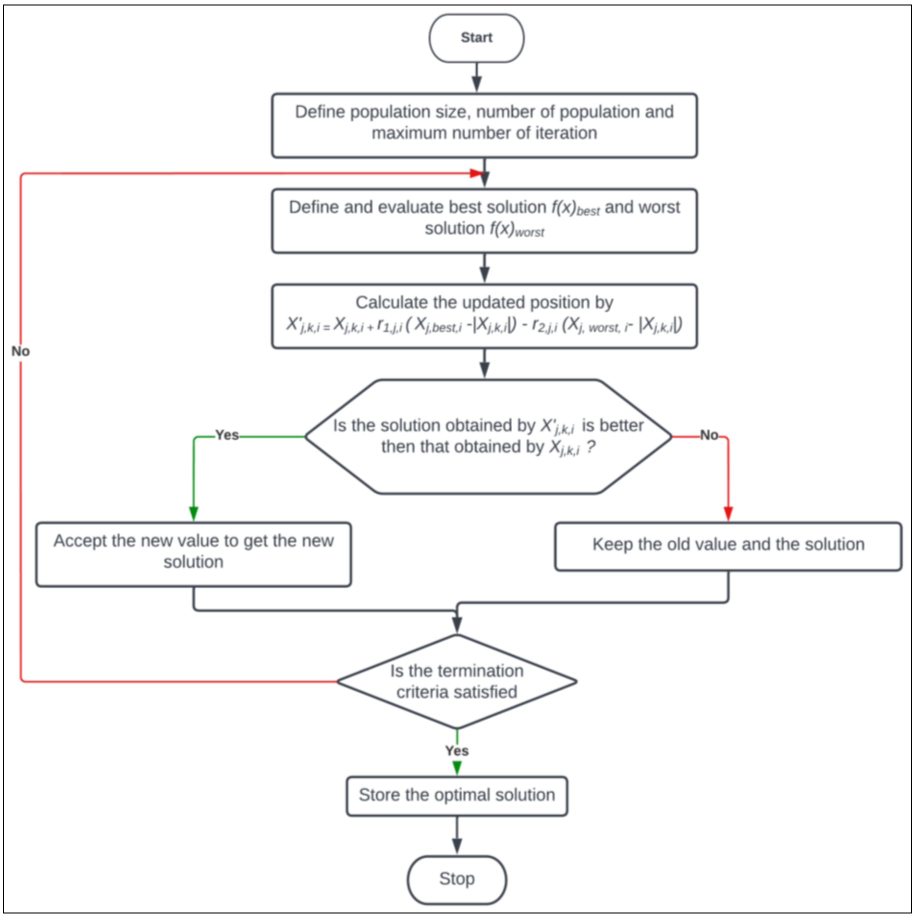

Fig 3: JAYA Algorithm flowchart

Problem Formulation

The expression for the cost function of the active power generated can be expressed as.

$$C_{Pn} = \alpha_n + \beta_n P_{gn} + \gamma_n P_{gn}^2 \quad \$/hr \tag{13}$$

Where, C_{Pn} is the active power generation cost for n^{th} generator, α_n, β_n and γ_n represents the cost coefficient for n^{th} generator. Therefore, expression for overall cost of the generation can be expressed as:

$$C_T = \sum_{n=1}^{N_G} C_{Pn} \tag{14}$$

As per the Siemens AG database the cost function of SVC and TCSC can be giving as [21].

$$C_{SVC} = (0.0003S^2 - 0.3051S + 127.38) * 88.2 \quad \$/kVAr \tag{15}$$

$$C_{tcsc} = (0.0015S^2 - 0.7130S + 153.75) * 88.2 \quad \$/KVAr \tag{16}$$

$$C_{FACTS} = C_{SVC} + C_{tcsc} \tag{17}$$

The objective function can be formulated as.

$$f_1 = C_{total} = \min\,(C_T + C_{FACTS}) \tag{18}$$

One of the negative consequences of congestion within the system is the unwanted modification of the voltage profile. Hence, the secondary goal is to reduce voltage deviation in the system, as formulated below.

$$f_2 = Min\ D_v = \sum_{n}^{N_B} \left|V_n - V_{ref}\right|^2 \tag{19}$$

Where, D_v is the voltage deviation, V_n represents the voltages at bus n and V_{ref} is the reference voltage. N_B is the number of buses in the system.

The enhancement of power loss in the transmission lines is a severe ill effect of congestion in power system. These losses can be expressed as follows.

$$Pl_{(m,n)} = g_{m,n}\{((V_m - V_n)^2 + V_m V_n (\theta_m - \theta_n)^2\} \tag{20}$$

Where, $Pl_{(m,n)}$ denotes the power loss occurring in the transmission line connecting bus m and bus n, V_m and V_n refer to the voltage levels at bus m and bus n respectively, θ_m and θ_n are voltage angles at bus m and bus n respectively, $g_{m,n}$ is the conductance of line between bus m and bus n.

The multiobjective function can now be written as:

$$f = min(\alpha C_{total} + \beta D_v + \gamma Pl_{(m,n)}) \tag{21}$$

Subject to the following constraints:

Equality constraint

$$\begin{cases} P_{gi} = V_m\{\sum_{n=1}^{N} V_n[G_{mn}cos(\delta_m - \delta_n) + B_{mn}sin(\delta_m - \delta_n)]\} + P_{di} \\ Q_{gi} = V_i\{\sum_{i=1}^{n} V_j[G_{ij}sin(\delta_i - \delta_j) - B_{ij}sin(\delta_i - \delta_j)]\} + Q_{di} \end{cases} \tag{22}$$

Where, P_{gi} and Q_{gi} are active and reactive power respectively generated at i^{th} bus, P_{di} and Q_{di} presents the respective active and reactive power demands at i^{th} bus, G_{mn} and B_{mn} are the conductance and susceptance part of the n^{th} element Y_{mn} of Y bus admittance matrix of the system.

Inequality constraints

$$\left.\begin{array}{c} P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \\ Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \\ V_i^{min} \le V_i \le V_i^{max} \\ V_{gi}^{min} \le V_{gi} \le V_{gi}^{max} \\ Q_{i,SVC}^{min} \le Q_{i,SVC} \le Q_{i,SVC}^{max} \end{array}\right\} \tag{23}$$

The active power P_{gi} and reactive power Q_{gi} generated should conform to specified acceptable minimum and maximum values. Stable power system operation requires bus voltages V_i and V_{gi} within prescribed limits. Reactive power $Q_{i,SVC}$ compensated by the ith SVC must adhere to defined limits. Generator active power P_{gi} and generated reactive power Q_{gi} should stay within pre-specified maximum and minimum values for reliable power system operation. It is crucial for the i^{th} SVC to effectively regulate $Q_{i,SVC}$ within specified limits for general system reliability and can be given as.

1. $V_{i,limits}$: (0.90 pu, 1.1pu)
2. $V_{gi,limits}$= (0.95 pu, 1.1pu)
3. $Q_{SVC,limits}$= (-80 MVAr, 80 MVAr)

Results and Discussion

The proposed approach has been tested and verified using the IEEE 30 Bus system. This system has 30 buses and 41 lines. The state of deregulation is simulated by intentionally creating an outage of line number 12, which in between bus 6 and bus 10. This created N-1 contingency in the system under study.

Voltage Deviation

The diagram in Fig. 4 illustrates the change in the system's voltage profile after congestion in the system. It's clear that the voltage profile of the system experiences a distortion when line number 12 is outed.

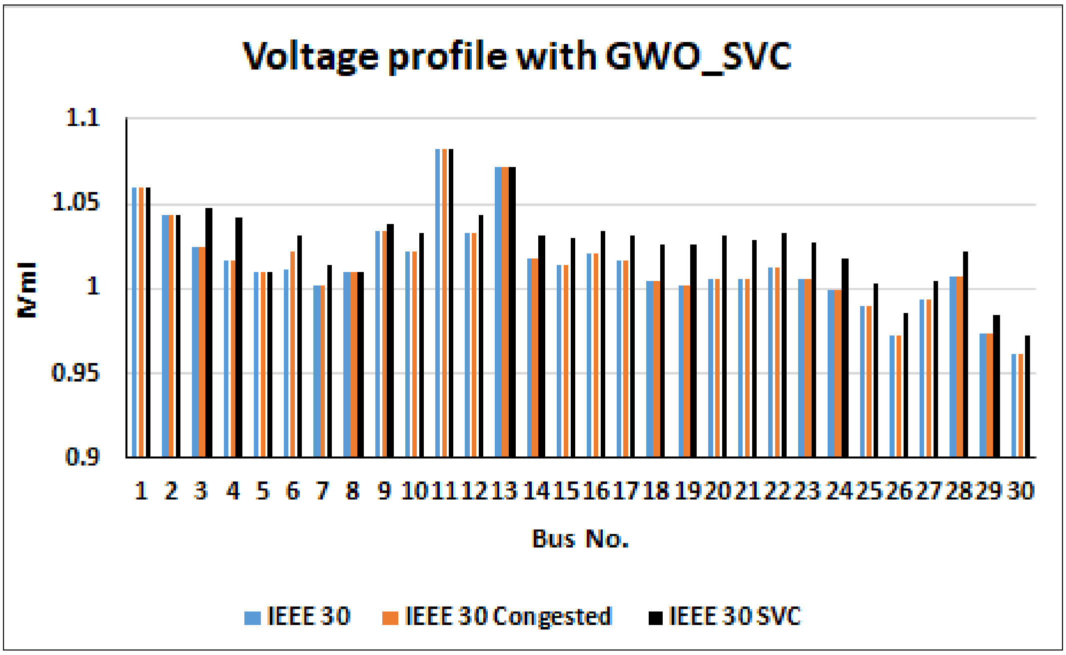

Fig 4: Voltage profile of the system with GWO employing SVC

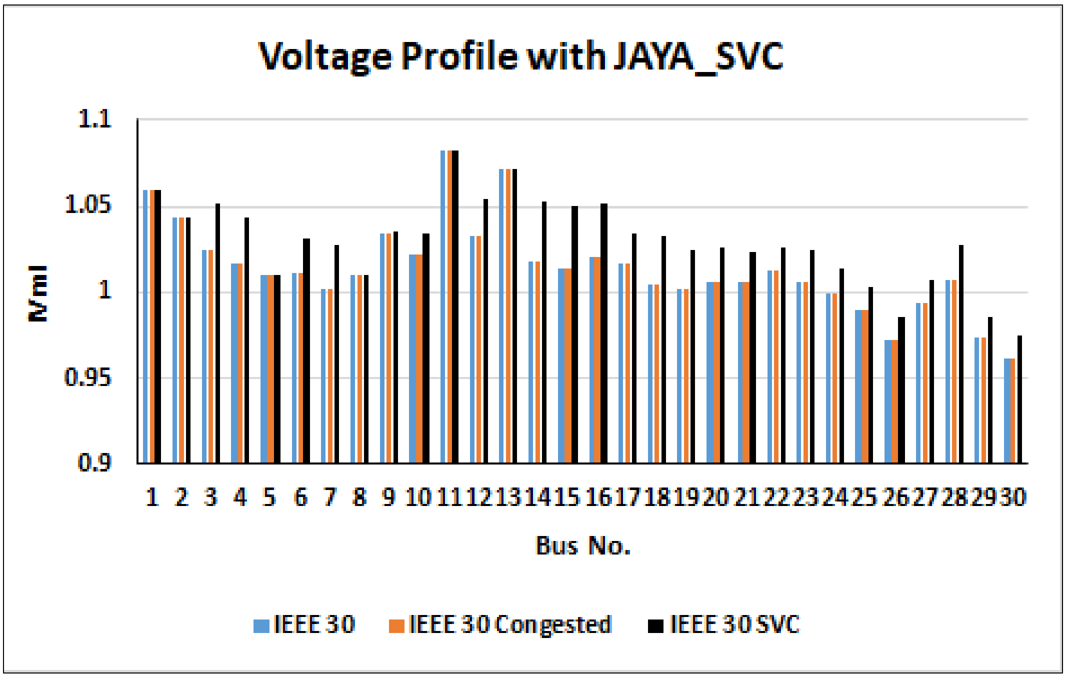

Fig 5: Voltage profile of the system with JAYA employing SVC

Utilizing the Grey Wolf Optimization (GWO) algorithm to enhance the performance of SVCs at bus locations 3, 6, and 7 resulted in significant improvements in the voltage profile. The initial fluctuations of 0.01125 per unit (pu) observed during network congestion were effectively reduced to 0.01058 pu, marking a noteworthy 5.96% decrease across the system. Furthermore, employing the JAYA algorithm for both location and parameter optimization yielded considerable enhancements in the voltage profile, leading to a notable 10.4% decrease in voltage deviation at bus numbers 3, 6, and 12, as illustrated in Fig 5.

The implementation of the GWO technique for assessing voltage stability has significantly enhanced the influence on the overall stability of the system, particularly in cases involving TCSC. Fig 6 illustrates the voltage profiles during congested conditions resulting from N-1 congestion and illustrates the enhanced voltage profile subsequent to the incorporation of TCSC. The introduction of TCSC leads to notable enhancements in voltage performance. Voltage fluctuation diminishes from 0.01125 per unit (pu) to 0.01110 pu, representing a significant decrease during periods of congestion. Installing TCSC on lines 3, 4, and 7 yields a noteworthy 1.3% reduction, thereby improving the overall stability of the system. Additionally, applying the JAYA algorithm further enhances TCSC effectiveness, resulting in a 2.186% reduction in voltage deviation to 0.011004 pu in congested scenarios, as illustrated in Fig 7. The TCSC optimized by JAYA is deployed on lines 3, 6, and 15.

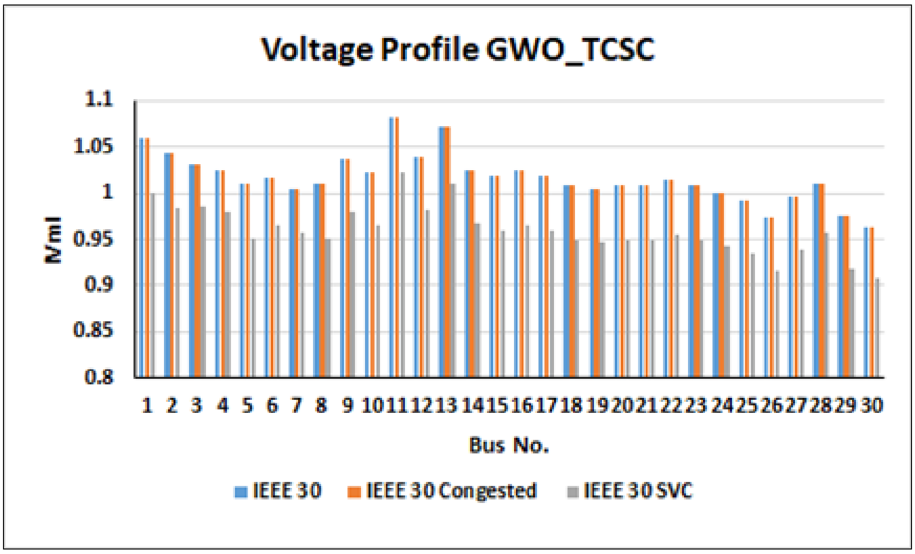

Fig 6: Voltage profile of the system with GWO employing TCSC

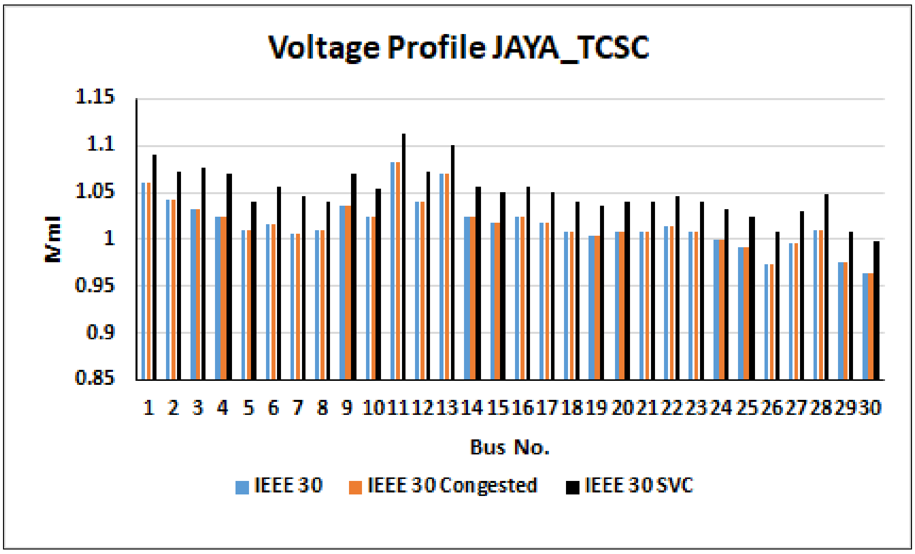

Fig 7: Voltage profile of the system with JAYA employing TCSC

Power Loss

Fig 8 displays the outcomes of employing GWO to refine both the placement and settings of SVCs with the aim of minimizing active power losses. In a scenario where SVCs are inactive during a contingency event, the total active power loss amounts to 7.019 MW. However, by implementing GWO-optimized SVCs, this loss diminishes to 6.661 MW. Prior to the contingency event, the power loss registers at 6.925 MW, underscoring the relatively minor impact of SVCs on loss reduction. Notably, within the congested Line 1, there is a significant decrease in active power loss from 5.155 MW to 1.268 MW.

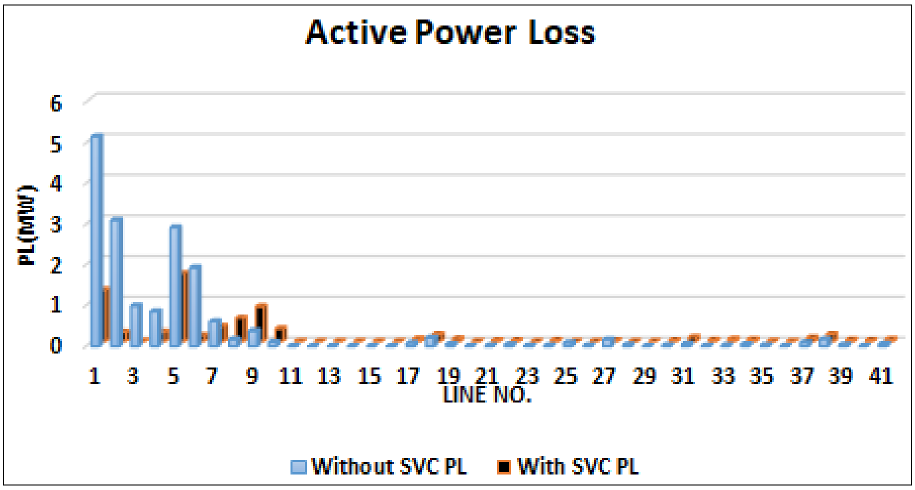

Fig 8: Active power loss of the system with GWO employing SVC

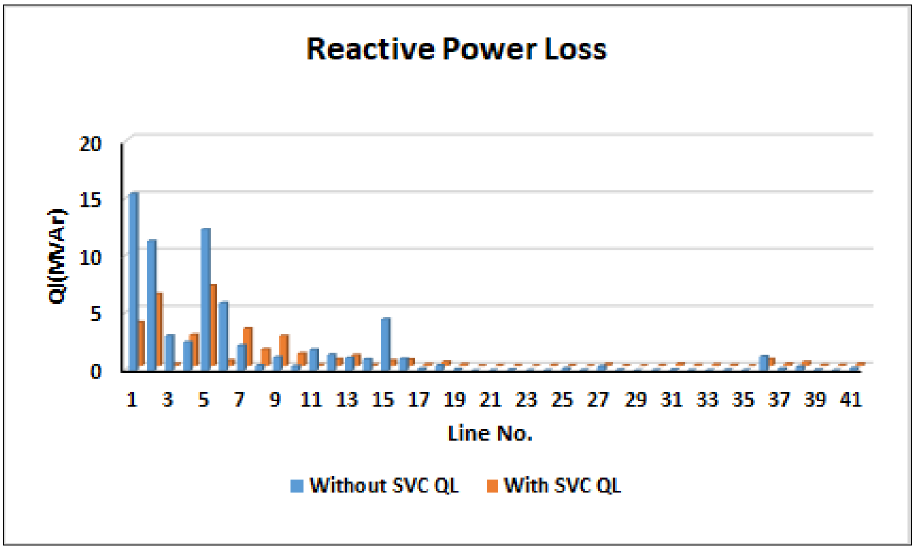

Fig 9: Reactive power loss of the system with GWO employing SVC

Utilizing the GWO method to optimize both the placement and settings of the SVC results in a significant reduction in reactive power losses. The data presented in Fig 9 illustrates a decrease from 69.2351 MVAr to 21.131 MVAr under contingency scenarios, marking a notable 50% improvement. Particularly noteworthy is the reduction in reactive power loss on Line 1, the most congested line, which decreases from 15.46 MVAr to 3.8 MVAr.

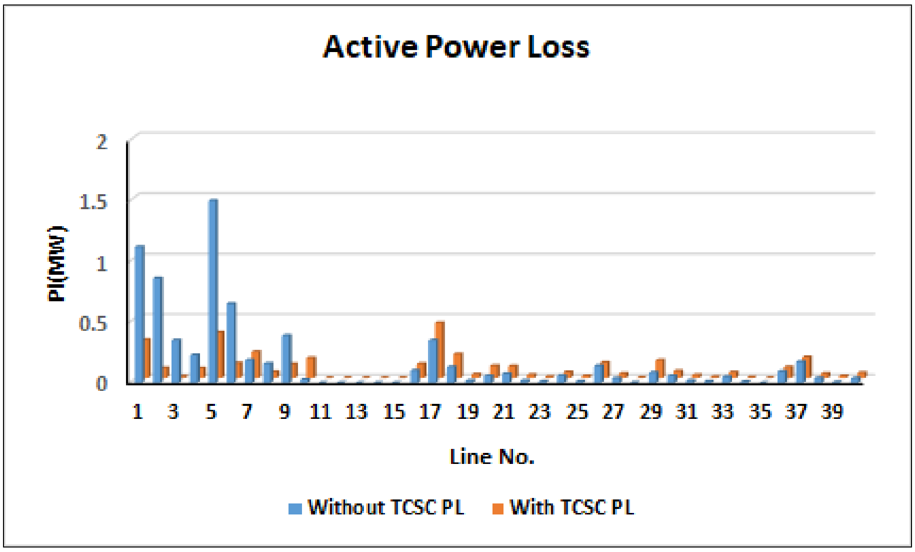

Fig 10: Active power loss of the system with JAYA employing TCSC

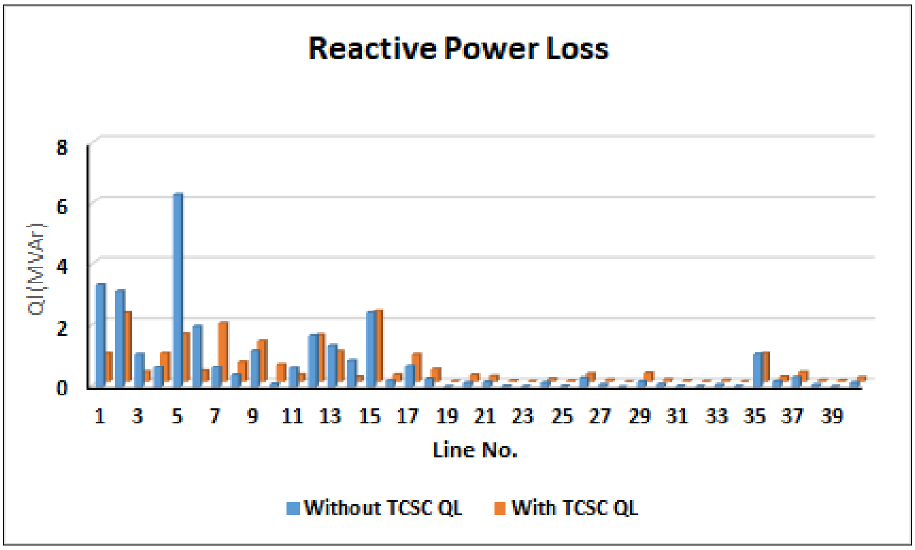

Fig 11: Reactive power loss of the system with JAYA employing TCSC

Fig 10 shows the results achieved by JAYA in optimizing TCSC, leading to a decrease in active power loss from 7.019 MW to 3.440 MW during contingency conditions. Furthermore, on the congested line, active power loss decreased from 5.155 MW to 1.7345 MW with TCSC, representing a significant reduction of 33.184%. Utilizing JAYA for TCSC optimization results in a notable decrease in reactive power loss as well. Specifically, the loss decreases from 69.2351 MVAr to 34.8859 MVAr during congestion. This reduction is clearly demonstrated in Fig 11. It is also noteworthy that there is a substantial decrease in reactive power loss on congested transmission lines.

Generation cost

The combined use of SVC and TCSC leads to cost savings by reducing generation expenses. The results presented in Table 1 show a decrease in generation costs when employing specific algorithms for SVC and TCSC. Prior to the implementation of FACTS, generation costs were at $880.212 per hour. By optimizing SVC and TCSC using GWO, voltage deviations of 5.96% and 1.3% were achieved, respectively. The application of JAYA yields even greater reductions: 10.4% for SVC and 2.180% for TCSC, surpassing GWO in minimizing deviations. Table 1 illustrates a total generation cost of $873.058 per hour with GWO-optimized SVC, comprising a generation cost of $837.04343 per hour and an additional SVC cost of $36.0153 per hour. When analyzing overall power generation costs, GWO-optimized TCSC results in $855.96243 per hour, JAYA-optimized SVC leads to $860.68103 per hour, and JAYA-optimized TCSC results in $848.48533 per hour. These findings underscore the efficiency of TCSC in reducing generation costs compared to SVC, particularly with JAYA optimization, which achieves the most significant reduction. Fig 12 provides a summary of the objective function minimization for cost reduction.

Table 1: Consolidated results for generation cost reduction and location of FACTS devices

Facts	Optimization Methods			
	GWO		JAYA (proposed)	
	SVC	TCSC	SVC	TCSC
Generation cost ($/hr)	837.043	830.8092	835.3195	824.1284
Device Cost ($/hr)	36.0153	25.1532	25.36145	24.35687
Total Cost ($/hr)	873.058	855.9624	860.6810	848.4853
Location	Bus no. (3,6,7)	Line no. (3,4,7)	Bus no. (3,6,12)	Line no. (3,6,15)
Voltage Deviation (pu)	0.01058	0.0111	0.01008	0.011004

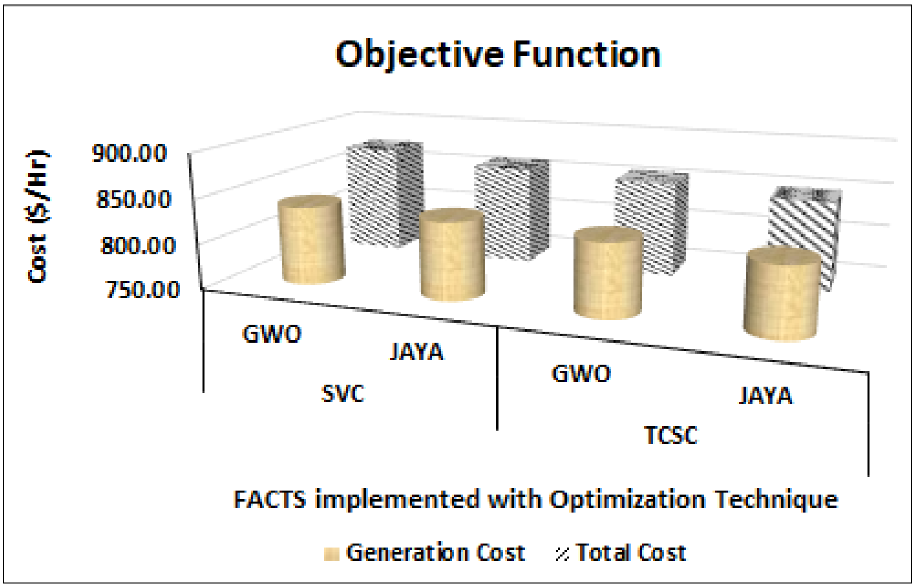

Fig 12: Minimization of objective function

Conclusion

In this research, we explore the utilization of shunt FACTS device SVC and series FACTS device TCSC in the IEEE 30 Bus system with the aim of lowering operational expenses for generators. Ensuring that voltage levels remain within predefined thresholds is crucial for maintaining stability and reliability in electrical power systems. Our investigation showcases successful implementation of SVC and TCSC, with the utilization of JAYA optimization for SVC resulting in significant reductions in voltage fluctuations and losses of reactive power. Integration of TCSC leads to notable decreases in generation costs, active power losses, and overall operational expenditures. The proposed JAYA-optimized SVC proves highly effective in minimizing voltage fluctuations and reactive power losses, while JAYA-optimized TCSC efficiently reduces total generation costs and active power losses across the system

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