



Application Of Whale Optimization Algorithm For Loss Minimization And Allocation In Deregulated Power Systems

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Abstract: Transparent loss allocation, effective market functioning, and equitable cost distribution among market participants, all depends on the fair and correct allocation of transmission losses in deregulated power networks. In order to identify the best and most reasonable strategies for loss allocation in competitive electricity markets, this article compares two popular loss allocation approaches: the Pro-Rata method and the Flow Tracing Technique method (FTT). Simple and easy to use, the Pro-Rata method distributes losses proportionately according to predetermined criteria like generation or demand. The Flow Tracing technique method, on the other hand, provides a more usage-based and physically precise allocation of losses by mapping the actual path of power flows from generators to loads. Standard IEEE 14 bus test system is used to compare the performance of both approaches and for optimal location and size of TCSC device, whale optimization algorithm is used for minimization of losses. The Pro-Rata approach is computationally efficient, but it is not sensitive to real network utilization, according to the results. The Pro-Rata approach is straightforward and simple to use, allocating losses proportionately according to predetermined criteria like generation or demand. In contrast, the Flow Tracing Technique provides a more usage-based and physically correct allocation of losses by allocating them according to the actual path of power flows from Generators to loads. Using standard IEEE-14 Bus systems, the effectiveness of both approaches is assessed for allocation in deregulated power systems.

Keywords: Deregulation, whale optimization algorithm, Pro-Rata method, Flow Tracing Technique method, loss allocation.

I. INTRODUCTION

The electrical power transmission system plays a critical role in the delivery of electricity from generation sources to distribution networks and ultimately to end-users. It acts as the backbone of the power grid, facilitating the bulk transfer of electrical energy over long distances through high-voltage transmission lines. The

primary objective of a transmission system is to ensure the reliable, secure, and economic transfer of electric power while maintaining system stability and power quality. In deregulated power systems, fair and accurate allocation of transmission losses is essential for transparent pricing, efficient market operation,

and equitable cost distribution among market participants. This paper presents a comparative analysis of two widely used loss allocation techniques—Pro-Rata Allocation and Flow Tracing Technique (FTT)—with the objective of determining optimal and justifiable methods for loss allocation in competitive electricity markets.

The Pro-Rata method allocates losses proportionally based on predefined parameters such as generation or demand, offering simplicity and ease of implementation. Conversely, the Flow Tracing Technique method allocates losses based on the actual path of power flows from generators to loads, providing a more physically accurate and usage-based allocation. The performance of both methods is evaluated using standard IEEE test systems under different loading and dispatch conditions. Results indicate that while the Pro-Rata method is computationally efficient, it lacks sensitivity to actual network usage. The Flow Tracing Technique method, although more complex, offers greater fairness by linking losses to the true contributors of system loading. This study highlights the importance of selecting an appropriate loss allocation mechanism to support economic efficiency, encourage responsible grid usage, and promote fairness in deregulated electricity markets.

One of the major concerns in transmission networks is power loss, which not only reduces efficiency but also leads to

II. PROBLEM FORMULATION

2.1 TCSC MODELLING:

The increasing demand for electrical energy and the integration of renewable energy sources have posed significant challenges to the secure, reliable, and economic operation of modern power systems. One of the key limitations in power transmission networks is the inability to control power flow flexibly and efficiently under varying load conditions. To overcome such limitations, Flexible AC Transmission Systems (FACTS) have emerged as a vital technological advancement, enabling improved control over power system parameters and enhancing system performance.

increased operating costs and environmental impact. To address these challenges, the implementation of advanced control devices and optimization techniques has become essential. Flexible AC Transmission Systems (FACTS), [1] such as the Thyristor Controlled Series Capacitor (TCSC), have emerged as key technologies that provide dynamic control over power flows and improve the utilization of existing transmission assets. Moreover, the integration of metaheuristic optimization algorithms, such as the Whale Optimization Algorithm (WOA), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA), has proven effective in solving complex problems related to power flow control, transmission loss minimization, and optimal device placement in large-scale power networks. As power systems continue to evolve toward smart grid architectures, the transmission system remains a vital component requiring continuous innovation in modeling, control, and optimization to meet future energy demands sustainably.

Based on past research work with the study of Transmission Loss Allocation and Transmission Loss Reduction, it starts with the review of Flexible Alternating Current Transmission System (FACTS) [2] devices to solve power system problems. Consequently, the work on optimal location and sizing of FACTS devices using Meta-Heuristic Algorithms is further discussed and the methods for allocating transmission losses have been discussed.

Among the various FACTS devices, the Thyristor Controlled Series Capacitor (TCSC) is one of the most widely studied and implemented technologies for enhancing the power transfer capability, system stability, and loss minimization in transmission lines. A TCSC is a series compensation device consisting of a conventional capacitor in parallel with a thyristor-controlled reactor (TCR). By adjusting the firing angle of the thyristors, the effective reactance of the TCSC can be dynamically controlled, allowing real-time modulation of the transmission line impedance.

TCSC is a series connected device, which explains the concept of a variable series reactance using modeling of TCSC, to satisfy the active power limits, series reactance is adjusted automatically to limit the power flow for the

reduction of losses in the system. Here newton's method is used to determine the amount of reactance. The range of TCSC is restricted to be -0.7 to 0.3 of the line reactance [13]. The Modelling of TCSC as a controllable reactance XTCS is shown in Fig. 1.

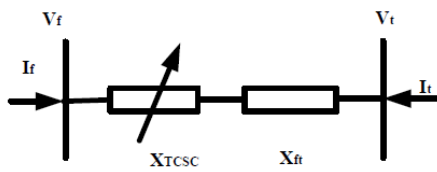


Fig1. TCSC's Variable reactance model

The transmission line's reactance can be expressed as:

$$X_{line} = X_{TCSC} + X_{ft} \quad (1)$$

Where,

X_{ft} = line Reactance between buses f and t

X_{TCSC} = Reactance of TCSC

X_{line} = Total reactance after placement of TCSC

Now, the problem is identified and simplified model of TCSC has been explained. In the next section, Whale optimization algorithm is discussed and how it can be applied to the problem for optimal placement of TCSC

2.2. OBJECTIVE FUNCTION:

The objective is to determine the optimal location and reactance setting of the TCSC device to minimize the transmission loss in power system network which can be evaluated from the power flow solution and written as

$$P_{loss} = \sum_{i=1}^n G_k (V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}) \quad (2)$$

Where

n = number of transmission lines

GK = conductance of Kth transmission line

V_i and V_j = voltages at bus i and bus j

δ_{ij} = power angle

B. Objectives

The proposed work's objective is to determine the optimal reactance setting and optimal location of the TCSC device to reduce transmission losses in the power system [8], and for the allocation of the transmission losses fairly, Postage Stamp method and Flow tracing Technique methods are used.

The performance equation is given as

$$\min F = \sum_{l=1}^{ntl} P_{Ll} \quad (3)$$

Subject to the equality constraints

$$P_{Gi} - P_{Di} - \sum_{j=1}^N V_i V_j (\bar{x}_{tcsc}) \cos(\delta_{ij} + \gamma_j - \gamma_i) = 0$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^N V_i V_j (\bar{x}_{tcsc}) \sin(\delta_{ij} + \gamma_j - \gamma_i) = 0$$

Subject to the inequality constraints

$$\min P_{Gi} \leq P_{Gi} \leq \max P_{Gi} \quad \forall i \in NG \quad (4)$$

$$\min Q_{Gi} \leq Q_{Gi} \leq \max Q_{Gi} \quad \forall i \in NG \quad (5)$$

$$\min V_i \leq V_i \leq \max V_i \quad \forall i \in N \quad (5)$$

$$\min \delta_{ij} \leq \delta_{ij} \leq \max \delta_{ij} \quad \forall i \in N \quad (6)$$

$$\min x_{tcsc} \leq x_{tcsc} \leq \max x_{tcsc} \quad (7)$$

Where

PLl is lth line' active power loss

ntl is total no of transmission lines in the system

N is the no of buses

NG is no of generator buses

QGi and PGi are the reactive and active power generation at bus i.

QDi and PDi are the reactive and active power load at

bus i

V_i is the magnitude of voltage at bus i

δ_{ij} is the power angle

x_{tcsc} is the reactance of TCSC

III.WHALEOPTIMIZATION ALGORITHM

It is a nature-inspired meta-heuristic optimization technique. The algorithm simulates the social behaviour and hunting mechanism of humpback whales, specifically their bubble-net feeding strategy, which is one of the most sophisticated feeding techniques in the marine world. Due to its simplicity, global convergence capability, and low computational complexity, WOA has attracted increasing attention across various scientific and engineering disciplines. In the bubble-net hunting process, humpback whales create a spiral pattern of bubbles to encircle their prey and then swim towards them along this spiral path. The WOA mathematically mimics this behaviour through a combination of shrinking encircling, spiral updating, and random search mechanisms, which respectively correspond to intensification (exploitation) and

diversification (exploration) phases of the algorithm.[7-8]

The search mechanism in WOA is guided by adaptive coefficients that help balance exploration and exploitation over the course of iterations. During the initial stages of the algorithm, exploration is emphasized to allow global search of the solution space, while in the later stages, the focus shifts to exploitation to refine the best solutions found so far. These dynamics make WOA especially effective for solving nonlinear, multi-modal, and constrained optimization problems, such as those frequently encountered in power system planning and operation, including optimal placement and sizing of FACTS devices like the Thyristor Controlled Series Capacitor (TCSC).

3.1 ALGORITHM

Start

Initialize parameters:

Number of whales (population), Maximum iterations, Bounds of TCSC reactance (Xtsc_min, Xtsc_max)

Search space (location and size)

Generate initial population:

Each whale represents a candidate solution (TCSC location and reactance value)

Evaluate fitness of each whale using:

Newton-Raphson power flow, objective function (e.g., minimize power loss)

Identify the best whale (best solution so far)

For each whale in the population:

Update position based on WOA equations, Encircling prey, Bubble-net attack (exploitation)

Search for prey (exploration)

Fitness of new positions

Update the best whale if a better solution is found

Repeat until maximum iterations is reached

Output optimal TCSC location and size

End

IV. TRANSMISSION LOSS ALLOCATION METHODS

In deregulated environments, researchers have also examined transmission loss allocation

strategies, including Pro-Rata Method and Power Flow Tracing (PFT) methods, which aim to fairly distribute loss costs among market participants. These methods, while not directly reducing losses, play a vital role in encouraging efficient grid usage and supporting economically sound operations.[12-13]

4.1 PRO-RATA METHOD

Here the total losses are first divided in to half of the total losses to Loads and remaining half to the Generators, which is to be predefined, losses then allocated to each generator and load proportionally based on their generation and consumption. This method is easily understandable and it is transparent and no complex calculations involved. Though it is simple but it has certain disadvantages.

$$LP_{Gj} = \frac{TL}{2} \frac{PG_j}{PG} \quad (8)$$

$$LP_{Di} = \frac{TL}{2} \frac{PD_i}{PD} \quad (9)$$

Where, PG_j, PD_i – generation of power and load at buses j and i respectively

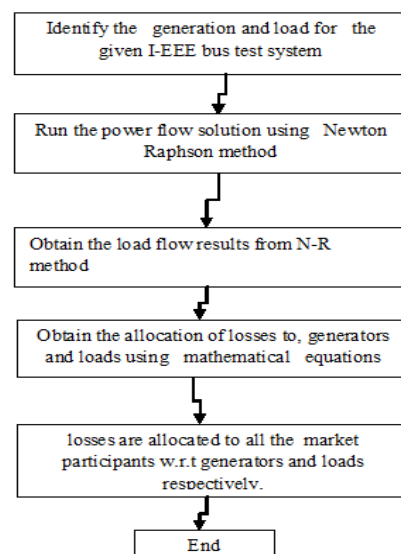
PG, PD – generation of total power, load of this system

LPG_j – Allocation of real power Losses to the generator j

LPD_i – Allocation of real power demand i

L – Total real power losses

4.1.1 ALGORITHM FOR PRO-RATA METHOD



This approach is easy to apply to any kind of system and has a straightforward structure.

According to the active power generation, the postage stamp approach divides the transmission losses between the generation and the load.

However, this kind of allocation does not take into account the network structure, and it will not be advantageous for two identical loads that are located close to generators and far from generators, respectively, because the same amount of loss will be distributed for both loads regardless of the transmission distance in the system.

4.2 FLOW TRACING TECHNIQUE METHOD

Flow Tracing Technique method takes the Kirchhoff's principle in to consideration by equally sharing the losses to the Generator and loads respectively. Here in this method, after equally sharing the total losses, these losses are shared fairly by analysing the system structure of the system fairly. Thus loss allocation can be done fairly to all the participants.

In this method the distribution factors can be determined by simple mathematical calculations of the network structure. Here the bus in which Zero injection power is made are given zero contribution for the allocation of losses. This is the advantage of this method.

Consider a network, which consists of b branches, n nodes, P_G, Q_G, P_D, Q_D are nodal power generation of real and reactive power and load of real and reactive powers respectively. [5]

$$P_{r-s}^{(gross)} = (P_{rs}/P_r) \sum [I_{u(r,k)}] P_{GK} \text{ for } s \in \alpha_r^d \quad (10)$$

Where,

α_r^d = set of nodes

P_r = nodal power

K = Buses

P_{GK} = power generation

P_{sr} = branch power flow

I_u = distribution of upstream matrix

$$P_{r-s}^{(net)} = (P_{rs}/P_r) \sum [I_{d(r,k)}] P_{DK} \text{ for } s \in \alpha_r^u \quad (11)$$

Where,

P_{DK} = load at bus K .

K = buses

P_{rs} = branch power flow

α_r^u = set of nodes.

I_d = distribution of downstream matrix

From the Kirchhoff's current law principle, the FTT Method allocates half of the total losses to loads and remaining half of the total losses to the generators

respectively. The Generation and demand at each bus are calculated as

$$P'_{Gr} = (P_{r-s}^{net} + P_{Gr})/2 \quad (12)$$

$$P'_{Ds} = (P_{r-s}^{(gross)} + P_{Dr})/2 \quad (13)$$

Finally for each generator and demand, the real power losses allocation are computed as

$$L'_{Gr} = P_{Gr} - P'_{Gr} \quad (14)$$

$$L'_{Ds} = P'_{Ds} - P_{Ds} \quad (15)$$

By using mathematical equations, this algorithm is tested for IEEE 14 Bus system with MATLAB in the following sections of the paper.

V. RESULTS AND DISCUSSIONS

The IEEE-14 Bus system consists of [8] two generators and 13 loads. Whale optimization algorithm is tested for IEEE 14 Bus system in MATLAB environment and the results of real power losses and voltage profile with and without TCSC device are shown in table-5.1 and table-5.2 respectively. The loss allocation of real power losses are shown in table-5.3, table-5.4, table-5.5 and table-5.6 respectively. Here using Whale optimization algorithm, TCSC Device is placed in line 3-4 with the optimal size of -0.0412 p.u.

Table-5.1 Power flow profile for IEEE 14 Bus system

From bus	To bus	Without FACTS devices	With FACTS devices
		power loss MW	With TCSC power loss MW
1	2	4.293	4.187
2	3	2.318	1.975
2	4	1.674	1.581
1	5	2.771	2.590
2	5	0.903	0.829
3	4	0.372	0.400
4	5	0.502	0.502
5	6	0.000	0.000
4	7	0.000	0.000
7	8	0.000	0.000
4	9	0.000	0.000
7	9	0.000	0.000
9	10	0.042	0.024
6	11	0.050	0.035
6	12	0.074	0.065
6	13	0.222	0.182
9	14	0.106	0.174
10	11	0.011	0.023
12	13	0.007	0.003
13	14	0.064	0.030
Total losses		13.410	12.602

Table–5.2 Voltage magnitude profile of IEEE 14 Bus system

Bus No	Without TCSC device	With TCSC
	Voltage(p.u.)	Voltage(p.u)
1	1.0	1.0
2	1.045	1.100
3	1.01	1.0564
4	1.0189	1.0721
5	1.0216	1.0807
6	1.07	1.0555
7	1.0587	1.0750
8	1.090	1.1
9	1.0492	1.063
10	1.0565	1.0655
11	1.0597	1.0572
12	1.0547	1.0421
13	1.0494	1.0389
14	1.0312	1.0345

Table–5.3 Allocation of losses to Generators for IEEE-14 Bus System without TCSC device

Transmission loss Without TCSC Device		
Generator No	Pro-rata Method	Flow Tracing Technique Method
1	5.7210	6.1061
2	0.9842	0.5984
Total	6.705	6.705

Table–5.4 Allocation of losses to Loads for IEEE-14 Bus System without TCSC device

Transmission loss without TCSC Device		
Load No	Pro-rata Method	Flow Tracing Technique Method
2	0.5616	0.2420
3	2.4378	2.6257
4	1.2370	1.5540
5	0.1967	0.0829
6	0.2898	0.1222
7	0.0000	0.000
8	0.0026	0.0033
9	0.7634	0.9591
10	0.2329	0.3324
11	0.0906	-0.0333
12	0.1579	0.0961
13	0.3494	0.2348
14	0.3856	0.4859
Total	6.705	6.705

Table– 5.5 Allocation of losses to Generators for IEEE-14 Bus System with TCSC device

Transmission loss With TCSC Device		
Generator No	Pro-rata Method	Flow Tracing Technique Method
1	5.3734	5.7432
2	0.9276	0.5583
Total	6.301	6.301

Table-5.6 Allocation of losses to loads for IEEE-14 Bus System with TCSC device

Transmission loss With TCSC Device		
Load No	Pro-rata Method	Flow Tracing Technique Method
2	0.5277	0.2373
3	2.2909	2.4198
4	1.1625	1.5428
5	0.1848	0.0466
6	0.2724	0.0687
7	0.000	0.000
8	0.0024	0.0032
9	0.7174	0.9525
10	0.2189	0.3060
11	0.0851	-0.0001
12	0.1483	0.0647
13	0.3283	0.1581
14	0.3624	0.5014
Total	6.301	6.301

The results obtained from IEEE-14 bus system with optimal location of TCSC Device, the Pro-rata method and Flow Tracing Technique method, allocated the losses equally to the loads and generators respectively and counter flow exist in Flow Tracing Technique method where as in Pro-rata method it doesn't exist. It shares the losses of 6.301MW to the generators and loads equally.

VI. CONCLUSIONS

In this paper whale optimization algorithm is used for optimal location and setting of TCSC device to reduce the transmission losses. From the results obtained for the test system of IEEE -14 bus system, it is observed that losses are reduced from 13.410MW to 12.602 MW and from the loss allocation methods.

Pro-rata method gives fixed amount of loss irrespective of the network structure of the system. Whereas Flow tracing Technique method

gives allocation of power losses fairly to all market participants based on the network usage of the system. Thus it can be concluded that whale optimization algorithm gives best results in determining the location of the TCSC Device compared to conventional methods and Flow tracing Technique method gives best results in the allocation of losses to all the transactions and counter flows also observed in the system.

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