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Optimal Generator Reallocation And Power Management Using Harris Hawks Optimization And TCSC Under Normal Operating Conditions

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Abstract

This paper presents an advanced Optimal Power Flow (OPF) strategy that integrates the Line Utilization Factor (LUF) index with the Harris Hawks Optimization (HHO) algorithm for optimal reallocation of generator outputs in the presence of a Thyristor Controlled Series Capacitor (TCSC). The objective is to minimize real power losses and voltage deviation while enhancing system stability. The proposed method is implemented on the IEEE 57-bus system under normal operating conditions. The LUF index is utilized to identify the most critical transmission line, with the weakest line (8–9) compensated by installing a TCSC. The HHO algorithm is employed to solve the multi-objective OPF problem, ensuring efficient generator dispatch and improved voltage profiles. Simulation results demonstrate that the inclusion of TCSC, guided by LUF and optimized via HHO, significantly improves power system performance by reducing losses, stabilizing voltages, and lowering generation costs. This study confirms the effectiveness of combining LUF-based line assessment with HHO for robust and intelligent power system optimization.

Key Words: Harris Hawks Optimization (HHO), Thyristor-Controlled Series Capacitor (TCSC), Optimal Power Flow (OPF), Power Management, Voltage Stability, Real Power Losses, Line Utilization Factor (LUF), Generator Reallocation, Transmission Line Optimization, Multi-Objective Optimization, Power System Performance, IEEE 57-Bus System.

1. INTRODUCTION

In modern power systems, efficient management of real power losses, voltage deviations, and optimal generator placement is crucial for ensuring system reliability, stability, and economic operation [1]. With the increasing complexity and size of electrical networks, optimization techniques have become essential tools for solving these complex power flow problems [2]. Among various optimization approaches, nature-inspired algorithms have gained significant attention due to their robustness and efficiency in addressing multi-objective problems [3]. Optimal Power Flow (OPF) is a critical optimization problem in power system operation, aimed at determining the optimal generation dispatch and system configuration that minimizes generation costs, power losses, and voltage deviations, while satisfying system constraints [4]. However, the presence of contingency conditions, network constraints, and the dynamic nature of the system adds complexity to OPF solutions, making the optimization process even more challenging [5].

The integration of Flexible AC Transmission System (FACTS) devices, such as the Thyristor-Controlled Series Capacitor (TCSC), has proven effective in enhancing power system stability, improving voltage profiles, and reducing transmission line losses [6]. TCSC, a power flow controller, dynamically adjusts the impedance of transmission lines, enabling better control over power transfer and alleviating congestion, thereby optimizing the flow of electrical power [7].In this paper, we propose a novel approach that combines Harris Hawks Optimization (HHO) and TCSC to manage power flow in a power system. HHO is a metaheuristic algorithm inspired by the hunting behaviour of Harris hawks, offering high efficiency in solving complex optimization problems [8]. By integrating HHO with TCSC, we aim to optimize generator reallocation, reduce power losses, improve voltage stability, and enhance the overall performance of the system [9]. The proposed method is tested on the IEEE 57-bus system under normal operating conditions, and its effectiveness is compared with traditional optimization methods [10]. The Line Utilization Factor (LUF) analysis is used to identify critical transmission lines, with the TCSC placed on the most vulnerable lines to improve system performance [11].The results demonstrate that the HHO-based OPF method with TCSC integration significantly enhances voltage profiles, reduces active power losses, and ensures efficient power generation [12]. This approach highlights the potential of combining advanced optimization algorithms with FACTS devices to improve power system management, making it a valuable tool for modern power systems facing increasing demand and complexity [13].

2. MODELLING OF TCSC

The primary TCSC system put forth by Vithayathil and the rest in 1986 was a technique related to “rapid adjustment of network impedance”. In addition to controlling the line power moving capacity, the TCSC goes on to enhance the system firmness. The primary unit of TCSC is displayed through Fig.1. It makes up a series recompensing capacitor that is shunted via the thyristor-controlled reactor. Thyristor incorporation in TCSC module facilitates smooth and steadier control of reactance against system criteria differences. In case of a massive power system, TCSC execution needs numerous similar primary compensators in order to get linked in series for acquiring required voltage rating as well as operating traits. It has been modelled in the form of a controllable reactance, gets included in series with the transmission line to fine-tune line impedance and thus controls the power flow.

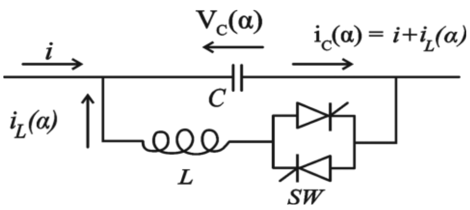

Fig.1: Basic TCSC model

Here, there is a straight fine-tuning of the reactance of the transmission line with the use of TCSC. The TCSC is modelled as varied impedance and its rating relies on the reactance of the transmission line where the TCSC is situated. From Fig.2, the impedance equations are written as in equations 1 to 3.

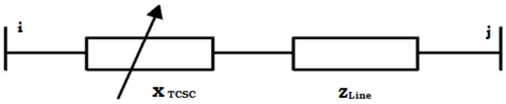

Fig.2: Block diagram of TCSC

$$Z_{ij} = R_{ij} + X_{ij} \quad (1)$$

$$Z_{line} = R_{line} + X_{line} \quad (2)$$

$$X_{ij} = X_{line} + X_{TCSC} \quad (3)$$

Where X_{TCSC} is reactance of TCSC, without over compensation, the working range of the TCSC is selected to lie within -0.8$X_{line}$and 0.6X_{line}. The transfer admittance matrix of the TCSC is given by

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} jB_{ii} & jB_{ij} \\ jB_{ji} & jB_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (4)$$

For capacitive operation, equations are given in (5) and (6)

$$B_{ii} = B_{jj} = \frac{1}{X_{TCSC}} \quad (5)$$

$$B_{ij} = B_{ji} = -\frac{1}{X_{TCSC}} \quad (6)$$

For inductive operation, the signs are inverted or reversed.

The active and reactive power equations at bus k are:

$$P_i = V_i V_j B_{ij} \sin(\theta_i - \theta_j) \quad (7)$$

$$Q_i = -V_i^2 B_{ii} - V_i V_j B_{ij} \cos(\theta_i - \theta_j) \quad (8)$$

When the series reactance controls the amount of active power flowing from bus i to bus j the change in reactance of TCSC is:

$$\Delta X_{TCSC} = X_{TCSC}^{i} - X_{TCSC}^{(i-1)} \quad (9)$$

Based on optimization rules, the state variable X_{TCSC} of the series controller is updated.

the Line Utilization Factor is an index used for determining the congestion of the transmission lines.

LUF is given by equation (10)

$$LUF = \frac{MVAij}{MVAij^{max}} \quad (10)$$

MVAij (max): Maximum MVA rating of the line between bus i and busj.

MVAij : Actual MVA rating of the line between bus i and bus j.

LUF gives an estimate of the percentage of line being utilized.

3. PROBLEM FORMULATION:

For the best generator tuning, a multi-objective function that considers the fuel cost, real power loss, and voltage variation was employed.

$$\text{Min } F = \text{Min } (W1 * F1 + W2 * F2 + W3 * F3) \quad (11)$$

Where, F1 is the Fuel cost given by

$$F1 = \min\left(\sum_{i=1}^{ng}(a_i + b_i P_{Gi} + C_i P_{Gi}^2)\right) \quad (12)$$

The number of generators in the power system is represented by Ng and the fuel cost coefficients are a, b, and c. Table.1 lists the values of the coefficients for the several generators.

In this case, there are ntl transmission lines and Sjk is the total complex power flowing from bus j to bus k in line i, where F2 denotes the voltage variance.

$$\text{F2} = \min\ (\text{VD}) = min\left(\sum_{k=1}^{Nbus}(V_K - S_k^{ref})^2\right) \quad (13)$$

The reference value of the voltage magnitude at bus is V_k^{ref}, whereas the actual voltage magnitude at bus k is V_k.

The true power loss is F3.

$$\text{F3} = min\left(\sum_{i=1}^{ntl} \text{real}(S_{jk}^i + S_{kj}^i)\right) \quad (14)$$

Equality constraints:

Power Balance Constraint

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \quad (15)$$

$$\sum_{i=1}^{N} Q_{Gi} = \sum_{i=1}^{N} Q_{Di} + Q_L \quad (16)$$

Where i=1, 2, 3... N and N = no. of. PL indicates the active power loss of the system, Q_L is the total reactive power loss, P_{Gi} is the active power generated at bus i, Q_{Gi} is the reactive power generated at bus i, P_{Di} is the power demand at bus i, Q_{Di} is the power demand at bus i, and N is the number of buses.

Inequality constraints:

Voltage balance constraint

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \tag{17}$$

Where Gi=1, 2, 3... ng and ng = number of Generator buses.

Real power generation limit:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \tag{18}$$

Where, Gi=1, 2, 3... ng

where ng is the number of generator buses.

Reactive Power generation limits:

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \tag{19}$$

HHO algorithm

Initialization: The first step in the HHO algorithm is to create a group of "hawks," which are potential solutions to the problem. Each hawk is placed randomly in the solution space. Along with this, we set up some important settings like how many hawks there are, how many iterations the algorithm will run, and other problem-specific details. This sets up the starting point for the algorithm to begin its search for a good solution.

Exploration Phase: In the exploration phase, the hawks search widely across the solution space to find good solutions. They make big, random moves to cover a large area, which helps them avoid getting stuck in one place. This phase is about exploring new possibilities and not focusing on the best solution just yet, but rather looking for promising areas where better solutions might exist.

Exploitation Phase: Once the hawks have explored enough, they move into the exploitation phase. In this phase, they start focusing on the best solution they have found so far and make smaller, more precise moves to improve it. The goal is to get closer and closer to the optimal solution by refining their current position based on what they've learned.

Switching Between Exploration and Exploitation: The algorithm switches back and forth between exploration and exploitation, depending on what's needed at the moment. If the hawks need to look for better solutions, the algorithm will explore more. If the hawks are already close to a good solution, the algorithm will focus on refining it. This balance between exploring new areas and improving existing solutions helps the algorithm find the best possible result.

Termination: Finally, the algorithm stops when it reaches a stopping point, such as when it has completed a set number of iterations or when the solution is good enough. The best solution found during the process is returned as the final result. This can also depend on other criteria, like when improvements are so small that continuing wouldn't make a significant difference.

4. RESULTS AND DISCUSSION

Table.1 LUF Index values for all lines-IEEE 57 bus system

Rank	Line Connected		LUF	Rank	Line Connected		LUF	Rank	Line Connected		LUF	Rank	Line Connected		LUF
	FB	TB			FB	TB			FB	TB			FB	TB	
1	8	9	1.1658	21	12	17	0.3189	41	6	8	0.1856	61	24	26	0.1048
2	12	13	0.7608	22	3	15	0.2995	42	1	2	0.1629	62	5	6	0.1023
3	13	15	0.5629	23	13	14	0.2465	43	29	52	0.1136	63	35	36	0.0738
4	41	43	0.1099	24	38	44	0.2207	44	4	18	0.0842	64	48	49	0.0399
5	1	17	0.5618	25	39	57	0.0277	45	27	28	0.1575	65	47	48	0.0638
6	11	41	0.0987	26	11	43	0.138	46	38	49	0.0567	66	4	5	0.0422
7	1	15	0.4794	27	24	25	0.0457	47	38	48	0.1018	67	56	41	0.0292
8	9	12	0.3149	28	24	25	0.0439	48	54	55	0.0558	68	19	20	0.0227
9	44	45	0.2848	29	50	51	0.085	49	18	19	0.0416	69	31	32	0.0077
10	1	16	0.4887	30	14	46	0.1877	50	3	4	0.1124	70	34	35	0.0406
11	7	29	0.3966	31	46	47	0.1836	51	9	55	0.0968	71	56	42	0.0124
12	7	8	0.4054	32	37	38	0.1258	52	23	24	0.0384	72	49	50	0.0449
13	15	45	0.3171	33	40	56	0.0238	53	6	7	0.0756	73	57	56	0.017
14	9	10	0.3835	34	12	16	0.2432	54	36	37	0.0973	74	21	20	0.0096
15	9	11	0.3613	35	34	32	0.0406	55	53	54	0.0347	75	22	38	0.0323
16	13	49	0.194	36	10	51	0.1805	56	30	31	0.026	76	22	23	0.0372
17	1	15	0.2831	37	4	18	0.1083	57	4	6	0.0865	77	37	39	0.0278
18	10	12	0.2361	38	28	29	0.1875	58	25	30	0.0476	78	36	40	0.0239
19	11	13	0.2596	39	26	27	0.1051	59	41	42	0.0493	79	32	33	0.0213
20	9	13	0.2995	40	2	3	0.1367	60	52	53	0.0812	80	21	22	0.0096

The Line Utilization Factor (LUF) values in the IEEE 57-bus system provide important insights into the efficiency and usage of transmission lines. Table 1 shows the LUF index values for all lines, ranking them by their utilization. The highest LUF value is 1.1658 for the connection between buses 8 and 9, indicating a highly utilized transmission line that may require more attention for potential upgrades or monitoring.

Other lines with significant utilization include those between buses 12 and 13 (0.7608), 13 and 15 (0.5629), and 1 and 17 (0.5618).On the other hand, several lines exhibit very low LUF values, indicating underutilization, such as the connection between buses 21 and 22 (0.0096), 31 and 32 (0.0077), and 19 and 20 (0.0227). These lines could be optimized by redistributing power flow from highly used lines to those with low utilization, potentially improving overall grid efficiency. This analysis highlights the potential for both upgrading heavily used connections and optimizing underutilized lines for better performance and grid stability.

Table 2: Comparison of Objective Function Parameters using HHO-OPF Considering Without and With TCSC for Without Contingency – IEEE 57-Bus System

Parameters	HHO-OPF without TCSC	HHO-OPF with TCSC at Line No 8-9
PG1(MW)	252	250
PG2(MW)	78.06	78.24
PG3(MW)	65	75.2
PG6(MW)	72	89
PG8(MW)	466	462
PG9(MW)	200	200
PG12(MW)	109.953	87.23
Total real power generation (MW)	1243.01	1241.67
Total real power generation cost ($/hr)	46328	45925
Active power Loss (MW)	47.213	45.87
Voltage deviation (p.u)	5.713	5.485
Rating of TCSC (p.u)	-	X=0.05
Objective function value	6983.1	6921.6

The comparison between the Harris Hawks Optimization (HHO)-based Optimal Power Flow (OPF) results with and without the integration of TCSC (Thyristor-Controlled Series Capacitor) at line 8-9 reveals several important insights into system performance and efficiency. When comparing the power generation from the various generators, we observe a slight reduction in the generation from PG1 (252 MW to 250 MW) and a small increase in PG2 (78.06 MW to 78.24 MW). However, more noticeable changes occur with PG3 (65 MW to 75.2 MW) and PG6 (72 MW to 89 MW), which see significant increases in output. This suggests that the TCSC’s integration helped redistribute power more effectively across the system. On the other hand, PG8 sees a minor decrease (466 MW to 462 MW), while PG12 experiences a substantial reduction in generation (109.953 MW to 87.23 MW). This variation is likely due to the TCSC's effect on optimizing power flows and reducing congestion in the system. Regarding the overall system performance, the total real power generation slightly decreases from 1243.01 MW to 1241.67 MW with the inclusion of the TCSC. This is accompanied by a small reduction in the total real power generation cost, from $46,328/hr to $45,925/hr, indicating a more cost-efficient system when the TCSC is deployed. Furthermore, the active power losses decrease from 47.213 MW to 45.87 MW, which demonstrates an improvement in system efficiency. Likewise, the voltage deviation, a critical indicator of voltage stability, improves from 5.713 p.u to 5.485 p.u, suggesting that the TCSC plays a role in stabilizing voltage levels across the network.The rating of the TCSC is specified as X = 0.05 p.u, which shows that the device is operating at a relatively modest capacity but still manages to yield noticeable improvements in the system. Lastly, the objective function value, which represents the overall system performance, decreases from 6983.1 to 6921.6 with the TCSC, indicating that the inclusion of the TCSC has optimized the power flow and system performance to some extent. Overall, the integration of TCSC at line 8-9 has led to several positive outcomes, including a reduction in power losses, improved voltage stability, and a slight reduction in the overall cost of generation. These changes reflect the ability of TCSC to enhance system performance, making it a valuable tool for optimizing power flow and stability in electrical networks.

5. CONCLUSION

The analysis of the IEEE 57-bus system with the Harris Hawks Optimization (HHO)-based Optimal Power Flow (OPF) and the integration of Thyristor-Controlled Series Capacitor (TCSC) at line 8-9 has yielded significant findings on the system's performance. The results indicate that the inclusion of TCSC has led to notable improvements in grid efficiency and stability. By redistributing power more effectively across generators, especially at lines 8-9, the TCSC helped to optimize the power generation and reduce congestion, thus lowering active power losses and improving voltage stability.Specifically, the total real power generation was reduced slightly from 1243.01 MW to 1241.67 MW with the introduction of TCSC, which was accompanied by a small reduction in the total generation cost, from $46,328/hr to $45,925/hr. These reductions reflect a more cost-efficient system. Moreover, the active power loss decreased from 47.213 MW to 45.87 MW, highlighting the TCSC's effectiveness in reducing transmission losses. The voltage deviation, a key indicator of voltage stability, also improved from 5.713 p.u to 5.485 p.u, further demonstrating the TCSC's role in enhancing system stability. Additionally, the Line Utilization Factor (LUF) analysis provided valuable insights into line usage across the system. The highest LUF values were observed for certain lines, indicating high utilization, while other lines showed very low LUF values, suggesting underutilization. Optimizing these underutilized lines could further enhance overall grid performance by redistributing power from heavily used lines.In conclusion, the integration of TCSC into the IEEE 57-bus system demonstrated tangible benefits in terms of cost efficiency, reduction in power losses, and improved voltage stability. The study emphasizes the importance of TCSC as a tool for optimizing power flow and ensuring the stability and efficiency of electrical transmission networks. Future work could explore the application of TCSC at other critical points in the grid to further improve system performance and stability.

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