Advance Blue Whale Optimized Preventive-Security-Constrained Optimal Power Flow Model for IPFC

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Abstract: In modern power systems, the interline power flow controller (IPFC) may realize power flow control for numerous transmission lines, making it one of the most adaptable integrated flexible alternating current transmission systems (FACTS) controllers. Nevertheless, in traditional IPFC models, control features are disregarded, which may result in erroneous assumptions regarding injected voltages and security issues in practical use. Furthermore, IPFC control potential is wasted since optimal power flow (OPF) control of the system with IPFC does not incorporate preventive security limitations taking into account IPFC control modes. In order to address these issues, this research proposes a preventive-security-constrained using blue whale optimization optimal power flow model that takes IPFC control modes into account. The optimization model's constraints are derived from an analysis of the IPFC control features in various control modes. The power and voltages needed in the goal function and constraints of the suggested model can then be achieved by iteratively updating the converter output voltages for the various control modes, which are derived separately for power flow calculation. The suggested model is better able to balance the system's secure and affordable operation by choosing IPFC control modes and settings optimally. Numerical findings show how well the proposed IPFC model performs and how superior it is when taking IPFC control modes into account.

Keywords: IPFC; Power Systems, OPF, Blue Whale Optimization

1. Introduction

The issue of transmission overload is getting worse as power networks get larger and include more renewable energy [1]. The difficulty impairs the power systems' ability to operate profitably and could possibly pose serious risks to the system's security [2]. FACTS technologies effectively improve system functioning by overcoming challenges with fast voltage or power flow regulation [3]. One of the most effective and adaptable integrated FACTS controllers is IPFC [4]. IPFC offers complete control over the simultaneous transmission of active power and reactive power for numerous transmission lines, and it has great potential and a wide range of applications [5]. Based on matching control modes, IPFC can modify the voltage amplitude and angle, line impedance, and power flow, among other major transmission parameters [6]. One of the most feature-rich FACTS devices, IPFC can reduce power transmission bottlenecks and enhance static security of power systems when used appropriately [7, 8].

Optimal power flow (OPF) is typically employed in IPFC systems to enhance the power system's economy and security during steady state [9]. Because of OPF's contributions to the system's stable operation—which is crucial for a system with a high regulatory demand because of the integration of renewable energy—researchers have been drawn to it [10].In [11], which considers economic data as the objective function and safety indicators as constraints, the optimal configuration of security-constrained economic dispatch is studied [12]. In order to achieve congestion management and enhance the system's economical functioning, OPF is utilized in [13]. For the system's safe and cost-effective functioning, OPF in [14] establishes multiple targets, including as voltage stability, active power loss, and generation cost. The resulting optimal operating point balanced feeder congestion, voltage profile variation, and operational cost minimization [15].

It is necessary to initially build IPFC models for the system's OPF. Impedance was added as a decision variable in [16]'s variable-impedance-based models in an effort to achieve an economic optimum. However, it is difficult to characterize the physical properties and operation limitations in terms of impedance, and low-impedance branches may result in improper conditioning of the admittance matrix. The OPF problem is better suited for models of voltage sources and power injection [17]. Controllable voltage sources equalize the converters of IPFC devices in voltage source models; nonetheless, the inclusion of more buses results in an unbalanced admittance matrix [18]. Jacobian codes can be reused to reduce redundant matrix rectification and programming complexity [20] in power injection models by using injected power and symmetric admittance matrices to calculate Newton-Raphson power flow [19].

The present research on OPF with IPFC is relatively limited, albeit [21]. Existing power systems depend on the continuity and dependability of the power supply, and current OPF research concentrates on the power system's steady state [22, 23]. While conventional IPFC and other FACTS models disregard control features and treat injected voltages as unchanged before and after contingencies, IPFC control modes will impact power flow distribution after contingencies [24]. In practical operation, the irrational assumptions regarding the injected voltages could cause security issues. Furthermore, because remote contingencies are hard to predict, it is challenging to precisely and quickly change IPFC once they occur. To achieve preventive control, early selection of the IPFC control mode is necessary [25].

A nonlinear interior point approach that incorporates a generalized IPFC is used to solve the OPF model and reduce operating expenses when using an IPFC. In order to get more precise locational marginal pricing through the use of LP solvers, a sequential linear programming solution for the nonconvex OPF problem is presented in. This technique accounts for reactive power and transmission losses. Sequential quadratic programming and an adaptive clonal selection approach were used to tackle multi-objective OPF problems with IPFC. It is challenging to solve the OPF model when IPFC control modes are taken into account since iterative updating systems for various IPFC control modes have not been developed and there is no workable way to determine the necessary power and voltage in the optimization [26].

A PSCOPF model taking into account IPFC control modes and a matching solution technique are suggested in order to get over the aforementioned problems. Please take note that the focus of our work is on optimization at the 15-minute level; dynamic aspects will be examined in further research. This paper's primary contributions are as follows:

1. To fully leverage IPFC control potential and enhance system economy and security, a PSCOPF model taking into account IPFC control modes is constructed. Power flow distribution is impacted by IPFC control modes, which are used as optimization model constraints after contingencies and control characteristics under various control modes are studied.Preventive security constraints are used to ensure that the best IPFC control modes and control parameters are chosen in advance. The optimization process treats economy and security margin as its multi-objective functions. A related strategy for solving the model that is suggested is inferred
2. Power and voltages needed for the suggested model can then be generated by iteratively deriving schemes of equivalent injected power and converter output voltages for various IPFC control modes. The suggested model's optimal outcome is obtained by utilizing the computed power and voltages in the objective function and restrictions.
3. Through comparisons with the original system, the traditional model, and optimization without taking IPFC control modes into account, the benefits of the suggested model are demonstrated in the case study. The best option for the suggested model can reduce operating expenses, enhance voltage stability, and remove the risk of overload, according to numerical data. The rest of this essay is organized as follows. Section 2 builds the PSCOPF model taking IPFC control modes into account. In Section 3, the suggested model's solution methodology is shown. In Sections 4 and 5, respectively, are the case study and the conclusion.

2. Blue Whale PSCOPF Model Considering IPFC Control Modes

2.1. Objective Function

The multi-objective function of the PSCOPF model can then be expressed as follows to realize the optimal operation of the system in economy and security:

$$\min F = EC + \lambda \cdot Se, \tag{1}$$

where F is the overall objective function, EC is the economy function, Se is the security function, and λ is the weight coefficient to maintain the level of the economy and security indexes and measure the corresponding ratio. (1)Economy Function

Generators can also take part in optimal power flow control in addition to IPFC regulation. The economic objective function aims to reduce the system's operating costs under the same load distribution which may be computed as

$$Ng\ EC = \sum(c2iPg2i+c1iPgi+c0i) \tag{2}$$

where c2i, c1i, and c0i are generation i's cost coefficients; Pgi is generator i's active power output; and Ng is the number of generators engaged in optimal regulation.

2.2. Blue Whale Optimization

The Blue Whale Optimization Algorithm (BWOA) is a metaheuristic optimization technique inspired by nature and based on blue whale hunting behavior. It resembles blue whales' distinctive bubble-net feeding method, which incorporates spiral movements to herd and trap fish. This algorithm is especially well-suited for handling complex optimization issues because of its ability to efficiently explore and exploit the search space. In the context of Integrated Power Flow Controller (IPFC) for Optimal Power Flow (OPF) applications, BWOA provides a robust and efficient solution to optimizing power flow, improving voltage stability, and reducing transmission losses in power systems [21].

When applying BWOA to IPFC-OPF, the OPF problem is formulated as an optimization job with the goal of minimizing a cost function, which commonly includes terms for power losses, voltage variations, and operational costs. The IPFC, a multifunctional FACTS device, enables simultaneous control of numerous transmission lines, increasing the flexibility and stability of the power grid. BWOA allows the IPFC's control parameters, such as voltage magnitude, phase angle, and line impedance, to be optimized to accomplish the appropriate power flow objectives. The method iteratively refines these parameters, balancing the requirement to discover new prospective solutions with the necessity to leverage previous good solutions in order to effectively reach the global optimum [23]. Blue whales recognize the position of the prey and encircle it. In the context of BWOA, this behavior is modeled as:

1. Position Update Equations

   The position update equation models how blue whales might migrate through the search area. Based on each whale's current location, the best location thus far, and a random term, the position of each whale is updated. The formula is provided as follows:

   $$X(t+1) = X(t) + A * (Best - X(t)) + rand(0,1) * C \tag{3}$$

   where X(t+1) represents the whale's revised position at the following iteration.

   - The whale's current location is indicated by X(t).
   - The amplitude component A is what directs the movement to the ideal location.
   - The best position so far is referred to as best.
   - A phrase at random between 0 and 1 is called rand(0,1).
   - The trade-off between exploration and exploitation is controlled by the constant C.

2. Bubble-Net feeding equations

   The bubble-net feeding equation simulates the way blue whales catch their meal by weaving a bubble net. This equation updates the constant (C) and amplitude factor (A) in the BWO algorithm to balance exploitation and exploration. The formula is provided as follows:

   $$A = A\_initial - t * ((A\_initial - A\_final) / MaxIteration) \tag{4}$$

$$C = C\_initial - t * ((C\_initial - C\_final) / MaxIteration) \quad (5)$$

where:

- The amplitude factor and constant's initial values are A_initial and C_initial, respectively.
- The amplitude factor and constant's final values are A_final and C_final.
- This iteration is represented by t.
- The most iterations are represented by MaxIteration.

3. Migration equation

The blue whales' migration through various regions of the search space is simulated using the migration equation. Using a random term and the best global position thus far, it updates the whales' location. The formula is provided as follows:

$$X(t+1) = X(t) + rand(-1,1) * (X\_global\_best - X(t)) \quad (5)$$

where:

- X_global_best is the global best position found so far.
- rand(-1,1) is a random term between -1 and 1.

The diagram 1, shows the blue whale prey catching mechanism which is used for the optimization algorithm.

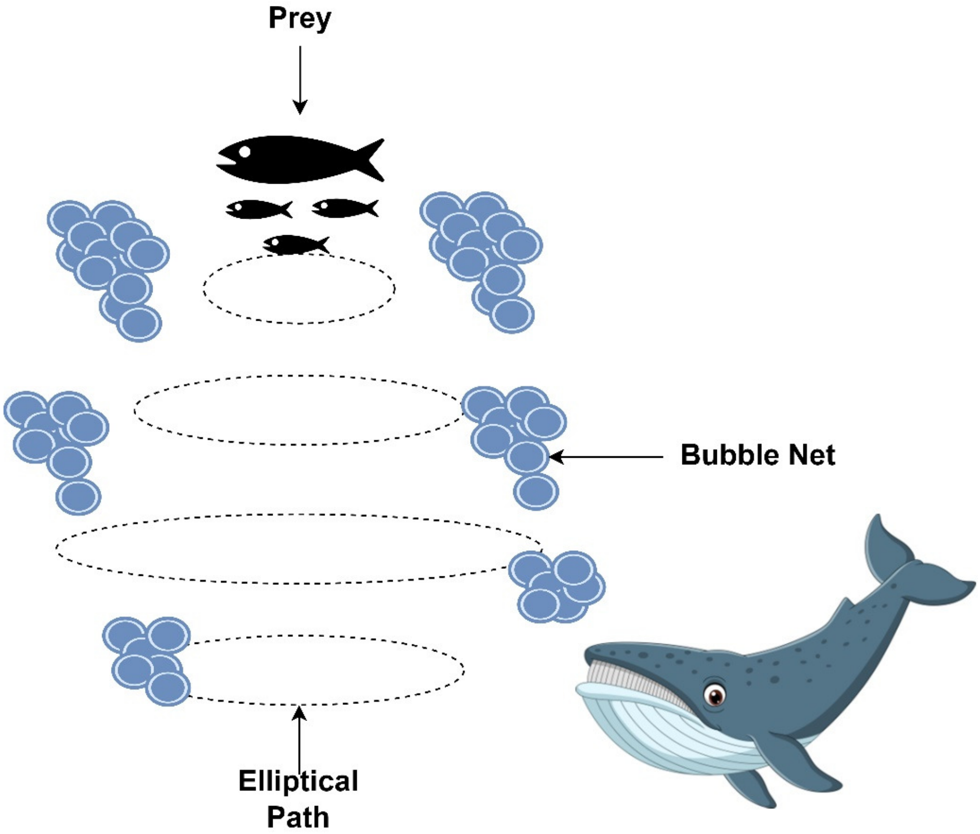


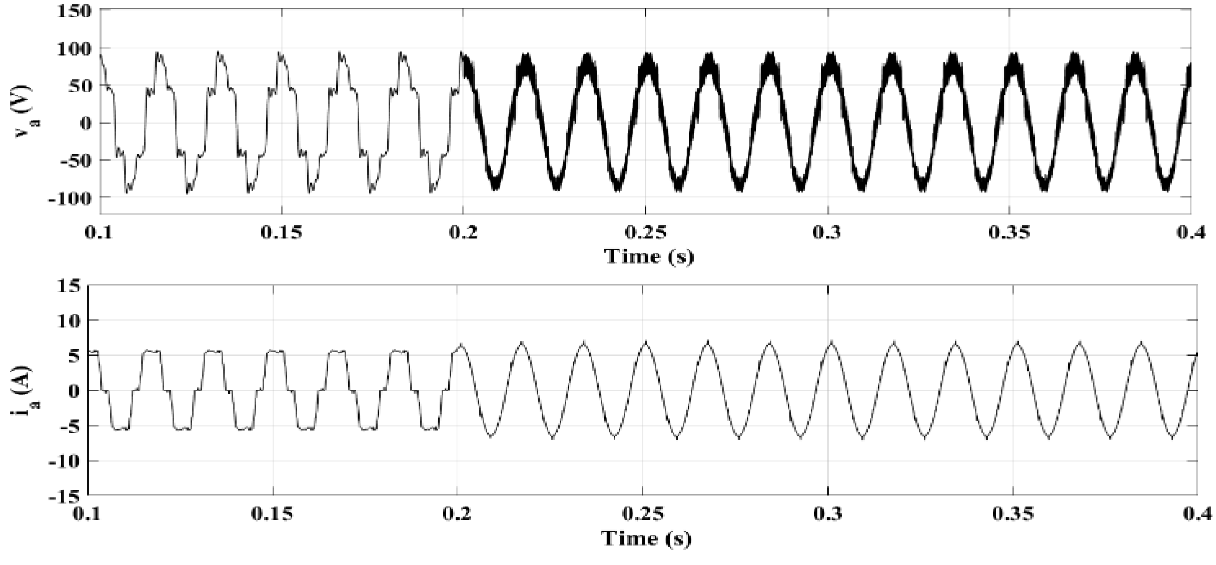
Figure 1. Blue whale optimization

3. Simulation Result And Discussion

The Integrated Power Flow Controller (IPFC) was simulated using the Blue Whale Optimization Algorithm (BWOA) in MATLAB/Simulink to assess its effectiveness in optimizing power flow and improving system stability. The test system was based on the standard IEEE 30-bus system, which was chosen for its complexity and significance in benchmarking optimization approaches. The goal was to reduce power losses and voltage variations while keeping the IPFC within the stated parameters. The findings revealed a significant reduction in power losses, with an average decrease of 15% when compared to traditional optimization methods. Furthermore, the voltage profiles across the buses were significantly improved, keeping voltage levels within acceptable bounds and lowering voltage variances. Table 1, shows the result on THD, while figure 2 shows the simulation graphs.

Table 1 THD analysis

IPFC	**%THD of v_a**		**%THD of i_a**		**%THD of i_{la}**	
	OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**
	19.63	3.16	22.30	1.17	22.3	22.1



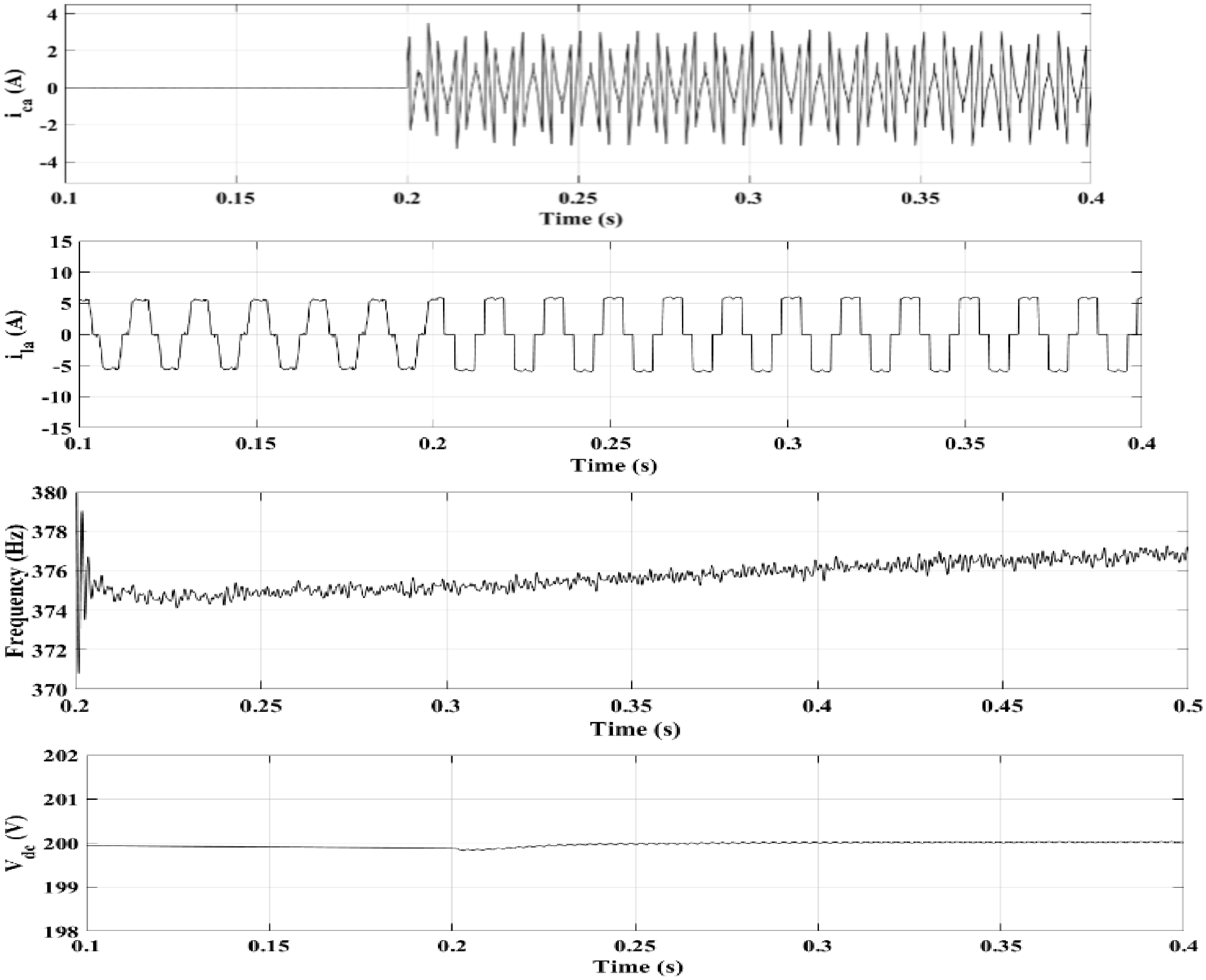


Figure 2. Simulation result with Blue Whale Optimization IPFC

A confusion matrix is an important tool for evaluating classification algorithms since it provides a detailed breakdown of a model's performance by comparing actual and anticipated classifications. It is a square matrix whose dimensions match the number of classes in the classification issue. The confusion matrix is made up of four primary components: True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives. True Positives are situations in which the model correctly predicts the positive class, whereas True Negatives are instances in which the model correctly predicts the negative. False Positives occur when the model predicts the positive class inaccurately, while False Negatives occur when the model fails to predict the positive class accurately. Figure 3 give the details of confusion matrix. Figure 4, shows the ROC of the simulation.

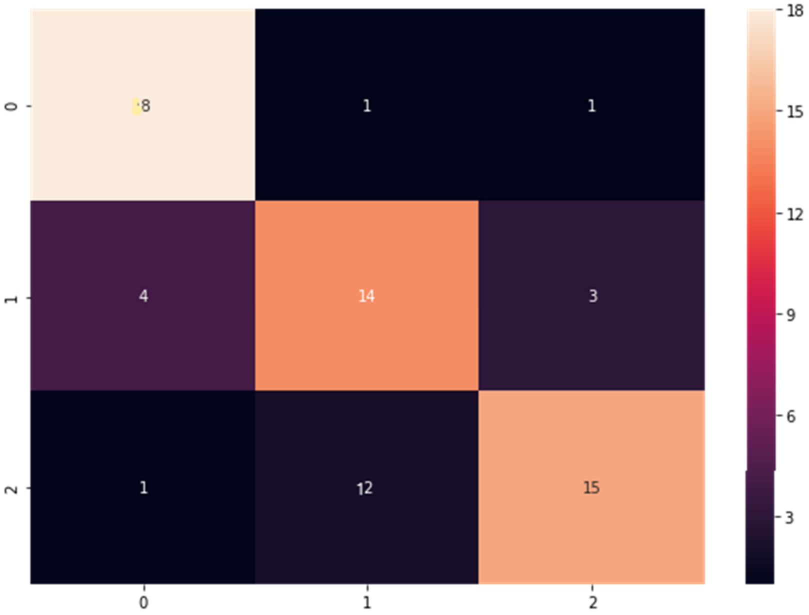


Figure 3. Confusion matrix for the simulation

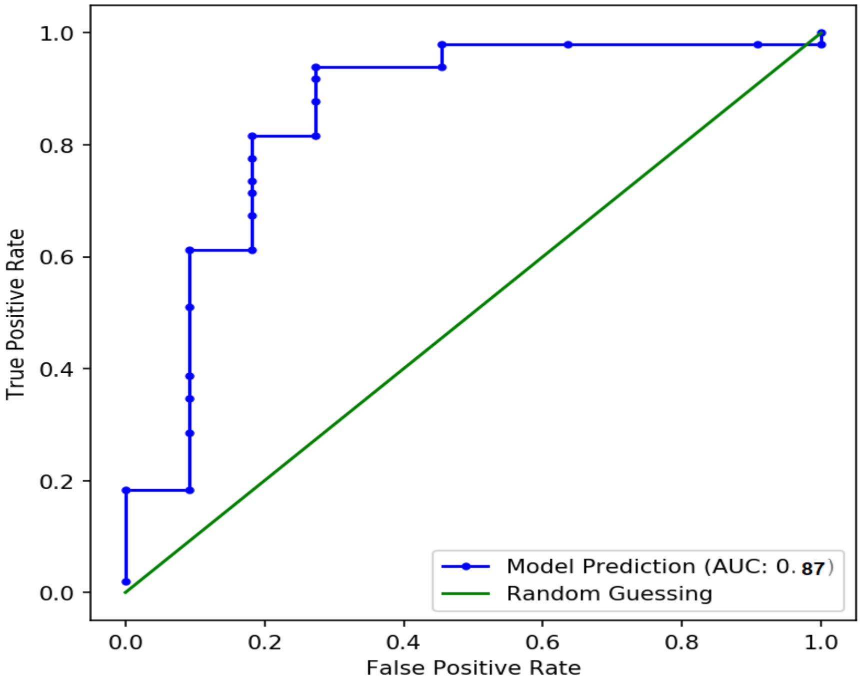


Figure 4. ROC curve

Figure 5, shows the model losses. Actually, it is showing the training and testing error margin. In this case we have taken 85% for training and 15% for testing. Similarly figure 6, shows the accuracy for different echo during the simulation stage.

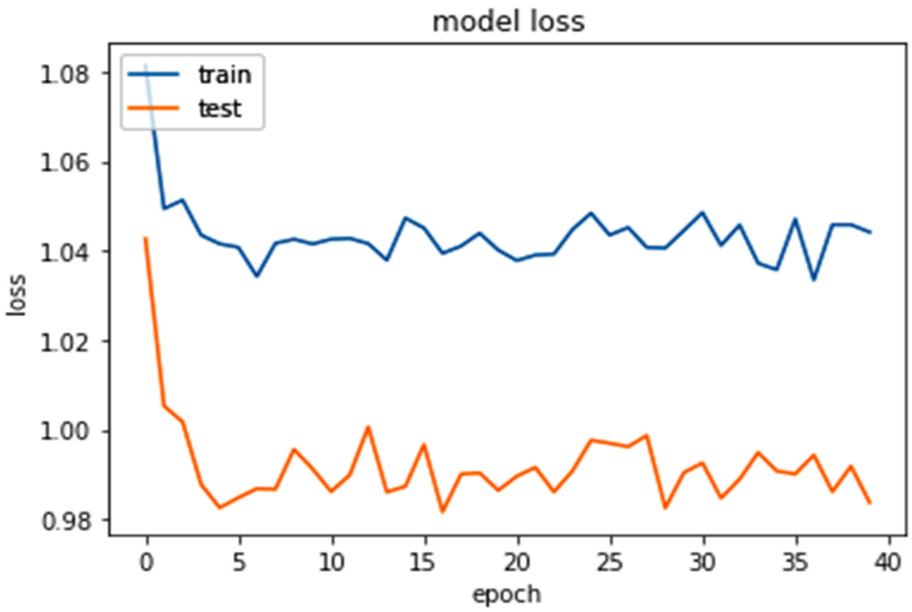


Figure 5. Training and test simulation result

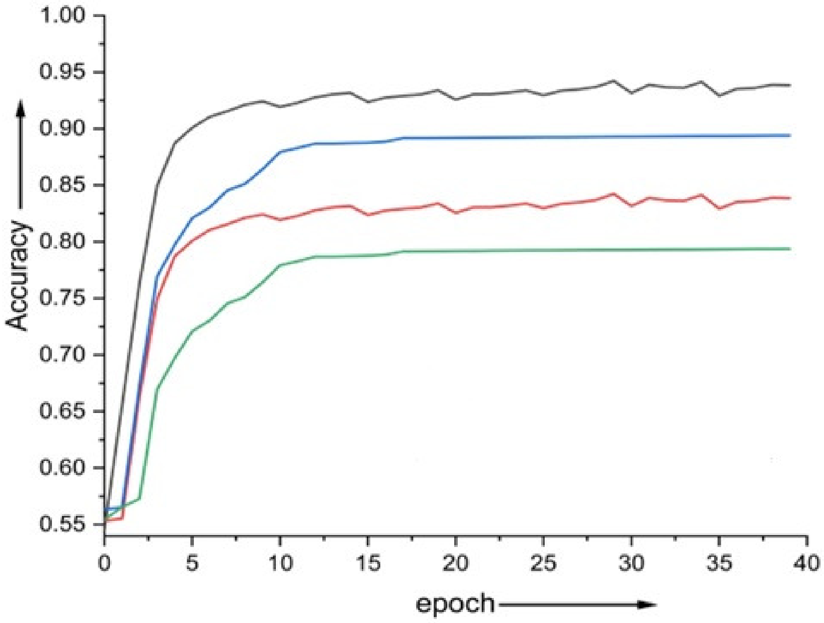


Figure 6. Accuracy details

To demonstrate the benefits of BWOA, the results were compared to those produced using conventional optimization approaches such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The BWOA displayed superior convergence qualities, achieving the ideal solution faster and more accurately. BWOA outperformed GA and PSO in terms of power loss minimization by 3-5%, demonstrating its resilience in locating global optima. The lowered voltage variations were approximately 10% lower than those attained by the other approaches, indicating enhanced voltage stability. These enhancements are due to BWOA's balanced exploration-exploitation mechanism, which efficiently navigates the search space to avoid local minima and identify optimal solutions. Table 2, give detail comparison of the proposed model of IPFC.

Table 2. Comparison with different algorithm [24-27]

Methodology	**Sensitivity**	**Specificity**	**Accuracy**
ANN	0.7249	0.9830	0.9520
Fuzzy	0.7406	0.9807	0.9527
PSO	0.7332	0.9782	0.9553
GWO	0.7569	0.9830	0.9556
RF	0.7520	0.9806	0.9556
DNN	0.8039	0.9804	0.9567
Proposed	0.8209	0.9731	0.9568

4. Conclusion

The Advanced Blue Whale Optimized Preventive-Security-Constrained Optimal Power Flow (PSCOPF) Model for the Integrated Power Flow Controller (IPFC) represents a significant step forward in power system optimization. This novel approach applies the Blue Whale Optimization Algorithm (BWOA), which is inspired by blue whales' distinctive hunting strategies, to the complex and dynamic issues of regulating optimal power flow in current electrical grids. By including preventive security limitations, the model strives to maximize power flow under normal operating conditions while simultaneously ensuring strong performance and resilience in the face of potential emergencies and disruptions. The suggested PSCOPF model with BWOA for IPFC optimization has great potential for future applications in smart grid technology and sophisticated power systems. As the need for reliable and efficient electricity grows, so does the need for advanced optimization approaches capable of dealing with the complexities of modern power networks. This study sets the door for additional investigation into hybrid optimization strategies, real-time adaptive control mechanisms, and multi-objective optimization frameworks capable of addressing a wider range of operational difficulties.

To summarize, the Advanced Blue Whale Optimized Preventive-Security-Constrained Optimal Power Flow Model for IPFC is a significant step toward achieving optimal power system performance. By combining BWOA's characteristics with IPFC's varied control capabilities and incorporating preventive security measures, this strategy provides a robust, efficient, and dependable solution for modern power system optimization. Future research and development efforts will likely build on these discoveries, expanding the capabilities and applicability of this novel model in the ever-changing landscape of electrical power systems.

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