MULTI-OBJECTIVE METAHEURISTIC ALGORITHMS BASED OPTIMAL PLACEMENT OF FACTS DEVICES IN TRANSMISSION NETWORKS

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Abstract
As the installation of FACTS devices in power system structures progresses towards goals such as superior controllability, minimizing active and reactive power losses, and improving voltage stability, the proper placement of these devices It will be indispensable. This document proposes the best FACTS device among TCSC, SVC, and UPFC to achieve a single goal and all goals at the same time. It has also been proposed to search for optimal spots and sizes from metaheuristic methods such as the Multipurpose Bias Random Key Genetic Algorithm (BRKGA), Multipurpose Particle Swarm Optimization (MPSO), NSGII, and Gray-Wolf Optimization (GWO). A method for FACTS devices to improve voltage stabilization margins and active and reactive power losses in IEEE 118 bus networks. The characteristics of FACTS devices are also compared based primarily on the proposed algorithm. Further, in this paper satisfaction, overall cost, location and sizing are discussed in detail with these objectives and the three FACTS Devices with BRKGA, MPSO, NSG-II and GWO algorithms. The software of the proposed technique has been investigated on widespread 118-bus structures. It is found that individually UPFC is better device to compensate real, reactive power losses and to improve stability but is a costlier device. To achieve these, multiple FACTS devices is most optimal solution to achieve all the objectives at a time as it is expected with GWO algorithm.

Keywords: FACTS, SVC, UPFC, MPSO, GWO algorithm.

1. Introduction

Transmission networks as the main body of the power system are of special importance in transferring power from production centres to consumption centres, the control of which is one of the most important tasks and challenges of power system users. In order to control the various parameters of these networks, FACTS devices have been widely used in transmission systems in recent years. These devices, which are placed in series and in parallel in the network, help to improve the network voltage profile, reduce losses and eliminate line blockages by controlling the power flow in the network.

So far, the issue of placement of FACTS devices in transmission networks has been studied by considering one of the various goals such as increasing network load and reducing line congestion, reducing network losses, improving voltage profiles and also reducing investment costs of FACTS devices. Has been due to the fact that by placing these devices in the network, all these items (the amount of power through the lines, voltage profile, the amount of network losses and the cost of FACTS devices) will be affected, addressing only one of them and not paying attention. In other cases, it may have adverse effects on three other goals while improving the target. Also, in limited cases, the combination of two or more goals has been studied as a single-objective optimization using a goal function including the weighted sum of different goals. Due to the difficulty of determining and adjusting the weight coefficients of different objectives in the objective function and the dependence of these coefficients on the network structure is not practically applicable and will not lead to acceptable results.

According to the cases mentioned in this dissertation, the problem of location of FACTS devices in transmission networks has been studied using multi-objective optimization methods. It should be noted that in these methods, a set of optimal solutions will be determined as the output of the problem, and finally the designers and planners of the transmission network, given the importance of different goals, one of the optimal solutions. Reactive power compensation (RPC) plays a vital role in improving voltage profile under steady state and voltage collapse and voltage instability under transient conditions. In addition, by integrating the RPC with the ideal placement and sizing of the energy machine, within the overall performance of a normal machine, especially improving the voltage profile of the bus, minimizing energy loss, and voltage balancing. We can provide additional development in the improvement of. And charge margin. Also, the profitability factor, primarily based on reliability, quality and availability, is an additional feature that highlights the desire to achieve RPC's number one and greatness in power systems.

RPC optimization problems are expressed using a mathematical summing approach, weight functions, fuzzy aim programming strategies, and the Pareto principle. Not uncommon objective features provided in the latest paper are aimed at limiting energy loss, beautifying voltage profiles, improving voltage balance, and increasing device durability. Several various factors consisting of actual and reactive energy balance, bus voltage and segment perspective bus restrict, technology value, energy waft restrict, voltage balance restrict. The actual and reactive energy call for restrict, thermal restrict, DG restrict, loading aspect restrict, actual and reactive generator restrict, value of RPC, RPC capacity, variety of RPC restrict, cutting-edge restrict, energy aspect restrict, general actual energy restrict and general reactive energy restrict are often taken into consideration in maximum research because the constraints of the optimization problem.

Metaheuristic optimization techniques are generally natural stimulus techniques that can be further introduced into three mainstream areas: (i) biologically stimulated algorithms, (ii) physics-mainly based master algorithms, and (iii) Chemistry-Mainly based master algorithm. Genetic Algorithm (GA), Evolutionary Programming (EP), Evolutionary Strategies (ES), Particle Swarm Optimization (PSO), Whale Optimization Algorithm (WOA), Ant Colony Optimization (ACO), Wolf Search Algorithm (WSA), Bee Colony Optimization (BCO), Cuckoo Search Algorithm (CSA), Bat Algorithm (BAT), Re Algorithm (FA), Bacteria Search Algorithm (BFOA), Artificial Bee Colony (ABC), Cat Swarm Optimization (CAT), Gray Wolf Optimization (GWO), Especially the best space and size problem used in Ref., is a rare space optimization algorithm. The objectives like minimization of the costs, reliability of the transmission system, losses minimization, environmental impact, voltage and electrical parameters performance improvement and so on. Various types of objectives are achieved using indices like Total System Loss Sensitivity Factor Method, Voltage Stability Indices, Power Loss Index, Voltage Profile, Line Security and Line Severity Index. Few interesting works on the present theme of the paper with multi-objective optimization, allocation of FACTS devices for a large power system network.

Select as the final answer and install the FACTS devices in the network accordingly.For this purpose, in this dissertation, four objectives of increasing network load, improving voltage profile, reducing network losses and also reducing the investment costs of FACTS devices are considered as multi-objective planning goals and using two. The second multi-objective Biased Random key Genetic Algorithm (BRKGA) method, the multi-objective particle cluster optimization (MOPSO), NSG-II and GWO have been solved. It should be noted that three types of FACTS devices including SVC devices, TCSC devices and UPFC devices are considered as devices that can be installed in the transmission network and simulation results will be presented in order to locate and find the capacity of these devices.

In the following, we will first express and describe the modelling of FACTS devices considered in this thesis. The various objective functions and constraints of the FACTS device location problem will then be described. The following is a brief description of the BRKGA, MPSO, NSGAII and GWO multi-objective optimization algorithms. After that, the simulation results will be presented in different scenarios and scenarios, and finally, general conclusions will be presented.

2. Modelling of FACTS devices

In this section, we will present the models of FACTS devices considered in this dissertation. In general, FACTS devices are divided into three categories according to how they are located in the transmission network [36-38]:

1. FACTS series devices: These elements are placed in series in the transmission line and usually by changing the line reactance, the power flow in the lines changes. The most widely used member of this family is the TCSC.
2. Parallel FACTS devices: These elements are placed in parallel in the network and are usually connected to one of the network busbars and control the connection point voltage by absorbing or injecting reactive power into the network. The most famous member of this family is called SVC.
3. FACTS series-parallel devices: These elements are a collection of the previous two categories and the most important member of this family is UPFC, which is very strong in terms of performance and its only limitation is its high cost.
4. As mentioned in this thesis, the three types of FACTS devices mentioned above, including SVC devices, TCSC devices and UPFC devices, have been considered, and in the following, each of them will be modelled.

A. TCSC equipment

As shown in Figure.1, the TCSC consists of a branch containing a capacitive bank and parallel branches including a controlled thyristor and a self-bank, which modifies the line reactance by controlling the self-branch. The TCSC reactance is calculated using Equation (1).

$$X_{TCSC} = \frac{X_C X_L}{\frac{X_C}{\Pi}\left[2(\Pi-\alpha)+\sin 2\alpha\right]-X_L} \qquad (1)$$

In the above relation, the thyristor fire angle is the capacitive reactance and the inductor reactance. The TCSC is placed in series on the line and will affect the line reactance according to Equation (2).

$$X_{ij}^{new} = X_{ij}^{old} + X_{TCSC} \qquad (2)$$

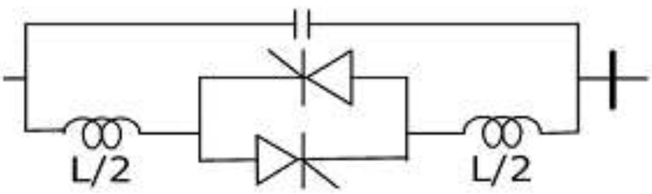

Figure1. TCSC Device structure

It should be noted that in order to be easier to use in optimization problems, modelling of TCSC devices is usually done in the form of equation (3) in which it is called compensation factor and usually in the range between 7 / 0- to 0.2 can be changed.

$$X_{TCSC} = r_{TCSC} \times X_{line} \qquad (3)$$

B. SVC equipment

As shown in Figure.2, the SVC consists of a reactive impedance the size of a two-way thyristor switch (TCR), parallel to a capacitive bank, and in the circuit as a variable reactance parallel to the absorption or Reactive power generation regulates the voltage of its connection point to the network. In other words, the main application of these devices is fast reactive power and voltage support, which is achieved by controlling the fire angle of the thyristor.

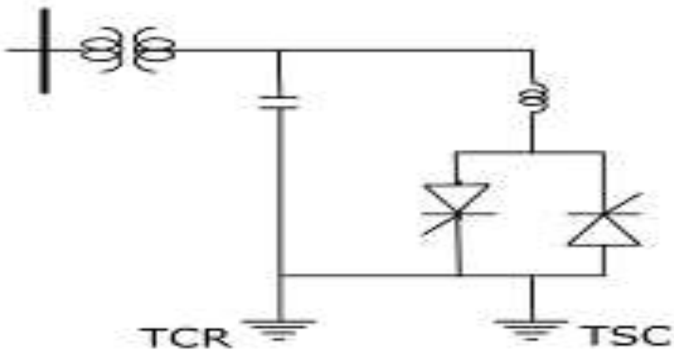

Figure2. SVC Device structure

The controllable part of the reactance is called the TCR, which is described using Equation (4).

$$X_V = \frac{\Pi}{2\Pi - 2\alpha + \sin(2\alpha)} \tag{4}$$

Which in the above relation is the thyristor fire angle. By determining the controllable part, the effective susceptibility B in TCR is calculated by Equation (5).

$$B = \frac{X_V + X_C}{X_V \times X_C} \tag{5}$$

It should be noted that in practice in the optimization process, SVC devices are usually modeled as absorption or injection sources of reactive power in the desired bus according to Equation (6).

$$-Q_{SVC}^{\max} \le Q_{SVC} \le Q_{SVC}^{\max} \tag{6}$$

Which is considered to be about 300 MW.

C. UPFC equipment

As shown in Figure 3, the UPFC has two inverter voltage sources (VSI) and a common DC capacitor between them.

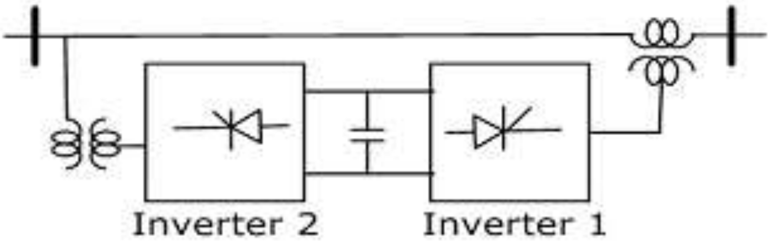

Figure3. UPFC Device structure

Usually for the study of UPFC, two methods of modelling are coupled (coupled) and decoupled (separate). In the first model, due to the need to modify the Jacobin matrix, it is more complex, while in the second modelling method, there is no need to modify the Jacobin matrix and these devices can be easily inserted in the load distribution process. Figure4 illustrates the equivalent circuit of UPFC devices for modelling based on a separate method.

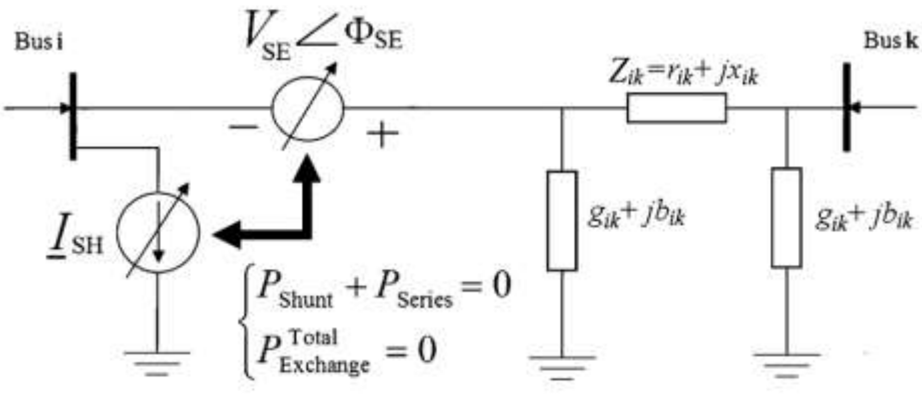

Figure4. Equivalent circuit of UPFC devices

Based on the equivalent circuit shown in Figure (5), the UPFC equipment located between the i and k axes of the network can be injected as active and reactive powers in these axes according to equations (7) to (10) modelled.

$$P_i^{inj} = -V_k V_{SE}\left[G\cos(\delta_k - \phi_{SE}) - B\sin(\delta_k - \phi_{SE})\right] + G_F V_{SE}^2 + 2V_i V_{SE} G_F \cos(\delta_i - \phi_{SE}) \tag{7}$$

$$Q_i^{inj} = V_i V_{SE}\left[G_F \cos(\delta_i - \phi_{SE}) - B_F \sin(\delta_i - \phi_{SE})\right] - V_i I_{SH} \tag{8}$$

$$P_k^{inj} = -V_k V_{SE}\left[G\cos(\delta_k - \phi_{SE}) + B\sin(\delta_k - \phi_{SE})\right] \tag{9}$$

$$Q_k^{inj} = -V_k V_{SE}\left[G\cos(\delta_k - \phi_{SE}) - B\sin(\delta_k - \phi_{SE})\right] \tag{10}$$

Where, and UPFC adjustment parameters, which are limited to 0.3 and 0.15, respectively, due to physical constraints such as insulation constraints. We also have:

$$G + jB = \frac{1}{Z_{ik}} \tag{11}$$

$$G_F = g_{ik} + G \tag{12}$$

$$B_F = b_{ik} + B \tag{13}$$

3. Objective functions and problem constraints

This section describes the objective functions and constraints intended to determine the optimal location and size of FACTS devices in transmission networks. As mentioned in this dissertation, four objectives of increasing network load, improving voltage profile, reducing network losses and also reducing the investment costs of FACTS devices are considered as multi-objective planning goals, which are as follows: We will describe the relevant relationships.

A. Aim to increase network load:

Transmission line congestion is one of the topics that has always been considered as an important challenge by designers and operators of transmission networks. As mentioned, the use of FACTS devices in the network is one of the effective solutions to manage line clogging, which is provided by changing and adjusting the power flow in the network lines. Equation (14) describes the objective function that covers this objective in the process of determining the location and capacity of FACTS devices.

$$J_P = \sum_{j=1}^{NoL} w_j \left(\frac{S_j}{S_j^{\max}}\right)^2 \tag{14}$$

In the above relation, the number of network lines is the apparent power passing through my line, the maximum capacity of my line and the coefficient of importance of my line. By minimizing the above index through the optimal location and capacity of FACTS devices, the load of the transmission network can be increased.

B. The purpose of improving the network profile:

Improving the voltage profile is another important goal of using FACTS devices in transmission networks. In other words, considering this goal, in the process of locating and finding the capacity of FACTS devices, it tries to bring the voltage of the network basses as close as possible to their reference and default values. Equation (15) describes the objective function that covers this objective in the process of determining the location and capacity of FACTS devices.

$$J_V = \sum_{i=1}^{NoB} w_i \, |V_i - V_i^{ref}|^2 \tag{15}$$

In the above relation, the number of network buses is the size of the bus voltage, the reference voltage of the bus and the importance factor of the bus. By minimizing the above index through optimal location and capacity-finding of FACTS devices, the magnitude of network voltages can be made as close as possible to the reference values.

C. Aim to reduce network losses:

Loss reduction has always been considered as a traditional goal in various transmission network operation and planning processes. In this dissertation, as the third goal in the process of locating and finding the capacity of FACTS devices, reducing the active losses of the transmission network has been considered. Active network losses can be calculated using Equation (16a).

$$P_{Loss} = \mathrm{Real}\left[\sum_{j=1}^{NoL} Z_j \, |I_j|^2\right] \tag{16a}$$

Where is the impedance of my line (Z_j) and the current (I_j) passing through my line.

The real power loss, voltage deviation, SVC sizing in terms of sending (i) and receiving (i) end voltage and line admittance (g_k) at k^{th} line with voltage (v), load angle (δ), impedance angle (θ) are

Real power Loss $F_1(u,v)=\sum_{k=1}^{NTL} g_k(v_i^2+v_j^2-2v_iv_j\cos(\delta_i-\delta_j))$ (16b)

Voltage Deviation $F_2(u,v)=\sum_{k=1}^{NL}(v_k-v_k^*)$ (16c)

SVC Size F3(SVC size)= rating of SVC Size (16d)

Multi-Objective Function(MOF) $F(u,v)=F_1(u,v)+F_2(u,v)+F3(SVCSize)$ (16e)

The real power loss, voltage deviation, SVC and any other FACTS devices placing sizing objective functions are described using the equations (16b) to (16d). If more than one objective is considered for optimization, then it is called as Multi-Objective Function (MOF) which is the sum of all the objective functions and optimizing them as given by equation (16e).

If the FACTS devices are placed in a transmission line to meet the objectives like FACS cost, generation cost, real power loss, voltage deviation, installation cost, reactive power loss with over-voltage control are discussed using the equations (17a) to (17h).

$C_1(f)=$ FACTS Cost Function (17a)

$C_2(f)=$ Generation Cost Function (17b)

Total Cost Function $C_3(f)=C_1(f)+C_2(f)$ (17c)

Reactive Power Loss Objective $O_1=\sum_{i=1}^{k}(v_i^2+v_j^2-2v_iv_j\cos(\delta_i-\delta_j)(g_{ij}\cos\theta_{ij})$ (17d)

Voltage Deviation $O_2=\sum_{i=1}^{n}\left(\frac{v_{iref}-v_i}{v_{iref}}\right)^2$ (17e)

Installation Cost based on reactive power support (Q) $O_3=0.003Q^2-0.315Q+127.38$ (17f)

Reactive Power Loss $OV_{Line}=e^{\lambda_{out}(100-BL)}>100\%$ Loading (17g)

Voltage Bus Indexing $\begin{Bmatrix} vtg_{bus}=1, 0.95<v_t<1 \\ vtg_{bus}=e^{\lambda_{vtg}|(1-vl)-0.05|} otherwise \end{Bmatrix}$ (17h)

The objective functions, objectives and indices parameters shown from equation (17a) to (17h) are used to improve the overall performance of the power system. In this reactive power loss, voltage at the bus and installation of FACTS devices cost are expressed in terms of voltage, branch line (BL) and coefficient to adjust the slope of exponential voltages (λ_{out} and λ_{vtg}). Further, minimization function objective functions for reactive power loss as a function of reactive power (Q), voltage stability loss index as a parameter of L-index and Cost of FACTS Controller are expressed as shown in the equations (18a) to (18c) and overall objective to minimize is given by the equation (18d).

Reactive Power Loss $f_1(x)=\sum_{i=1}^{N_{line}} Q_{i\_loss}$ (18a)

Voltage Stability margin (L_{index}) $f_2(x)=\max(L_j)$ (18b)

Cost of FACTS Controller $f_3(x)=C_{TCSC}+C_{SVC}+C_{UPFC}$ (18c)

Minimizing Objective (MOF) $f(x)=f1(x)+f2(x)+f3(x)$ (18d)

D. Aim to reduce the investment cost of FACTS equipment:

As the fourth and last goal in this dissertation, the investment cost related to the installation of FACTS devices in the network has been considered. In other words, considering this goal, it is tried to determine the capacity and location of FACTS devices in the network in such a way that the relevant investment cost is minimized as much as possible. References (19a) to (19c) describe the cost of installing TCSC, SVC and UPFC devices in the network, respectively.

$$C_{TCSC}=0.0015S^2-0.713S+153.75 \quad \text{(a19)}$$

$$C_{SVC}=0.0003S^2-0.3051S+127.38 \quad \text{(b19)}$$

$$C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22 \qquad \text{(c19)}$$

It should be noted that S in high relationships is the power performance of the equipment in terms of MVA and high relationships show the cost of installation of each device per kilowatt. In order to better understand this issue, the diagram of changes in relationships (19a) to (19c) is shown in Figure (5). As can be seen in this figure, as the performance of the equipment increases, the investment cost per kilowatt of their capacity decreases.

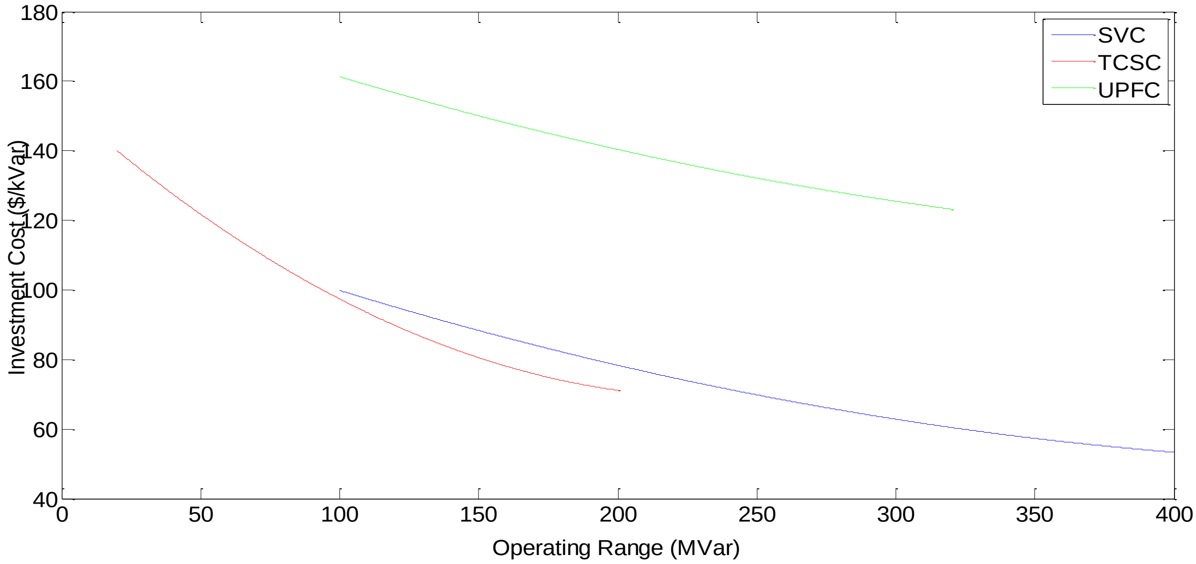

Figure5. FACTS device cost function

Finally, the investment cost of all FACTS devices installed in the network is calculated using Equation (20).

$$TotalCost = \sum_{i=1}^{N_{TCSC}} S_i \times C_{TCSC} + \sum_{n=1}^{N_{SVC}} S_n \times C_{SVC} \sum_{m=1}^{N_{UPFC}} S_m \times C_{UPFC} \qquad (20)$$

Which in the above relations, and respectively the number of TCSC, SVC and UPFC equipment installed in the network.

4. Multi-objective optimization problem analysis methods

Multi-objective optimization problems usually have a variety of answers according to different objective functions, neither of which is superior to the other. Two sets of methods have been proposed to obtain the answers to this problem. The first category is how to transform a multipurpose problem into a single purpose problem by combining objective functions. The most common method in this category is the weighted sum method. That is, this method uses the appropriate weighting factors to combine different goals into the objective function and uses a single-purpose optimization method to investigate the problem. The main drawback of this method is that these methods give the proper coefficients of the objective function and, as a result, the proper response requires a great deal of knowledge of the optimization problem. In other words, determining the final answer depends on the choice of appropriate weighting coefficients and is possible, and usually by changing the sample under study, the coefficients need to be readjusted.

Another category of multi-objective problem-solving methods is to use the concept of dominance and consider all objective functions of a problem to achieve problem-based solving. This is usually a more effective method. The most important of these methods are multipurpose genetic optimization (NSGAII) and multipurpose particle community optimization (MOPSO). Solving a multi-objective optimization problem creates a set of optimal answers. Considering all objective functions, this set is called the optimum response, or valid response, at the optimum point of the ray because of the property that the response does not take precedence over the other responses. Most multi-objective optimization algorithms use the concept of dominance to find the best ray point. Mathematically, the concept of dominance for the minimization problem can be expressed as:

We say that the answer set prevails over the answer set if the following two conditions are met simultaneously:

- The answer for all objective functions is superior to.

$$\forall i \in [1,2,...,m]:\ f_i(X_1) \le f_i(X_2) \tag{21a}$$

- The answer is better than at least one objective function.

$$\exists i \in [1,2,...,m]:\ f_i(X_1) < f_i(X_2) \tag{21b}$$

All non-dominant responses form a region called the affected region (beam surface). In this area, none of the answers dominate the others, leaving the final decision of the best answer to the decision maker.

A. General algorithm of meta-innovative optimization methods

As mentioned in this dissertation, two optimization methods NSGAII and MOPSO have been used to solve the problem of determining the capacity and location of FACTS devices in transmission networks. These two methods, which originally originate from the two methods of BRKGA and particle aggregation (PSO), respectively, are called meta-heuristic optimization algorithms. In general, the optimization process in meta-processing methods is as follows:

1- Creating an initial population in which each member of the population represents a possible answer to the problem.
2- Estimating the population using the objective functions of the problem
3- Selecting the top members of the population from among the main population
4- Upgrading and improving the top members of the population by using different operators
5- Selection of new core population members from the core population and upgraded members
6- Completion of the algorithm if the termination condition is met and otherwise return to the third stage

It should be noted that all the above steps are common in meta-heuristic optimization algorithms. However, the difference between single-objective and multi-objective algorithms in the method of selecting the top members of the population from the main population (third stage) is simple and clear in single-objective algorithms based on the objective function of the problem and In multi-objective algorithms, it is based on the concept of dominance. Also, there are differences between different types of optimization algorithms in the operators used to enhance population members (stage 4), which are briefly followed by population improvement methods in the BRKGA with pseudo-code as in Algorithm-1, particle community algorithms as in Algorithm-2 used in this end.

Algorithm 1: Biased Random key Genetic Algorithm (BRKGA)
Start Initialize, generate and evaluate random key vectors crowding distance assignment decode each random key vectors **while** estimate population select parents; add offspring population to the next generation and population biased crossover; generate mutants; mutations; mutants generation; elite and non-elite solutions repeat till (crowding distance, elite solution, max-iteration or time is reached) **end** **end**

B. Improve population in particle clustering algorithm

In the PSO algorithm, members of the population move in the search space so that the position of each member of the population, called the particle, changes based on the experience of the particle and its neighbors. Defined as the position of a particle in the search space in time, the position of a particle changes to its current position by adding velocity according to Equation (22).

$$V_i(t) = V_i(t-1) + C_1(Xpbest - X_i(t)) + C_2(Xgbest - X_i(t)) \quad (22)$$

Where the previous particle velocity is the best particle position, the best position among all the particles, and and random numbers. The intended structure for each population member in determining the optimal location and capacity of FACTS devices in the network is shown in Figure (6). As can be seen in this figure, each member of the population has two main sections. The first part is related to the location of FACTS devices in the network and the second part is related to the specifications of the equipment. As described in the modeling section, there is only one characteristic parameter for each of the TCSC and SVC devices, which are respectively for these two devices. There are also three characteristics that must be specified for each UPFC device on the network.

TCSC 1 Place	**...**	**SVC Place**	**...**	**UPFC Place**	**...**	r_{TCSC1}	**...**	Q_{SVC1}	**...**	V_{SE1}	ϕ_{SE1}	I_{SH1}	**...**

Figure6. The structure of population members in the location of FACTS devices

```
Algorithm 2: Non-dominated Sorting Genetic Algorithm –II (NSGA-II)
Begin
Initialize population
while
create random weight;
evaluate population;
generate offspring using tournament selection and genetic
algorithm operators, crossover and mutations;
generate new random weight;
repeat till (maximum number of generations are reached)
end
end
```

Multipurpose particle swarm optimization (MOPSO) has been used by many authors to solve two or more objective issues such as cost, CO2 emissions, and reliability, and is described in such studies. Masu. Economically and environmentally constrained NSGAII multi-objective optimization algorithms using various FACTS devices such as SVC and TCSC are described in. The pseudocode is the same as Algorithm 2, and the Graywolf optimization algorithm is the same as Algorithm 3.

```
Algorithm 3: Non-dominated Sorting Genetic Algorithm –II (NSGA-II)
Begin
    Initialize population of Grey Wolves
    while
        Calculate fitness function for search and grading agents
        evaluate population;
        generate best solution among the search agents;
        generate new search till the best search agent is identified;
        repeat till (maximum number of generations are reached)
    end
end
```

5. Simulation and numerical results

This section presents the results of the simulation. The network intended for optimal placement of FACTS devices is the IEEE 118 bus network shown in Figure7. The study network has 54 generators and 186 transmission lines. Information about generators, buses and grid lines are given in Tables (1), (2) and (3) of the thesis appendix, respectively. In the continuation of this section, the results of simulations in different scenarios related to the use of FACTS devices are examined.

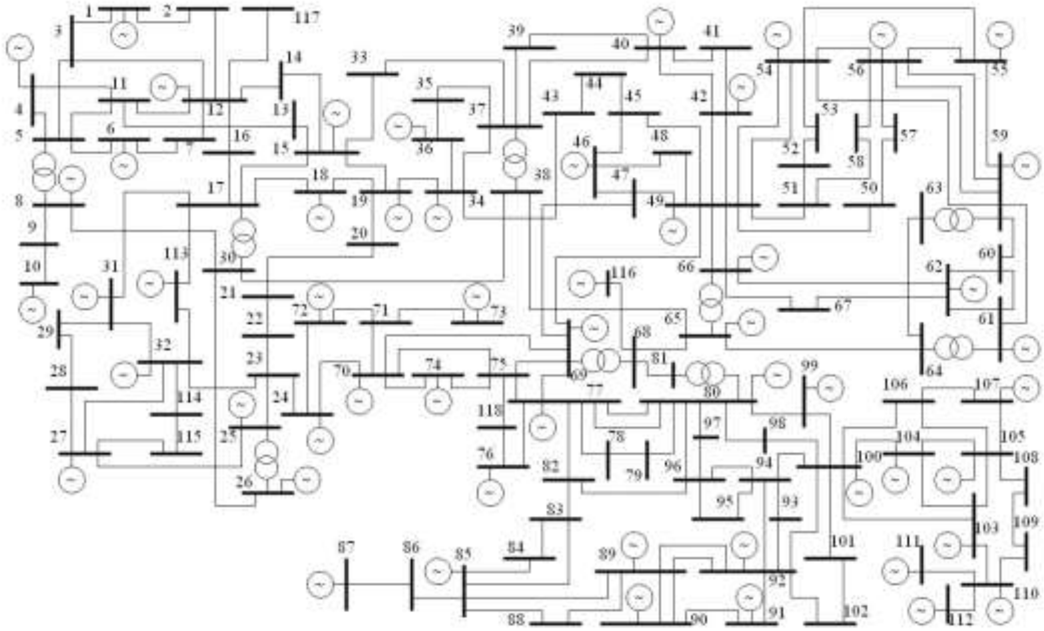

Figure7. IEEE 118 bus network

A. Locate a TCSC, SVC and UPFC equipment on the network:

This section presents the results of locating a TCSC, an SVC and a UPFC in the network. Figures (8) and (9) show the beam fronts related to the objectives of increasing the load and improving the voltage profile, as well as the objectives of reducing the investment cost and reducing the losses due to the NSG-II algorithm, respectively. Figures (10) and (11) also illustrate the results of the GWO algorithm similarly. It should be noted that due to the impossibility of showing all four goals in a 4-dimensional diagram, two 2-dimensional diagrams have been used for this purpose.

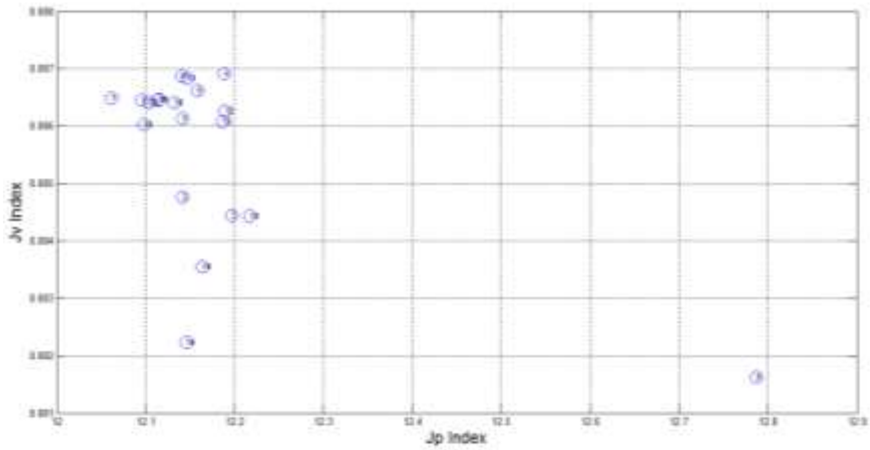

Figure8. Objective to increase the load and improve the voltage profile using the NSGAII algorithm

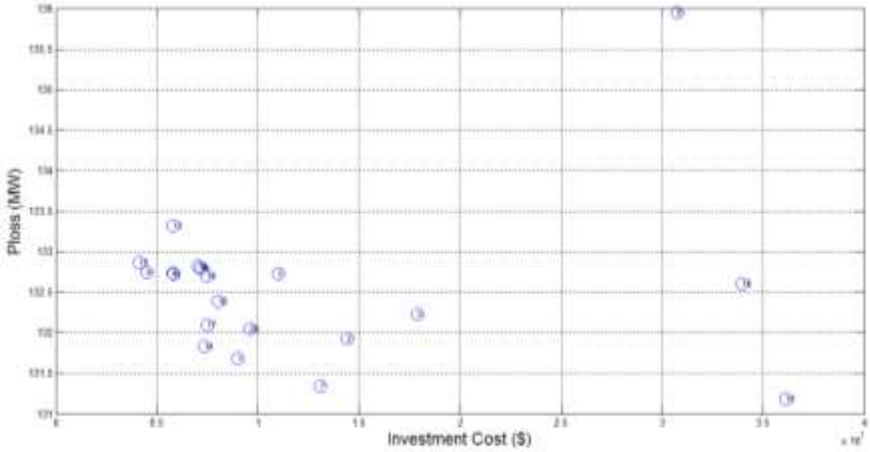

Figure9. Objective to reduce investment costs and reduce losses in the NSGAII algorithm

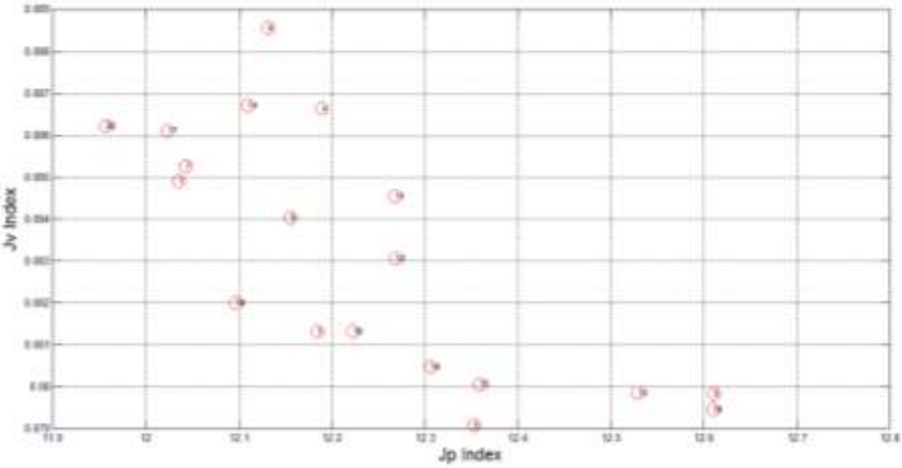

Figure10. Objective to increase the load and improve the voltage profile in the GWO algorithm

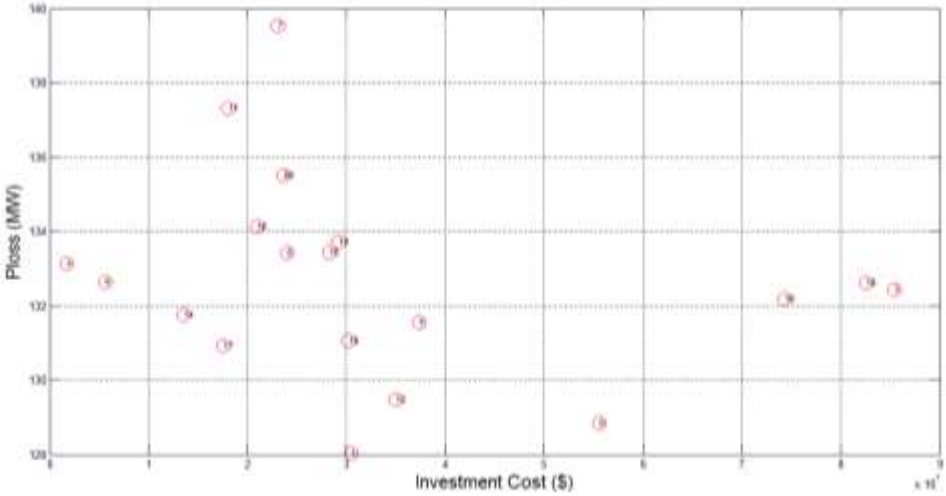

Figure11. Objective investment cost reduction and loss reduction objectives in GWO algorithm

The first noteworthy point in the above figures is that the beam fronts obtained from the NSGAII algorithm are more scattered, which gives more decision-making flexibility to transmission network designers and programmers to select the design. The final one is from the set of beam answers. On the other hand, it is carefully observed in the diagrams of the NSGAII and MOPSO algorithms that the NSGAII algorithm provides a set of more optimal answers to transmission network designers and programmers.For example, it can be seen accurately in the axis related to the goal of reducing losses that the NSGAII algorithm offers a selective amount of 128 MW of losses, which in the MOPSO algorithm is at best about 131 MW. Based on this, it can be concluded that the NSGAII algorithm performs better in the issue of location and capacity of FACTS devices considered in this dissertation. It should be noted that this issue cannot be easily generalized to other problems and depending on the conditions and structure of the problem, each of the two algorithms may be preferred over the other. However, due to the better performance of the NSGAII algorithm in the issue of this dissertation, the results of this algorithm will be discussed below.

B. Select the final answer from the Beam Answers front

As stated in the previous section and observed in the previous section, the output of multi-objective optimization algorithms is a set of optimal solutions that ultimately transmission network designers and planners based on the importance of the objectives. Different - must select one of the optimal answers from the set of beam answers and install FACTS devices based on it in the network. In this section, we will discuss this issue as much as possible and analyze the adoption of different approaches in choosing the final answer. It should be noted that as mentioned in the previous section, the beam fronts obtained from the NSGAII optimization algorithm are used in this section.

C. Select the final answer with the approach of high importance of profile improvement

In this section, it is assumed that the importance of the goal of improving the network voltage profile for transmission network designers and programmers is of the highest degree. It is carefully seen in Figure (12) that answer number 5 has the best status in terms of indicators related to the improvement of the network voltage profile. By looking closely at the values of the other objective functions of Answer 5, it can be seen that this answer is not in a very unfavorable position in terms of other objectives. In other words, considering the fact that considering one goal may lead to an adverse effect on other goals, it is necessary to examine the status of other goals. Table1 shows the specifications for Answer 5.

Table1. Selection of the final answer with the approach of high degree of importance of improving the voltage profile (Answer No. 5)

Parameter	The amount of	Parameter	The amount of
SVC Location	21 bus	ISH	0/0036
Q_{SVC}	39	JV	0/0790
TCSC Location	96 line	JP	12/35
γ_{TCSC}	-0/8	SVC Investment Cost	$4531437
UPFC Location	71	TCSC Investment Cost	$18755534
V_{SE}	0/3	UPFC Investment Cost	$14063206
ϕ_{SE}	112/95 Degrees	Network Losses	131/55 MW

Also, the network voltage profile before and after installing FACTS devices in the network based on answer number 5 is as in Figure (12). Based on this figure, the network busses voltages are in this range has been improved by placing the SVC on bus 21.

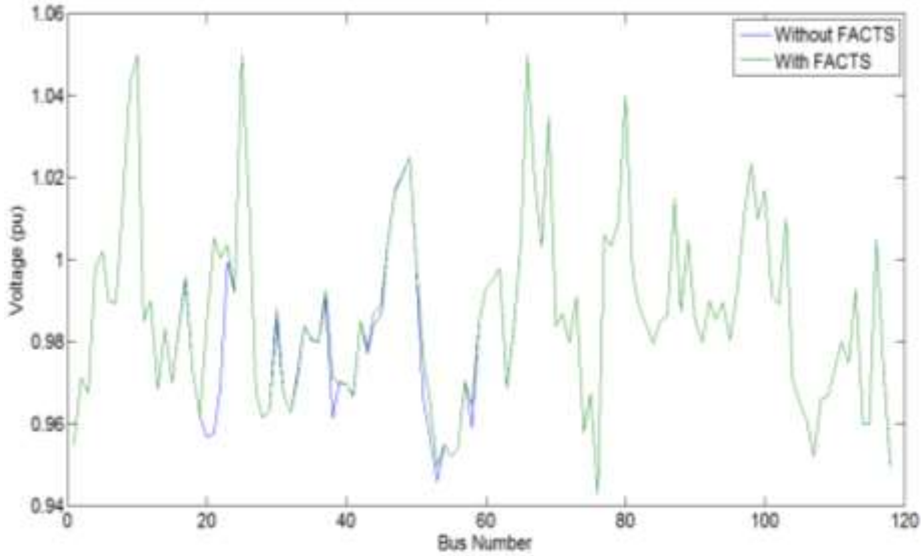

Figure12. Network voltage profile before and after installation of FACTS devices based on answer number 5

D. Select the final answer with the approach of high degree of importance of increasing load

In this section, it is assumed that the importance of the goal of increasing network load and relieving line congestion for transmission network designers and programmers is of the highest degree. It is carefully seen in Figure (10) that Answers 20 and 17 are in the best position in terms of the index, which is related to increasing the load of network lines. Carefully in the values of the other objective functions of the answer number 20, it is observed that this answer is not in a favorable position in terms of the amount of losses, and therefore selecting the answer number 17, which is in a better position in terms of losses as well as the other two goals. Is, it seems a more sensible choice.However, if the sole purpose of increasing network load is important for transmission network designers and programmers and the increase in network losses is not significant in this case, the choice of answer number 20 will be justified. Table (2) shows the specifications for Answer 20.

Table2. Selection of the final answer with the approach of high importance of increasing network load (Answer No. 20)

Parameter	The amount of	Parameter	The amount of
SVC Location	49 bus	J_{SH}	-0/124
Q_{SVC}	28MVAR	J_V	0/0862
TCSC Location	33 line	J_P	11/95
γ_{TCSC}	-0/52	SVC Investment Cost	$3332006
UPFC Location	135	TCSC Investment Cost	$14251849
V_{SE}	0/3	UPFC Investment Cost	$6094326
ϕ_{SE}	126/12 Degrees	Network Losses	135/50 MW

Also, the network voltage profile before and after installing the FACTS devices in the network based on the answer number 20 is as in Figure (13). Based on this figure, compared to the voltage profile obtained in the case of installing FACTS devices in the network based on Answer 5, the rate of improvement of the voltage profile in this case is much less. The reason for this is clear and justifiable due to the approach of increasing the network load and not improving the voltage profile.

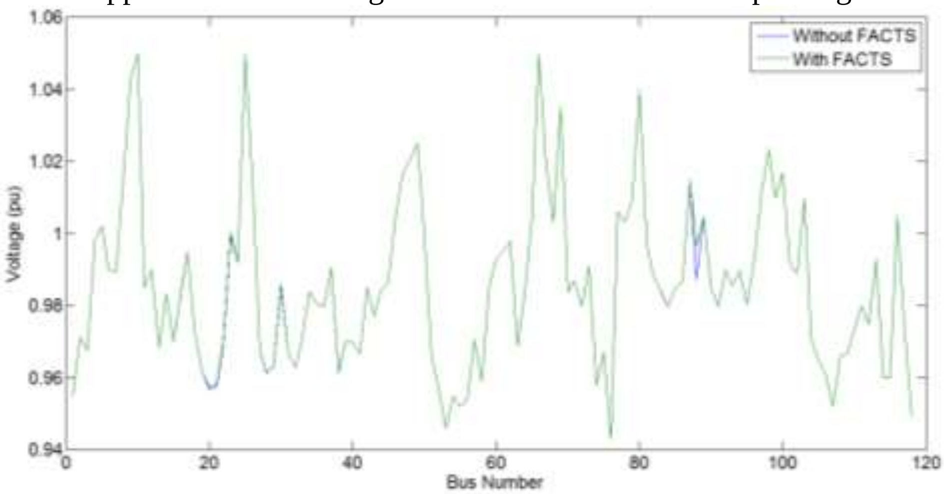

Figure13. Network voltage profile before and after installation of FACTS devices based on answer number 20

E. Select the final answer with the approach of high importance of reducing network losses

In this section, it is assumed that the importance of the goal of reducing active network losses for transmission network designers and planners is of the highest degree. It is carefully seen in Figure (11) that the answer number 1 is in the best position in terms of casualties. Carefully in the values of the other objective functions of Answer 1, it can be seen that this answer is not in a very unfavourable situation in terms of other objectives, and therefore the designers and planners of the transmission network can reduce the network losses with sufficient confidence. Install FACTS based on this answer in the network. Table (3) shows the specifications for Answer 1.

Table3. Selection of the final answer with the approach of high importance of reducing network losses (Answer No. 1)

Parameter	The amount of	Parameter	The amount of

ISSN : 2347-7180
Vol-13, Issue-1, No. 3, January 2023

SVC Location	11 bus	I_{SH}	0/0171
Q_{SVC}	38	J_V	0/0848
TCSC Location	96 line	J_P	12/03
γ_{TCSC}	-0/8	SVC Investment Cost	$4430614
UPFC Location	67	TCSC Investment Cost	$18224253
V_{SE}	0/3	UPFC Investment Cost	$7811800
ϕ_{SE}	119/77 Degrees	Network Losses	128 MW

Also, the network voltage profile before and after installing FACTS devices in the network based on answer number 1 is as in Figure (14). Based on this figure, compared to the voltage profile obtained in the case of installing FACTS devices in the network based on the answer number 20, the rate of improvement of the voltage profile in this case is higher. Also, by comparing the results obtained in this case with the results of the previous cases, it can be concluded that the goals of improving the voltage profile and reducing network losses are goals in line with each other, but this is true of the goal of increasing network load.In other words, by selecting any of the targets to improve the voltage profile or reduce network losses in order to locate FACTS devices, another target will be improved, but selecting the target to increase the network load may worsen the voltage profile of either or both. Reduce network losses.

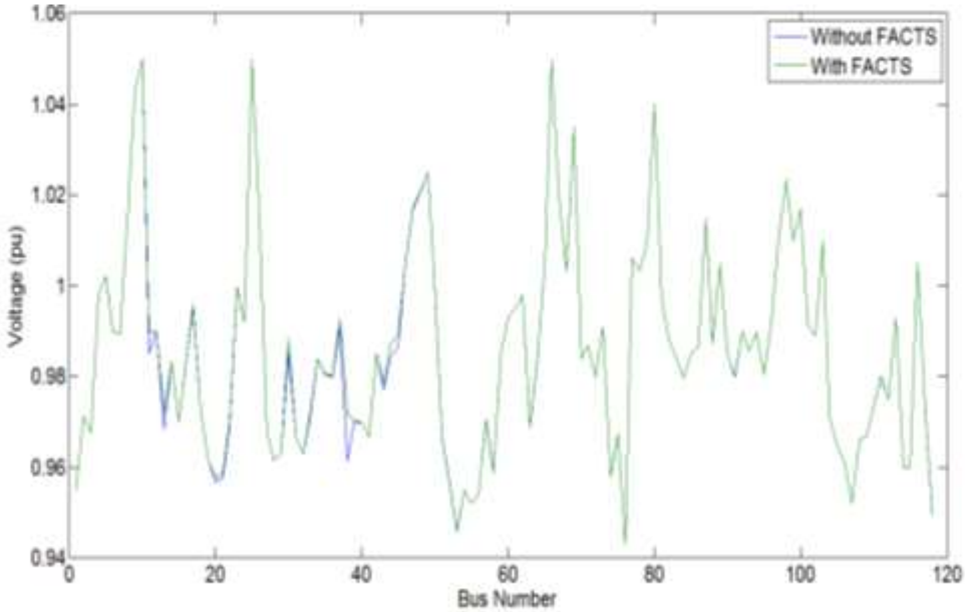

Figure14. Network voltage profile before and after installation of FACTS devices based on answer number 1

F. Select the final answer with the approach of reducing investment costs

It is clear that considering the reduction of investment costs will in itself lead to the non-installation of FACTS devices in the network. However, considering economic evaluation along with technical goals can avoid unnecessary costs. For example, in choosing the final answer with the network loss reduction approach, answer number 9 may be chosen, which, if the investment costs are not considered, will lead to an unnecessary increase in investment costs. Therefore, it is necessary to consider the investment costs when selecting the final designs for the installation of FACTS devices in the network, taking into account the technical objectives, so that the mentioned process can be done technically-economically.

Without FACTS devices, power loss (MW) is 7.44, voltage deviation is 0.0317 and cost is 5.8671x106$. The summarised results are shown in Table (4) for IEEE 118 bus network using different FACTS devices like TCSC, UPFC and UPFC with algorithms like multiple objective GA, PSO, NSGA-II and GWO. With all these methods with multiple objective functions such as real power loss, overall voltage deviation and overall cost with fitness function, the GWO is observed to perform better with same size of TCSC installation at optimal location at bus 16. Similarly for UPFC and SVC placement also, GWO algorithm method is showing better results than NSG-II, MPSO and BRKGA.

Table4. Optimal location of FACTS devices and results like power loss, voltage deviation, overall cost and final settled fitness function value under optimal conditions

FACTS Device	Algorithm	LOC Line	Size	Power Loss (MW)	Voltage Deviation (pu)	Overall Cost (x10^{6}\$)	Fitness Value
TCSC	BRKGA	16	-0.6347	7.2042	0.0281	5.8234	0.9798
	MPSO	16	-0.6347	7.1931	0.0280	5.8230	0.9801
	NSG-II	16	-0.6347	6.9983	0.0275	5.8218	0.9812
	GWO	**16**	**-0.6347**	**6.9912**	**0.0271**	**5.8191**	**0.9814**
UPFC	BRKGA	Bus 6, line 11	-28.1142 -0.8	6.9593	0.0245	5.6985	0.9458
	MPSO	Bus 6, line 11	-23.9493 0.4013	6.9330	0.0244	5.7720	0.9518
	NSG-II	Bus 6, line 11	-29.6346 -0.8	6.9140	0.0241	5.7040	0.9452
	GWO	**Bus 6, line 11**	**-23.5126 -0.8**	**6.9133**	**0.0241**	**5.7054**	**0.9451**
SVC	BRKGA	8	-28.7126	6.8943	0.0241	5.6848	0.9387
	MPSO	8	-27.9154	6.8726	0.0238	5.6324	0.9388
	NSG-II	8	-26.6328	6.8424	0.0231	5.5738	0.9397
	GWO	**8**	**-24.9490**	**6.8414**	**0.0231**	**5.5737**	**0.9394**

Without FACTS devices, power loss (MW) is 7.44, voltage deviation is 0.0317 and cost is 5.8671x106$.

Mean Absolute Error (MAE), Mean Squared Error (RMSE), Root Mean Squared Error (RMSE) and standard deviation (SD) based error indices are compared with BRKGA, MPSO, NSG-II and GWO. in most of the cases, GWO is found to give better optimal solution than NSG-II, MPSO and BRKGA as shown in Table (5).

Table5. Optimally located FACTS devices with different error estimation indices with various meta-heuristic algorithms under optimal conditions

FACTS Device	Error Method	BRKGA	MPSO	NSG-II	GWO
SVC	MAE	6.1905X10^{-2}	6.0205X10^{-4}	4.0808X10^{-10}	1.1067X10^{-12}
	MSE	6.0198X10^{-4}	4.5171X10^{-4}	3.9683X10^{-12}	1.0762X10^{-14}
	RMSE	3.2937X10^{-3}	2.4715X10^{-3}	9.6048X10^{-12}	4.9343X10^{-14}
	SD	3.2936X10^{-3}	2.4714X10^{-3}	8.8962X10^{-12}	4.8975X10^{-14}
TCSC	MAE	3.5401X10^{-2}	1.2001X10^{-3}	1.6626X10^{-12}	1.9754X10^{-13}
	MSE	3.4685X10^{-4}	1.1795X10^{-4}	1.6577X10^{-12}	1.9355X10^{-15}
	RMSE	1.8898X10^{-3}	1.7650X10^{-4}	1.6864X10^{-12}	2.9254X10^{-15}
	SD	1.8997X10^{-3}	1.3355X10^{-4}	1.1503X10^{-13}	2.2360X10^{-15}
UPFC	MAE	8.7419X10^{-2}	6.3382X10^{-2}	5.9018X10^{-12}	7.2659X10^{-13}

	MSE	8.2622X10^{-4}	5.9905X10^{-4}	5.9780X10^{-14}	6.8762X10^{-15}
	RMSE	2.8540X10^{-3}	2.1702X10^{-3}	1.9965X10^{-13}	1.9492X10^{-14}
	SD	2.8381X10^{-3}	2.7957X10^{-3}	1.9498X10^{-13}	1.8554X10^{-14}

Among different objectives like, real power loss, reactive power loss and L-Index based voltage stability, if only one objective is considered and optimality is expected, with the use of multiple FACTS devices and without FACTS devices, the parameter values are summarised and tabulated as shown in Table 6.

Table6. Single objective functions like real power loss, reactive power loss and L-index with and without FACTS device placement and the degree of satisfaction under optimal conditions

Parameter		Application of the FACTS device		Value
P_{loss} (MW)		Without FACTS Device		392.08
		With FACTS Device		331.51
Q_{loss} (MVAr)		Without FACTS Device		984.94
		With FACTS Device		660.55
L-Index		Without FACTS Device		0.1071
		With FACTS Device		0.1042
Total Cost of FACTS Devices (X10^6 US \$)				19.13
Degree of Satisfaction				
µP	µQ	µL		µG
0.8927	0.8634	0.9131		0.9158

It can be observed that, the real and reactive power losses and the L-Index parameter value decreased considerably with the application of FACTS devices even though the cost of FACTS devices is high with a value of \$19.13X10^6. Further the satisfaction levels with real power parameter (µP), reactive power parameter (µQ), L-Index parameter (µL) and overall index with GWO (µG). The µG is the cubic root of product of the remaining indices parameters (µP* µQ* µL)$^{1/3}$.

Under multiple objective constraints such as real power loss, reactive power loss and L-index with any one parameter as major objective, the results are summarised as in Table (7).

Table (7): Multiple objective functions like real power loss, reactive power loss and L-index under major objective constraint with and without FACTS device placement

Objective	Location From (i) to (j)	Size (pu)	Cost of UPFC (X10^6 US\$)	Comparison of Results: Parameter	Without UPFC	With UPFC
Q_{loss} Min	3-5	0.02	**26.68**	**Q_{loss}**	**984.94**	**495.95**
	5-11	0.26		P_{loss}	392.08	320.61
	11-13	0.29				
	16-17	0.36		L-Index	0.1071	0.1038
	30-17	0.57				
P_{loss} Min	3-5	0.04	36.60	Q_{loss}	984.94	508.12
	5-11	0.11		**P_{loss}**	**392.08**	**317.23**
	11-13	0.16				
	21-22	0.29		L-Index	0.1071	0.1037
	22-23	0.28				
L-Index	5-11	0.30	24.13	Q_{loss}	984.94	791.05
	43-44	0.17		P_{loss}	392.08	360.08
	44-45	0.15				
	63-64	0.46		**L-Index**	**0.1071**	**0.0819**
	82-83	0.26				

Here, with respect to the UPFC based FACTS device at location in 5- lines, the parameter values like real power loss, reactive power loss and L-index can be seen. It can be observed that, if major objective parameter is chosen with limited constraints on other objective function, the respective objective function value is showing better performance. It can also be considered that voltage stability based cost optimization is better than reactive power loss minimization, while the real power loss minimization is expensive of all.

If single or multiple FACTS devices are used and the combination and with 5 placed location as in Figure (6) and Table (7) are summarised as in table 8. It can be observed that the overall satisfaction is better with TCSC, overall cost is satisfactory with SVC and in terms of required overall capacity for installation, UPFC is better. However, if multiple FACTS devices are used in the IEEE 118 bus network, it shows most optimal among these three parameters.

Table (8): With respect to 5 locations placement of individual FACTS devices, the parameters like overall satisfaction, overall cost and installed capacity parameters are shown

Devices at 5 locations	TCSCs	SVCs	UPFCs	**Multiple**
Highest degree of overall satisfaction	**0.9792**	0.4726	0.8123	**0.9158**
Overall cost (X10^6 US$)	17.5	**14.44**	26.68	**19.13**
Total installed capacity (pu)	1.75	1.13	**1.05**	**1.26**

G. Summary from the work

Setting up a FACTS device is very important in your appliance planning to improve the overall performance of your appliances and to get the maximum possible profit in terms of justifying your capital investment. This white paper uses a complete method-based, multipurpose GA, PSO, NSGII, and GrayWolf optimization technique to identify the high-value locations and sizes of TCSC, SVC, and UPFC, and the combination of these three FACTS devices. By comparison, the TCSC, SVC, and UPFC attributes are also largely based entirely on the formalized optimization framework. The following summary points can be derived from the provided works.

- UPFC firmly believes that it is the best FACTS device of TCSC and SVC to minimize Lindex and limit active and reactive power losses. However, the UPFC setup price can be very high.
- TCSC is the cheapest of the SVC and UPFC to improve voltage stability and reduce loss due to reactive power.
- For the active power injection or to reduce the active power losses, the TCSC is not a better alternative compared to SVC and UPFC.
- The TCPS gives a better solution in terms of minimization of line losses and the installation price.
- To achieve all one or all the objectives simultaneous with the use of TCSC, SVC, and UPFC, the Grey-wolf optimization is a better alternative compared to NSG-II and it is better than multi-objective PSO and GA optimization methods. The maximum price of fitness function is acquired with the use of the multiple (more number of types of) FACTS devices primarily based totally on the proposed method, which suggests better satisfaction level achieved with TCSC and with combination of these devices compared to UPFC and SVC. Therefore, the GWO approach may be very powerful for finding foremost places of more than one FACTS device when more than one objective are contradictory in nature.

6. Conclusion

In this dissertation, modelling and simulation of the location and capacity of FACTS devices in the transmission network using multi-objective optimization methods were studied. For this purpose, four objectives of increasing network load capacity, improving voltage profile, reducing network losses and also reducing investment costs of FACTS devices were considered as multi-objective planning goals and using two methods of multi-objective genetic optimization. And the multi-objective optimization of the particle community has been solved. It should be noted that three types

of FACTS devices including SVC devices, TCSC devices and UPFC devices were considered as devices that can be installed in the transmission network and simulation results were presented in order to locate and find the capacity of these devices in the network.
The simulation results show that the NSGAII optimization and GWO algorithm performs better than the MOPSO and BRKGA algorithm in locating FACTS devices in the network. In other words, this algorithm provides more efficient answers and a more scattered beam response set for transmission network designers and programmers to select the final answer.

Also, the multi-objective optimization approach used in this dissertation in order to locate FACTS devices, considering that it provides a set of optimal answers to transmission network planners, provides this possibility. Make the designers and operators of the transmission network choose the appropriate approach to install these devices in the network based on the importance of different goals and monitoring other goals. In other words, if a single-objective approach is adopted due to the issue of misalignment of different goals, it may lead to the weakening of other goals, which highlights the need to adopt a multi-objective optimization approach in the location of FACTS devices.

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