Application of JAYA algorithm for optimizing allocation and size of thyristor-controlled series compensator devices

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ABSTRACT

Electricity serves as the backbone and essential energy source for various sectors, including transportation, residential areas, manufacturing, and industry. As engineering and technology advance, the demand for electricity continues to rise. Expanding the electricity grid to meet transmission needs and provide high-quality service has become a fundamental challenge in the power system domain. However, load expansion introduces issues such as line overloads when demand surges, compromising power quality, system security, and reliability during operation, potentially leading to system failures. Addressing these load-related problems is crucial for enhancing power system stability, reducing troubleshooting expenses, and improving operational efficiency. This study proposes the utilization of thyristor-controlled series compensator (TCSC) as a solution to enhance power system efficiency. Furthermore, to optimize TCSC placement and determine the appropriate compensation level for devices on transmission lines, the research suggests employing the JAYA optimization algorithm. MATLAB software is utilized to investigate the IEEE standard 30-node transmission lines case. The obtained results have demonstrated the effectiveness of the solution in enhancing electrical transmission capacity, improving stability, and reducing energy losses within the system at a low operational cost.

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1. INTRODUCTION

In recent decades, the deregulation of the power market has spurred intensified competition among utilities, leading to a notable surge in the transmission of unplanned electricity. However, the absence of adequate regulation in these transactions increases the risk of overloading certain power lines [1], [2]. This poses a significant threat to the safety and stability of the current power system, as it may lead to voltage collapse due to insufficient reactive power [3]. While generators have the capacity to supply reactive power, their capabilities are constrained by inherent generation limits. Moreover, the effectiveness of reactive power produced by generators diminishes when the demand for it is situated far from the generation source [4], [5] Consequently, the prevention of voltage collapse and the preservation of grid integrity have become paramount concerns for power grid operators and researchers in numerous countries worldwide [6]. However, solutions reliant on grid disconnection are viewed as undesirable and are typically considered as a last resort to ensure the stability of the power system when no immediate alternatives are available [7]. Therefore, a viable strategy to alleviate line congestion involves redistributing transmission power across multiple lines. Expanding the network through the construction of new transmission lines is a straightforward approach to address network limitations [8]. However, this endeavor entails significant time and construction costs. A more feasible alternative solution, which requires less capital expenditure and shorter implementation time, is to increase the power flow of congested lines [9]. This alternative approach helps defer the need for expanding capital investment in new network infrastructure and enhances the utilization of existing power grid assets. This is crucial because improving asset utilization not only enhances investor profitability but also reduces costs for consumers [10].

Devices aimed at enhancing the electrical transmission capacity of power transmission lines are commonly referred to as flexible AC transmission systems (FACTS) [11]–[13]. Installing FACTS devices not only improves current management within the network but also aids in voltage stabilization and temporary power balance, while managing network reactive power [14]. However, the installation of FACTS requires capital investment. This investment exhibits diminishing returns, suggesting that as the number of installations increases, the marginal cost reduction diminishes [15]. Therefore, to meet capital investment budgets, it is crucial to determine the optimal sequence for the location and scale of FACTS installations. Regarding the location aspect of the problem, identifying the optimal transmission lines for FACTS placement is key, while the allocation aspect involves determining the optimal setting or compensation level required for each installed FACTS device to alleviate congestion and facilitate generation redispatch [16].

Since the 1950s, a commonly used type of FACTS device involves the addition of series capacitance to the transmission line, thereby reducing its overall reactance. To maximize flexibility in managing line reactance, a thyristor-controlled series compensator (TCSC) is employed instead of fixed series compensation [17]. The TCSC, an advanced power electronics device [18], [19] within the energy conversion system [20]–[22], enables real-time responsiveness to network conditions by dynamically adjusting compensated reactance levels [23]. In the current energy landscape, the rapid expansion of renewable energy sources [12], [24] and the growing adoption of electric vehicles (EVs) [25]–[27] are creating unprecedented demands on the stability and flexibility of power systems. To address these challenges, TCSCs have become critical for regulating power flow, stabilizing voltage, and improving transmission efficiency in fluctuating conditions [28]. As renewable energy and EV penetration continue to rise, TCSC technology plays a vital role in maintaining grid stability and supporting the sustainable growth of these technologies. The cost of TCSCs generally correlates with the maximum compensation they can provide [29]. Consequently, the TCSC location allocation problem plays a significant role in optimizing operational costs and ensuring reasonable electricity prices for consumers. This study applies TCSC as a solution to enhance electrical transmission capacity and increase reliability during system operation. Addressing the location allocation problem, research suggests utilizing the JAYA optimization algorithm to optimize the placement of TCSCs and their compensation levels in transmission power systems. This optimization aids in minimizing investment costs and consumer electricity prices. The proposed procedure is demonstrated using the IEEE standard 30-node transmission lines case to develop new insights into the TCSC location allocation problem.

2. OVERVIEW OF ELECTRICITY MARKET AND TCSC DEVICE

A power plant is a facility designed for large-scale electricity production. The central component of most power plants is the generator, a device that converts mechanical energy into electrical energy using electromagnetic induction principles [20]. However, the energy sources utilized by these generators vary significantly, depending largely on the available fuel types and technological capabilities of the plant [21]. In traditional systems, the management of active dynamics within the electricity generation system is typically overseen by the national electric utility. This entity is responsible for various aspects, including production coordination, transmission load management, and facilitating electricity distribution [22]. The organizational structure of the active dynamics within the electricity generation system resembles a hierarchical tissue, where coordination and communication occur vertically. This organizational framework aims to streamline operations and enhance international interoperability [23]. To optimize the efficiency and effectiveness of electricity generation systems, many countries are implementing reforms to decentralize the control mechanisms. This involves delegating responsibility for electricity generation to regional or local authorities, thereby enhancing signal transmission efficiency and promoting international standards. Through these reforms, detailed coordination and management practices are refined to better serve the needs and preferences of consumers. Within this organizational structure, various entities, including power generation facilities, transmission networks, and distribution companies, each play specific roles in providing reliable electricity services to consumers.

Today, commonly used FACTS devices have become widespread in power grid operations. These devices are advanced power electronics, similar to those used in energy conversion systems. To achieve maximum control over the management of line reactance, TCSCs are utilized instead of fixed series capacitors placed on the transmission lines. Although TCSCs are more expensive than traditional fixed capacitors, they offer real-time responsiveness to various operating conditions within the power grid by flexibly adjusting the amount of reactive power compensation. The characteristic feature of the TCSC is its ability to swiftly regulate the line impedance while operating under stable power system conditions [28]. Comprising one or more TCSC modules, each module consists of two primary components. The inductance component can adjust the total resistance through the thyristor valve regulator. Additionally, the control components encompass electronics such as thyristor valves and GTO opening and closing gates. The primary structure of the TCSC is demonstrated in Figure 1.

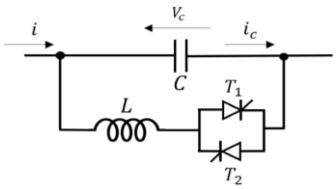

Figure 1. Basic configuration of TCSC

3. UTILIZATION OF JAYA ALGORITHM FOR TCSC SIZE AND LOCATION ALLOCATION ON TRANSMISSION NETWORKS

The installation of TCSC devices can ensure effective management of the network's reactive power, voltage stability, and enhance the operational capacity of the power grid. However, it is essential to note that installing TCSC devices on the grid requires initial capital investment. Additionally, suboptimal placement can undermine device efficiency, limiting their full potential. Consequently, installation and operational costs increase while profitability decreases. Therefore, addressing the problem of determining the optimal location allocation and size for TCSC devices on a transmission network is important. In this section, the JAYA algorithm is presented for determining the size and location allocation of TCSC devices.

3.1. JAYA algorithm

The JAYA algorithm is a metaheuristic-based approach that blends the principles of evolutionary algorithms, emphasizing survival of the fittest, with swarm intelligence, where the swarm typically follows a leader in pursuit of the optimal solution. Introduced by Rao in 2016, this algorithm has garnered significant attention across diverse research communities due to its straightforward nature and user-friendly attributes. Notably, it operates without derivative information during the initial search and requires no parameterization. Its adaptability, flexibility, and soundness make it an attractive choice for optimization tasks. Recent studies have demonstrated the efficacy of the JAYA algorithm across various domains, yielding superior results compared to other optimization techniques [13]–[15]. Therefore, employing the JAYA algorithm to address optimization challenges such as the size and location allocation of TCSC devices is a promising endeavor worthy of pursuit. Here, the specifics of the algorithm can be condensed into four steps, outlined as follows:

a. Step 1: this step involves constructing the population. Initially, the population comprises NP randomly generated individuals within the defined search space. Each individual within the population is represented as a vector of n variables, denoted as $X_j = [x_1, x_2, \dots, x_n]$, where $i = 1,2,\dots,NP$ and $j = 1,2,\dots,n$, and is formed according to (1).

Within the parameter's search space, x_j^l and x_j^u denote the lower and upper bounds, respectively, for the variable x_j. The expression rand [0,1] indicates the selection of a random value from the range [0,1].

$$x_{j,i} = x_{j,i}^l + rand[0,1] \times \left(x_{j,i}^u - x_{j,i}^l\right) \tag{1}$$

b. Step 2: a vector denoted as $x'_{i,G}$ is formed based on the guidelines provided in (2), where $x_{j,i,G}$ represents the value of the jth element within the ith individual during the Gth iteration. $x_{j,best,G}$ and $x_{j,worst,G}$ represent the values of the j th element for the best and worst individuals, respectively. r_1, r_2 are random numbers ranging from 0 to 1. The term $+r_1.\left(x_{j,best,G} - \left|x_{j,i,G}\right|\right)$ indicates a tendency towards the best outcome, while the term$-r_2.\left(x_{j,worst,G} - \left|x_{j,i,G}\right|\right)$ moves away from the worst outcome.

$$x'_{j,i,G} = x_{j,i,G} + r_1.\left(x_{j,best,G} - \left|x_{j,i,G}\right|\right) - r_2.\left(x_{j,worst,G} - \left|x_{j,i,G}\right|\right) \tag{2}$$

c. Step 3: the correction process involves adjusting the values of elements that fall outside the defined search space, either below the minimum or above the maximum specified values. This correction ensures that these values are brought back within the iterative search space. The method for performing this adjustment is illustrated as (3).

$$x'_{j,i,G} = \begin{cases} x_j^l + \left|x_j^l - x'_{j,i,G}\right| & if\, x_j^l > x'_{j,i,G} \\ x_j^u - \left|x_j^u - x'_{j,i,G}\right| & if\, x_j^u < x'_{j,i,G} \\ x'_{j,i,G} & \text{otherwise} \end{cases} \tag{3}$$

d. Step 4: the obtained objective function value determines whether the vector $X'_{i,G}$ is compared with the objective function value of the standard individual $X_{i,G}$. If $X'_{i,G}$ yields a superior objective function value, it replaces the original individual. Conversely, should the individual function value prove inferior to the original value, the latter remains preserved within the population. This implementation process is mathematically formalized as shown in (4), where $F(x)$ represents the objective function of individual x.

$$X_{i,G+1} = \begin{cases} X'_{i,G} & if\, F\left(X'_{i,G}\right) < F\left(X_{i,G}\right) \\ X_{i,G} & \text{otherwise} \end{cases} \tag{4}$$

The flowchart of the JAYA optimization algorithm, following the outlined steps, is illustrated in Figure 2.

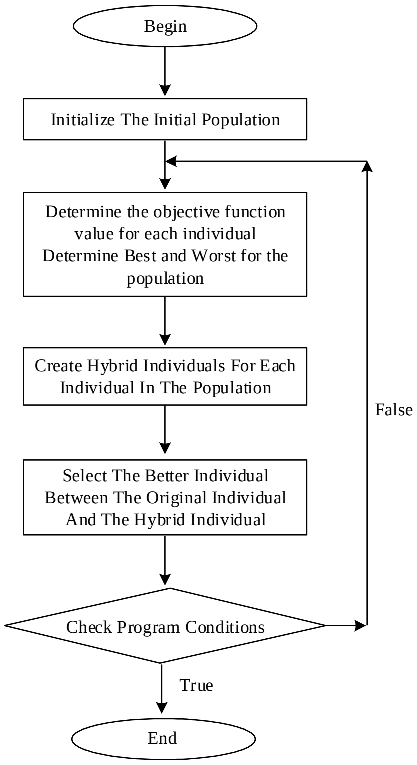

Figure 2. Flowchart of JAYA algorithm

3.2. Objective function

The objective of this problem is to identify the entity with the minimal total operational expenditure, all while ensuring that the node voltage and transmission power on the branches adhere to standard operational thresholds. The operational costs of the electrical system encompass various elements, such as:

- TCSC equipment procurement cost function: the TCSC equipment procurement cost function is determined based on research findings presented by Cai and Erlich [18]. It involves calculating the investment cost per unit of TCSC capacity, denoted in USD/KVAR.

$$C_{TCSC} = 0.0015S^2 - 0.713S + 153.75 \tag{5}$$

where the parameter S represents the reactive power compensated by TCSC for both the power system configurations, with and without TCSC installed. This implies that the value of S is determined by computing the variance in reactive power transmitted through the line connected to the TCSC, observed in two scenarios: before and after the installation of TCSC.

$$S = \left|Q_{D,0} - Q_{D,1}\right| \tag{6}$$

Hence, the investment cost for a TCSC with capacity S is computed as (7).

$$IC_{TCSC} = C_{TCSC}.S.1000 \tag{7}$$

Typically, the operational lifespan of such devices is contingent upon their quality as provided by the manufacturer. In this study, the lifespan of TCSC is assumed to be five years based on the average parameters provided by certain manufacturers. Consequently, the depreciation of the TCSC per operating hour is computed in USD according to (8), considering an average annual operational time of 8,760 hours.

$$C_{H,TCSC} = \frac{IC_{TCSC}}{8760*5} \tag{8}$$

In (8) provides the cost function for the installation and ongoing operation of TCSC, calculated per hour of operation.

- Cost function of active power loss: the cost function related to active power loss is pivotal in transmission processes, as a certain amount of active power dissipates due to losses along the transmission line. This loss signifies a missed opportunity to utilize capacity that could otherwise be sold to consumers, thereby enhancing profits. Various strategies exist to mitigate such losses, including augmenting wire cross-sections to diminish line resistance, substituting conductors with higher-quality wires, and minimizing the transmission of reactive power through the lines, among others. When integrating TCSC to enhance voltage stability at nodes, it introduces a certain level of reactive power into the system, which aids in curbing the transmission of reactive power across the lines. To enhance transmission efficiency, the evaluation function for TCSC location and capacity will incorporate active power loss. Assuming an electricity price of 50 USD/MW, the monetary equivalent of active capacity loss per operational hour of the power system is computed as (9).

$$C_{P\_loss} = P\_loss * 50 \tag{9}$$

where P_loss represents the aggregate active power loss across all lines within the power transmission system.

- Penalty function for voltage violations on nodes: to evaluate the impact of TCSC installation on enhancing voltage quality at nodes and to identify potential violations of the permissible voltage limits within the power system, an incremental cost function is incorporated when voltage deviations occur at nodes beyond the allowable thresholds. This signifies that the current installation plan's effectiveness falls short of meeting the problem's requirements. Equation (10) represents a function utilized to assess the adherence to voltage constraints within the power grid, where λ_V denotes the voltage violation penalty coefficient, and nb signifies the total number of nodes present in the power system.

$$C_V = \lambda_V.\sum_{i=1}^{nb} V_i^* \tag{10}$$

The voltage violation penalty at node i, denoted as V_i^*, is defined according to (11).

$$V_i^* = \begin{cases} \left(V_{i,min} - V_i\right)^2 & if \quad V_{i,min} > V_i \\ 0 & if \quad V_{i,min} \le V_i \le V_{i,max} \\ \left(V_i - V_{i,max}\right)^2 & if \quad V_i > V_{i,max} \end{cases} \tag{11}$$

The upper and lower boundaries of the voltage at node i are denoted as $V_{i,max}$ and $V_{i,min}$, respectively.

- Penalty function for violation of transmission capacity on branches: each transmission line is designed with a maximum transmission capacity, known as its rated capacity, to ensure normal operation. However, if the transmitted power exceeds this limit, protective devices are triggered, potentially causing damage to both the electrical system and the line itself due to overheating caused by overload. To effectively assess a line's congestion-handling capability, the penalty cost function for surpassing the rated capacity is provided in (12).

$$C_P = \lambda_P . \sum_{i=1}^{np} P_i^* \tag{12}$$

The penalty for exceeding capacity at the ith branch, denoted as P_i^*, is determined based on (13), where $P_{i,max}$ represents the rated capacity of the ith branch.

$$P_i^* = \begin{cases} \left(P_i - P_{i,max}\right)^2 & if \quad P_i > P_{i,max} \\ 0 & if \quad P_i \le P_{i,max} \end{cases} \tag{13}$$

- Generator cost function: the generator cost is defined by a quadratic function of its generating capacity, as detailed in (14).

$$C_{Gi} = A_i P_i^2 + B_i P_i + C_i \tag{14}$$

where C_{Gi} represents the electricity generation cost of the ith factory; the variables A_i, B_i, and C_i represent the coefficients of the cost function specific to the ith factory; and P_i signifies the capacity of the ith factory.
The total electricity generation cost of the power system is determined by (15).

$$C_G = \sum_{i=1}^{N_G} (A_i P_i^2 + B_i P_i + C_i) \tag{15}$$

where N_G is the number of power plants in the power system.

- Identification of the objective function for studying power system stability with TCSC application: the objective function of the problem is defined as the aggregate cost of the aforementioned components. This function is shown as (16).

$$fitness = C_{H,TCSC} + CV_{P_{G_{P\_loss}}} \tag{16}$$

4. SIMULATION RESULTS AND DISCUSSIONS

To showcase the efficacy of the proposed optimal algorithm, the evaluation model utilized is the 30-node IEEE system model. Simulation experiments are conducted on a 30-node IEEE power grid to assess the performance of the JAYA optimization algorithm. Furthermore, to gauge the comparative effectiveness of the proposed optimization algorithm against others, the particle swarm optimization (PSO) algorithm is also implemented and contrasted with the JAYA algorithm. The article employs equivalent parameters, including the number of individuals in a population and the maximum number of iterations, to fairly evaluate the effectiveness of the optimization algorithms. Figure 3 show the diagram of the 30-node system, which is used in the simulation experiments to evaluate the proposed method.

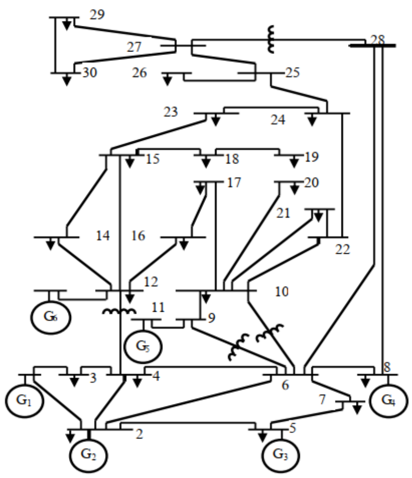

Figure 3. Diagram of 30-node system

The results indicate that the PSO algorithm achieves convergence at a quicker rate compared to the JAYA algorithm. This can be attributed to the PSO algorithm's tendency to approach extreme points more rapidly than the JAYA algorithm. However, due to this accelerated convergence, the PSO algorithm frequently becomes trapped in local optima and struggles to escape, unlike the JAYA algorithm. This assertion is supported by the results depicted in Figure 4, where the objective function outcomes obtained by the JAYA algorithm outperform those of the PSO algorithm. Consequently, this highlights the superior efficiency of the JAYA algorithm in detecting global extrema.

The outcomes of conducting power distribution on the lines are illustrated in Figure 5. It is observed that by implementing optimal power redistribution to generators and incorporating TCSC onto the grid, the transmitted power through the lines consistently remains below the rated capacity. This underscores the operational stability of the power system. As observed in Figure 5, it can be noted that electricity generation costs are optimized more effectively with the JAYA algorithm, at increasing iterations, the results obtained are superior to those of PSO.

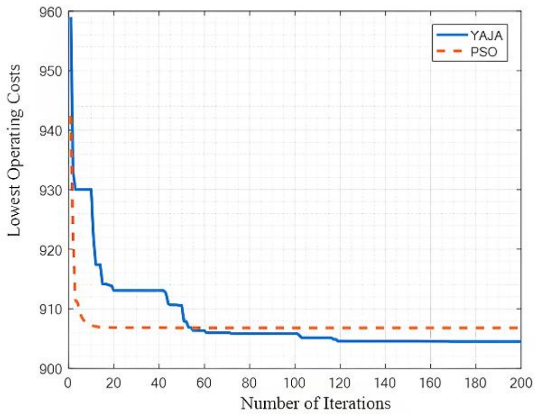

Figure 4. Comparative results of electricity generation costs between two methods through iterations

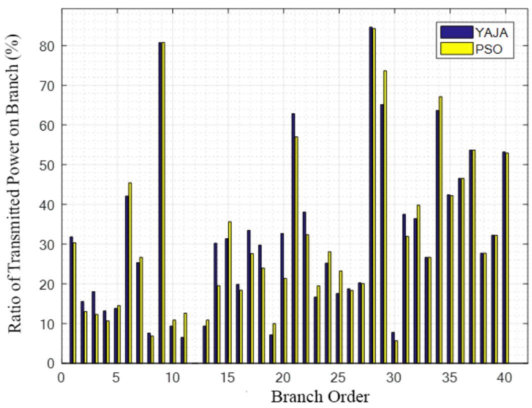

Figure 5. Distribution of transmission power across system branches

The optimization of power distribution on power lines within an electrical system is crucial to ensure system stability. Based on the conducted analyses, the optimal power generation capacity and the installation of TCSC have proven effective in reducing power transmitted through the power lines while still maintaining operation below their rated capacity. However, the slight deviation observed in the results of power distribution on the power lines is noteworthy. This variability could be explained by the flexibility and dynamic nature of the electrical system, as well as the complexity of factors influencing power distribution, such as load levels, network conditions, and other technical constraints. Despite utilizing two different optimization algorithms, the negligible deviation in results may indicate the effectiveness of JAYA algorithms. Nevertheless, continuous monitoring and refinement of the optimization process are important to ensure the stable and efficient operation of the electrical system.

5. CONCLUSION

This study proposes the utilization of TCSC to enhance power system efficiency, with a focus on optimizing TCSC placement and compensation levels using the JAYA optimization algorithm. By applying TCSC as a solution, this study aims to enhance electrical transmission capacity and increase system reliability. Utilizing the JAYA optimization algorithm for location allocation problem, the research minimizes investment costs and consumer electricity prices. Survey results from the IEEE standard 30-node transmission lines case demonstrate the effectiveness of the JAYA optimization algorithm in optimizing TCSC electricity generation costs and location allocation on transmission networks. Future work could focus on the real-time implementation of the proposed JAYA optimization algorithm in practical power systems. This would help validate the theoretical results in more dynamic and real-world scenarios.

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AUTHOR CONTRIBUTIONS STATEMENT

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Thanh-Lam Le	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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