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Optimal Voltage and Reactive Power Management using Harris Hawks Optimization (HHO) with Generator Reallocation and Hybrid Index Driven UPFC Placement for Enhanced Power System Stability

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Abstract: - From the operation and control of the power systems, the optimization of significant parameters like voltage profiles, reactive power, and real power losses assures stability, efficiency, and dependability. Following operational limits, including producing limits, transmission line capacities, and voltage requirements, the Optimal Power Flow (OPF) problem aims to minimize generating costs, system losses, and voltage deviations. This paper presents an improved OPF solution for the IEEE 30-bus system using the Harris Hawks Optimization (HHO) method, a modern metaheuristic driven by Harris hawks cooperative hunting activity. First stressing lowering real power losses and voltage aberrations, the technique then integrates generator reallocation to optimum power generation under system constraints. Integrated into the OPF framework, a flexible FACTS device able to manage voltage magnitude, line reactance, and phase angle, a Unified Power Flow Controller (UPFC) enhances system stability. The best location of the UPFC is discovered by using Hybrid Index (HI), which combines the L-index for voltage stability and the Line Utilisation Factor (LUF) for line congestion, therefore enabling the appropriate detection of stressed network points. Performance of the Harmony Search (HS) algorithm is compared with that of the HHO based OPF approach. Results on the IEEE 30-bus system reveal that HHO trumps HS in terms of solution quality, reduction in real power losses, voltage profile enhancement, and general system robustness both with and without UPFC inclusion.

Keywords: Optimal Power Flow (OPF), Harris Hawks Optimization (HHO), Unified Power Flow Controller (UPFC), Line Utilization Factor (LUF), Hybrid Index (HI).

INTRODUCTION

Operation and administration of power plants determines the stability, efficiency, and dependability of electrical systems. Optimizing important elements including voltage profiles, reactive power, and real power losses guarantees best performance of power systems. Essential for power system management, the Optimal Power Flow (OPF) problem tries to lower generation costs, system losses, and voltage fluctuations while adhering to certain operational limitations like generating limits, transmission line capacities, and voltage standards. Mostly depending on mathematical programming methods like linear programming (LP) or quadratic programming (QP), traditional optimal power flow (OPF) approaches find limits when tackling the complex, non-linear, and expanding character of modern power systems [1],[2]. These techniques may be computationally intensive and dependent on correct beginning calculations; hence they are inappropriate for modern power systems marked by uncertainty and various limitations. As power systems have become increasingly complex, metaheuristic optimization strategies have become more common. These techniques offer a fast and flexible means to negotiate

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the large, non-convex solution spaces of real-world Optimal Power Flow (OPF) problems [3], [4] in the absence of derivative knowledge.

Notable success has come from the Harris Hawks Optimisation (HHO) technique. Inspired by the cooperative hunting behaviour of Harris hawks, HHO harmonises exploration and exploitation, hence aiding the search for ideal solutions in difficult optimization issues [5], [6]. The adaptability of the HHO approach makes it especially appropriate for non-linear, multi-objective optimization problems including the OPF problem in power systems, which entails concurrently lowering power losses and improving voltage profiles [7], [8]. This work presents for the IEEE 30-bus system an improved Optimal Power Flow (OPF) solution using the Harris Hawks Optimization (HHO) technique. Reducing real power losses and voltage fluctuations is the main aim, thereby guaranteeing the system runs within its limits. Additionally included in the study is generator reallocation, which maximises output at every bus to satisfy system restrictions and hence improve general system performance [9], [10]. By varying generation within specified system restrictions, the suggested approach guarantees effective functioning, hence reducing voltage variations and losses.

Flexible AC Transmission System (FACTS) devices like the Unified Power Flow Controller (UPFC) very greatly increase system stability and lower transmission congestion. Designed to enable dynamic control of power flow in the system by means of voltage magnitude, line reactance, and phase angle [11], [12], the UPFC is a flexible FACTS device. The best location of the UPFC determines system performance since its location significantly affects power distribution and system stability. This work presents a hybrid index (HI) combining the L-index for voltage stability with the Line Utilisation Factor (LUF) for line congestion evaluation, thereby precisely pointing stressed locations in the network and guiding the UPFC [13], [14] deployment. The proposed HHO-based OPF solution is contrasted with the well-known metaheuristic technique Harmony Search (HS). Simulation findings on the IEEE 30-bus system show that the HHO-based OPF method outperforms the HS algorithm for solution quality, lowering of real power loss, enhancement of voltage profile, and general system robustness. These results are compatible both with and without UPFC [15], [16], [17].

2. PROPOSED HYBRID INDEX FOR PLACEMENT OF THE UPFC

HI is a combination of line loading index and voltage stability index. It gives an accurate measure of the stress on a bus. Thus, accurately defining its weakness with respect to others.

The UPFC has been placed on the basis of an index which is a combination of L-index and LUF index.

L-index

$$Lindex = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \tag{1}$$

L-index has value between 0 to 1. Lower is the value of the index enhanced is the stability of the system. Fji represents complex elements, Vi represents voltage magnitude at bus I and Vj represents voltage magnitude at bus j.

Line Utilization Factor (LUF)

LUF is an index used for determining the congestion of the transmission lines as given in equation 2.

$$LUF = \frac{MVAij}{MVAij^{\max}} \tag{2}$$

LUF is the ratio of apparent power flow in the line to the maximum LUF of the line. When the power flow in the line is within its maximum limits, the system is said to be stable and the value of LUF is less than 1. LUF gives an estimate of the percentage of line being utilized.

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

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.

$$Min\ F = Min\ (W1 * F1 + W2 * F2 + W3 * F3) \quad (3)$$

Where, F1 is the Fuel cost given by

$$F1 = min\left(\sum_{i=1}^{ng} (a_i + b_i P_{Gi} + C_i P_{Gi}^2)\right) \quad (4)$$

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.

Table.1: Fuel Cost Calculation Values for a, b, and c

Generator bus no	a (p.u)	b (p.u)	c (p.u)	P_G^{min} (MW)	P_G^{max} (MW)
1	0.005	2.45	105	10	200
2	0.005	3.51	44.1	10	50
5	0.005	3.89	40.6	10	50
8	0.005	3.25	0	10	50
11	0.005	3	0	10	100
13	0.005	2.45	105	0	10

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.

$$F2 = \min(VD) = min\left(\sum_{k=1}^{Nbus} \left(V_K - S_k^{ref}\right)^2\right) \quad (5)$$

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.

$$F3 = min\left(\sum_{i=1}^{ntl} real\left(S_{jk}^i + S_{kj}^i\right)\right) \quad (6)$$

Equality constraints:

Power Balance Constraint

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \quad (7)$$

$$\sum_{i=1}^{N} Q_{Gi} = \sum_{i=1}^{N} Q_{Di} + Q_L \quad (8)$$

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

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \quad (9)$$

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

Real power generation limit:

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (10)$$

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

where ng is the number of generator buses. The voltage limits of the generator buses are taken between 0.9 p.u and 1.1 pu.

Reactive Power generation limits:

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (11)$$

Modelling of UPFC

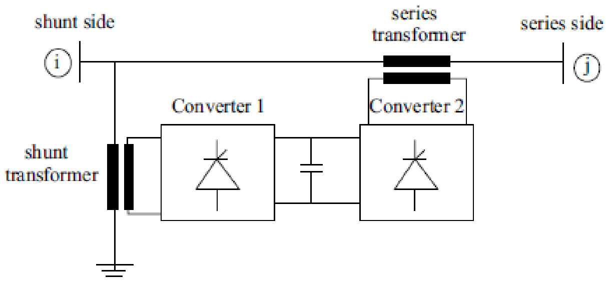

Figure.1. Schematic arrangement of the Unified Power Flow Controller

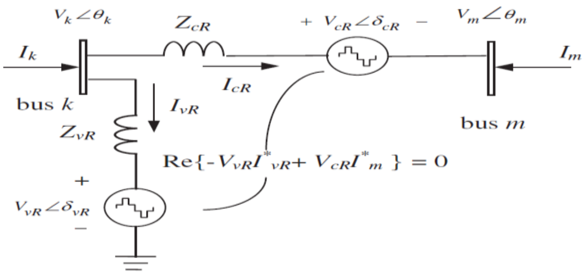

Figure.2 Equivalent circuit of the Unified Power Flow Controller

UPFC voltage sources are written in equations 12 & 13

$$V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \tag{12}$$

$$V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \tag{13}$$

Where V_{vR} and δ_{vR} points to the controllable voltage magnitude and phase angle of the voltage source that depict the shunt converter. Similarly, V_{cR} and δ_{cR} pinpoints to the controllable voltage magnitude and phase angle of the voltage source that define the series converter. Source impedance is considered to be resistance less. (i.e R_{vR}=0, R_{cR}=0)

The active and reactive power equations are,

At bus k

$$P_k = [V_k V_m B_{km} \sin(\theta_k - \theta_m)] + [V_k V_{cR} B_{km} \sin(\theta_k - \delta_{cR})] + [V_k V_{vR} B_{vR} \sin(\theta_k - \delta_{vR})] \tag{14}$$

$$Q_k = \quad V_k^2 B_{kk} - [V_k V_m B_{km} \cos(\theta_k \quad \theta_m)] \quad [V_k V_{cR} B_{km} \cos(\theta_k \quad \delta_{cR})] \quad [V_k V_{vR} B_{vR} \cos(\theta_k \quad \delta_{vR})] \tag{15}$$

At bus m

$$P_m = [V_m V_k B_{mk} \sin(\theta_m - \theta_k)] + [V_m V_{cR} B_{mm} \sin(\theta_m - \delta_{cR})] \tag{16}$$

$$Q_m = \quad V_m^2 B_{mm} - [V_m V_k B_{mk} \cos(\theta_m \quad \theta_k)] \quad [V_m V_{cR} B_{mm} \cos(\theta_m \quad \delta_{cR})] \tag{17}$$

At Series converter:

$$P_{cR} = [V_{cR} V_k B_{km} \sin(\delta_{cR} - \theta_k)] + [V_m V_{cR} B_{mm} \sin(\delta_{cR} - \theta_m)] \tag{18}$$

$$Q_{cR} = \quad V_{cR}^2 B_{mm} - [V_k V_{cR} B_{km} \cos(\theta_k \quad \delta_{cR})] \quad [V_m V_{cR} B_{mm} \cos(\theta_m \quad \delta_{cR})] \tag{19}$$

At Shunt converter:

$$P_{vR} = V_{vR} V_k B_{vr} \sin(\delta_{nR} - \theta_k) \tag{20}$$

$$Q_{vR} = V_{vR}^2 B_{vR} - V_{vR} V_k B_{vR} \cos(\delta_{vR} - \theta_k) \tag{21}$$

4. PROPOSED APPROACH

This work presents a four-step approach to improve power system performance by use of two optimization strategies: Harmony Search (HS) and Harris Hawks Optimisation (HHO). While keeping system stability under both normal and contingency conditions, the goals are to reduce power generation costs, decrease power losses, and improve voltage stability. Four separate phases define the technique:

First step: HHO and HS; leave UPFC off: First, we solve the Optimal Power Flow (OPF) issue for the IEEE 30-bus system under conventional running conditions applying both HHO and HS approaches. Reducing real power losses, lowering generating costs, and improving system voltage stability is the main goals here. Generator outputs are maximised and all system restrictions are followed. Following the use of these techniques, we assess their effectiveness in reducing losses and improving the voltage profile in the absence of the Unified Power Flow Controller (UPFC).

Second step: HHO and HS applied via UPF: The next stage is to include into the system the UPFC, a FACTS gadget controlling line reactance, voltage levels, and phase angles. The UPFC improves system stability and helps to reduce line of power line congestion. Using Harris Hawks Optimisation (HHO) and Harmony Search (HS), now including the Unified Power Flow Controller (UPFC), we re-examined the Optimal Power Flow (OPF) problem. The results are compared with those from Step 1 to assess the degree to which the UPFC improves the performance of the system concerning voltage stability and power flow.

Third step: HHO and HS using a contingency assessment Leaving out UPFC: Third phase is contingency analysis to assess the reaction of the system to unanticipated events including the breakdown of a single transmission line (N-1 contingency). Emphasising voltage stability and loss minimisation, both HHO and HS algorithms are used to improve system performance in faulty circumstances. This stage is carried out devoid of the UPFC to assess the performance of the system under these circumstances independently.

The fourth step is HHO and HS using UPFC with contingency assessment: Once more in the last phase, we perform the contingency analysis including the UPFC. The most stressed locations in the network are identified using the hybrid index (HI), which combines the L-index for voltage stability with the Line Utilisation Factor (LUF) for line congestion. UPFC devices abound in these sites to help to reduce voltage instability during breakdowns. The system is re-optimized using both HHO and HS; the results are compared to Step 3 to assess the degree of UPFC support during fault conditions.

HARRIS HAWKS OPTIMIZATION (HHO): Inspired by the group hunting behaviour of Harris hawks in nature, Harris Hawks Optimisation (HHO) is very helpful for addressing challenging problems including Optimal Power Flow (OPF) in electrical power systems, where the objective is to determine the best operating parameters.

HHO distributes a predefined number of hawks across the search region in the first stage; each hawk marks a possible solution. During what is known as the exploration phase, hawks seek extensively in order to identify areas that can profit from improved solutions.

The second action depends on which hawk is performing the best: they should be in constant communication and updating of each other on their locations. Their combined efforts help them to reach the ideal answer. Focussing narrowly helps them to get ready for the exploitation stage as the hunt goes on.

In phases three and four, you will learn gentle and forceful besiege, moves that replicate the way hawks encircle and attack their target. Hawkes can so adjust their positions such that they are close to the most likely right response. The group discovers the best alternative after several iterations, so the optimization is finished.

5. RESULTS AND DISCUSSION

5.1 OPF for Normal Condition (Without Contingency)

Table.2: Weak buses ordering in IEEE 30 bus system by using HS

Bus No	L-Index	Bus No	L-Index
30	0.0891	14	0.0523
26	0.0855	22	0.0474
9	0.0807	27	0.0468
29	0.0732	16	0.0449
24	0.0665	17	0.0439
19	0.0642	12	0.0374
18	0.0633	10	0.0369
25	0.0614	7	0.0336
23	0.0576	3	0.0164
20	0.0575	4	0.0142
21	0.0562	28	0.01
15	0.0548	6	0.0055

From Table 2 and Table 3, the Harmony Search (HS) algorithm is used to identify voltage-weak buses and highly loaded lines in the IEEE 30-bus system. Based on the L-index values in Table 2, bus 30 stands out with the highest L-index of 0.0891 p.u., indicating it is the most vulnerable to voltage instability. Bus 30 is directly connected to buses 27 and 29 through lines 27–30 and 29–30, making it a critical point for voltage support intervention.

According to the Line Utilization Factor (LUF) values in Table 3and table 4, line 27–30 shows a higher LUF of 0.0352 p.u. compared to line 29–30, which has a LUF of 0.0173 p.u. This suggests that the 27–30 line contributes more significantly to the power flow into the weakest bus (bus 30). Hence, placing a Unified Power Flow Controller (UPFC) at bus 30 and along the 27–30 line is a suitable strategy to enhance voltage stability and effectively manage power flow under stressed conditions in the system.

Table.3: All lines LUF values in the IEEE 30-Bus System Using the HS Algorithm

Line Connected			**Line Connected**		
From bus	**To bus**	**LUF**	**From bus**	**To bus**	**LUF**
9	10	0.2307	10	17	0.0423
3	4	0.3012	10	22	0.0377
4	6	0.2832	27	29	0.0308
4	12	0.144	25	27	0.0228
6	7	0.2064	12	14	0.0376
28	27	0.0931	19	20	0.0367
10	21	0.1195	12	16	0.0364
6	10	0.0614	23	24	0.0129
12	15	0.0887	15	18	0.0296
6	28	0.078	16	17	0.0194
6	9	0.0694	29	30	0.0173
10	20	0.0494	24	25	0.0033
12	13	0.0986	15	23	0.0205

22	24	0.0371	21	23	0.0164
27	30	0.0352	18	19	0.0134
25	26	0.0199	14	15	0.0054

Table.4: Severe Line (30 bus connected lines) using HS

Rank	Line connected		LUF Value
	FB	TB	
1	27	30	0.0352
2	29	30	0.0173

Based on Table 5, the Harris Hawks Optimization (HHO) algorithm is applied to identify voltage-weak buses in the IEEE 30-bus system using L-index values. Bus 30 again emerges as the most voltage-unstable with an L-index of 0.0825 p.u., followed by bus 26 (0.0793 p.u.). This consistency across optimization techniques confirms bus 30 as the most critical node needing voltage support. The ranking also reveals other significantly weak buses like 9, 29, and 24, though their instability is slightly lower, helping prioritize voltage enhancement strategies across the network.

Table 6 and Table 7 detail the Line Utilization Factor (LUF) analysis from the HHO approach, showing that among the lines connected to bus 30, line 27–30 has a higher LUF (0.0382 p.u.) than line 29–30 (0.0203 p.u.). These two lines are ranked as the top critical connections to bus 30 in Table 6. This reinforces the selection of bus 30 and line 27–30 as suitable sites for installing a Unified Power Flow Controller (UPFC), aiming to reduce voltage instability and better control power flow.

Table.5: Weak buses ordering in IEEE 30 bus system by using Using the HHO Algorithm

Bus No	L-Index	Bus No	L-Index
30	0.0825	14	0.0472
26	0.0793	22	0.0428
9	0.0721	27	0.0421
29	0.0678	16	0.0405
24	0.0619	17	0.0396
19	0.0595	12	0.0339
18	0.0584	10	0.0334
25	0.0571	7	0.0301
23	0.0529	3	0.0135
20	0.0526	4	0.0118
21	0.0513	28	0.0085
15	0.0497	6	0.0044

Table.6: All lines LUF values in the IEEE 30-Bus System Using the HHO Algorithm

Line Connected		LUF	Line Connected		LUF
From bus	To bus		From bus	To bus	
9	10	0.2437	10	17	0.0453
3	4	0.3042	10	22	0.0407
4	6	0.2862	27	29	0.0338

4	12	0.147	25	27	0.0258
6	7	0.2094	12	14	0.0406
28	27	0.0961	19	20	0.0397
10	21	0.1225	12	16	0.0394
6	10	0.0644	23	24	0.0159
12	15	0.0917	15	18	0.0326
6	28	0.081	16	17	0.0224
6	9	0.0724	29	30	0.0203
10	20	0.0524	24	25	0.0063
12	13	0.1016	15	23	0.0235
22	24	0.0401	21	23	0.0194
27	30	0.0382	18	19	0.0164
25	26	0.0229	14	15	0.0084

Table.7: Severe Line (30 bus connected lines) using HHO

Rank	**Line connected**		**LUF Value**
	FB	**TB**	
1	27	30	0.0382
2	29	30	0.0203

Table.8: Optimized Generator Outputs and Total Generation for HS and HHO Methods With and Without UPFC

Method	PG1 (MW)	PG2 (MW)	PG5 (MW)	PG8 (MW)	PG11 (MW)	PG13 (MW)	Total Generation (MW)
HS without UPFC	137.412	33.392	30.053	43.798	44.821	10	299.4785
HS with UPFC	135.238	30.825	30.836	39.743	45.632	10	292.274
HHO without UPFC	132.1714	15.3346	24.7193	31.9864	78.8158	10	293.0275
HHO with UPFC	128.879	16.095	27.3	31.37	78.122	10	291.766

Table 8 presents the optimized generator outputs and total power generation obtained using the Harmony Search (HS) and Harris Hawks Optimization (HHO) algorithms, both with and without the integration of a Unified Power Flow Controller (UPFC). The results show that the inclusion of UPFC leads to a reduction in total generation for both methods, indicating improved system efficiency. Specifically, the total generation using HS decreases from 299.48 MW (without UPFC) to 292.27 MW (with UPFC), while the HHO method reduces total generation from 293.03 MW to 291.77 MW after UPFC deployment. This highlights that HHO not only achieves lower total generation compared to HS but also benefits more from UPFC integration, confirming its effectiveness in optimizing generator dispatch and enhancing power system performance.

Table 9: UPFC Parameters using HS and HHO

UPFC Rating	HS	HHO
Series converter voltage in p.u	0.04	0.04
Series converter angle	-87.1236	-87.1236

Shunt converter voltage in p.u	1.0068	1.0065
Shunt converter angle	-11.9980	-11.3174

Table 9 displays the optimized UPFC (Unified Power Flow Controller) parameters obtained using the Harmony Search (HS) and Harris Hawks Optimization (HHO) algorithms. Both methods yielded the same series converter voltage of 0.04 p.u. and angle of -87.1236°, indicating similar compensation on the series side. However, slight differences are noted in the shunt converter parameters, where the HS method produced a voltage of 1.0068 p.u. and angle of -11.9980°, while the HHO method resulted in a voltage of 1.0065 p.u. and angle of -11.3174°. These minor variations suggest that both methods provide effective UPFC settings, with HHO offering slightly better fine-tuning of shunt compensation.

Table.10: Power Parameters Comparison of HS and HHO Methods With and Without UPFC

Parameter	HS without UPFC	HS with UPFC bus 30 and line 27-30	HHO without UPFC	HHO with UPFC bus 30 and line 27-30
Total Real Power (MW)	299.4785	292.274	293.0275	291.766
Real Power Loss (MW)	16.0785	8.874	9.6275	8.366
Reactive Power Loss (MVAR)	33.35	16.26	17.38	8.76
Voltage Deviation (p.u.)	2.444	1.723	1.8947	1.212
Fuel Cost ($/hr)	1361.9	1342.3	1355.7	1321.7

Table 10 presents a comparison of key power system performance parameters using HS and HHO algorithms with and without the implementation of a Unified Power Flow Controller (UPFC) at bus 30 and line 27–30. From the results, it is evident that the inclusion of UPFC significantly improves overall system performance for both algorithms. Specifically, real and reactive power losses are substantially reduced, with HHO and UPFC achieving the lowest losses (real power loss: 8.366 MW, reactive loss: 8.76 MVAR). Additionally, voltage deviation is minimized to 1.212 p.u. using HHO with UPFC, indicating better voltage stability. Fuel cost also decreases with UPFC deployment, with HHO and UPFC yielding the most economical operation at $1321.7/hr, showcasing its superior optimization capability compared to the HS method. Overall, UPFC integration enhances efficiency, reduces losses, and improves voltage stability in the IEEE 30-bus system.

Figure.3 illustrates the improvement in the objective function value when a Unified Power Flow Controller (UPFC) is integrated into the IEEE 30-bus system. The objective function value drops notably from 216.5883 to 208.1728 using the HS algorithm, and from 210.7651 to 204.6507 using the HHO algorithm. Among all cases, the HHO with UPFC configuration achieves the lowest objective function value, highlighting its effectiveness in optimizing the power flow and enhancing overall system performance.

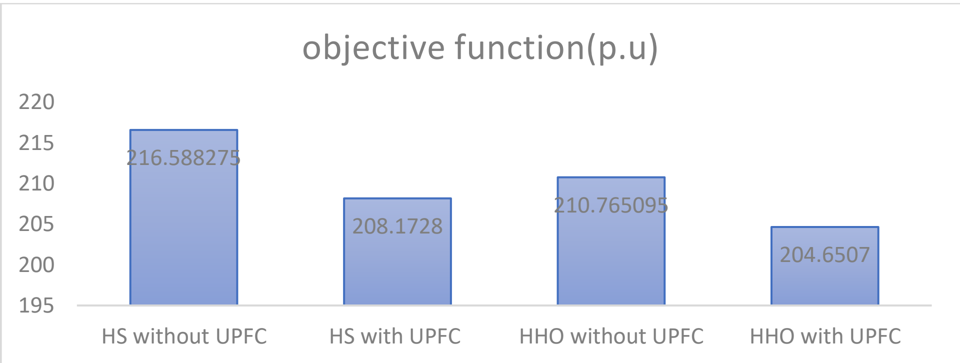

Figure.3: Objective Function (F) Comparison for HS and HHO Algorithms with and Without UPFC

Table 11 shows the improvement in bus voltage magnitudes in the IEEE 30-bus system using the Harmony Search (HS) based Optimal Power Flow (OPF) method, both without and with the inclusion of a Unified Power Flow Controller (UPFC). It is evident that with UPFC, the voltage profile significantly improves across most buses. Notably, bus 30, the weakest bus identified in earlier analysis, experiences a substantial voltage rise from 0.90055 p.u. to 1.0 p.u. with the deployment of UPFC. Similarly, other critical buses like 26, 24, and 18 show remarkable voltage enhancement, demonstrating the UPFC's effectiveness in enhancing system voltage stability and supporting weak buses.

Table.11: Bus voltage magnitudes in state in Harmony Search algorithm based OPF without & with UPFC

Bus No	Pre-Contingency Voltage (p.u.)		Bus No	Pre-Contingency Voltage (p.u.)	
	HS-based OPF without UPFC	HS-based OPF with UPFC		HS-based OPF without UPFC	HS-based OPF with UPFC
1	1.06	1.06	16	0.93834	1.039
2	1.02812	1.033	17	0.93935	1.052
3	1.00123	1.031	18	0.92247	0.959
4	0.98731	1.024	19	0.9218	0.992
5	0.95289	1.01	20	0.92758	0.955
6	0.97485	1.017	21	0.92863	0.949
7	0.95112	1.004	22	0.93617	1
8	0.96394	1.01	23	0.92741	0.995
9	0.98105	1.087	24	0.91964	0.972
10	0.94802	1.092	25	0.92319	0.941
11	1.05587	1.082	26	0.90326	0.976
12	0.94418	1.098	27	0.93521	1.074
13	0.94409	1.071	28	0.96742	1.044
14	0.93095	1.013	29	0.91321	0.998
15	0.92958	1.008	30	0.90055	1

Table.12: Bus voltage magnitudes in pre & post contingency state in HHO algorithm based OPF without & with UPFC

Bus No	Pre-Contingency Voltage (p.u.)		Bus No	Pre-Contingency Voltage (p.u.)	
	HHO-based OPF without UPFC	HHO -based OPF with UPFC		HHO-based OPF without UPFC	HHO -based OPF with UPFC
1	1.06	1.06	16	0.93541	1.0144
2	1.02431	1.043	17	0.93657	1.0032
3	0.99792	1.035	18	0.92103	0.995
4	0.98156	1.0279	19	0.92027	0.9907
5	0.95289	1.01	20	0.92617	0.9938
6	0.97418	1.0198	21	0.92734	0.9928
7	0.95053	1.0023	22	0.93447	0.9973
8	0.96261	1.01	23	0.92602	0.9931
9	0.97842	1.0278	24	0.91864	0.9845

10	0.94633	1.0064	25	0.92212	0.9902
11	1.05321	1.082	26	0.90376	0.972
12	0.94384	1.0336	27	0.93421	1.0031
13	0.94409	1.071	28	0.96637	1.0153
14	0.92983	1.0164	29	0.91282	0.9962
15	0.92644	1.0089	30	0.90075	1

Table 12 illustrates the improvement in bus voltage magnitudes using the Harris Hawks Optimization (HHO)-based OPF with and without UPFC under pre- and post-contingency states. The inclusion of UPFC significantly enhances voltage levels across all buses, especially at weaker buses such as 26, 30, and 24, where voltage magnitudes rise from critically low values (e.g., 0.90075 p.u. at bus 30) to stable levels (1.0 p.u.). This indicates the effectiveness of UPFC in improving voltage stability and maintaining system reliability under stressed operating conditions.

5.2. OPF for 27-28 (Line outage) Contingency Condition

Table.13: HI-Based Contingency Severity Ranking using HS based OP for the IEEE 30-bus system.

Line No	From Bus to Bus	Lj Value	Bus No (Lj max)	Line No	From Bus to Bus	Lj Value	Bus No (Lj max)
36	27 to 28	0.438	30	28	10 to 22	0.095	26
14	9 to 10	0.182	19	31	22 to 24	0.095	26
38	27 to 30	0.168	30	3	2 to 4	0.087	30
5	2 to 5	0.111	30	18	12 to 15	0.087	30
15	4 to 12	0.151	15	12	6 to 10	0.086	30
37	27 to 29	0.154	29	32	23 to 24	0.085	30
2	1 to 3	0.106	30	29	21 to 23	0.084	30
4	3 to 4	0.108	30	8	5 to 7	0.083	30
27	10 to 21	0.131	21	17	12 to 14	0.083	30
35	25 to 27	0.129	26	19	12 to 16	0.083	30
41	6 to 28	0.122	30	22	15 to 18	0.082	30
25	10 to 20	0.127	20	30	15 to 23	0.082	30
6	2 to 6	0.098	30	23	18 to 19	0.082	30
7	4 to 6	0.099	30	20	14 to 15	0.082	30
39	29 to 30	0.106	30	40	8 to 28	0.082	30
24	19 to 20	0.109	19	21	16 to 17	0.082	30
10	6 to 8	0.121	30	11	6 to 9	0.078	30
26	10 to 17	0.108	17	33	24 to 25	0.075	30

Table 13 presents the HI based contingency severity ranking using the Harmony Search (HS)-based Optimal Power Flow (OPF) method for the IEEE 30-bus system. The Lj values indicate the severity of contingencies, with higher values suggesting more critical lines. Line 36 (from bus 27 to bus 28) has the highest Lj value of 0.438, signaling it as the most severe contingency in the system. Other lines such as 9 to 10 (Line 14) and 27 to 30 (Line 38) also rank high in severity with Lj values of 0.182 and 0.168, respectively. Bus 30 is the bus with the highest Lj max value in many of the critical lines, indicating its significant role in the network's vulnerability to disturbances. The ranking helps prioritize lines and buses that are most susceptible to power flow disruptions and would benefit from further monitoring or control strategies to improve system stability and resilience.

Table.14: HI-Based Contingency Severity Ranking using HHO based OP for the IEEE 30-bus system.

Line No	From Bus to Bus	Lj Value	Bus No (Lj max)	Line No	From Bus to Bus	Lj Value	Bus No (Lj max)
36	27 to 28	0.432	30	28	10 to 22	0.099	26
14	9 to 10	0.182	19	31	22 to 24	0.098	26
38	27 to 30	0.174	30	3	2 to 4	0.089	30
5	2 to 5	0.117	30	18	12 to 15	0.088	30
15	4 to 12	0.153	15	12	6 to 10	0.087	30
37	27 to 29	0.156	29	32	23 to 24	0.087	30
2	1 to 3	0.111	30	29	21 to 23	0.086	30
4	3 to 4	0.108	30	8	5 to 7	0.084	30
27	10 to 21	0.137	21	17	12 to 14	0.083	30
35	25 to 27	0.133	26	19	12 to 16	0.083	30
41	6 to 28	0.125	30	22	15 to 18	0.083	30
25	10 to 20	0.128	20	30	15 to 23	0.082	30
6	2 to 6	0.099	30	23	18 to 19	0.08	30
7	4 to 6	0.098	30	20	14 to 15	0.08	30
39	29 to 30	0.11	30	40	8 to 28	0.08	30
24	19 to 20	0.111	19	21	16 to 17	0.08	30
10	6 to 8	0.121	30	11	6 to 9	0.07	30
26	10 to 17	0.112	17	33	24 to 25	0.07	30

Table 15 Severe Line (30 bus connected lines)

Rank	**Line connected**		**LUF Value**
	FB	**TB**	
1	27	30	0.0389
2	29	30	0.0291

Table 14 shows the severity of different line disruptions in the IEEE 30-bus system using the HHO-based Optimal Power Flow (OPF) method. The Lj values represent how serious each disruption is, with higher values meaning more severe disruptions. The most severe disruption happens in Line 36 (between bus 27 and bus 28), with an Lj value of 0.432. Other important disruptions are in Line 14 (bus 9 to bus 10) and Line 38 (bus 27 to bus 30), with Lj values of 0.182 and 0.174, respectively. Bus 30 is often linked to the most severe disruptions.

Table 15 ranks the most vulnerable lines based on their LUF value. The line between buses 27 and 30 is the most vulnerable (Rank 1), with a LUF value of 0.0389, followed by the line between buses 29 and 30 (Rank 2), with a LUF value of 0.0291. These rankings help identify which lines need closer attention to improve the system's stability.

Table.16: Generation Optimization during Line Outage (Bus 27–28) with UPFC Support

Method	PG1 (MW)	PG2 (MW)	PG5 (MW)	PG8 (MW)	PG11 (MW)	PG13 (MW)	Total Generation (MW)
HS without UPFC	138.7838	33.6619	30.2649	44.0519	45.5029	10	302.2654

HS with UPFC	135.7838	31.6619	30.1649	44.1519	46.5029	10	298.2654
HHO without UPFC	134.0653	15.4302	24.8722	32.0955	78.7936	10	295.2568
HHO with UPFC	131.1653	16.2302	24.1722	32.0955	79.7936	10	293.4568

Table 16 presents the optimization of power generation during a line outage between buses 27 and 28, comparing the results with and without the use of UPFC (Unified Power Flow Controller) for different methods. For the HS method without UPFC, the total generation is 302.27 MW, with the highest generation at PG1 (138.78 MW). When UPFC is used, the total generation decreases slightly to 298.27 MW, with a small drop in PG1 (135.78 MW). For the HHO method without UPFC, the total generation is reduced to 295.26 MW, with notable drops in PG1 (134.07 MW) and PG2 (15.43 MW). Finally, when UPFC is applied in the HHO method, the total generation further decreases to 293.46 MW, with the most significant reductions in PG1 and PG2. Overall, the results show that while UPFC helps manage the power flow, it slightly reduces the total generation, with the HHO method experiencing the greatest decrease in power generation during the outage.

Table.17: Total Power Generation and Losses

Parameter	HS without UPFC	HS with UPFC	HHO without UPFC	HHO with UPFC
Total Real Power (MW)	302.2654	298.2654	295.2568	293.4568
Real Power Loss (MW)	18.8654	14.8654	11.8568	10.0568
Reactive Power Loss (MVAR)	35.7	20.37	19.27	12.64
Voltage Deviation (p.u.)	4.782	1.631	2.8947	1.7821
Fuel Cost ($/hr)	1375.7	1367.2	1383.2	1352.7

Table 17 compares the total power generation, losses, and other performance metrics for two optimization methods (HS and HHO) with and without UPFC support. The highest total generation is achieved with HS without UPFC (302.27 MW), which decreases slightly with UPFC (298.27 MW). Similarly, HHO generates less power, with 295.26 MW without UPFC and 293.46 MW with UPFC. Real power losses are higher without UPFC, with HS losing 18.87 MW and HHO losing 11.86 MW, both decreasing when UPFC is used. Reactive power losses also decrease with UPFC, from 35.7 MVAR to 20.37 MVAR for HS and from 19.27 MVAR to 12.64 MVAR for HHO. Voltage deviation improves with UPFC, reducing from 4.78 p.u. to 1.63 p.u. for HS and from 2.89 p.u. to 1.78 p.u. for HHO. Fuel costs are slightly lower with UPFC, with HS costing $1367.2 per hour and HHO costing $1352.7 per hour, compared to higher costs without UPFC. Overall, the use of UPFC enhances system performance by reducing losses, voltage deviations, and fuel costs.

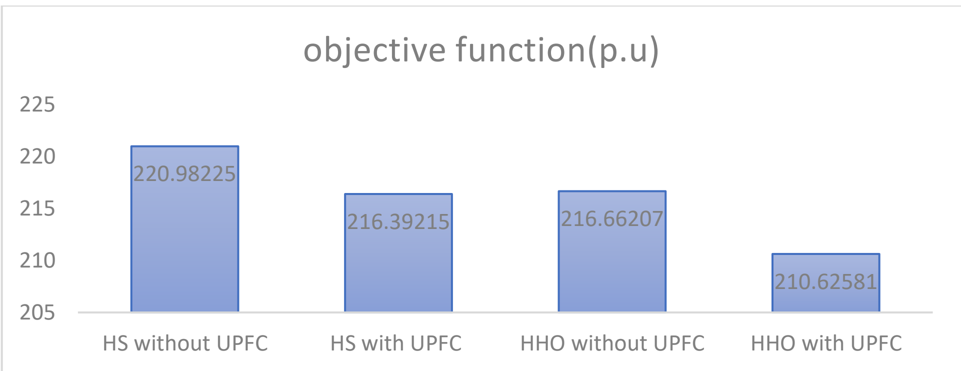

Figure.4: Objective Function (F) Comparison for HS and HHO Algorithms with and Without UPFC

Figure.4 data shows the objective function values for the HS and HHO methods with and without UPFC support. For HS, the objective function is 220.9823 without UPFC and improves to 216.3922 with UPFC. Similarly, for HHO, the objective function is 216.6621 without UPFC and reduces to 210.6258 with UPFC. This indicates that both HS and HHO methods perform better in terms of the objective function when UPFC is used, demonstrating the effectiveness of UPFC in improving the system's overall performance.

The results in Table 18 show a clear improvement in voltage stability when UPFC is used in the Harmony Search-based OPF optimization, both pre- and post-contingency. For example, the pre-contingency voltage at Bus 16 improves from 0.93834 p.u. without UPFC to 1.0139 p.u. with UPFC, and the post-contingency voltage improves from 0.8842 p.u. to 1.0142 p.u. Similarly, at Bus 18, the pre-contingency voltage increases from 0.92247 p.u. without UPFC to 0.9959 p.u. with UPFC, and the post-contingency voltage improves from 0.8633 p.u. to 0.9955 p.u. These trends are observed across the majority of buses, indicating that UPFC helps to mitigate voltage drops and improves the overall voltage profile, especially during post-contingency scenarios. For example, at Bus 29, the voltage improves from 0.91321 p.u. to 0.9988 p.u. pre-contingency, and from 0.6691 p.u. to 0.9781 p.u. post-contingency. This demonstrates that UPFC enhances the stability of the power system, particularly under contingency conditions, ensuring better resilience and reducing the risk of voltage collapse.

Table.18: Bus voltage magnitudes in pre & post contingency state in Harmony Search algorithm based OPF without & with UPFC

Bus No	Pre-Contingency Voltage (p.u.)		Post-Contingency Voltage (p.u.)		Bus No	Pre-Contingency Voltage (p.u.)		Post-Contingency Voltage (p.u.)	
	HS based OPF without UPFC	HS based OPF with UPFC	HS based OPF without UPFC	HS based OPF with UPFC		HS based OPF without UPFC	HS based OPF with UPFC	HS based OPF without UPFC	HS based OPF with UPFC
1	1.06	1.06	1.06	1.06	16	0.93834	1.0139	0.8842	1.0142
2	1.02812	1.043	1.0065	1.043	17	0.93935	1.0052	0.8794	1.0051
3	1.00123	1.0312	0.9751	1.0308	18	0.92247	0.9959	0.8633	0.9955
4	0.98731	1.0243	0.9558	1.0238	19	0.9218	0.992	0.8611	0.9916
5	0.95289	1.01	0.9169	1.01	20	0.92758	0.9955	0.8673	0.9952
6	0.97485	1.0174	0.9401	1.0174	21	0.92863	0.9949	0.861	0.9929
7	0.95112	1.0004	0.9155	1.0004	22	0.93617	1	0.8565	0.9957
8	0.96394	1.01	0.9284	1.01	23	0.92741	0.995	0.8574	0.9924
9	0.98105	1.0287	0.9321	1.0284	24	0.91964	0.9872	0.8141	0.9759
10	0.94802	1.0092	0.8872	1.009	25	0.92319	0.9941	0.7342	0.9634
11	1.05587	1.082	1.0139	1.082	26	0.90326	0.976	0.7091	0.9447
12	0.94418	1.0298	0.8991	1.0306	27	0.93521	1.0074	0.6997	0.9692
13	0.94409	1.071	0.8992	1.071	28	0.96742	1.0144	0.9402	1.0177
14	0.93095	1.013	0.8807	1.0136	29	0.91321	0.9988	0.6691	0.9781
15	0.92958	1.008	0.8736	1.0075	30	0.90055	1	0.6509	1

Table.19: Bus voltage magnitudes in pre & post contingency state in HHO algorithm based OPF without & with UPFC

Bus No	Pre-Contingency Voltage (p.u.)		Post-Contingency Voltage (p.u.)		Bus No	Pre-Contingency Voltage (p.u.)		Post-Contingency Voltage (p.u.)	
	HHO-based OPF	HHO - based OPF	HHO - based OPF	HHO - based OPF		HHO-based OPF without UPFC	HHO - based OPF	HHO - based OPF	HHO - based OPF

	without UPFC	with UPFC	without UPFC	with UPFC			with UPFC	without UPFC	with UPFC
1	1.06	1.06	1.06	1.06	16	0.93541	1.0136	0.8886	1.014
2	1.02431	1.043	1.0089	1.043	17	0.93657	1.0055	0.883	1.0056
3	0.99792	1.0323	0.9792	1.0322	18	0.92103	0.9957	0.8682	0.9956
4	0.98156	1.0257	0.9604	1.0255	19	0.92027	0.992	0.8653	0.9919
5	0.95289	1.01	0.9206	1.01	20	0.92617	0.9956	0.8705	0.9956
6	0.97418	1.0183	0.9443	1.0187	21	0.92734	0.995	0.8651	0.9934
7	0.95053	1.001	0.919	1.0012	22	0.93447	1.0001	0.86	0.9963
8	0.96261	1.01	0.9321	1.01	23	0.92602	0.995	0.8612	0.9928
9	0.97842	1.0269	0.9352	1.0267	24	0.91864	0.9865	0.8176	0.9765
10	0.94633	1.0097	0.8912	1.0097	25	0.92212	0.9916	0.738	0.9642
11	1.05321	1.082	1.0176	1.082	26	0.90376	0.9734	0.7132	0.9455
12	0.94384	1.0287	0.9025	1.0295	27	0.93421	1.0039	0.7036	0.9701
13	0.94409	1.071	0.902	1.071	28	0.96637	1.0149	0.943	1.0187
14	0.92983	1.0117	0.8849	1.0124	29	0.91282	0.9966	0.6729	0.9785
15	0.92644	1.0075	0.8782	1.0072	30	0.90055	1	0.6552	1

The results from Table 19 show the voltage magnitudes at various buses in both pre- and post-contingency states for the HHO-based OPF optimization, with and without UPFC. In the pre-contingency state, the voltage at most buses remains stable with the HHO algorithm, with minimal differences when UPFC is included. For instance, Bus 16 has a pre-contingency voltage of 0.93541 p.u. without UPFC, which improves to 1.0136 p.u. with UPFC. Similarly, Bus 18's voltage improves from 0.92103 p.u. without UPFC to 0.9957 p.u. with UPFC. The post-contingency voltage also improves with UPFC at most buses, such as at Bus 17, where the voltage improves from 0.883 p.u. without UPFC to 1.0056 p.u. with UPFC. The same trend is visible in Bus 19, where the post-contingency voltage improves from 0.8653 p.u. without UPFC to 0.9919 p.u. with UPFC. These results suggest that the addition of UPFC enhances voltage stability, particularly during post-contingency conditions, ensuring better voltage profiles and contributing to the overall robustness of the power system.

6. CONCLUSION

Applied to Optimal Power Flow (OPF) problems, both the Harmony Search (HS) and Harris Hawks Optimization (HHO) algorithms show advantages in voltage stability and general system performance during contingency scenarios. This is the situation independent of the positive or negative contingency scenario. The results show that the voltage profiles are much improved when UPFC is included into both optimization strategies. Most buses, in both pre- and post-contingency situations, show this improvement. Conversely, especially in post-contingency stages, the HHO-based OPF outperforms the HS-based OPF in terms of voltage stability, hence generating more steady voltage levels. This is the situation when contrasting the two optimizing approaches. Furthermore, the HHO technique provides a more effective optimization process, which finally results in higher system robustness and better voltage control. Consequently, HHO is found to be more efficient in optimizing power flow and guaranteeing voltage stability even if both methods improve the dependability of the system. Consequently, for this specific use it is a better choice than Harmony Search.

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