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A novel meta-heuristic approach for optimal RPP using series compensated FACTS controller

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ABSTRACT

One of the most important aspects of power system planning is reactive power (VAR- Volt Ampere- Reactive) optimization and voltage control, which has an influence on both economics and stability of the transmission systems. It is perhaps one of the most difficult optimization problem to solve since it is nonlinear and includes both consistent and sporadic choice parameters. The goal is to primarily calculate the cost components, such as operating cost due to energy loss, series compensation (Thyristor-Controlled series Capacitor-TCSC) device operating costs, and actual power loss cost. In the proposed work, to enhance system voltage profile, TCSC is deployed at weak points across several echelon after computing mathematical models for standard benchmark functions. The paper goes into great depth with application of Oppositional based learning on Harris Hawks Optimizer (OHHO). This meta heuristic optimization approach, has been used to solve the VAR optimization issue. Finally, the benchmark functions outputs are thoroughly examined for two test systems like Ward Hale 6 bus system and modified IEEE- 30 bus test system to demonstrate the validity of the proposed hybrid intelligent approach for series compensated FACTS controller.

1. Introduction

Electrical power networks face several issues because of their complicated design and functioning. Reactive power planning (RPP), a specialized and substantially restricted large-scale non-linear optimization issue, has evolved as one of the key difficulties and extensively researched areas in modern power system management and planning. The purpose of RPP is to discover the best configuration for a power system considering certain equality and inequality criteria to minimize active power loss, operational cost, and enhanced voltage profile. Beside technical concerns, economic benefit is also a significant factor. As a result, assessing reactive and active power has become increasingly important in order to create fair electricity markets.

The researchers in Dash et al. (2020) postulated an innovative operation for achieving an optimal balance between power accessibility and cost procured by modeling hybridized form of optimization techniques, with implementation of FACTS controllers to improve the loadability in standard bus test system. The authors provide a novel reactive power loss index based on a fuzzy logic technique in Moger and Dhadbanjan (2015) for detecting weak buses. In Bhattacharyya and Kumar (2016) the author proposes a gravitational search algorithm (GSA)-based augmentation technique for the optimal coordination of cross-functional FACTS devices with existing reactive power sources in an electrical network. In Karmakar and Bhattacharyya (2020a,2020b), RPP in transmission lines is discussed by authors. The work in Devarapalli et al. (2021) describes an improved GWO approach for improving power system sustainability. As a result, the traditional goal of the RPP issue is to achieve the lowest initial investment for supplementary supply sources while also lowering the total system running cost. The writers of (Bharti & De, 2018) have attributed their work in 3 main ways: first, by using graph theory to calculate electrical centrality measures; second, by using this indexing method to identify locations for

Abbreviations: OHHO, oppositional Harris hawks' optimization; VAR, volt ampere- reactive; TCSC, thyristor-controlled series capacitor; OBL, oppositional based learning; HHO, Harris Hawks' optimization; ORPD, optimal reactive power dispatch; RPP, reactive power planning; GSA, gravitational search algorithm; FACTS, flexible AC transmission system; GWO, grey wolf optimization; PSO, particle swarm optimization; BBO, Bio-geography based optimization; DE, differential evolution; VCPI, voltage collapse proximity indicator.

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reactive power compensation; and third, by maintaining the voltage profile throughout the system for multiple test systems. A thorough analysis of recent research on reactive power management in power networks with substantial REG deployment was published in Sarkar et al. (2018). The authors in Shekarappa et al. (2021) have used the VCPI method for the investigating the weak nodes for the RPP solution.

The above extensive literature survey as provided in Table 1, clearly depicts that HHO algorithm has been successfully implemented in various application domain. This motivated the authors to seek its application in a complex power system optimization problem of RPP. To further deliver promising results, the authors have merged OBL technique with HHO as a proposed method in the current research work.

RPP has been described in a variety of ways, according to a comprehensive literature review. The paper demonstrates the following highlights:

- Optimal allocation of the VAR sources.
- Reduction of real power loss and operating cost.
- Detection of the weak node bus.
- Placement of the series compensation type of the FACTS device.
- Minimizing the deviation of the load voltage by enhancing the stability of the voltage profile at each bus system.

As evident from literature not much work is reported with respect to HHO technique blended with OBL for obtaining RPP solution. Authors recommended a deployment plan for FACTS devices in the Indian power industry, based on a literature review, in order to help the country's economy. The following are the implications of the suggested method:

- This work is validated on standard Benchmark functions. In this regard the authors have compared their work with various optimization techniques to accomplish the objective.
- The proposed execution of OHHO metaheuristic algorithm, particularly emphasizes on the best reactive power planning solution, in the case study.
- By integrating optimum or suitable placement of FACTS devices in the power system network, the major purpose of this proposed study is to decrease active power loss and total operating expenses of the network.
- Further the improvement in the voltage profile is also implemented by proposed approach.

The paper is organized and presented as follows: Section 1 describes the literature review and the motivation which is also incorporated with the contribution work. Section 2 depicts the HHO and OHHO implemented for enhanced optimization which is also tested on standard benchmark functions. Further, in Section 3 the mathematical problem formulation for the proposed OHHO is stated. Section 4 gives the statistical studies followed by conclusion and future scope.

Table 1
Various application domain using HHO technique.

Technique	Application Domain	Refs. No
Artificial Neural Network	Stability of the soil slopes	Moayedi et al. (2021)
HHO	Microgrid design optimized	Çetinbaş et al. (2021)
HHO	Design of microchannel heat sinks	Ahmad Abbasi et al. (2021)
Gaussian HHO	Design optimization of tapered roller bearing	Ahmad Abbasi et al. (2021)
Multi-objective Non-sorted HHO	Global optimization	Jangir et al. (2021)
HHO based on Bitwise operations and Simulated Annealing	Feature selection	Abdel-Basset et al. (2021)
Ameliorated HHO	Reactive power planning	Swetha Shekarappa et al. (2021)

2. Proposed OHHO approach for the current work

The following section discuss about HHO followed by proposed OHHO technique.

2.1. Harris Hawk's optimization

The HHO is a revolutionary population-based, nature-inspired optimization methodology introduced in this study proposed by Heidari et al. (2019). The collaborative behavior and pursuit manner of Harris' hawks in essence, known as shock dive, is the fundamental influence for HHO technique. Multiple hawks work together to attack on bunny from numerous angles in an endeavor to catch it off guard. Relying on the variable complexity of events and the predator's escape behaviors, Harris hawks can display diverse pursuit strategies. To design an optimization method, this work statistically duplicates such dynamic patterns and behaviors. When evaluated to well-established metaheuristic approaches, the HHO algorithm produces highly intriguing and infrequently competing performance. The optimizer of Harris Hawks can be mathematically described, in two stages, namely exploratory and exploitative.

Exploratory Phase: They check dependent on the placements of other family individuals and the bunny, which is described in Eqs. (1) and (2) if we adopt a fair probability for every roosting technique.

$$S(t+1) = (S_c(t) - S_a(t)) - r_3(lb + r_4(ub - lb)) \tag{1}$$

$$S(t+1) = S_{random}(t) - r_1|S_{random}(t) - 2r_2S(t)| \tag{2}$$

Where in the S_t is the present position of the bunny, $S(t+1)$ is the vector setting of the eagle for the further iteration, $S_{random}(t)$is the random position selected by the eagle from the present position, r is the random numbers and $S_a(t)$ is the average position of the eagle. The random number used to maximize and convert the discovery in the search field is r_1, r_2, r_3 and r_4 which is the lower boundary limit and upper boundary limit of the inspection range. Which is illustrated as below:

$$S_a(t) = \frac{1}{V}\sum S_i(t)$$

Where $S_i(t)$ is the location of the eagle.

Further, the metamorphosis from the exploratory phase to exploitative phase is very essential and the act of the bunny is based on the delinquent strength in this process. Thus, this energy is illustrated as below Eq. (3), Where, E_a is the original stamina level of chase, and 't' is the maximum number of iterations in the interval from -1 and1, T is the latest iteration:

$$E_{energy} = 2E_a\left(1 - \frac{t}{T}\right) \tag{3}$$

Exploitative Phase: The Harris' hawks make a sneak leap in this period by striking the targeted bunny that was spotted in the prior stage. In order to represent the hunting phase, the HHO proposes four alternative techniques based on prey escape behaviors and Harris' hawk pursuit tactics. Here the energy of the bunny plays a major role and equations are also categorized based on the same as mentioned below:

(a) *Soft Besiege:* When $r > 0.5$, $|E_{energy}| \geq 0.5$, where the bunny has ample energy/strength to escape from the eagle. The behavior of eagle is illustrated as below equation:

$$S(t+1) = \Delta S(t) - E_{energy}[jS_c(t) - S(t)] \tag{4}$$

$$\Delta S(t) = S_c(t) - S(t) \tag{5}$$

Where $J = 2(1 - r_5)$, and it is the misleading jump strength during rescue process of bunny.

(b) *Hard Besiege:* When $r \geq 0.5$, $|E_{energy}| < 0.5$, where the bunny is impoverished and has reduced rescue energy.

$$S(t+1) = S_c(t) - E_{energy}[\Delta S(t)] \quad (6)$$

(b) *Soft Besiege with Progressive Rapid Dives:* When $r < 0.5$, $|E_{energy}| \geq 0.5$, where the bunny still addresses to have the rescue strength. Depending on the move of the eagle the equation is illustrated as:

$$Y = S_c(t) - E_{energy}[JS_c(t) - S(t)] \quad (7)$$

$$A = Y + S \times LF(D) \quad (8)$$

Where LF is the levy flight function.

$$X(t+1) = \begin{cases} Y \ if \ F(Y) \langle F(X(t)) \\ A \ if \ F(A) \langle F(X(t)) \end{cases} \quad (9)$$

(c) *Hard Besiege with Progressive Rapid Dives:* When $r < 0.5$, $|E_{energy}| < 0.5$, where the bunny drains the entire energy to escape and the eagle dive surprisingly and reduce the space between them and finally end up in killing the bunny. Which is illustrated as below:

$$Y = S_c(t) - E_{energy}[JS(t) - S_a(t)] \quad (10)$$

2.2. Oppositional based learning (OBL)

The notion of OBL has widely applied to improve the convergence speed of numerous meta-heuristic optimization techniques (Feng et al., 2021; Mahapatra et al., 2021). Tizhoosh (2005) presented a novel machine learning approach called oppositional based learning (OBL).The OBL concept is given for the dimensional search space as

$$X_j^o = X_j^{\max} + X_j^{\min} - X_j, \ Where \ x_1, x_2, \ldots\ldots X_d \text{ is the search are dimensionally.} \quad (11)$$

$X_j \in \left| X_j^{\max}, X_j^{\min} \right|; j = (1, 2, 3, \ldots\ldots d)$, where j is the number of Variables.

2.3. Proposed OHHO algorithm on testing benchmark functions

The proposed OHHO algorithm testing is carried out on standard benchmark test functions. The standard benchmark functions are adopted from Li et al. (2020) with formula, dimensions, and the limits for the unimodal functions. These are gauged for each function having only one global optimum and no local optima and portray the caliber of exploitation for various meta-heuristic approach. In continuation the multimodal functions and composite test functions are gauged with ample local optima along with one global optimum and etiquette the proposed meta-heuristic approach exploration caliber.

To perform statistical analysis on the test functions, it utilizes 30 search agents and 100 iterations. Each test function was performed 30 times to provide the statistical findings. The results of the research were produced using the equivalent 30 population-size method. For a valid comparison, all quantitative algorithms were simulated on the same system with the same processor, with equal parameters. Numerous evaluations are made between the original HHO and suggested OHHO algorithms, as well as the established PSO, DE, GSA, and BBO approaches. The statistical analysis for functions for F4, F7, F9, F10, F14, F22 is shown as a representative for each method which provides the superior value, inferior value, mean value, and standard deviation. The sample result for the various algorithm is mentioned in the Table 2.

Fig. 1 emphasizes the functional topology which is performed on the 2D using PSO, DE, GSA, BBO, HHO and proposed OHHO, examines the convergence curve characteristics of all the algorithms and explores the box plot for F4, F7, F9, F10, F14, F22 benchmark functions.

The convergence graphs of the benchmark functions are computed by evaluating the average value of ideal values in each iteration for the 30 different categories, the suggested algorithms' qualitative and quantitative results exhibit the blended behavior of unified algorithms, culminating in increased system effectiveness. It also clearly depicts that the OHHO convergences faster compared to other algorithms which also gives the result satisfactorily. The Fig. 1 shows only the representative results from each benchmark functions group. This clearly portrays the positive attributes of OHHO and its efficacy in various benchmark functions.

3. Optimal Sizing of facts device and mathematical problem formulation

Optimization is a critical responsibility for reactive power. i.e., to reduce the active power loss of all Var sources in the system as much as

Table 2
Statistical Analysis for Benchmark function.

Unimodal Benchmark function					
Function	Algorithm	Superior Value	Inferior Value	Mean Value	Standard Deviation
Schwefel 2.21	PSO	0.7512	4.5652	1.7488	0.7541
	DE	12.5953	46.1619	25.3963	6.7159
	GSA	6.9181	13.7767	9.6630	1.7440
	BBO	2.4183	13.3809	5.6265	2.1863
	HHO	74.3733	94.0689	87.3830	4.9155
	OHHO	0.4242	2.8366	1.3780	0.5928
Quartic	PSO	0.0094	0.0398	0.0213	0.0073
	DE	0.1079	0.5038	0.2607	0.0893
	GSA	0.1222	0.3103	0.2123	0.0437
	BBO	0.0208	0.0813	0.0442	0.0171
	HHO	31.6798	157.4161	113.3116	27.1001
	OHHO	0.0058	0.0410	0.0175	0.0083
Multimodal Benchmark function					
Function	Algorithm	Superior Value	Inferior Value	Mean Value	Standard Deviation
Rastrigin	PSO	48.2526	279.6656	101.2719	70.5696
	DE	132.1248	265.9563	202.2630	38.6729
	GSA	14.8006	97.0091	33.5112	13.7819
	BBO	54.0173	210.8891	111.4074	33.5053
	HHO	320.8084	485.6932	429.3536	35.9676
	OHHO	13.7422	84.1945	35.9322	15.9952
Ackley	PSO	5.4998	7.9169	6.4932	0.5751
	DE	3.3064	20.6703	9.5769	6.3019
	GSA	0.0264	0.1059	0.0522	0.0189
	BBO	0.1779	1.8473	0.7629	0.4324
	HHO	19.6448	20.5344	20.3668	0.2115
	OHHO	0.0128	0.0676	0.0265	0.0122
Fixed dimensional Multimodal Benchmark function					
Function	Algorithm	Superior Value	Inferior Value	Mean Value	Standard Deviation
Foxholes	PSO	0.9980	21.0740	10.6883	5.2301
	DE	0.9980	10.7632	2.1505	1.8734
	GSA	0.9980	17.3744	6.1383	5.0732
	BBO	0.9980	13.6186	4.7853	4.2092
	HHO	0.9981	21.0918	4.1106	4.7785
	OHHO	0.9980	10.7632	2.2444	2.4746
Shekel 10	PSO	-10.1684	-2.3215	-7.4328	2.8548
	DE	-10.2437	-2.5743	-8.7531	1.9714
	GSA	-10.3919	-2.3047	-9.8384	1.9865
	BBO	-10.2916	-2.5644	-8.1699	2.4750
	HHO	-10.2367	-0.8215	-3.3257	2.4478
	OHHO	-10.4010	-2.7509	-6.1325	3.8021

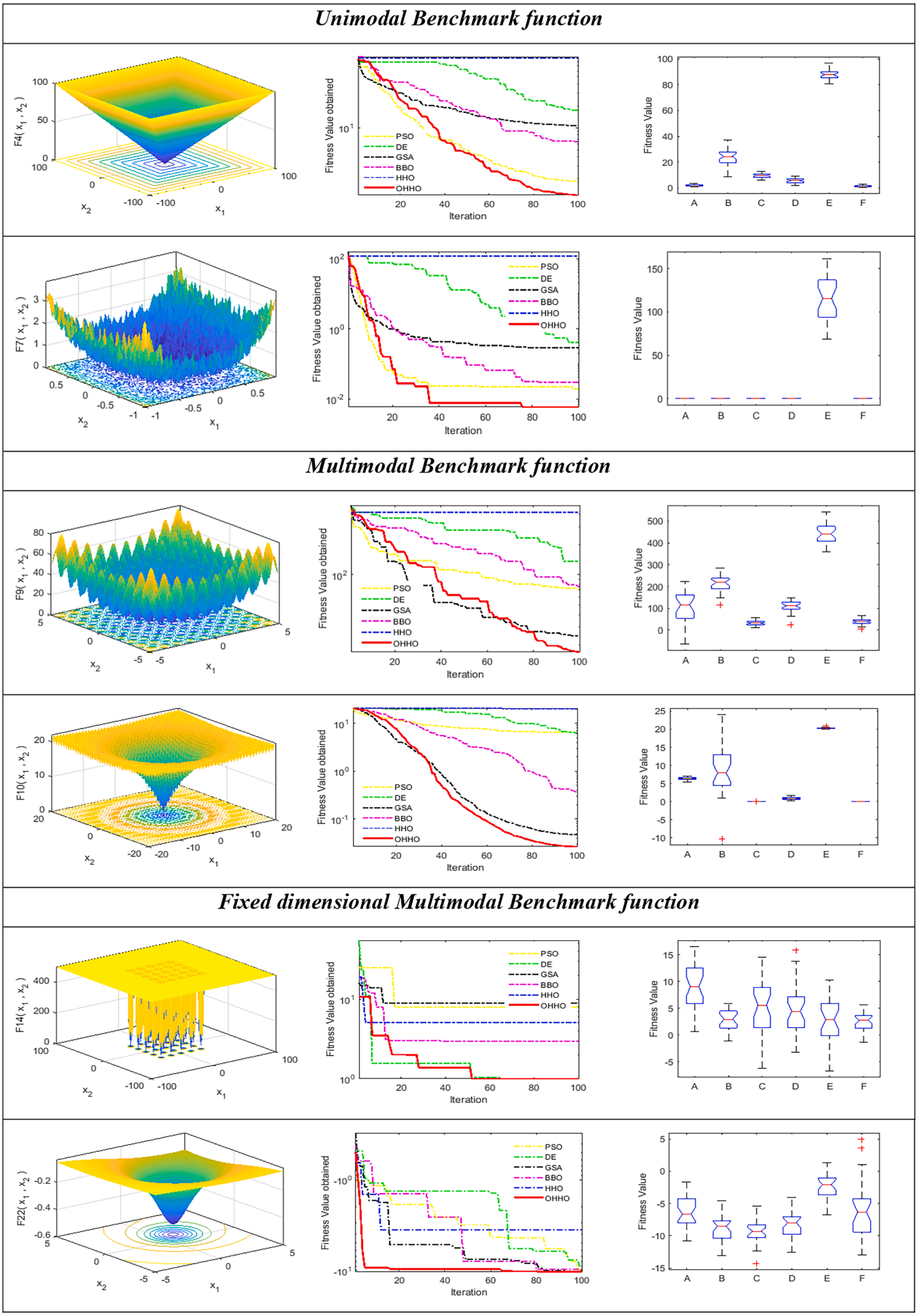

Fig. 1. Representative function topology for each functional group.

possible. In addition, the optimization should take into account the system's running costs and enhance the voltage deviation. Reduced active power loss (P_{loss}) in a transmission line may be expressed as

$$P_{loss} = \sum_{x}^{y} = (a,b)f_k\left[Z_a^2 + Z_b^2 - 2Z_aZ_b\cos(\delta_a - \delta_b)\right] \quad (12)$$

Where f_k represents the kth line, between ath and bth buses.

The main objective is to decrease active power loss and total operational expenses by coordinating TCSC at the optimal transmission network location. By regulating transformer tapping, by regulating shunt capacitors, by regulating generator bus, the main objective functions are minimized by allocation and installation of TCSC and operating cost.

The operating cost due to transmission losses in line is

$$F_{OC} = P_{loss} \times 0.06 \times 100000 \times 8760 \quad (13)$$

The cost of the TCSC is formulated based on (Cai & Erlich, 2003; Cai et al., 2004) as given below:

$$F_{TCSC} = 0.005S^2 - 0.7130S + 153.75 \quad (14)$$

Where F_{TCSC} is the cost due to TCSC device in \$. "S" is the operating range of TCSC in MVAR.

Thus, the minimized operating cost is given as

$$F_{Total} = \sum F_{OC} + \sum F_{TCSC} \quad (15)$$

Equality constraints: The load flow equation for equality constraints is illustrated as follows:

$$A_{GC} - A_{DC} - V_c \sum_{x=1}^{x_b} V_d[G_{cd}\cos(\delta_{cd}) + B_{cd}\sin(\delta_{cd})] = 0, X = 1, 2, 3.....X_b \quad (16)$$

$$B_{GC} - B_{DC} - V_c \sum_{x=1}^{x_b} V_d[G_{cd}\cos(\delta_{cd}) + B_{cd}\sin(\delta_{cd})] = 0, X = 1, 2, 3.....X_b \quad (17)$$

Inequality constraints: The inequality constraints illustrate the below mentioned operational variables:

$$\left.\begin{array}{l} V_{gc}^{\min} \le V_{gc} \le V_{gc}^{\max} \\ Q_{gc}^{\min} \le Q_{gc} \le Q_{gc}^{\max} \\ Tap_c^{\min} \le Tap_c \le Tap_c^{\max} \\ TCSC_c^{\min} \le TCSC_c \le TCSC_c^{\max} \end{array}\right\} \quad (18)$$

FACTS devices are a collection of stationary devices that increase the network's power transmission capability. Transmission loss is reduced, and voltage depiction is enhanced when this method is used. Easily controlled reactance with series recouping capacitors is used to simulate TCSC. By connecting this to the transmission line in series, it regulates the line's impedance and so controls power flow. Fig. 2 shows the complete flowchart of the proposed OHHO work.

4. Result and discussion

The performance and efficiency of proposed OHHO technique in suitably handling multi-constrained, complex, and challenging power system optimization problem is depicted by performing RPP on two test system like: Ward hale 6 bus test system and modified IEEE-30 bus test system. All the simulations are carried out by using MATLAB 2020a, computed on core (Tm) i5-3520 M CPU with 2.9GHz and 8GB RAM. For establishing the superiority of the proposed algorithms for various bus test systems, it is performed for 30 independent trial runs for all the test cases with a comparative study reported in the following section.

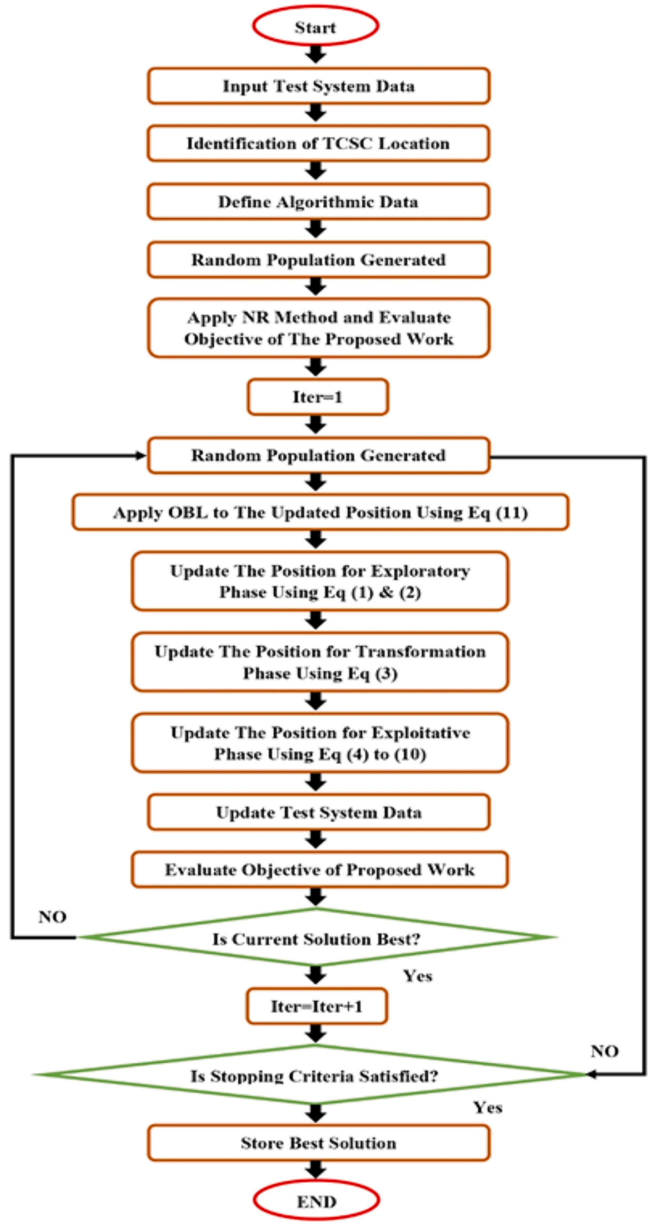

Fig. 2. Flowchart of the proposed OHHO work.

4.1. Case study for ward hale 6 bus test system

Ward hale 6 bus system consists of three generating units at buses 1, 2 and 3 interconnected with seven transmission lines of which two branches (3–5 and 4–6) are equipped with tap changing transformer. This is considered as test system 1. Bus 1 is selected as the slack bus. At first the weak branch is identified by using voltage collapse proximity indicator (VCPI) method. So TCSC has been placed in branch 7 and 9. This location is determined by VCPI method. The total demands of this test system are P_{load}=2.1p.u. and Q_{load}=2.1p.u. at 100MVA base (Wang et al., 2008; Qiu & Shahidehpour, 1987). For the test system considered shunt var sources are placed at the 10th bus and thereafter, PSO, DE, GSA, BBO, HHO, IHHO and OHHO techniques are implemented to minimize transmission loss as well as operating cost. Table 3 presents the optimal setting for system constraints.

The variation of transmission loss at all the buses without TCSC is represented by the convergence curve as given by Fig. 3. Similarly, Fig. 4 provides the convergence curve for total system operating cost without TCSC for different optimization techniques. Fig. 5 depicts the voltage

Table 3
Optimal Sizing of Var sources for Ward hale 6 Bus System.

Control variables (p.u.)	Minimum	Initial (Cai et al., 2004)	PSO	DE	GSA	BBO	HHO	IHHO	Proposed OHHO	Maximum
Tap (3–5)	0.9	1.010	0..9967	0.9923	0.9961	0.9861	0.9941	0.9919	1.0	1.1
Tap (4–6)	0.9	1.01	0.9967	0.9923	0.9961	0.9862	0.9941	0.9919	1.0	1.1
VG (1)	0.95	1.05	1.0486	1.0777	1.0782	1.0822	1.0831	1.0832	1.10	1.1
VG (2)	0.95	1.125	1.0546	1.0746	1.0709	1.0822	1.0831	1.0832	1.10	1.1
VG (3)	0.95	1.07	1.0768	1.0813	1.0805	1.0822	1.0831	1.0832	1.0869	1.1
QC (10)	0.0	0.939	0.0242	0.0160	0.0419	0.0258	0.0297	0.0444	0.0405	0.05
Transmission Loss (MW)		10.250	05.78	05.37	05.36	05.34	05.24	5.20	**05.18**	
Total Operating Cost $\times 10^6$($)		5.3874	3.0380	2.8219	2.8154	2.8086	2.7519	2.7327	**2.7223**	

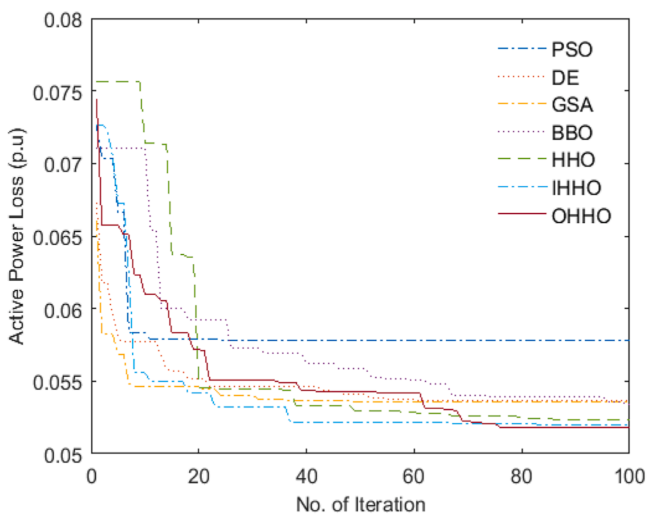

Fig. 3. Convergence Curve for Transmission Loss without series compensation for ward hale 6 bus system.

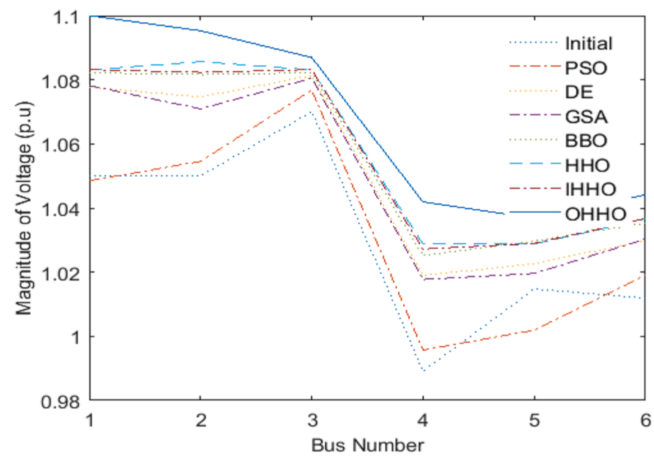

Fig. 5. Magnitude of Voltage in each Bus for ward hale 6 bus system.

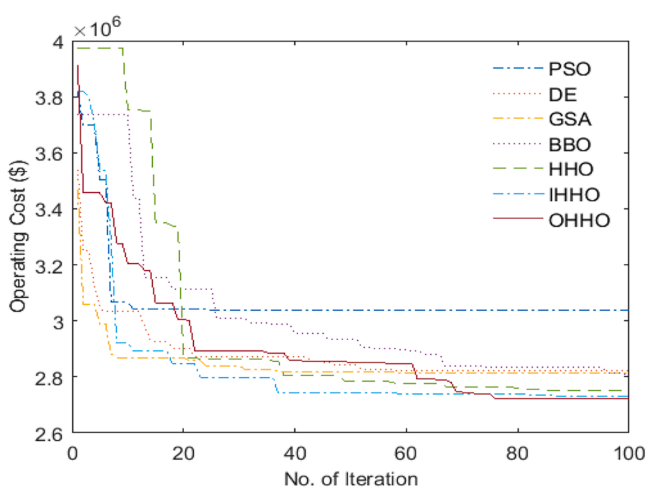

Fig. 4. Convergence Curve for Operating Cost without series compensation for ward hale 6 bus system.

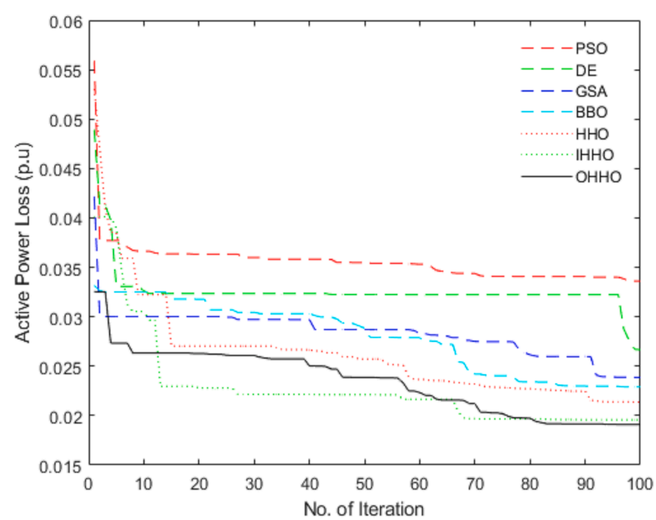

Fig. 6. Convergence Curve for Transmission Loss with series compensation for ward hale 6 bus system.

profile at all the buses without TCSC for base case, with PSO, DE, GSA, BBO, HHO, IHHO and OHHO optimization.

Fig. 6 draws the convergence curve for the OHHO technique proposed by detecting the weak branches by the VCPI method and obtain the transmission loss for the Ward Hale 6 bus system. Also, the Fig. 7 depicts the convergence curve for the operational cost with TCSC device. Fig. 8 portrays the voltage profile in each bus. The result obtained is run for 30 trails and for 100 iterations, which clearly shows that the proposed OHHO algorithm approaches to reduce the active power loss and the overall operating cost upon the detecting the weak branches by VCPI method. Thus, the below mentioned Table 4(a) and (b), demonstrates the comparison for the Optimal performance of the ward hale 6 bus system of the various algorithm without TCSC and with TCSC for transmission loss and operating cost, where in OHHO algorithm depicts considerable reduction thus leading to optimal and secured reactive power dispatch with TCSC. The proposed OHHO technique for uncompensated system obtained with the loss is 5.18MW and it is providing the better result on using series compensated FACTS controller devices of 01.91MW loss. The proposed OHHO technique for uncompensated system obtained with the cost is 2.7223×10^6\$ and on using series compensated FACTS controller cost is 1.0036×10^6\$

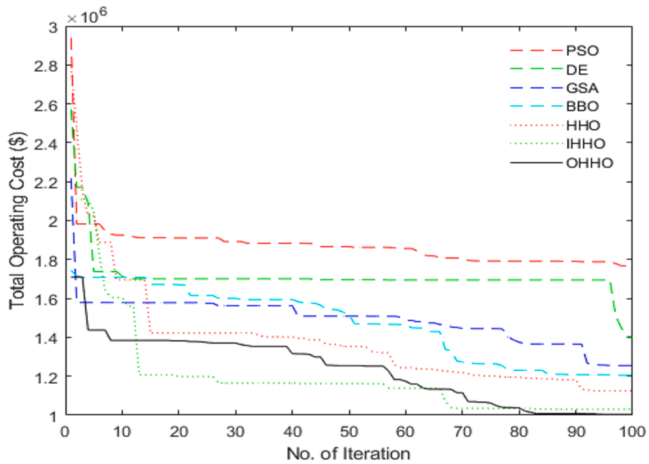

Fig. 7. Convergence Curve for Operating Cost with series compensation for ward hale 6 bus system.

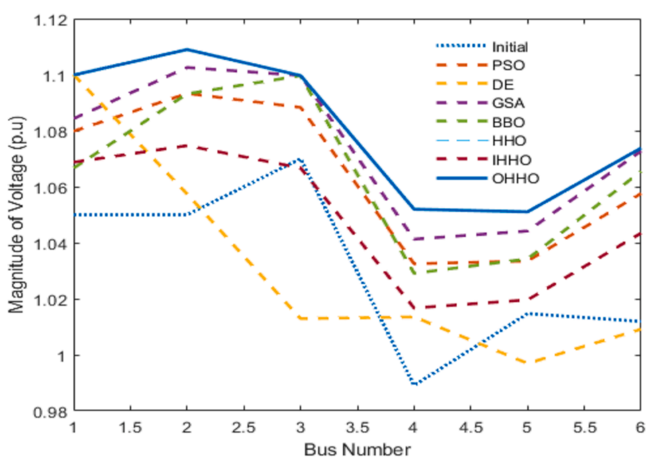

Fig. 8. Magnitude of Voltage in each Bus for ward hale 6 bus system.

Table 4(a)
Comparison of transmission loss for proposed method with and without TCSC with other established algorithms for ward hale 6 bus system.

Initial	Algorithm	Without TCSC (MW)	With TCSC (MW)
10.250MW	PSO	05.78	03.36
	DE	05.37	02.67
	GSA	05.36	02.39
	BBO	05.34	02.29
	HHO	05.24	02.14
	IHHO	05.20	01.96
	Proposed OHHO	05.18	01.91

Table 4(b)
Comparison of operating cost for proposed method with and without TCSC with other established algorithms for ward hale 6 bus system.

Initial Cost	Algorithm	Without TCSC ($\times 10^6$\$)	With TCSC ($\times 10^6$\$)
5.3874×10^6\$	PSO	3.0380	1.7672
	DE	2.8219	1.4026
	GSA	2.8154	1.2553
	BBO	2.8086	1.2045
	HHO	2.7519	1.1244
	IHHO	2.7327	1.0296
	Proposed OHHO	2.7223	1.0036

4.2. *Case study for modified IEEE-30 bus test system*

The modified 30 bus system is considered for the case study in the proposed work. TCSC has been placed in branches 29, 4, 41 and 24. This location is determined by VCPI method. For the test system considered shunt var sources are placed at the 10, 12, 15, 17, 20, 21, 23, 24 and 29th buses and thereafter, PSO, DE, GSA, BBO, IHHO, HHO and OHHO techniques are applied to reduce transmission loss and operating cost. The total real and reactive power demand of this test system are 2.834pu and 1.262 p.u. at 100MVA base respectively. All the load data, line data and initial values of control variables may be found in Duman et al. (2012). The variation of transmission loss at all the buses without TCSC for modified IEEE-30 bus system is represented by the convergence curve as given by Fig. 9. Similarly, Fig. 10 provides the convergence curve for total system operating cost without TCSC for different optimization techniques. Fig. 11 depicts the voltage profile at all the buses without TCSC for base case, with PSO, DE, GSA, BBO, HHO, IHHO and OHHO optimization.

Fig. 12 draws the convergence curve for the OHHO technique proposed by detecting the weak branches by the VCPI method and obtain the transmission loss for the IEEE-30 bus system. Also, the Fig. 13 depicts the convergence curve for the operational cost with TCSC device. Fig. 14 portrays the voltage profile in each bus. The Table 5(a) and (b) demonstrates the comparison for the Optimal performance of the modified IEEE-30 bus system of the various algorithm without TCSC and with TCSC for transmission loss and operating cost, where in OHHO algorithm depicts considerable reduction thus leading to optimal and secured reactive power dispatch with TCSC. Hence, this justifies the robustness of the algorithm in handling large, interconnected power system problem.

5. Conclusion

In this paper the VCPI method for detection of weak branch has been proposed based on the Oppositional based Harris Hawks Optimization (OHHO) for solving the RPP problem on 2 test systems of ward hale 6 bus test system and modified IEEE 30 bus test system. The proposed method is compared with the various other recent optimization techniques. The proposed OHHO method generates promising results for uncompensated system. It is also observed that on placement of TCSC device the proposed OHHO technique provides the minimum active power loss and minimal total operating cost compared to the other techniques The proposed OHHO technique, which is proven to be an

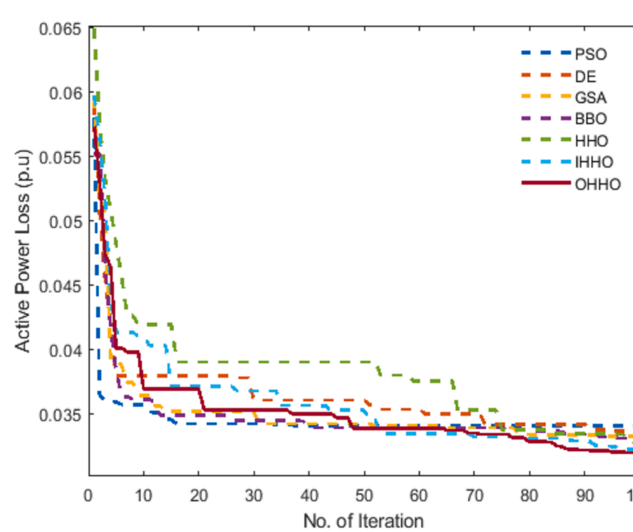

Fig. 9. Convergence Curve for Transmission Loss without series compensation for modified IEEE-30 bus system.

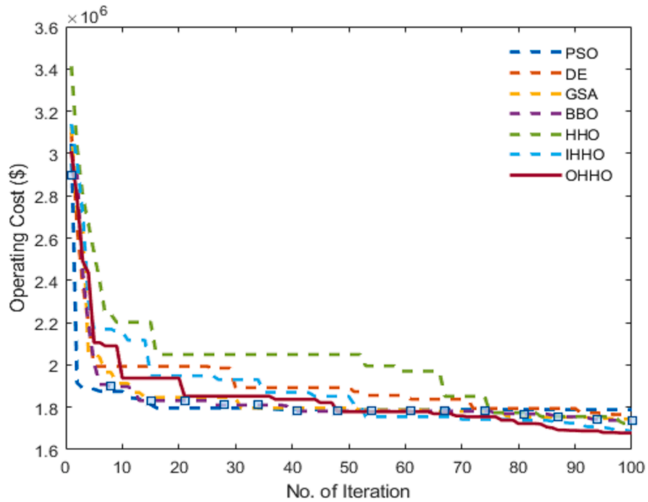

Fig. 10. Convergence Curve for Operating without series compensation for modified IEEE-30 bus system.

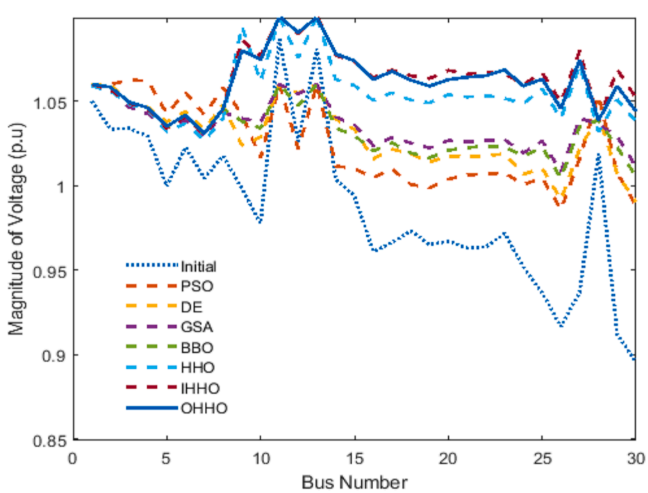

Fig. 11. Magnitude of Voltage in each Bus for modified IEEE-30 bus system.

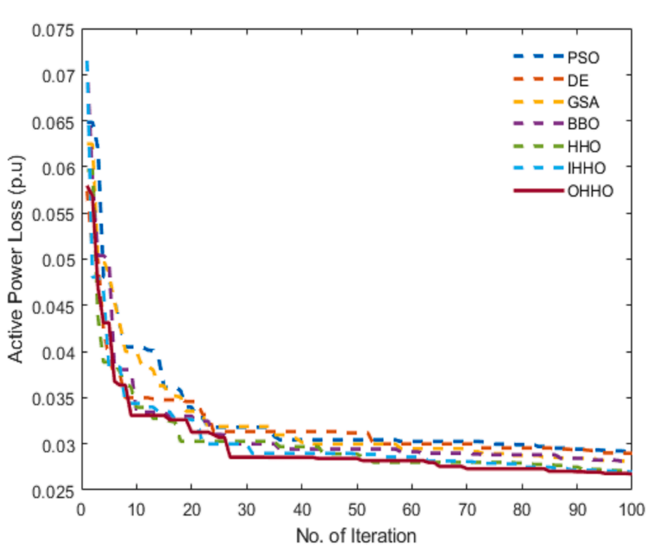

Fig. 12. Convergence Curve for Transmission Loss with series compensation for modified IEEE-30 bus system.

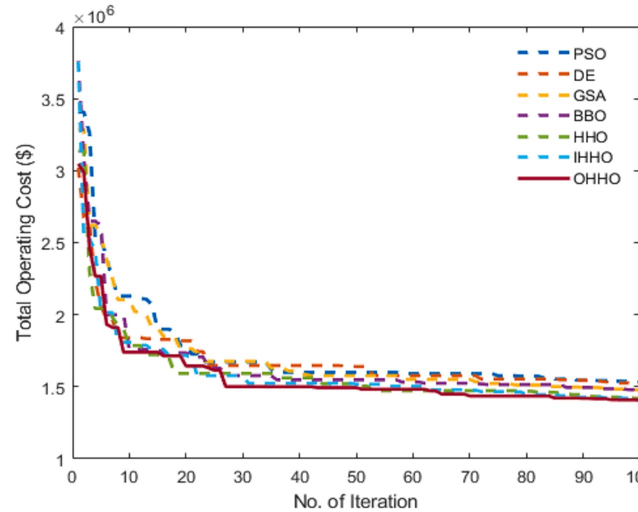

Fig. 13. Convergence Curve for Operating with series compensation for modified IEEE-30 bus system.

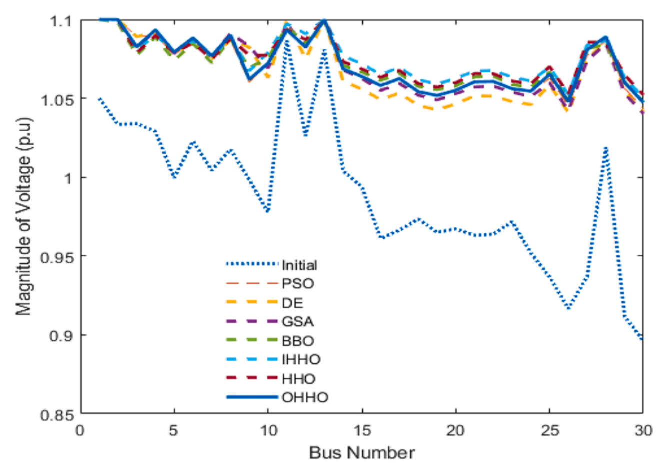

Fig. 14. Magnitude of Voltage in each Bus for modified IEEE-30 bus system.

Table 5(a)
Comparison of transmission loss for proposed method with and without TCSC with other established algorithms for modified IEEE-30 bus system.

Initial (p.u)	Algorithm	Without TCSC (p.u)	With TCSC (p.u)
0.05811	PSO	0.0340	0.0291
	DE	0.0336	0.0290
	GSA	0.0332	0.0281
	BBO	0.0330	0.0280
	HHO	0.0326	0.0270
	IHHO	0.0321	0.0269
	Proposed OHHO	0.0319	0.0267

Table 5(b)
Comparison of operating cost for proposed method with and without TCSC with other established algorithms for modified IEEE-30 bus system.

Initial Cost	Algorithm	Without TCSC ($\times 10^6$\$)	With TCSC ($\times 10^6$\$)
3.0542×10^6\$	PSO	1.7886	1.5327
	DE	1.7660	1.5237
	GSA	1.7430	1.4758
	BBO	1.7360	1.4732
	HHO	1.7156	1.4201
	IHHO	1.6866	1.4168
	Proposed OHHO	1.6782	1.4057

effective and reliable technique in the prevailing VCRPP using the series compensated FACTS controller challenge, can also be used to address more sophisticated reactive power planning challenges in deregulated electricity markets, including concerns with economic load dispatch, load forecasting, power system stability, and other issues related to practical optimization.

CRediT authorship contribution statement

Swetha Shekarappa G: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Validation. **Sheila Mahapatra:** Methodology, Writing – original draft, Writing – review & editing. **Saurav Raj:** Conceptualization, Methodology, Software, Writing – review & editing, Validation.

Declaration of Competing Interest

There is no conflict of interest

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