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OPTIMAL LOCALIZATION OF FACTS DEVICES FOR IMPROVING POWER SYSTEM SECURITY USING META-HEURISTIC OPTIMIZATION ALGORITHM

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ABSTRACT

The optimal placement of Flexible AC Transmission System (FACTS) devices plays a critical role in enhancing power system security and stability. This research focuses on leveraging meta-heuristic optimization algorithms to determine the optimal locations for FACTS devices within the power grid. Meta-heuristic algorithms, renowned for their ability to efficiently explore complex solution spaces, are applied to minimize system vulnerability while maximizing power flow control capabilities. The study compares various meta-heuristic techniques, such as genetic algorithms, particle swarm optimization, and simulated annealing, to evaluate their effectiveness in achieving optimal FACTS device placement. Through simulations and case studies, the research demonstrates significant improvements in power system security metrics, highlighting the efficacy of meta-heuristic optimization in addressing real-world power system challenges.

Keywords— power system security, optimal power flow, flexible ac transmission system, fuel cost reduction, Meta-heuristic optimization algorithm.

I. INTRODUCTION

The stability and security of power systems are paramount to ensuring reliable electricity supply in modern societies. As the demand for electricity continues to grow, the complexity of power systems increases, posing significant challenges for grid operators. One of the primary concerns in power system operation is maintaining stability and security under various operating conditions, including load changes, faults, and other disturbances. To address these challenges, advanced technologies and strategies are essential. Among these, the deployment of Flexible AC Transmission System (FACTS) devices has emerged as a highly effective solution.[1]

FACTS devices, such as Static Var Compensators (SVCs), Thyristor-Controlled Series Capacitors (TCSCs), and Unified Power Flow Controllers (UPFCs), offer numerous advantages in enhancing the controllability and flexibility of power systems.[2] These devices can regulate voltage levels, control power flows, and improve dynamic performance, thereby contributing significantly to the overall security and stability of the grid. However, the benefits of FACTS devices are highly dependent on their optimal placement within the power network. Suboptimal placement can lead to inefficient utilization of resources and may not yield the desired improvements in system performance.[3]

The problem of optimal FACTS device placement is a complex optimization challenge that involves multiple objectives and constraints. Traditional optimization methods often struggle to find optimal solutions due to the non-linear and high-dimensional nature of the problem. In recent years, meta-heuristic optimization algorithms have gained popularity for their robustness and efficiency in solving complex optimization problems. These algorithms, inspired by natural phenomena and processes, offer a powerful means to explore large solution spaces and find near-optimal solutions within reasonable computational times.

This research investigates the application of meta-heuristic optimization algorithms for the optimal placement of FACTS devices in power systems. The study aims to enhance power system security by determining the most effective locations for FACTS devices using advanced optimization techniques. Specifically, the research explores the use of various meta-heuristic algorithms, including Genetic Algorithms (GAs), Particle Swarm Optimization (PSO), and Simulated Annealing (SA), among others. These algorithms are chosen for their proven ability to handle complex optimization tasks and their adaptability to different problem settings.

The objectives of this research are multifaceted. Firstly, it aims to develop a comprehensive framework for the optimal placement of FACTS devices using meta-heuristic optimization algorithms. Secondly, it seeks to evaluate the performance of different meta-heuristic techniques in terms of their ability to enhance power system security metrics. Thirdly, the research aims to provide practical insights and recommendations for grid operators on the effective deployment of FACTS devices.[4]

To achieve these objectives, the study employs a rigorous methodological approach, combining theoretical analysis with practical simulations. Case studies based on real-world power system models are used to validate the proposed optimization framework and to compare the performance of different meta-heuristic algorithms.[5] The results of this research are expected to demonstrate significant improvements in power system security, highlighting the potential of meta-heuristic optimization in addressing critical challenges in power system operation.[6]

In conclusion, the optimal localization of FACTS devices is crucial for enhancing the security and stability of power systems. [7] By leveraging the capabilities of meta-heuristic optimization algorithms, this research aims to provide a robust solution to this complex problem, contributing to the advancement of power system technology and ensuring reliable electricity supply in the face of growing demand and evolving challenges.

II. RELATED WORK

Several techniques were discovered to mitigate cost and improve the security. Among them some of them are reviewed as below.

Varma et al. [8] had presented a FVSI method to improve voltage profile, increase power transfer capability, and boost overall power transmission efficiency using FACTS devices in an IEEE 14 bus system. However, the method not give an effective outcome and consume more time. Nadeem et al. [9] had presented a method for find the location and size of FACTS compensators to improve the system security. However, the method only consider a few objective function, and the algorithm was consume more time for convergence. Parastvand et al. [10] had developed that the controllability of wide-area power networks requires the deployment of FACTS compensator and the security of accompanying data transfer. However, this model take a long time for convergence.

Coronado de Koster et al. [11] had suggested a FACTS and distributed generation units in power systems to improve the security. However, the method cannot fully solve the issues and difficult to specify constraints even after the resolution of the objective function. Bavithra, K., Charles et al. [12] had suggested a deregulatory efforts in the electrical sector aimed to develop profitable marketplaces for the sale of electricity. However, the method cannot find a satisfied outcome under all condition with as compared to other alternatives

The relevant works listed above have a number of benefits while also having some drawbacks. The limitations are not survive during overloading and cannot adjust the position of FACTS devices under various loading conditions in real time. The suggested model successfully addresses these issues and offers excellent security in all situations.

III. PROPOSED MODEL FOR POWER SYSTEM SECURITY IMPROVEMENT

Five major types of FACTS compensator are considered in the power system in the proposed study to enable the security and dependability of the system. The objective functions are used to determine where the FACTS devices should be placed in the bus system. META-HEURISTIC OPTIMIZATION is used to choose a good site for FACTS device with minimal cost and high security.

A. Modelling of FACTS Devices

There are five different types of FACTS devices that are widely used in power systems: STATCOM, UPFC, IPFC, SVC, and TCSC. These five FACTS devices are employed in this model for security analysis, and they are succinctly examined below.

1. *STATCOM*

This device is generally used in locations with a poor voltage regulator and low power factor.

$$P = (V_{bus} \times V_{OSTAT} \div X_l) \sin \alpha \qquad (1)$$

$$Q = \left(V_{bus} \times \frac{V_{bus}}{X_l}\right) - (V_{bus} \times V_{OSTAT} \div X_l) \cos \alpha \quad (2)$$

Let, V_{bus} signifies bus bar voltage, V_{OSTA} denotes STATCOM output voltage, X_l signifies the Inductive voltage and V_{dc} denotes the capacitor dc voltage and $X_l = R + j\omega l$.

2. *UPFC*

It controls the active and reactive power flows in a transmission line and enables high-voltage electricity transmission networks to quickly compensate for reactive power.

$$V_{sr} - V_{sr1} = R_{sr} I_{sr1} + I_{sr} \frac{d}{dt} \qquad (3)$$

Where, I_{sr} is series current, V_{sr} is series voltage.

3. *IPFC*

IPFC has the ability to simultaneously control the flow of electricity in two or more transmission lines.

$$P_{ir} = \frac{v_r}{|z|} \left[V_{ipq} \sin\left(\frac{\delta}{2} + \theta_{ipq} - \varphi\right) + V_1 \sin\left(\varphi - \frac{\delta}{2}\right)\right] \ (4)$$

$$Q_{ir} = \frac{v_r}{|z|} \left[V_{ipq} \cos\left(\frac{\delta}{2} + \theta_{ipq} - \varphi\right) + V_1 \cos\left(\varphi - \frac{\delta}{2}\right)\right] \ (5)$$

Where i represent line index, θ_{ipq} is the phase difference between V_{ipq} and V_1.

4. *SVC*

A shunt-connected FACTS controller called SVC's main function is to modify a bus's equivalent reactance in order to control its voltage.

$$Q_{SVC} = -V_i^2 \times B_{SVC} \qquad (6)$$

Where, B_{SVC} can be considered of as the SVC’s susceptance, V_i stands for the magnitude of voltage. The SVC's suspectance can be expressed as follows:

5. *TCSC*

It is used to regulate line impedance by induction in a series of thyristor-controlled capacitors.

$$P = V_1 V_2 \sin \varphi / x \qquad (7)$$

$V = f(P, Q)$ Where, V_1, V_2 is denote voltage either the interconnection, φ is Angular difference.

B. Problem Formulation

The major goal of the multi-objective function in this section is to use the employed technique to minimise or reduce the severity index, voltage deviation, real power loss, line overload investment costs, sensitivity index (LOSI), constraints and fuel cost. The following equation is shown by the objective function

$$\text{objectives} = \min(\text{P1} + \text{P2} + \text{P3} + \text{P4} + \text{P5} + \text{P6}) \qquad (8)$$

Where $\text{P1}, \text{P2}, \text{P3}, \text{P4}, \text{P5}, \text{P6}$ characterizes as voltage deviation, real power loss, LOSI, severity index, investment cost, and fuel cost.

1. *Real power loss*

Equation (9), which describes the transmission lines initial objective function, states that it is to minimise real power loss.

$$P_1 = p_{loss} = \sum_{\substack{k=1,\\ j\neq i}}^{n_{line}} X_{kj}\left[(V^k)^2 + (V^j)^2 - 2\,V^k.V^j\cos(\delta_k - \delta_j)\right] \qquad (9)$$

Where, δ_j and δ_k denotes the angles of bus j and k, X_{kj} denotes the conductance among the bus k and j, V^k and V^j denote the bus k and j voltages.

2. *Voltage deviation*

By using magnitude voltage, as is demonstrated in the provided equation (10), the variation of the load buses is minimised.

$$P_2 = V^{dev} = \sum_{i=1}^{n^l} \left| V^i - V_i^* \right| \qquad (10)$$

The load buses are indicated by n^l, and V^i is the nominal magnitude voltage

3. *Severity index*

To lower the severity index, the system has been implemented. The function of severity index is carried out using the following equation (11),

$$P_3 = si = \sum_{L=l_0}^{N} \left(\frac{s_L}{s_L^{max}}\right)^{2M} \qquad (11)$$

Where M stands for the inline flow 1, s_L stands for the line rating, l_0 denotes the overload lines set, s_L^{max}denotes the line exponent, and (MVA).

4. *LOSI*

LOSI is used to find the best location of compensators, and each transmission line's LOSI is assessed in light of various situations, which is shown in the following equation (12),

$$P_4 = LOSI_i^{bl} = \sum_{n=1}^{n_c} \left(\frac{S_i^n}{S_i^{max}}\right) \qquad (12)$$

If line-i has the maximum power flow and S_i^{max}, S_i^n contains the potential power flow.

5. *Investment cost*

One of the main objective functions of the FACTS appliances at the point of investment cost is the cost of the compensators like IPFC, UPFC, SVC, TCSC, and STATCOM that is estimated by the following equation (13), [6].

$$P_5 = cost^{STATCOM} + cost^{UPFC} + cost^{IPFC} + cost^{SVC} + cost^{TCSC} \qquad (13)$$

6. *Fuel cost*

At this case, the cost of generator fuel is minimized. Equation (14), which is shown below, illustrates how the generating units' quadratic fuel cost functions work.

$$P_6 = mincost^F(X) = \sum_{i=1}^{n_G} [A^i (p^{gi})^2 + B^i p^{gi} + C^i] \qquad (14)$$

Where $p^{gi}$is the limit for the i^{th} generators active power output, A^i ,$B^i$and $C^i$are the ith generators fuel cost coefficients, i is the bus number index, and n_G is the number of generators.

C. Constraints

In order to enhance the security of power system, the suggested model uses the following restrictions.

1. ***FACTS device limits***

Equation (15) provided below reveals the FACTS device limits.

$$\left.\begin{array}{c} x_f^{min} \le x_f \le x_f^{max} \\ v_{Vr}^{min} \le v_{Vr} \le v_{Vr}^{max} \\ v_{Cr}^{min} \le v_{Cr} \le v_{Cr}^{max} \\ \delta_{Vr}^{min} \le \delta_{Vr} \le \delta_{Vr}^{max} \\ \delta_{Cr}^{min} < \delta_{Cr} < \delta_{Cr}^{max} \end{array}\right\} \quad (15)$$

Where x_f the reactance of the compensators.

2. ***Reactive power generation limits***

The following equation (16) accurately illustrates the reactive power generation constraints.

$$q_{gi}^{min} \le q_{gi,T} \le q_{gi}^{max}, gi \in n_{gi} \quad (16)$$

The parameters $q_{gi}^{min}, q_{gi}^{max}$ define the minimum and maximum thresholds for the reactive power i, n_{gi} denotes total generator buses.

3. ***Real power generation limits***

The real power generation limits are demonstrated by the equation (17), which is written as follows.

$$p_{gi}^{min} \le p_{gi,T} \le p_{gi}^{max}, gi \in n_{gi} \quad (17)$$

Where the term n_{gi} denotes the quantity of generator buses.

4. ***Security constraints***

Equations (18) and (19) determine the security limitations.

$$(V^i)^{min} \le V^{i,t} \le (V^i)^{max}, i \in n_{bus-1} \quad (18)$$

$$\left|bf^{(i,T)}\right| \le (bf^i)^{max}, i \in n_{bus} \quad (19)$$

Where, $(bf^i)^{max}$ denotes the ith branches power flow (MVA), the power flow in a ith branch at time t (MVA) is represented by $bf^{(i,T)}$.

5. ***Voltage constraints***

The magnitude voltage restrictions at all the buses are specified by the provided equation (20),

$$\left.\begin{array}{l} (V^j)^{min} \le V^j \le (V^j)^{max}, j = 1,2,\ldots\ldots, n_{bus} \\ (V^i)^{min} \le V^i \le (V^i)^{max}, i = 1,2,\ldots\ldots, n_{bus} \end{array}\right\} (20)$$

6. ***Load flow constraints***

The equation below correctly handles the load flow limitations

$$\left.\begin{array}{r} p_i - V^i \sum_{j=1}^{n_{bus}} V^j \left(X_{ij} \cos\theta_{ij} + Y_{ij} \sin\theta_{ij}\right) = 0, \; i = 1,2, \quad \ldots\ldots, n_{bus-1} \\ q_i - V^i \sum_{j=1}^{n_{bus}} V^j \left(X_{ij} \sin\theta_{ij} - Y_{ij} \cos\theta_{ij}\right) = 0, \; i = 1,2,\ldots\ldots, n_{pq} \end{array}\right\} \quad (21)$$

Where, the total amount of buses is denotes as n_{pq}.

7. Solution of optimal FACTS problem

The optimal problem of FACTS localization and sizes are computed through the use of META-HEURISTIC OPTIMIZATION method. META-HEURISTIC OPTIMIZATION is inspired by the hunting activity of the Meta-heuristic optimization animals. Hunting strategy is split into three phases like chasing and approaching, encircling and harassing, and attack. The location of various FACTS compensators is chosen in the proposed work with the least expensive and severity function. The upcoming section describe the proposed optimal FACTS localizations through META-HEURISTIC OPTIMIZATION method.

8. *Steps by step procedure of META-HEURISTIC OPTIMIZATION for optimal placement*

Here, the major goal is to reduce the severity function and fuel cost by integrating FACTS devices at appropriate transmission network sites.

Step 1: Initialization

In proposed model, the bus data, line data, load data and FACTS ranges are initialized.

Step 2: Fitness Function

Six various objective functions are used to determine the FACTS compensators ideal locations and ranges. The objective functions mathematical expression is provided below.

$$Fitness = \min(objectives) \qquad (22)$$

Where, $objectives$ is expressed as eqn.(8)

Step 3: Updation

The two best Meta-heuristic optimization solutions in this phase are alpha and beta, which are indicated in the formulas by their subscripts.

$$\vec{x}_i(t) = \overrightarrow{x_*}(t) + \frac{1}{2}\left[\vec{x}_{r_1}(t) - (-1)^{\sigma} * \vec{x}_{r_2}(t)\right] \qquad (23)$$

If the search agent with low survival rates that will be updated is$\vec{x}_i(t)$, r_1 and r_2 Random numbers between 1 and the largest size of search agents. $\overrightarrow{x_*}(t)$ is the top agent discovered in the previous iteration, $\vec{x}_{r_1}(t)$ and $\vec{x}_{r_2}(t)$are the r_1, r_2-th search agents chosen and σ denote random value.

Step 4: Termination

Repeat the procedure until the bus number and FACTS device are at their finest. Once the ideal answer has been found, the procedure is finished.

IV. RESULT AND DISCUSSION

In this study, the security guards of five devices are utilised to protect the security of the power system. Finding a suitable placement for FACTS devices is the first stage in order to minimise losses and transport as much reactive power as possible. IEEE 30 and 118 bus systems are two separate bus systems that are taken into consideration. The performance of test buses IEEE 30 and 118 is calculated with or without FACTS devices based on the META-HEURISTIC OPTIMIZATION accurate location of FACTS devices. Three separate scenarios are used to validate the suggested strategy, including Scenario 1- Analysis of security under normal and contingency conditions, Scenario 2- Analysis of security with the best power flow and Scenario 3- Using FACTS devices to improve security. To validate the performance, each situation is separately examined and contrasted with existing approaches.

A. Performance evaluation of the IEEE 30 bus system

Following a number of tests, the success of the suggested technique is examined in this section. The proposed method is used to evaluate the objective functions, including the voltage deviation and severity index in the IEEE 30 bus system. The outcomes are contrasted and compared to those of the suggested system.

Case1: *Analysis of security under normal and contingency conditions*

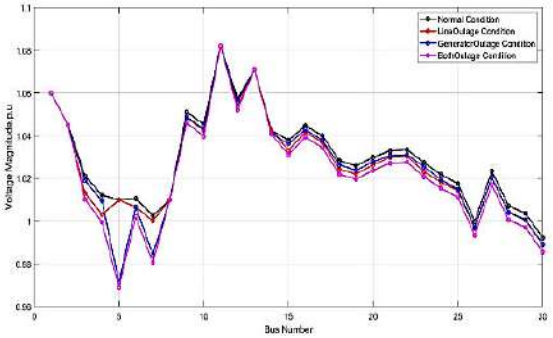


Fig. 1. Variation of voltage magnitudes.

Figure 1 depicts the variation in voltage magnitudes under several contingency scenarios, including normal, line, generator, and both outage states. In typical circumstances, the magnitude is gradually changed from 1 to 30 buses. The voltage magnitude varies in a minor way after 16 buses.

Case2: *Analysis of security with the best power flow*

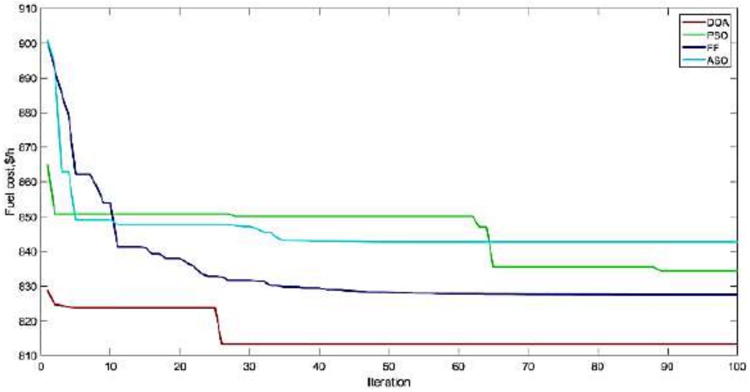


Fig. 1.

Fig. 2. (a)

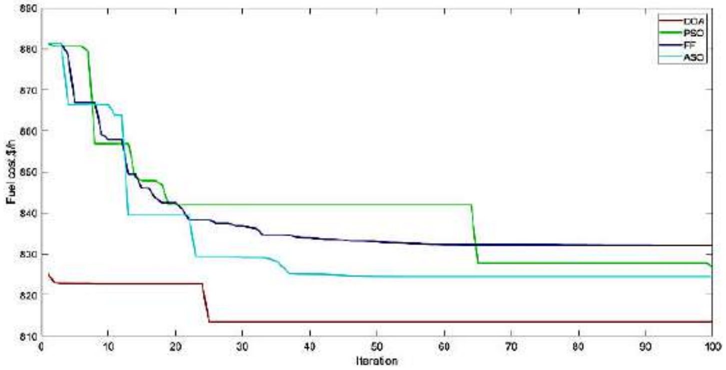


Fig. 3.

Fig. 4. (b)

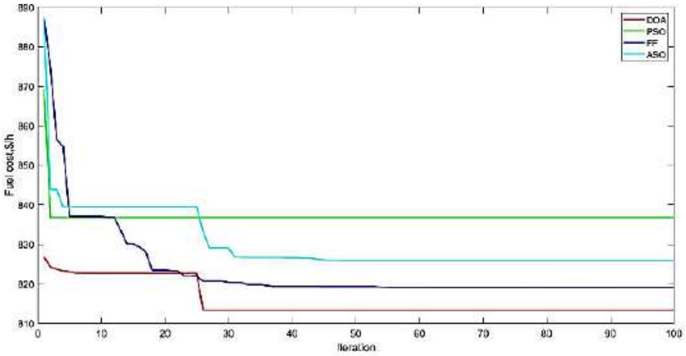


Fig. 5.

Fig. 6. (c)

Fig. 2. Convergence characteristics of generation fuel cost under (a) line outage (b) generator outage (c) both outage.

Figure 2 illustrates the convergence properties of generating fuel cost for recommended META-HEURISTIC OPTIMIZATION and existing techniques such as PSO, FF, and ASO in realistic scenarios. The generation fuel cost in the planned META-HEURISTIC OPTIMIZATION is lowered after 25 iterations in normal condition. The generating fuel cost in the proposed META-HEURISTIC OPTIMIZATION is cut to 825 at the 25th iteration in line outage condition. At the 23rd iteration of the proposed META-HEURISTIC OPTIMIZATION, the generation fuel cost drops to $815, in generator outage condition. The generation fuel cost in the planned META-HEURISTIC OPTIMIZATION drops to 815 after the 25th iteration, in both outage condition.

Case3: *Using FACTS devices to improve security*

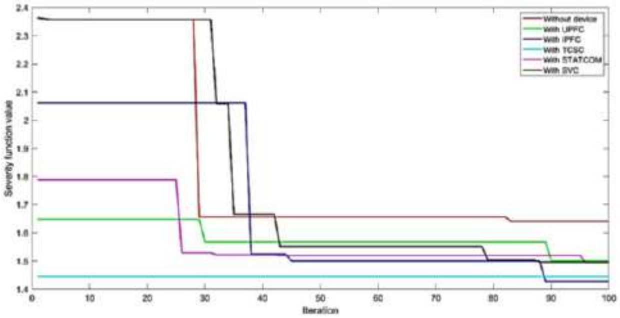


Fig. 7.

Fig. 8. (a)

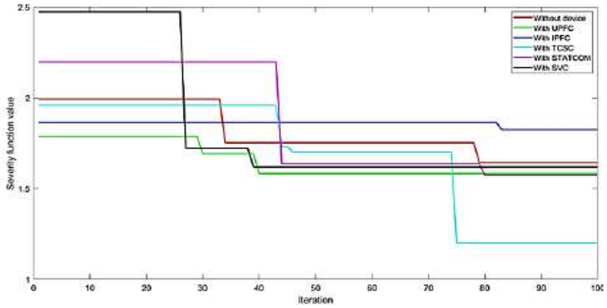


Fig. 9.

Fig. 10. (b)

Fig. 3. Proposed Convergence characteristics of system severity functions with and without FACTS under normal conditions and contingency condition.

Figure 3 illustrates how the system severity performs both with and without FACTS devices under normal circumstances utilising proposed META-HEURISTIC OPTIMIZATION. The graph shows the ultimate best value requires more interactions because NR load flow is solved while taking into account various FACTS devices. Compared to the existing algorithms, this is better.

B. Analysis of the IEEE 118 bus system performance

The goals of this work are to increase system security and, using our suggested system, to locate or position the FACTS devices in the most advantageous manner. The suggested approach is used with the IEEE 118 bus system to analyse the performance of the objective functions such as severity index, voltage, and voltage deviation.

Case1: *Security analysis under normal and contingency conditions*

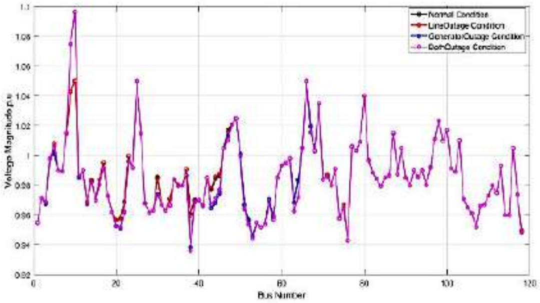
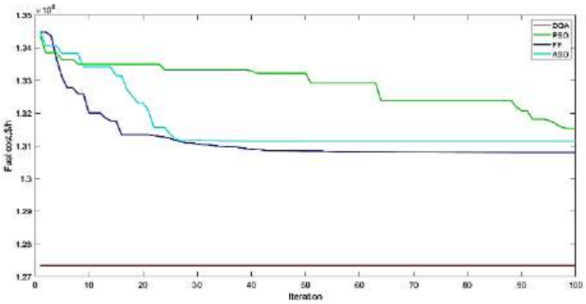


Fig. 4. Variation of voltage magnitudes.

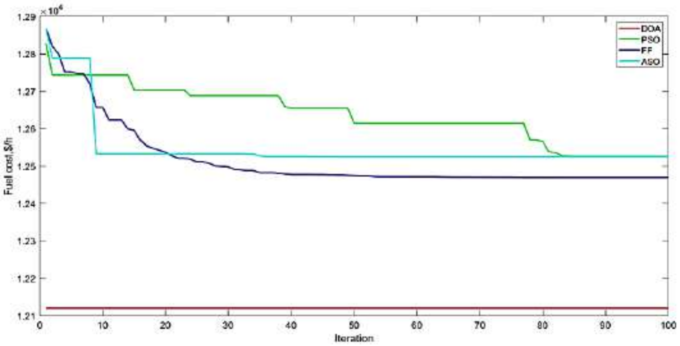
For the IEEE 118 bus system, Figure 4 depicts the variation in voltage magnitudes under various contingency scenarios, including the normal condition, line outage condition, generator outage condition, and both outage condition. The magnitude of a bus generator outage is gradually increased from 1 to 70 buses. Additionally, the magnitude of both outages is steadily increased up to 118 buses.

Case2: *Security analysis using optimal power flow*

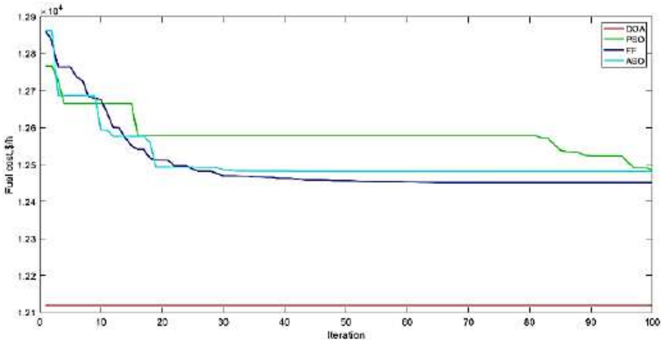
Figure 5 displays the convergence properties of generating fuel cost for suggested META-HEURISTIC OPTIMIZATION and existing methods like PSO, FF, and ASO for IEEE 118 bus system under various conditions.



(a)



(b)

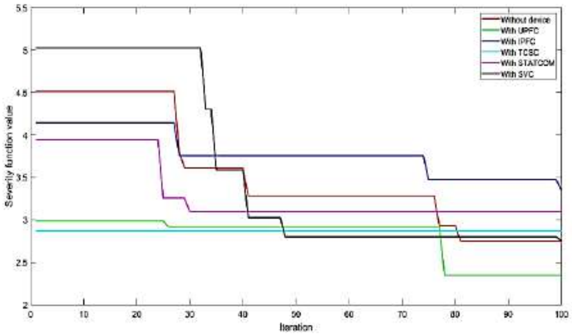


(c)

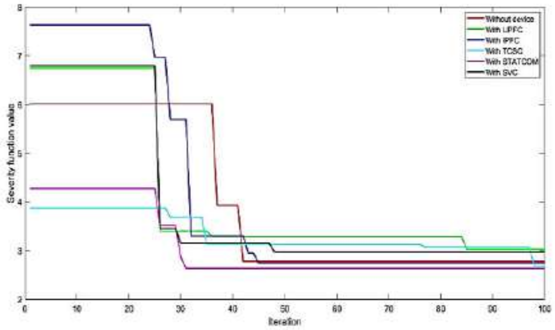
Fig. 5. Convergence characteristics of generation fuel cost under (a) line outage (b) generator outage (c) both outage.

Case3: *Using FACTS devices to improve security*

Figure 6 illustrates the proposed convergence properties of the system severity functions with and without FACTS devices under typical conditions using the proposed META-HEURISTIC OPTIMIZATION for the IEEE 118 bus system.



(a)



(b)

Fig. 6. Proposed Convergence characteristics of system severity functions with FACTS under normal and contingency condition.

V. CONCLUSION

To increase the security of the power system, a unique META-HEURISTIC OPTIMIZATION technique was used in this work to position the FACTS devices optimally. Voltage deviation, sensitivity index, and restrictions are just a few of the several types of objective functions used to identify where FACTS devices should be put in a system. The META-HEURISTIC OPTIMIZATION approach can help you choose the ideal position for FACTS devices. The proposed model is evaluated using the IEEE 30 and IEEE 118 bus systems, as well as its cost fitness function. The comparison study demonstrates that the suggested strategy achieves the lowest cost function when compared to other current methods. In future work, fresh strategies and optimizations will be applied to further reduce the cost functions.

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