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RESEARCH ARTICLE

Optimal Power Flow in the Presence of HVDC Lines Along With Optimal Placement of FACTS in Order to Power System Stability Improvement in Different Conditions: Technical and Economic Approach

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ABSTRACT Due to the high cost of investment for the development of the transmission network and the key role of transmission networks in the restructured environment, the use of FACTS devices is considered a key issue. In this paper, two issues of location and optimal capacity of TCSC in transmission networks has been investigated. In the proposed method, the objective function is defined in order to reduce losses and increase network load ability. This problem was studied in two technical and economic approaches and its results were presented. For this purpose, first, the problem of locating in peak load conditions of the network was done separately and then simultaneously in the technical approach. Next, in the economic approach, the cost of installing the equipment in question was also included in the optimization problem. In this approach, the profit from installing TCSC is considered as the objective function of the problem and the best place and capacity of the equipment was determined in order to achieve the maximum amount of profit. Average models available in the references have been used to model FACTS devices. Also, due to the contingency in the network, the improvement of the maximum load ability of the network lines under the outages conditions of the line and generator has been discussed. In order to two-objective optimization in the technical approach, the genetic algorithm based on the Pareto front and the multi-objective HSA has been used. This algorithm has a good speed in the convergence of large nonlinear problems. Also, a comprehensive and new model with the combination of TCSC-high-voltage direct current (HVDC)- static VAR compensators (SVC) has been introduced and the intended simulation has been performed. Finally, with the help of a new meta-heuristic algorithm, the topic of optimal power flow in the presence of these devices has been comprehensively presented and the results have been compared with similar methods. The results of numerical studies show that FACTS devices can have a significant effect in reducing losses and increasing network load ability.Also, the type of equipment used has a great impact on the outcome of the problem. As it is clear from the results of the simulations, in the technical approach, in order to achieve the lowest amount of losses in the IEEE 30-buses network by installing the equipment, TCSC should be installed in line number 15 between buses 4 and 12. The best amount of reactance compensation of this line was about 79.90% of the line reactance, as a result of which the network power loss was reduced by about 4.17%. Also, in the continuation of the simulations, the best place and capacity to install TCSC in the network was determined in order to improve the network load ability. As a result of this simulation, the best location of line 36 between buses 27 and 28 was determined, and the best amount of reactance compensation

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for this line was also 80% of the line reactance. As a result of this compensation, the load index value of the network improved by 23.02%. Also, in the economic approach, the best location and capacity to obtain the maximum profit was obtained in order to reduce power losses and improve the loadability of the network. The simulation was implemented by MATLAB software and the results showed the effectiveness of the proposed method in all case studies.

INDEX TERMS Power losses, flexible ac transmission system (FACTS), load ability, optimal power flow (OPF), contingency, thyristor controlled series capacitor (TCSC), optimal placement, technical and economic approach, strength pareto evolutionary algorithm (SPEA), harmony search algorithm (HSA).

I. INTRODUCTION

On the one hand, the rapid growth of the industry in recent years has led to the linking of the power networks of neighboring countries and the formation of integrated and integrated networks, increasing the production capacity and putting the lines under heavy loading and on the other hand, efforts to strengthen the voltage and improve stability increased in interconnected networks. On the other hand, budget limitations and sometimes technical limitations of building new lines and the need to improve the economic parameters of the power system were also among the things that were an obstacle in the way of reforming the power system and occupied the minds of the users of the power system. Reactive power supply and common problems in transmission systems that cause improper operation along with low efficiency, high cost of repairs and maintenance of traditional compensators led to the introduction of a new generation of compensators based on power electronic equipment in the late seventies. These devices were called FACTS devices because of the flexibility and high efficiency they provide to the ac power transmission system. These devices can be effective in changing the active and reactive power of the lines by controlling the size and angle of the voltage of the buses and the impedance of the lines. In the 80s, the main goal of providing FACTS tools was to increase the power transfer capability of existing lines, in order to postpone investment and prevent the construction of new lines and increase the level of power exchanges between producers and consumers [1].The paper is presented for the development of the research conducted in the field of optimal placement of FACTS devices in order to reduce power losses and improve network load ability, which is the improvement of static voltage stability, and the performance of TCSC in improving the target functions will be evaluated. So far, a lot of research has been done in this field, including: In [2], the optimal location and capacity of TCSC is determined in order to increase network load. FACTS tools such as TCSC are one of the introduced tools that can increase the network's load at a lower cost. In [3], introduces the SPEA method in solving multi-objective optimization problems with the Pareto front approach. In this reference, the results of simulations using this method have been compared with the results of non dominated sorting genetic algorithm (NSGA) and NSGAII methods, which has proven the efficiency of the mentioned method. In [4], has found the weak bases of the network by using modal analysis. The results of this article have shown that the modal analysis has provided an acceptable performance in determining the weak bases of the network. Modal analysis is one of the methods used to improve the static stability of the voltage, which is the result of improving the load capacity of the network. In [5], has also introduced some indicators of load ability and static stability of voltage and the phenomenon of voltage collapse and has examined them. In [6], the power system equipped with TCSC is investigated. In this article, the GA is used to adjust the controller parameters.The damper controller is also assumed to be a PID. In [7], the issue of electric cars has also been evaluated. In this reference, the impact of electric vehicle charging stations on network load ability and static voltage stability has been studied and evaluated. In [8], also deals with the static stability of power grid voltage in the presence of wind power plants. This authority has studied the effect of the presence of wind generating units on the load capacity of the network and the static stability of the voltage. In [9], an efficient and reliable optimization algorithm using Levy flight distribution and particle spiral motion is proposed to solve the optimal reactive power dispatch (ORPD) problem and identify the optimal location and ratings of the SSSC device. In this paper, an efficient model of SSSC based on power injection approach is used for representation the SSSC in ORPD. In [10], has also discussed the location of TCSC and SVC in order to improve network load, voltage profile and reduce losses. This authority has performed simulations using the particle swarm optimization (PSO) algorithm based on the Pareto front, which is one of the intelligent and evolutionary algorithms. The results of these simulations show that the PSO algorithm has a better performance than the GA based on NSGA and NSGAII methods. In [11], a comprehensive review of FACTS device models including SVC, TCSC, and HVDC has been done and their simultaneous application in the network has been investigated. In [12], Profits from installing TCSC and wind generators in competitive markets have been calculated. The objective functions of the network are to maximize profit and social welfare, the efficiency of its installation has been proven using simulations on two networks of 14 and 118 buses. In [13], TCSC is also used in order to increase transient stability in the power system. One of the criteria of voltage stability is that in any bus, when the reactive power injected into that bus increases, the voltage range also increases. But if the voltage decreases with the increase of the reactive power injected into the bus, the system becomes unstable [14]. In [15], in order to improve network load ability and reduce power losses, different types of SVC and TCSC equipment and other FACTS devices have been compared with each other. The optimal location and capacity of this equipment has been calculated. In [16], the ability to improve the voltage stability of two FACTS devices such as SVC and static synchronous compensator(STATCOM) has been compared. In [17] and [18], using two static synchronous series compensator (SSSC) and current source converter (CSC) devices, he improved the static stability of the voltage in the network. This reference has provided a mathematical model of the voltage dependence of SSSC and CSC devices. The results of the simulations of this article have shown that each of these two equipment's have their desired performance, but as the best equipment selection in improving the objective function of the problem, the SSSC equipment is superior to the CSC. In [19], the effect of series, parallel and series-parallel FACTS devices on improving the static stability of voltage has been investigated. In [20], a new probabilistic approach is presented to find the optimal location and capacity of several types of FACTS devices, to improve the static voltage characteristics of a power network. In [21], the use of two FACTS devices named SVC and TCSC has been studied in order to improve the static stability of voltage. The results have shown that as a better option, it should be said that the SVC equipment has performed better than the TCSC in improving the static stability of the voltage. The reason for this is that SVC is a device that is placed in parallel in the network and injects reactive power exactly at the same bus of the network that needs reactive power (weak bus of the network). FACTS devices such as SVC and TCSC have been used in the network in order to manage congestion and improve power distribution and static voltage stability in the network [22]. In [23], the issue of finding the optimal location and configuration of TCSC in a power system has been studied. In [24], introduced the optimization algorithm of PSO in order to distribute optimal reactive power in order to reduce losses and prevent voltage instability. In [25] and [26], describe how to model multi-objective functions using intelligent algorithms. In these articles, mathematical and intelligent methods are used to solve multi-objective problems. In the references [27] and [28] different types of HSA have been introduced and various problems have been solved with it. In these articles, basic and advanced harmony search algorithm is introduced. Each of the articles has changed the efficiency of the algorithm and made the algorithm more suitable for use by making changes in the steps of the algorithm. The objective functions used in some of these articles are also multi-part functions, by studying them, one can see how to model multi-objective functions by the harmony search algorithm. In [29], the author studied the linear modeling of SSSC in single-machine and multi-machine power systems and modified the Hefron-Phillips model. So that for this device, a structure similar to the modified Hefron-Phillips model has been obtained with minor differences. In this paper, different methods are used to select the feedback signal for the complementary controller. The supplementary controller used in this paper is designed in only one working point, which is tested in the nonlinear model in several working points to evaluate the performance of this controller. In [30], the issue of congestion in transmission networks and the effect of FACTS devices on reducing congestion have been investigated. This article has investigated the issue of locating FACTS devices in a restructured environment. The main goal of the authors of this problem was to find the best place for FACTS devices in such a way that the access of participants in the electricity market to the transmission network is increased. The objective function is defined in order to reduce the compression cost. In [31], extensively investigates the calculations of the compensation factor of the TCSC, which are used to accurately evaluate the negative impacts of the TCSC on the performance of conventional distance relays. In addition, IEEE 39-bus system, as a large interconnected system, is also examined to generalize the TCSC impact on different interconnected systems. In [32] and [33], the brainstorm optimization algorithm (BSOA) is used to solve the placement problem and adjust the parameters of FACTS devices. In this paper, a TCSC is used as a series device and an SVC is used as a parallel device. For simplicity, very simple models have been used for the mentioned equipment. In [34], the adaptive neural fuzzy inference system (ANFIS) method (combined fuzzy-neural method) based on artificial networks is used to control the SSSC compensator to strengthen the transient stability. The proposed ANFIS controller is a combination of the advantages of fuzzy controller and neural network. It has been observed that the ANFIS structure is trained by the data generated by the SSSC fuzzy controller. The proposed SSSC controller sufficiently improves the voltage profile of the disturbed system and its results show that the SSSC compensator with the ANFIS controller is capable of finding fault locations and changes in performance location. In [35], The effect of SSSC to reduce the inrush current and improve the voltage sag has been investigated. In this way, by injecting voltage during start-up, it improves the voltage drop and by shifting the voltage angle, it reduces the inrush current. In order to study and simulate this article, powerful software for transient states analysis PSCAD haes been used. In [36], has studied the issue of finding the optimal location and settings of TCSC in the power system. In this reference, the reduction of losses in transmission lines has been discussed using evolutionary algorithms.This authority has used one of the latest algorithms called evolutionary-differential (ED) algorithm to solve the problem. Reference simulations [36] have been performed on IEEE standard 14-bus network. The taxonomy of related research works is given in Table 1.

A. TCSC INSTALLATION PROJECT IN DIFFERENT COUNTRIES

Also, TCSC installation projects have been carried out worldwide, for example: In China's power grid, the limit of power transmission by the Yimin-Fengtan line to maintain transient stability is 1600 MW, which reaches 2024 MW after the installation of TCSC, equal to the maximum output of the Yimin power plant (without considering internal consumption) [31]. In the South China network, to overcome the problem of inter-regional fluctuations, a study was conducted which led to the installation of a TCSC in the west-east line of this network. was installed, which, in addition to improving the stability of the network and eliminating inter-regional fluctuations, increased the power transmission capacity of this line to 242 megawatts [32]. In Sweden, a number of series compensators are connected to some nuclear power plants in 400 kV lines. To deal with the problem of sub-synchronous resonance of the network, it was decided to divide the line series capacitor into 2 fixed parts and TCSC to overcome this problem [33]. With the installation of fixed capacitor and TCSC at one end of the 412 km 400 KV Raipur-Roorkla two-circuit line that connects the east of India to the west, the compensation rate has been approximately 40% [34]. TCSC and fixed capacitor were used to solve the problem of damping power fluctuations in the communication line between the northern and southern areas of the Brazilian power grid. This compensation was done in such a way that 54% of the compensation is with the capacitor bank, which is divided into 5 capacitor banks, and 12% of it is done by one TCSC bank [35]. Due to the rapid growth of the load, the power systems are operating close to their limits. For this reason, the issue of network load ability or static voltage stability is one of the main concerns for the safe operation of power systems [36]. This paper is presented in order to develop the research done in the field of optimal placement of FACTS devices in order to reduce power losses and improve network load ability, which is the improvement of static voltage stability. In this paper, the performance of TCSC in improving the desired objective functions will be evaluated. Therefore, the objectives of this paper are as follows: Investigating the effect of TCSC on increasing network load ability separately-Investigating the effect of TCSC on reducing power losses separately- Investigating the effect of TCSC on increasing network load ability and reducing power losses simultaneously using SPEA method in genetic algorithm.

B. BACKGROUND OF THE POWER TRANSFER CAPABILITY CONTINGENCY ANALYSIS

Transmission networks, which are responsible for exchanging power between production and consumption points, play an important role in power systems. Transfer capability (TC) index is defined to ensure the proper and safe operation of the transmission network and prevent the occurrence of overloads or unauthorized voltage drops in the network. Total transfer capability (TTC) is used as an index to perform electric power exchanges in the interconnected transmission network [37]. The occurrence of fault in network equipment is inevitable, therefore, it is necessary to take into account the contingency conditions governing the network in the calculation of transfer capability. Choosing the base network is one of the important steps in TTC evaluation, because with the change of the base network, The possibility of TTC change is very high. In the power system, we are constantly faced with changes in network conditions. Usually, the uncertainty in the calculated TTC is greater for long periods, because it is more difficult to predict the system conditions for long periods of time. Since there is always a contingency of an fault in the system equipment,It is necessary to evaluate TTC in the conditions of the occurrence of faults by considering different faults in the network and in fact defining different basic networks. In the common methods of calculating the TC, the maximum amount of the TC is evaluated based on the system events, which studies are mainly based on the N-1 security standard; In the sense that to calculate the interchangeability index in a route, after the exit of each equipment, the amount of this index is calculated, then the lowest value obtained from this stage is selected as the interchangeability of that particular route. Such a choice leads to setting unrealistic and strict values for TTC value. The TTC determined by contingency evaluation methods is closer to the real conditions of the system. In [38], a contingency assessment of TC has been made and by solving a bi-objective optimization problem, different amounts of TTC have been obtained for different risks. The goals considered in this optimization are increasing the PTC and reducing the risk. In the contingency evaluation of TTC, the uncertainty of the production units and lines has been taken into consideration and some of the important faults of the network have been noted. To select faults, the probability of fault occurrence and TTC corresponding to that error have been used. To show the efficiency of the proposed methods, a 24-bus RTS-IEEE network has been used. In [39], using the sensitivity method, the location of TCSC has been determined and its effect on TTC has been investigated. In [40], based on Monte Carlo simulation, different base states of the selection network and TC have been calculated in them. In [41], sequential Monte Carlo method is used to simulate the events and TTC is calculated for each event considering the AC network and dynamic limitations. In [42], has used the Monte Carlo method for event selection and DC load spreading to optimize load reduction and maximum TC. In [43], FACTS series devices including SSSC and TCSC are implemented. The main goal of this article is to increase the electric power of the lines. In addition, probabilistic analysis using TCSC has been implemented to improve system stability. The system in question is a radial network with a generator that supplies electricity to the load system. In [44], a TCSC Optimal placement method in the test network is proposed. Power transfer distribution factor and line outage distribution factor are used to build available transfer capability (ATC) mathematical model considering N-1 security limitations.GA is used to calculate the optimal placement and capacity of TCSC. The proposed method is applied to IEEE 14-bus system.

C. THE WEAKNESSES OF PREVIOUS RESEARCH AND THE IMPORTANCE AND NECESSITY OF RESEARCH

In the reviewed articles, the differences between the articles in the following categories are mainly evident:

1) THE DIFFERENCE IN THE TIME DIMENSION OF THE PROBLEM

Some articles have examined the problem at a work point and others have modeled the problem dynamically. Due to the fact that modeling the problem in a dynamic way makes the mathematics of the problem heavier, therefore, simplifications have usually been made in this category of articles.

2) THE DIFFERENCE IN THE DEVICES USED

Some articles have used secret tools in their research. Serial devices improve the load situation of network lines and mainly have an effect on reducing network losses and freeing the capacity of network lines. Some articles have used parallel tools. Parallel devices are more effective in supplying the network's required reactive power locally, and this also partially improves the network's voltage status and reduces network losses. A group of articles have also used the combination of series and parallel devices.

3) DIFFERENCE IN THE SOLUTION METHOD

In the reviewed articles, there are different approaches to solve the problem of positioning and determining the parameters of FACTS devices in the network. In some articles, the authors have used intelligent algorithms such as genetics and PSO to solve their problem. In this category of articles, the problem is usually defined as mixed integer non-linear programming (MINLP). Some other authors have used exact mathematical methods or general algebraic modelling system (GAMS) optimization software to solve the problem. In general, it can be said that each of the mentioned methods has its advantages and disadvantages.

4) THE DIFFERENCE IN THE OBJECTIVE FUNCTION

The objective function in the reviewed articles is diverse. The following four main parameters are used in the objective functions: Reduction of network losses - reduction of investment cost for FACTS devices - reduction of fuel cost - improvement of network voltage - improvement of total transmission capability - improvement of network voltage stability - increase of network load ability limit. As mentioned, in some reviewed articles, one-objective function has been used. This causes the facts devices to not be used optimally. Therefore, it is better to use multi- objective functions in optimization. Also, regarding the time dimension of the problem, it has been stated statically in many articles. Considering that with the change of the working point of the network, the adjustment parameters of the FACTS devices must also be changed, it is clear that the static modeling does not give good results. Also, some dynamic limitations of network generators cannot be expressed in static modeling. Most of the articles have not seen the effect of Facts devices on the transferability of lines. The viewpoint of most of the articles is an exploitation viewpoint, less than the restructuring viewpoint is used. Finally, after summarizing the articles, it is clear that a comprehensive study with a multi-part objective function is needed for the development of FACTS devices in transmission networks. Investigating transmission lines and the concept of maximum load ability and its solutions is one of the objectives of this research. As mentioned, one of these methods is the use of FACTS devices in power systems. In this paper, we seek to optimize the static stability of voltage using FACTS devices such as TCSC. Determining the optimal placement of these devices in the transmission system can lead to improving the load ability of transmission lines. Since many studies have focused on locating these devices, in this paper, finding the best location of TCSC in normal and single emergency conditions will be investigated. On the other hand, power loss is one of the other indicators considered in this paper, which is a very important indicator and always imposes a lot of costs on the system. Therefore, we are looking to reduce network power losses as much as possible. Therefore, in order to reduce power losses in the network, we will use TCSC and evaluate its effect in reducing this objective function. Although improving the objective functions as much as possible is the main objective of this article, but as we know, economics is always one of the main topics in solving problems related to power grid. Therefore, the costs of installing the equipment should also be considered in solving the problems related to the article. In this research, the contingency condition is modeled once as a generator outage and another time as a line outage. Due to the complex and non-linear nature of the problem, differential evolution algorithm will be used. In order to perform optimization, the use of genetic algorithm (GA) and HSA and their performance in improving the objective function have been evaluated and compared. The simulations will also be performed on the IEEE standard 30-bus network. The assumptions of the research are stated below: The studied network is the IEEE 30-buses test network, which is a stable network, TCSC static model is considered as an impedance in the lines, Installing this equipment and optimizing it using the SPEA method will improve network parameters, The non-linear and complex problem will be solved by the differential evolution algorithm, The use of FACTS devices will lead to the improvement of the loading index in the system, With FACTS devices in the right place, it improves voltage stability.

II. MATERIALS AND METHODS

A. TCSC MODE

Fig.1 shows a sample of TCSC and the (P-V) diagram of the transmission system equipped with TCSC. This equipment compensates in the network by changing the impedance structure of the network. By changing its impedance, this

TABLE 1. Taxonomy of related research works.

Ref.	FACTS devices	OA	Cost ($/h)	OPF	MM		Control Techniques
					OF	SM	
[11]	SSSC	--	Yes	--	Yes	Yes	Modified SSA
[12]	TCSC	Yes	Yes	Yes	Yes	--	SPEA-GA
[16]	SVC-TCSC	Yes	---	Yes	Yes	Yes	DPSO
[18]	TCSC	--	--	Yes	Yes	--	LFDC-COA-FUZZY
[20]	SVC	--	Yes	Yes	Yes	Yes	TSSA
[23]	--	--	Yes	Yes	Yes	--	SPEA-EGA–DQLF
[25]	TCSC-UPFC	--	Yes	Yes	Yes	Yes	OPM
[27]	--	Yes	---	Yes	Yes	Yes	SFOA-GA-PSO
[35]	SSSC	--	Yes	--	--	Yes	ANFIS
[38]	SSSC	--	Yes	Yes	Yes	Yes	MOBBO -WOA
[40]	TCSC	Yes	Yes	--	Yes	--	TLBO -ABC
[42]	SVCTCSC	Yes	Yes	--	Yes	Yes	JBMFO
[44]	SVC,UPFC,TCSC	Yes	--	Yes	Yes	Yes	PSO
[45]	TCSC, SVC	Yes	Yes	--	Yes	Yes	DEA
[56]	TCSC , SVC	Yes	--	Yes	--	--	BSOA
[57]	IPFC,SVC,TCSC	Yes	--	Yes	Yes	Yes	New GSA algorithm
Current paper	TCSC-SVC-HVDC	Yes	Yes	Yes	Yes	Yes	SPEA-DEA-HSA

OF: Objective Function. SM: Solution Methods. OA: optimal allocation.
MM: mathematical modeling. SSA: SALP swarm algorithm.
NSHFABC: non-dominated sorting hybrid fruit fly-based artificial bee colony algorithm. SFOA: sunflower optimization algorithm
BSOA: brain storm optimization algorithm
JBMFO: Jaya Blended Moth Flame optimization
TSSA: hybrid tabu search and simulated annealing
DEA: differential evolution algorithm
GSA: gravitational search algorithm
LFDC: local fuzzy based damping controller
EGA-DQLF: enhanced genetic algorithm- decoupled quadratic load flow.
COA: chaotic optimization algorithm
DPSO: discrete particle swarm optimization
OPF: Optimal Power Flow
MOBBO: multi-objective biogeography-based optimization
ABC: artificial bee colony
TLBO: teaching learning based optimization

equipment changes the impedance of the line and in this way is able to control the power passing through the line. Increasing the distance between the curved bend (P-V) and the working point of the line means increasing the power transmission capacity of the line [31].

Fig.2. illustrates the block diagram of the TCSC based damping controller.

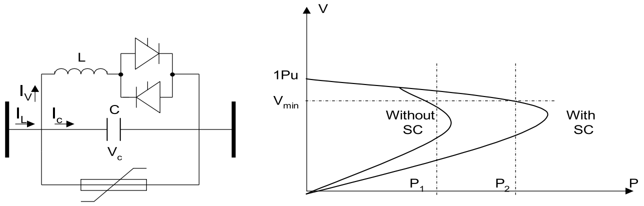

FIGURE 1. TCSC structure and diagram of P-V [31].

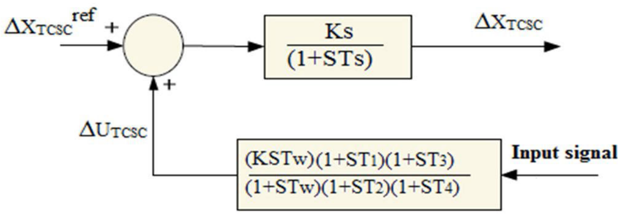

FIGURE 2. Block diagram of TCSC.

The dynamic equation of TCSC reactance can be expressed as follow:

$$\Delta \dot{X}_{TCSC} = \frac{1}{\mathrm{Ts}}\left(\mathrm{Ks}\left(\Delta \mathrm{X}_{\mathrm{TCSC}}^{\mathrm{ref}} + \Delta \mathrm{U}_{\mathrm{TCSC}}\right) - \Delta \mathrm{X}_{\mathrm{TCSC}}\right) \quad (1)$$

where, $\mathrm{X}_{\mathrm{TCSC}}^{\mathrm{ref}}$ is the reference reactance of the TCSC, KS and TS are the gain and time constants of TCSC. Because of more flexible control with faster response speed than series capacitors, TCSC has more applications to improve system parameters such as reducing line losses [37]. At the time of fault occurrence, TCSC can improve the power quality by limiting the current and help to keep the voltage as high as possible. TCSC may also be used to limit the fault current by adjusting its impedance dynamically to a high inductive value that depends on the TCSC design [32]. TCSC reduces the impedance of the source and reduces the instantaneous voltage drop during the energization of the transformer. TCSC reduces the effect of transformer inrush current on voltage [33]. With TCSC, the capacity of the lines can be freed in order to transfer the power from low-cost generators to different busses in order to avoid turning on expensive generators, which will reduce the price of electricity [34].

III. PRELIMINARY STUDIES WITHOUT THE PRESENCE OF THE TCSC IN THE NETWORK

In this case, initial studies are done without installing FACTS tools in the network. For this purpose, using the Newton-Raphson method, network load flow is solved. In the initial studies, the issues that are important are the amount of network losses and the amount of transfer capability of the entire network. After preliminary studies, it is determined that the value of total transfer capability (TTC) for the network is 61.1745 MW. It means that with the existing conditions, a maximum of 61.2 megawatts more power can be transferred in the network. If the network load ability exceeds this value, then one or more constraints in the network will be violated. Also, the amount of network losses is 9.6 MW in the basic state. Figure 3 shows the grid voltage before TCSC installation. As you can see, the network voltage has a big drop in some places. For example, in Bus 5, the network voltage is less than 0.95. This shows that this bus is far away from the generators. Therefore, one of the weakest network buses is obtained in terms of voltage [22].

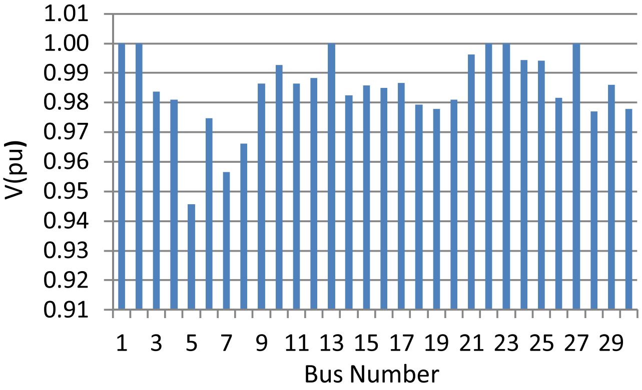

FIGURE 3. Mains voltage before TCSC installation.

Figure 4 shows the load ability of network lines. As you can see, the network lines have different load ability in different sections. The beginning lines of the network are more productive than the end lines. Because a large part of the network load is supplied from the primary lines of the network.

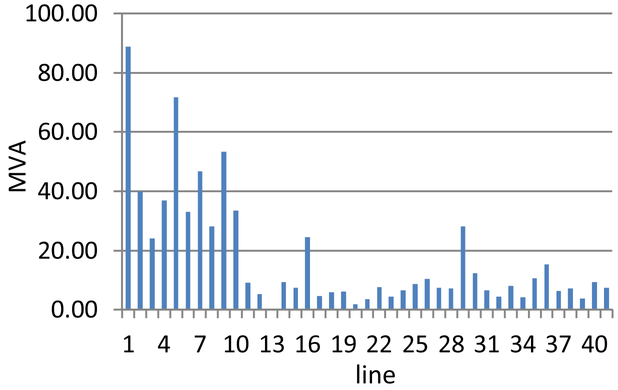

FIGURE 4. Load ability network lines in initial mode.

IV. PROBLEM FORMULATION

A. OBJECTIVE FUNCTION

The objective function of the optimization problem of this article in the technical approach includes two parts; network load ability and power losses, which are mentioned below [26].

$$\mathrm{Max}\,(\mathrm{F1})\ \text{ and } \mathrm{Min}(\mathrm{F2}) \tag{2}$$

$$\mathrm{F1} = \lambda \tag{3}$$

$$\mathrm{F2} = \mathrm{P_{loss}} = \sum_{i=1}^{b} \mathrm{R_i I_i^2} \tag{4}$$

where,

F1: Objective function of power loss
F2: Objective function of load ability

The first objective function is the network load ability index or static voltage stability limit. The higher the value of this index, the more we have moved away from voltage collapse, so its value should be increased as much as possible. Therefore, the objective of solving the problem in this paper is to maximize this index. λ shows a coefficient of buses load ability. This index, which is the output of continuous load distribution, is expressed in equation(5).

$$P_D = \lambda P_{D0} \tag{5}$$

$\mathrm{P_{D0}}$ Shows the amount of network load ability in the normal working mode of the network, and $\mathrm{P_D}$ shows the amount of the final load ability of the network. The second objective function is also the objective function of the network power loss, which is the total power loss in each network line. The number of grid lines is equal to parameter b. The aim of this objective function is to minimize it. In other words, TCSC should be installed in the network in such a way that the value of this objective function is reduced to the lowest possible value. In this paper, TCSC will be modeled as series reactance with line reactance.

The First Part: Income for increasing the load ability (improving the static stability of the network) due to the installation of the equipment: The more the network load ability increases with the installation of TCSC, the same amount of money is saved in network development. In other words, by increasing the network load ability by installing TCSC, there is no need to expand the network to increase the network load, and the amount needed for network development is saved. This amount is the cost that is taken from the network owner. The cost unit is dollars.

$$\mathrm{R_{PV-\lambda}} = \Delta\lambda^{*}\mathrm{P_{Load}}^{*}\mathrm{Pr_{\lambda}}^{*}\mathrm{S_{base}} \tag{6}$$

where,

$\mathrm{R_{PV-\lambda}}$:	Income from increasing network load ability by installing TCSC.
$\Delta\lambda$:	Amount of change in network load ability after installing TCSC.
$\mathrm{P_{Load}}$:	Total network power per unit.
$\mathrm{Pr_{\lambda}}$:	Cost of network development per unit of load increase,
$\mathrm{S_{base}}$:	Amount network reference power.

Second Part: Income for reducing power losses due to equipment installation: As we know, if energy is lost in the grid lines, it is as if all the investment made in the development of production and transmission network is wasted. Therefore, the income of installing equipment for reducing power losses is higher than the income of installing equipment for increasing network load. Usually, the costs of losses are considered to be twice the costs of network development. In other words, the cost of production development and network development are considered equal, which causes the cost of losses to double the cost of network development. Therefore, the revenues of equipment installation will be considered for reducing power losses according to equation (7).

$$\mathrm{R_{PV-loss}} = \Delta P_{\mathrm{loss}}{}^{*}\mathrm{P_{Load}}{}^{*}2^{*}\mathrm{Pr_{\lambda}}{}^{*}\mathrm{S_{base}} \tag{7}$$

where,

$\mathrm{R_{PV-loss}}$: Income from increasing and reducing power losses with the installation of TCSC.
$\Delta \mathrm{P_{loss}}$: The amount of change in power losses in the network after the installation of TCSC.

The Third Part: investment costs to install TCSC in the network: The equation(8) shows this cost. The unit of the following relationship is dollars per kVAr [31], [32].

$$\mathrm{C_{TCSC}} = 0.0015^{*}\mathrm{S_{TCSC}^{2}} - 0.7130^{*}\mathrm{S_{TCSC}} + 153.75 \tag{8}$$

where,

$\mathrm{C_{TCSC}}$: Cost of one TCSC kVAr,
$\mathrm{S_{TCSC}}$: TCSC power in MVAr,

In order to convert the equation(8) into dollar unit, the equation (9) is used.

$$\mathrm{Ct_{TCSC}} = \mathrm{C_{TCSC}}{}^{*}\mathrm{S_{TCSC}}{}^{*}1000 \tag{9}$$

where,

$\mathrm{Ct_{TCSC}}$: Total cost of TCSC in dollars.

Finally, the overall objective function related to the revenues and costs of this equipment can be written as the difference between the revenues and the costs in equation(10). It is obvious that we should seek to maximize the profit of installing this equipment.

$$\mathrm{Max}(\mathrm{R_{PV-\lambda}} + \mathrm{R_{PV-loss}} - \mathrm{Ct_{TCSC}}) \tag{10}$$

Table 27 (Appendix) shows the values of the maximum transmission power of the lines for the IEEE 30-buses test system. In order to establish safe conditions for the network, we define a safe zone for transmission lines, which is between zero and the maximum transmission power of the line. The power security index or transmission line load ability is shown as the following equation:

$$\lambda_i = \frac{P_i}{P_i^{\max}} \tag{11}$$

In this relation, P_i and $P_i^{\max}$ are respectively the power passing through line number i and the maximum power that can be passed through it (Table 28 in appendix). The following relation is defined for the optimization objective function.

$$\mathrm{Fitness} = \sum_{i=1}^{\mathrm{N_L}} \left(\mathrm{e}^{\mathrm{k}\lambda_i} - 1\right) \tag{12}$$

In this equation, N_L is the number of transmission lines and k is a coefficient to include the value of the lines in the objective function, and in this article it is considered equal to 2 by doing trial and error to improve the convergence.

B. LIMITATIONS

Optimization problems are always limited by constraints that confirm the validity of the responses to optimization problems. The limitations of the problem of this paper are given in equation(13) and equation(14). These limitations are the same as load flow limitations and equipment capacity limiting limitations [21].

$$\begin{aligned} P_{G_i} &= P_{D_i} + \sum_{j=1}^{n} P_{ij}P_{gi} - P_{di} \\ &\quad - \sum_{j=1}^{N} V_iV_jY_{ij}(x_{TCSC})\cos(\delta_{ij} - \gamma_j - \gamma_i) = 0 \\ &Q_{gi} - Q_{di} - \sum_{j=1}^{N} V_iV_jY_{ij}(x_{TCSC}) \\ &\sin(\delta_{ij} + \gamma_j - \gamma_i) = 0 \\ &\sum_{i=1}^{n} P_{G_i} = \sum_{i=1}^{n} P_{D_i} + P_{loss} \end{aligned} \tag{13}$$

$$\begin{aligned} \delta_i^{\min} &\le \delta_i \le \delta_i^{\max} \quad i = 1, 2, 3, \ldots, N_b \\ P_{G_{i_{min}}} &\le P_{G_i} \le P_{G_{i_{max}}} \\ Q_{G_{i_{min}}} &\le Q_{G_i} \le Q_{G_{i_{max}}} \\ V_{min} &\le V_i \le V_{max} \\ P_{ij} &\le P_{ij_{max}} \end{aligned} \tag{14}$$

In the above equations, Pgi and Qgi are the active and reactive powers generated at the *i-th* bus, respectively.

Pdi and Qdi are the active and reactive powers consumed at the i-th bus, respectively. Vi is the voltage of bus number i and δ_i its angle. X^{comp} is the value of the reactance of TCSC, which should be between its Min and Max value.

1) THE CONSTRAINT OF EQUALITY OF POWER GENERATION AND CONSUMPTION IN BUS

This limitation states, that the power generated in each bus must be equal to the total power consumed in the same bus and the power transmitted from that bus to other busses in the network.

2) LIMITATION OF EQUALITY OF GENERATION AND CONSUMPTION OF TOTAL POWER IN THE NETWORK

This limitation states, that all the power generated in the network is equal to the sum of all the power consumed in the network and network losses.

3) THE CONSTRAINT LIMITING THE ACTIVE AND REACTIVE PRODUCED IN GENERATORS

This limitations, shows the range of active and reactive power production in generators. Its maximum condition indicates the maximum capacity of the generator to produce active power, and its minimum condition indicates the economic limit of the generator in producing active power in the network.

4) LIMITATION OF THE MAGNITUDE OF THE NETWORK BUSES VOLTAGE

The voltage of the network buses should always be within the specified range. Voltage higher than the specified range will damage electrical equipment, and voltages lower than this limit will also lead to depreciation of the equipment. Safety issues are also considered in determining this range.

5) LIMITATION OF THE POWER TRANSMISSION OF NETWORK LINES

This constraint shows that electric power cannot be transferred from grid lines more than a certain limit.

6) THE LIMITATION SPECIFYING THE ALLOWED CAPACITY RANGE OF TCSC EQUIPMENT

This limitation states that the reactance of TCSC must be between 80% of the reactance of the line in which it will be installed in the form of capacitive, Up to 20% of the reactance of the line in which it will be installed should be in the form of inductive. In order to solve the problem, evolutionary algorithms should be used. The reason for using evolutionary algorithms for problem solving is two problem variables that have a wide range of selection for the optimal point of problem solving. The first variable is the location of the TCSC, which has 41 modes (by the number of network lines), and the second variable is the capacity of the TCSC, which has ten thousand modes. Therefore, the total number of modes is equal to: 10000*41. Finding an Optimal response among all these modes is possible only by using evolutionary algorithms [25], [26].

V. SIMULATION AND DISCUSSION

In this paper, the objective is to reduce power loss and improvement network load ability by installing TCSC. First, in the first approach (technical approach), these two studies are solved separately, and then using methods based on the Pareto front, they are solved simultaneously in peak load conditions. Then, in the second approach (economic approach), taking into consideration the costs of installing the equipment and the income from the use of the equipment in question, the optimal allocation of this equipment has been dealt with economically. In order to solve the optimization problem, evolutionary algorithm of genetics (EGA) is used in this article. The simulations have also been done in the power system analysis toolbox (PSAT). PSAT is a toolbox with open text codes for MATLAB software, which is widely used in the analysis of power and control systems. Therefore, the simulations of this paper include the following:

- Determining the optimal placement and capacity of TCSC in order to reduce power losses individually in the technical approach.
- Determining the optimal location and capacity of TCSC in order to improve the network load ability individually in the technical approach.
- Determining the optimal placement and capacity of TCSC in order to simultaneously reduce power losses and improve the network load ability at the same time in a technical approach.
- Determining the optimal location and capacity of TCSC in order to reduce power losses individually in an economic approach.
- Determining the optimal location and capacity of TCSC in order to improve the load ability capacity of the network individually in an economic approach.
- Determining the optimal location and capacity of TCSC in order to simultaneously reduce power losses and improve the network load ability at the same time in an economic approach.

A. MULTI-OBJECTIVE OPTIMIZATION ALGORITHM BASED ON PARETO FRONT

As stated, in order to carry out the simulations in this article, the evolutionary algorithm has been used [12], [13]. Multi-objective optimization algorithm with SPEA method is described here.

1) THE ALGORITHM OF THE SPEA [21]

The SPEA method algorithm is as follows:

a) We create the initial population P and the optimal set P'.

b) We transfer the optimal members of P to P'.

c) We remove members from P' that have become non-optimal due to the entry of new members.

d) If the number of members of the set P' exceeds the maximum value such as N', we delete the worse members.

e) We calculate the fitness of all members of P and P'.

f) We apply crossover and mutation operators.

g) If the number of reproduction reaches the final limit, stop the program, otherwise, we go to the second step.

h) End.

The flowchart of SPEA is shown in Fig.5.

The problem of optimization in the technical approach is given in (15) to (17).

$$Min\ (F_1)\,\&Max\,(F_2) \tag{15}$$

$$Min\ F_1 = \sum_i R_i * |I_i|^2 \tag{16}$$

$$Max\ F_2 = \lambda \tag{17}$$

In this paper, F1 is considered as the objective function of power loss. Network power loss is equal to the total power loss of network lines. The power loss in each network line is equal to the square of the line current in its resistance.

In normal mode and without installing additional equipment, the value of this objective function in the standard 30 bus network is equal to 0.0431 P.u. F2 is also the objective function of network load ability. With this objective

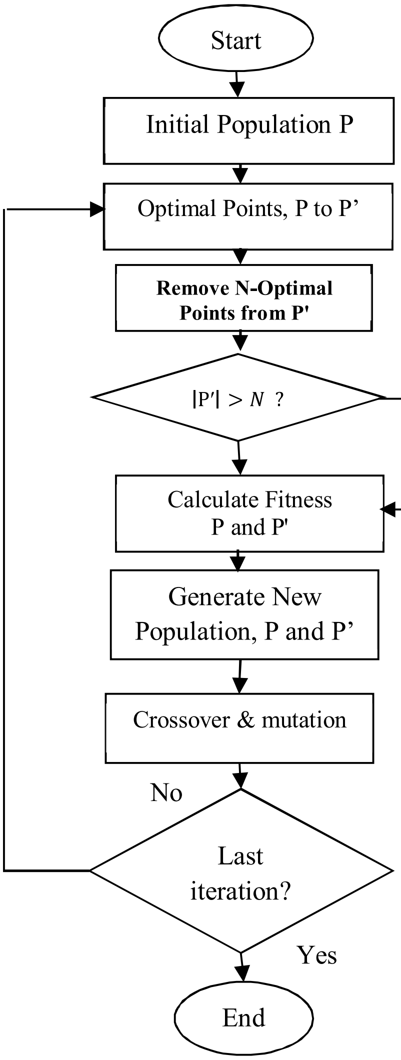

FIGURE 5. **Strength pareto evolutionary algorithm flowchart [17].**

function, we are looking to increase the load ability of the network as much as possible. This index shows the maximum load ability of the network from the current conditions of the network. In IEEE standard 30-bus network, this index is 3.0429. This amount means that this network is able to load ability up to 3.0429 times the current conditions. The more this index increases, the more investment in network development will be delayed. In this paper, the capacity of TCSC is considered between 80% of the capacitive mode and 20% of the inductive mode of the line reactance. The limits of this equipment are given in equation(18). Negative numbers indicate the capacitive mode of the equipment and positive numbers indicate the inductive mode of the equipment. The constraints of the problem are also given in equation(13) and equation(14).

$$-0.8X_{Line} \leq X_{TCSC} \leq 0.2X_{Line} \tag{18}$$

In the economic approach, the problem of optimization is also stated in equation(10).

B. OPTIMAL PLACEMENT OF FACTS DEVICES WITH DIFFERENTIAL EVOLUTION ALGORITHM

The proposed algorithm for optimal placement of TCSC type FACTS devices is as follows:

Step 1: DE algorithm parameters such as initial population number (N) and its initialization, crossover rate (CR) and mutation rate (F) are initialized.

Step 2: The location of TCSC is calculated depending on the defined scenario and is placed in the desired location with the value determined for it. For TCSC, the line reactance changes according to the TCSC value. Finally, the stated objective function is calculated for each member of the population.

Step 3: Mutation is performed on the particles. In this way, three random numbers are generated and the difference between their two numbers is added to the next number with the coefficient F.

Step 4: The crossover operation is performed. In this way, a random number is generated and if it is smaller than CR, the difference obtained in step 3 is replaced with the previous values.

Step 5: Selection is done. In this way, the value of the objective function for the number obtained in step 3 is compared with the corresponding previous value, and if it is smaller, it is replaced.

Step 6: If the maximum amount of repetitions has been reached, the algorithm ends and the outputs are displayed, otherwise it returns to step 3.

C. PROBLEM SOLVING USING HSA [28]

In this article, one of the objectives is to find the optimal location for installing FACTS devices, so the main variable is the problem of optimal locations. The harmony search algorithm is derived from the natural process of music performance. In general, an optimization problem by HSA algorithm is defined as follows [27], [28]:

$$min\, f\,(X)\,, X = [X_1, \ldots, X_n] \quad X_i \in [LB_i, UB_i] \tag{19}$$

where,

N : the number of variables in the problem
LB_i, UB_i : upper and lower limits for the variable Xi

The HSA algorithm has 5 general parameters as follows:

harmony memory size (HMS(- harmony memory considering rate (HMCR) - pitch adjusting rate (PAR) - bandwidth (BW) -number of improvisations (NI). Harmony search algorithm (HAS) is used to solve the optimization problem. Setting these parameters is necessary to solve any problem. The general steps of the algorithm are as follows:

Step 1: Initialization of parameters: In this step, the variables of the problem are assigned randomly within their allowed range.

Step 2: Algorithm memory formation: In this step, a vector of the best answer is stored in the memory of the algorithm.

Step 3: Improved memory formation:In this step, by using X values in the memory of the algorithm, new values are obtained in terms of the PAR parameter and a random part.

The new memory of the algorithm is updated based on the best answers and the above steps are carried out until the number of iterations of the algorithm ends. The following relation shows the merit function of each response.

$$F = \left(K_{ATC} \frac{TTC_0}{TTC} + K_{loss} \frac{Loss}{Loss_0} \right) .penalty_{fact}$$

$$TTC = \sum_{n} PD_i^{max} - \sum_{n} PD_i^0 \tag{20}$$

where,

TTC: total transfer capability.
PD_i^{max}: load value of bus i at the maximum point of load ability.
PD_i^0: load value of bus i in the basic state.
KATC: importance coefficient of available transfer capability.
Kloss: losses importance factor.
TTCo: total transfer capability without the FACTS.devices.

It can be seen that the coefficient of importance has been used. These coefficients can control the objective function of the problem. If we want to follow a part of the objective function with more importance, we use coefficients of importance. Regarding the importance coefficients, the following limitations must be observed.

$$KATC + Kloss = 1 \tag{21}$$

This equation shows that the sum of importance coefficients should be equal to 1. Also, by setting each of the importance coefficients to zero, the objective function actually works in a one-part manner.

To model the constraints in the problem, the method of penalty coefficients is used in the objective function. The following sets of relationships show how to model penalty coefficients for existing constraints.

$$\begin{aligned} penalty\_fact &= e^{-it.a} \\ \alpha &= \frac{c\,(x) + |c(x)|}{2} : \quad if\ c\,(x) \\ &\leq 0\ (ineq\ constraint) \\ \alpha &= |d\,(x)| : \quad if\ d\,(x) = 0\ \ (eq\ constraint) \end{aligned} \tag{22}$$

where,

it, is the coefficient of reducing the effect of constraints.

which has a larger value in the initial iterations of the algorithm, and its value becomes smaller as the algorithm approaches the end of the iterations. In order for the algorithm not to deviate from its main goal, these coefficients are used to reduce the effect of constraints in the objective function. This coefficient takes a value in the interval [0, 1]. To solve the problem, the HSA algorithm with the following specifications has been used: (Table 2)

TABLE 2. Specifications of the algorithm used to solve the problem.

The number of iteration	30
memory	6
The lowest pitch rate	0.4
The highest pitch rate	0.9
Minimum bandwidth	0.0001
Maximum bandwidth	1
Harmony rate consideration	0.9

D. NETWORK TESTING

Numerical studies are performed on the modified IEEE standard 30-bus network. Figure 6 shows the single-line diagram of this network [29]. The desired network has 6 generators and 41 transmission lines. The network load at the nominal working point is considered 283.4 MW Table 27 in the appendix shows the specifications of the network transmission lines. In this table, the parameters of the transmission line are in terms of perunits per unit of 100 MV. Also, the value of PMAX (capacity of each line) is expressed in MW. This network consists of two sections of 132 kV and 20 kV and includes two transformers. The mentioned transformers are placed between buses 10, 6, 4 and 12. In this article, the production power of generators and shown in Tables 3. Table 28 in the appendix shows the characteristics of the network load at different points. The values in this table are in MW.

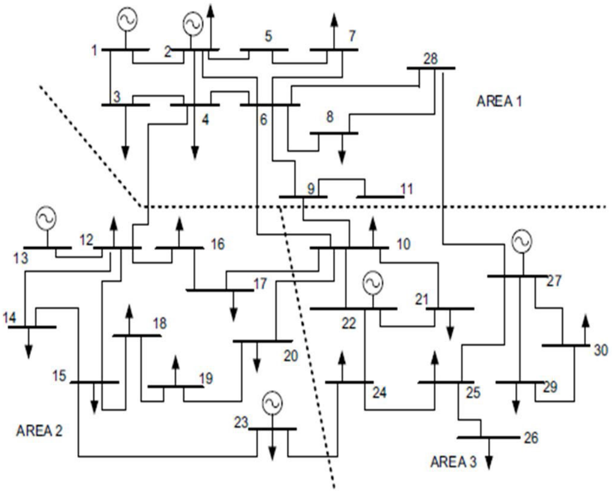

FIGURE 6. IEEE standard 30-Bus network [30].

E. SIMULATION RESULTS

As mentioned before, in this paper, the objective is to improve the network load ability at the same time, in addition to reducing power losses, by using TCSC. For this purpose, the location and capacity of this equipment should be optimized. In order to perform optimization, Pareto based

TABLE 3. The output power values of the generators in the network.

Generator. No.	P (MW)
1	23.5
2	61.0
22	21.6
27	26.9
23	19.2
13	37.0

TABLE 4. The results of the program to determine the optimal location and capacity of TCSC in order to reduce losses in the technical approach.

optimal placement of TCSC	optimal capacity of TCSC	power loss before TCSC installation	power loss after TCSC installation
Line 15 between buses 4 and 12	79.90%, capacitive	0.0431	0.0413

TABLE 5. The results of the program to determine the optimal location and capacity of TCSC in order to improve network load ability in the technical approach.

optimal placement of TCSC	optimal capacity of TCSC	network load ability before installing TCSC	network load ability after installing TCSC
Line 36 between buses 27 and 28	80%, capacitive	3.0429	3.7434

single-objective and multi objective genetic algorithm will be used. In all parts of the simulation, the inputs of the problem are the location and capacity of the equipment, and the outputs are the location and optimal capacity of this equipment and the objective function of power loss or network load ability or both simultaneously.

1) DETERMINING THE OPTIMAL PLACEMENT AND CAPACITY OF TCSC IN ORDER TO REDUCE POWER LOSSES IN THE TECHNICAL APPROACH

In the first step, we consider the objective function as the power loss in the technical approach. The trend of the power loss section is presented in Fig.7 and the others also change slightly depending on the objective function. Table.4 and Fig.8 show the results of simulations when the objective function is power loss in the technical approach. As the results have shown, by installing TCSC in line 15 between buses 4 and 12, the reactance of the line in the form of capacitive was reduced by 4.17% in the amount of 79.90%.

In the second step, we consider the objective function to improve the network load ability in the technical approach. The results of the simulations in this section are presented in Table.5 and Fig.9 as the results have shown, by installing TCSC in line 36 between buses 27 and 28, the reactance of the line in the form of capacitive improved by 23.02%.

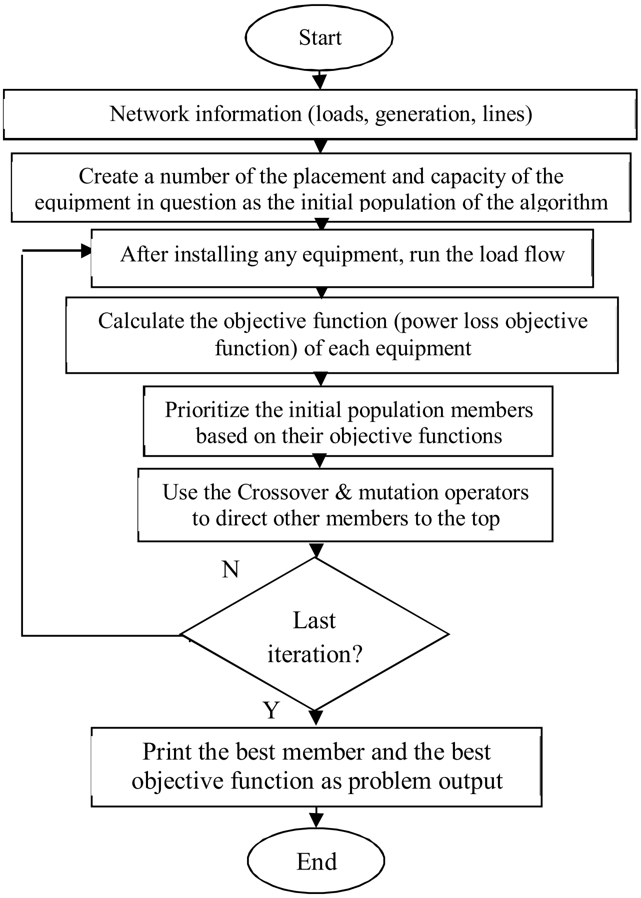

FIGURE 7. Process outline for determining the optimal location and capacity of TCSC in order to reduce power losses in the technical approach.

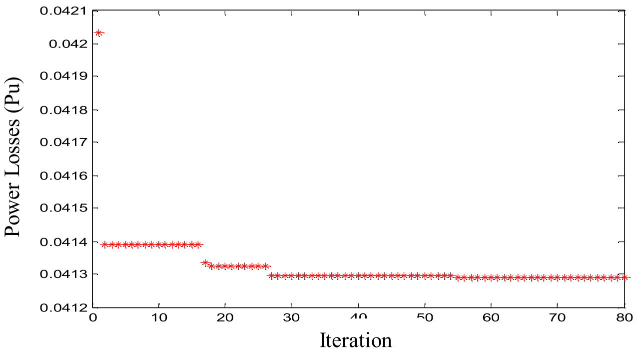

FIGURE 8. The output of the program to determine the optimal location and capacity of TCSC in order to reduce losses in the technical approach.

In the third stage, the inputs of the problem are the location and capacity of the equipment, and the outputs are the optimal location and capacity of TCSC and the objective functions of power loss and network load ability in the technical approach. In order to solve the optimization problem in this section, the two-objective genetic algorithm based on the Pareto front has been used. The outputs of the problem are members of the Pareto front as shown in Fig.10 and Table.6. The members of

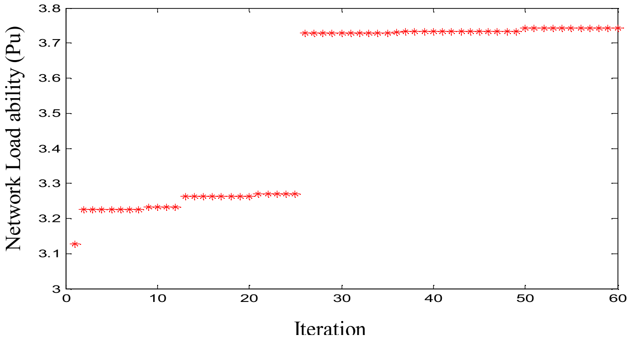

FIGURE 9. The output of the program to determine the optimal location and capacity of TCSC in order to improve the network load ability in the technical approach.

TABLE 6. Pareto front members in order to determine the optimal location and capacity of TCSC in order to improve network load ability and reduce losses in the technical Approach.

optimal location of TCSC	optimal capacity of TCSC	power loss index	load ability index
Line 36 between buses 27 and 28	80%, capacitive	0.0416	3.7434
Line 15 between buses 4 and 12	79.90%, capacitive	0.0413	3.1257
Line 36 between buses 27 and 28	79.80%, capacitive	0.0414	3.7428

the Pareto front are a set of points that are all optimal and have one advantage and one weakness when compared two by two. In other words, the network operator can select any of these points as the optimal point according to expectations from the optimal objective functions of his problem and install the equipment based on that point.

2) DETERMINING THE OPTIMAL LOCATION AND CAPACITY OF TCSC IN ORDER TO OBTAIN MAXIMUM PROFIT BY REDUCING POWER LOSSES IN AN ECONOMIC APPROACH

In the fourth stage, the goal is to determine the optimal location and capacity of TCSC in order to obtain maximum profit by reducing power losses in an economic approach that is subject to the profit goal. The results of the simulations in this section are presented in Table.7 and Fig.11.

In the fifth stage, the goal is to determine the optimal location and capacity of TCSC in order to obtain maximum profit by improving the network load ability in the economic approach, which is again subject to the profit goal, but at the same time, it is considered to improve the network load. The results of the simulations in this section are presented in Table.8 and Fig.12.

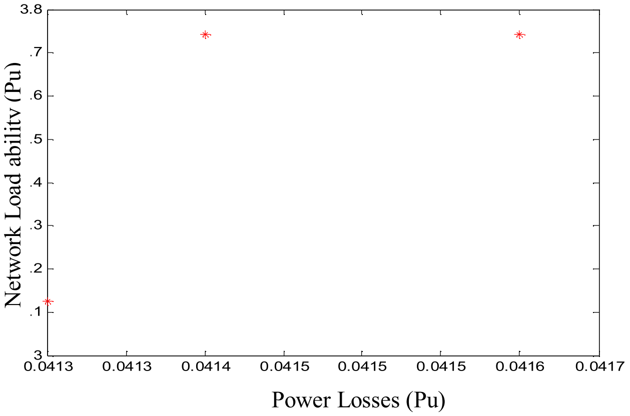

FIGURE 10. The set of Pareto front points in order to determine the optimal location and capacity of TCSC in order to improve network load ability and reduce power losses in the technical approach.

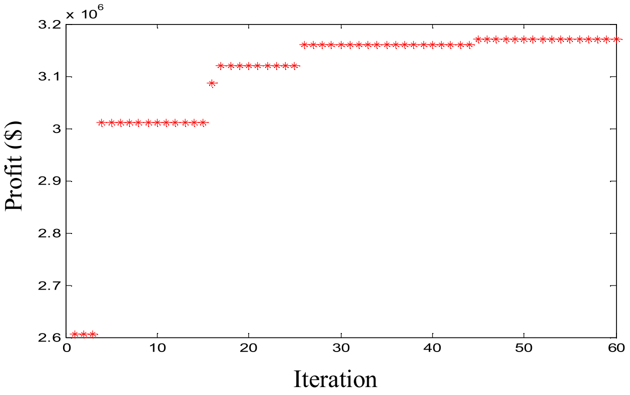

FIGURE 11. The output of the program to determine the optimal location and capacity of TCSC in order to obtain maximum profit by reducing losses in the economic approach.

TABLE 7. The results of the program to determine the optimal location and capacity of tcsc in order to obtain maximum profit by reducing losses in an economic approach.

optimal placement of TCSC	optimal capacity of TCSC	power losses after installing TCSC	The amount of profit obtained from the installation of TCSC
Line 15 between buses 4 and 12	78.63%, capacitive	0.0413	$3،171،100

3) OPTIMAL PLACEMENT OF TCSC UNDER SINGLE LINE CONTINGENCY

In this section of the article, the optimal placement of TCSC in the emergency situation of line outage has been done. Outage of line number 24 is intended for the line outage scenario. According to the simulation results, it can be seen that the objective function in Fig.13 has a good convergence process and finally reaches the value of 43.97 In this case, two numbers of TCSC have been used, and their optimal location is lines number 28 and 40, each with a value of 0.5pu compared to the impedance of the entire line. Fig.14 and 15 show the voltage and current values of different network buses after and before the optimal placement of TCSC.

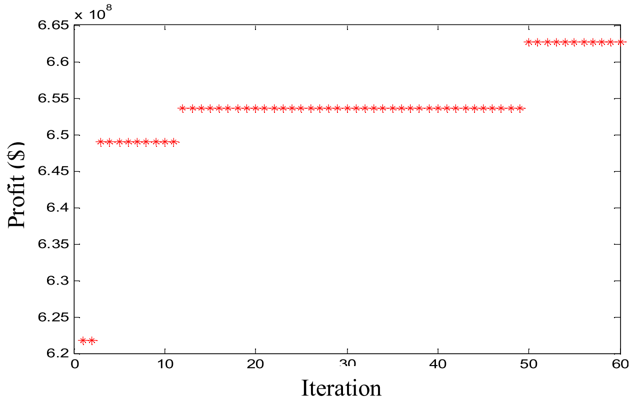

FIGURE 12. The output of the program to determine the optimal location and capacity of TCSC in order to obtain maximum profit by improving the network load ability in an economic approach.

TABLE 8. The results of the program to determine the optimal location and capacity of TCSC in order to obtain maximum profit by improving the network load ability in an economic approach.

optimal placement of TCSC	optimal capacity of TCSC	The amount of network load ability after installing TCSC (Pu)	The amount of profit obtained from the installation of TCSC ($)
Line 36 between buses 27 and 28	78.63%, capacitive	3.7394	$ 662،730،000

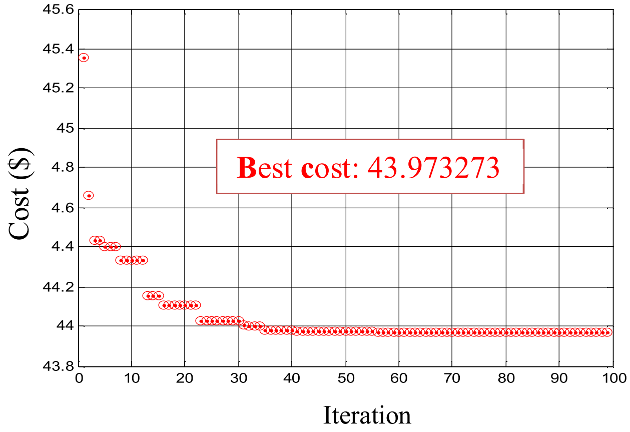

FIGURE 13. Process of objective function convergence for optimal placement of TCSC under single line contingency.

4) OPTIMAL PLACEMENT OF TCSC UNDER GENERATOR OUTAGE CONTINGENCY CONDITIONS

In this section, the optimal placement of TCSC for emergency generator exit conditions has been done. In the simulation, the fourth generator is considered to be out of operation. According to Fig.16, it can be seen that the final value of the objective function converges to 63.38. The optimal value of TCSC is equal to 0.5pu compared to the lines corresponding to them and their optimal location is lines number 7 and 41.

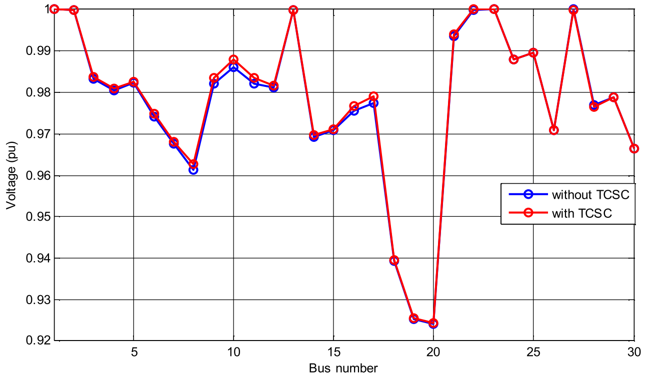

FIGURE 14. Voltage values of different busses for optimal placement of TCSC under contingency of single line outage.

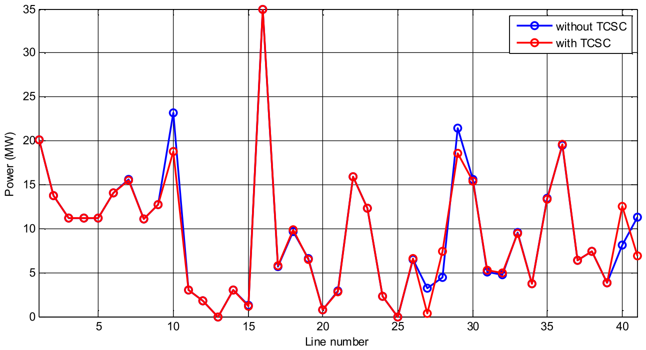

FIGURE 15. Current values of different lines for optimal placement of TCSC under contingency of single line outage.

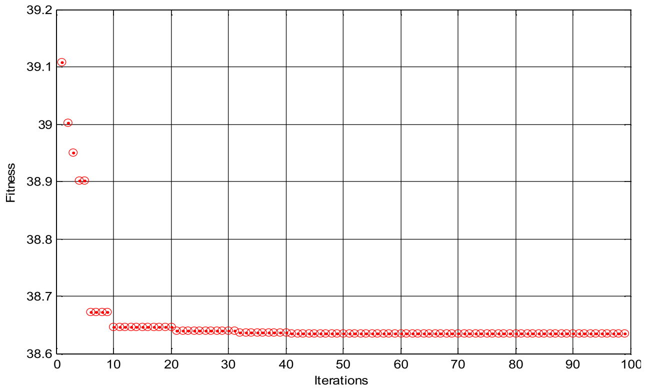

FIGURE 16. Convergence process of the objective function for optimal placement of TCSC under generator outage emergency conditions.

Also, in Figs.17 and 18, the bus voltage values and the current of different lines in the TCSC location process were checked compared to the state with and without FACTS devices.As a result of installing TCSC devices, the technical parameters of the network will change. According to the objective function, these changes should be in the direction

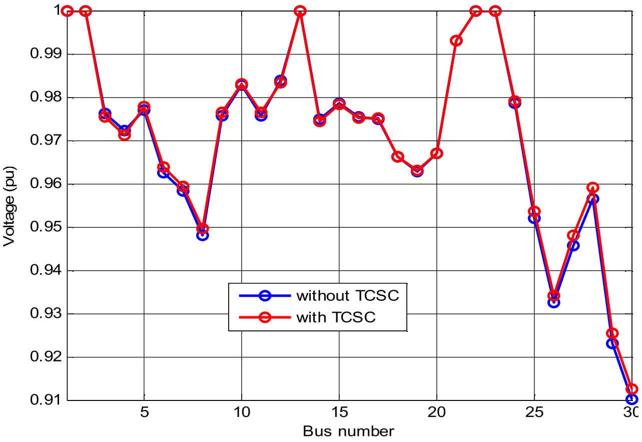

FIGURE 17. Voltage values of different busses for optimal placement of TCSC in single generator emergency situations.

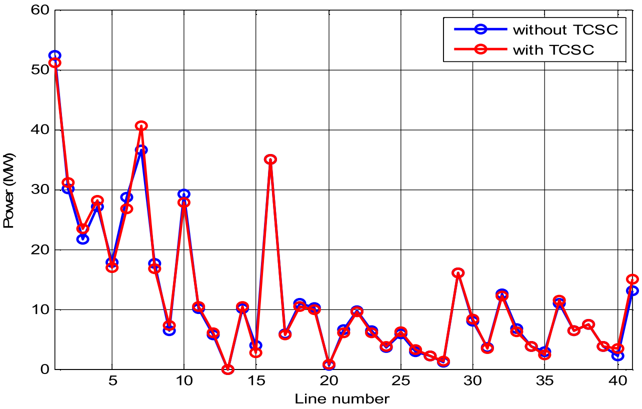

FIGURE 18. Voltage values of different busses for optimal placement of TCSC in single generator emergency situations.

of improving the stability of the network voltage and also reducing losses.

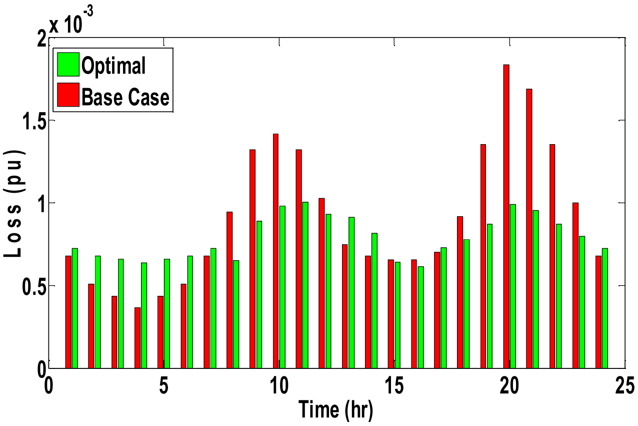

FIGURE 19. Comparison of losses at different hours between the basic network and the optimal network.

Figure 19 shows that network losses have decreased in most hours of the day and night, which has ultimately led to a decrease in total daily losses. The network voltage stability index after optimization is shown in Figure 20.

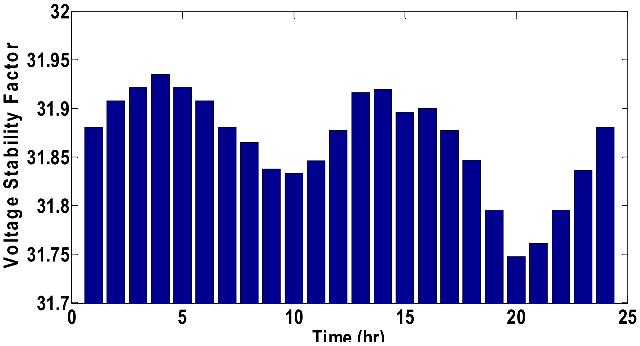

FIGURE 20. Voltage stability index after optimization.

It is clearly clear that the value of grid voltage stability index has improved compared to the base state of the grid. In other words, voltage stability is maximized. As we said before, due to the significant effect of the voltage profile on the voltage drop, system losses, voltage stability, etc., the voltage range is considered as a basic limitation. In order to prove that the voltage limit is observed in all the obtained optimal solutions, the voltage of all buses is presented.

It is clearly clear that the voltage of all buses is within the standard range. As a result of this optimization, the buses voltage will be as shown in Figure 21. As we said before, due to the significant effect of the voltage profile on the voltage drop, system losses, voltage stability, etc., the voltage range is considered as a basic limitation. In order to prove that the voltage limit is observed in all the obtained optimal solutions, the voltage of all buses is presented. It is clearly clear that the voltage of all buses is within the standard range. As a result of this optimization, the buses voltage will be as shown in Figure 21.

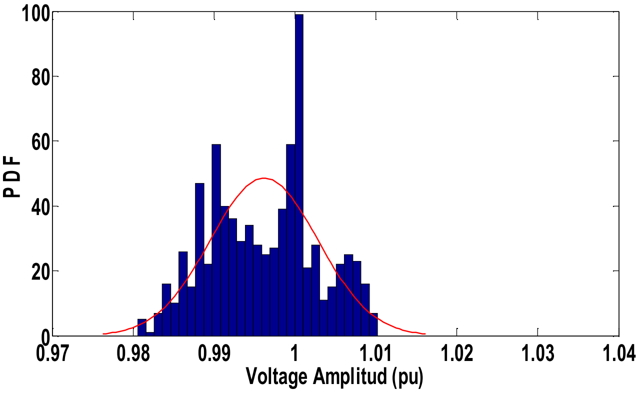

FIGURE 21. Buses voltage after network optimization.

It is quite evident that as a result of optimizing the voltage of the buses, it has improved. As a result, voltage stability is improved.

TABLE 9. The results of the program to determine the optimal.

Installation location	Number	$\emptyset_{TCSC}$	V_{TCSC}	Network losses	TTC
Line 35-Bus 25	1	0.5236	0.5000	8.73	66.15

VI. SIMULATION RESULTS USING THE HSS ALGORITHM

As you can see, the best place to install TCSC is line 35-bus 25. (Table 9) Also, network losses with the installation of TCSC equal to 8.73 megawatts. In this part, the transmission capacity in the network is equal to 66.15 megawatts. Comparison of the results shows that the use of TCSC in the network both reduces losses and increases transmission capability. Figure 22 shows the network voltage in this section.

Figure 23 shows the load ability of grid lines in this section.

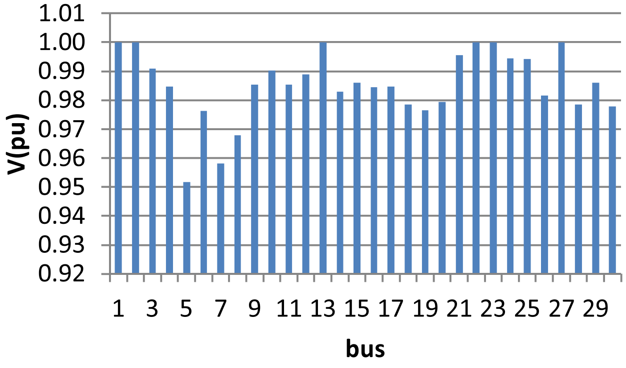

FIGURE 22. Network voltage by installing TCSC in the network.

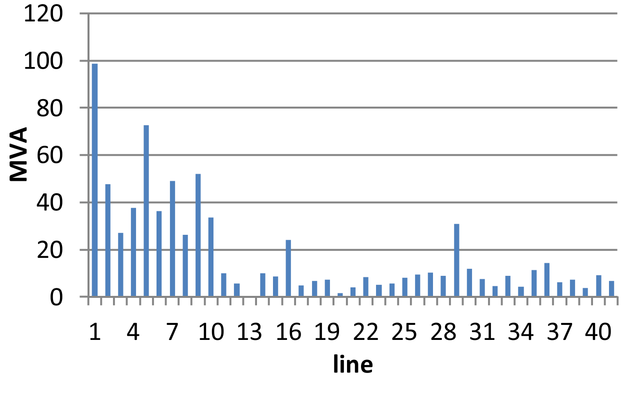

FIGURE 23. Load ability network lines after installing TCSC.

As you can see, the load ability of the network lines has changes compared to the initial state. These changes are relatively large. Because TCSC directly changes the series branch of the transmission line. The capacitive effect in series with the inductive effect of the transmission lines reduces the equivalent impedance, and this increases the line capacity and reduces network losses. Table 10 shows the amount of losses and TTC after solving the problem for the network of 30 buses compared to the basic mode.

TABLE 10. Amount of loss and TTC after solving the problem for 30-bus network.

	Losses	TCC
Base mode	9.6021	61.0745
Installing a TCSC in the network	8.7259	66.1492

TABLE 11. Amount of loss and TTC after solving the problem for 30-bus network.

	Network losses	TTC
Base mode	9.6021	61.0745
DEA	8.8659	67.4054
HSS	8.7077	64.3841
WOA	8.7259	66.1492
proposed controller (SPEATCSS)	7.8648	69.7979

Numerical studies were carried out on the network of 30 modified buses. The results of the studies show that in a network with this volume, the use of one device can affect the performance of the network to a great extent. So that the network losses are reduced and the network transmission capability increases appreciably. Table 11 shows the comparison of the obtained results for this network with different optimization algorithms.

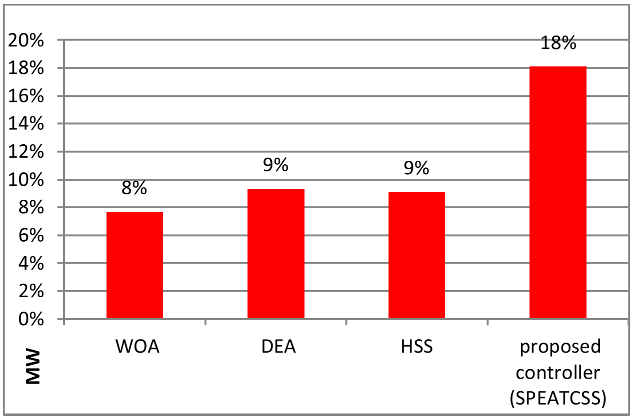

FIGURE 24. Comparison of network losses reduction in optimization control methods compared to the base case.

Figure 24 shows the comparison of loss reduction in the investigated methods compared to the base case. In this figure, it is clear that the amount of losses in the proposed method has been reduced more than other methods. Figure 25 shows the comparison of the transfer capability increase in different optimization methods. In this figure, it is clear that the network transfer capability has increased in the proposed method more than other methods.

VII. PROPOSED COMPREHENSIVE MODELING FOR LOAD FLOW

Unified power flow controllers (UPFC) have comprehensive control capabilities. It also has unique advantages such as

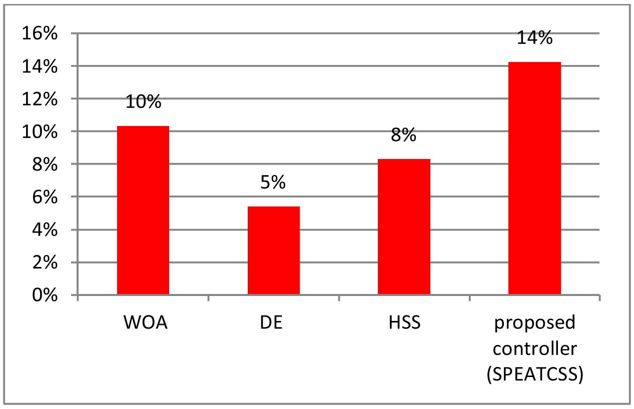

FIGURE 25. Comparison of the increase of the Total Transfer Capacity (TTC) of the network in different optimization methods.

accurate and flexible control of load flow, centralized design and effectiveness in short-circuit current. Therefore, it has a good application perspective in modern power systems [26]. In this section, a suitable modeling of the combination of FACTS devices including unified power flow controller (UPFC) as parallel and series compensator as well as HVDC is presented. A hybrid model of simultaneous applications of both cases is performed for load flow and the compensations effects are compared.(Fig.26.) The combined model obtained with the help of Newton-Raphson method was implemented on the test system in MATLAB software. Line overloads are removed by active power control of series compensators, and voltage drop is compensated by reactive power control of parallel compensators.

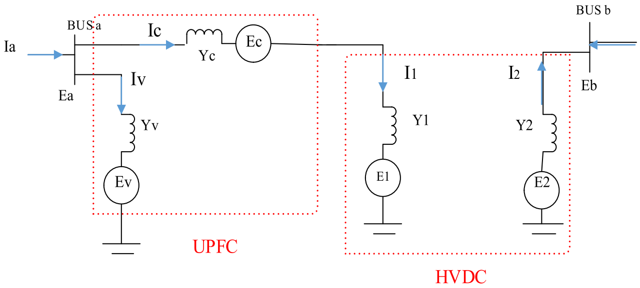

FIGURE 26. Proposed comprehensive model for load flow.

A 5-bus, 9-bus, and 30-bus network is considered as a test system (according to Figure 27 and 28), and the information of these networks was extracted in [4], which includes bus voltages and angles, as well as all line information, including reactance and are line resistance.

A. RESULTS AND DISCUSSION ABOUT THE PROPOSED COMPREHENSIVE MODELING FOR LOAD FLOW

The simulation of the test system in this section was done in two stages of Simulink and coding in MATLAB software. In the case of Newton-Raphson load distribution, the tested models are considered tolerance 1e-12. First, load flow was done without adding FACTS devices, then in these networks, we added UPFC and HVDC devices separately to the network and observed the results, and finally, based on the comprehensive model obtained in the previous section, both devices added to the system and the results were recorded in Table12 and Table 13.

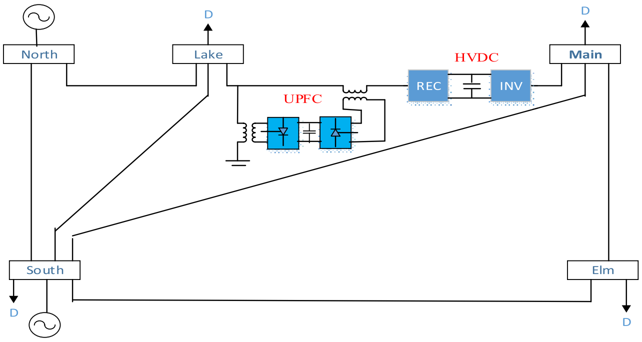

FIGURE 27. Proposed comprehensive model for load flow.

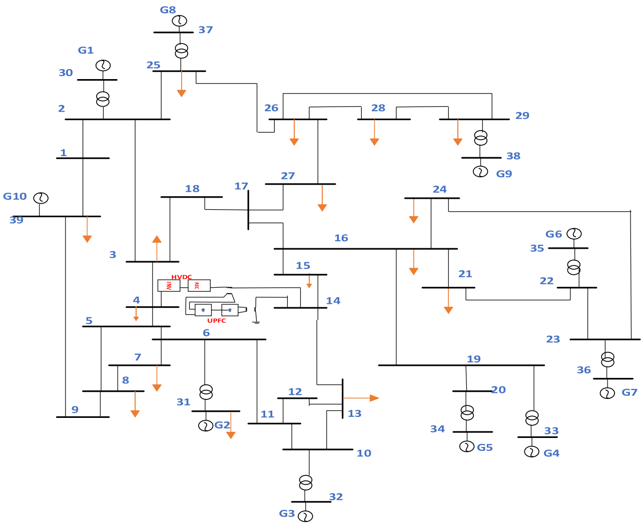

FIGURE 28. Adding a new proposed model to the IEEE standard network.

TABLE 12. Voltages and angles for the proposed comprehensive model.

Bus angle	Bus voltage	Bus No.
0/00 deg	V= 1/050 pu/10kV	BUS_1, Swing bus(North)
-5/75 deg	V= 1/045 pu/10kV	BUS_2(South)
-10/65 deg	V= 1/040 pu/10kV	BUS_3(Lake)
-9/45 deg	V= 1.00 pu/10kV	BUS_4(Main)
-9/23 deg	V= 1.001 pu/10kV	BUS_5(Elm)

TABLE 13. Load flow for the proposed comprehensive model.

Bus No.	Active power	Reactive power
1 --> BUS_2	P= 161/36 MW	Q= 76/11 Mvar
1 --> BUS_3	P= 100/53 MW	Q= 26/91 Mvar
2 --> BUS_3	P= 81/10 MW	Q= -22/63 Mvar
2 --> BUS_4	P= 69/54 MW	Q= 11/39 Mvar
2 --> BUS_5	P= 40/71 MW	Q= 3/57 Mvar
3 -->BUS_4	P= 41/99 MW	Q= 8/92 Mvar
4 -->BUS_3	P= 48/11 MW	Q= 11/99Mvar
4 --> BUS_5	P= 13/96 MW	Q= 1/96 Mvar
Generation 1	P= 157/90 MW	Q= 90/92 Mvar
Generation 2	P= 40/00 MW	Q= -66/36 Mvar
PQ load	P= 20/00 MW	Q= 10/00 Mvar
PQ load	P= 84/31 MW	Q= 15/00 Mvar
PQ load	P= 40/00 MW	Q= 5/00 Mvar
PQ load	P= 60/00 MW	Q= 10/00 Mvar
Total generation	P= 197/90MW	Q= 24/55 Mvar
Total PQ load	P= 204/31MW	Q= 40/00 Mvar
Total losses	P= 6/40 MW	Q= 15/54 Mvar

In Table 14, we have a check of load and voltage distribution by adding devices one by one (by keeping South's generator production constant at 40 MW), which shows that by adding UPFC, the values of active and reactive power between buses increase. With the addition of HVDC, in addition to the increase in active power between buses, we also see an increase in reactive power, and the amount of increase is less. Finally, by applying both devices at the same time, in addition to increasing the reactive and active power between the buses, the voltage in the destination bus becomes much closer to 1p.u (V = 1.00 P.U), which by comparing this model with the references in Table 15 we can see that a good compensation is obtained for the system and we see an increase in active and reactive power between buses and lines as well as stabilization of voltage in main, lake and buses simultaneously in this comprehensive model and in comparison with [20] that UPFC was used, we can see that the results caused the voltage to be adjusted in the range of 1p.u and also caused the active and reactive load distribution to be adjusted, which results show the correctness of the claim. According to the results of the proposed comprehensive model, the generators are forced to produce more power, which increases the costs of the system and due to the increase of equations and the addition of new terms to the load flow equations in the simulation comprehensive model, the equations of the model are more complex and It has more convergence time than normal modes (in 12 iterations) and by comparing the losses with other modes and single application modes, it was observed that the losses of the whole system are lower than the previous modes. By comparing the previous works, it was found that the proposed comprehensive model has a lower convergence speed, which is one of the disadvantages of the mentioned model. One of the most important advantages of the proposed comprehensive model is the simultaneous use of both types of fax equipment for load flow as well as the simultaneous control of active and reactive power, which was not done in any of the previous researches. Also, according to the results obtained in this section, there is a need to check the optimal mode of load flow by checking the costs of installing devices at the same time, as well as the optimal placement of these devices in the entire studied network, so that it can act in the direction of reducing losses. which can be investigated in a separate research. Also, by adding devices to the 9-bus and 39-bus test systems, according to Table 17, we will see an increase in bus voltage close to their nominal value. And we had more production of active power in 9 bus in generator 1, and in generator 2, the production of active power has decreased and we had more absorption of reactive power. In the 39-bus system, according to Table 16, the active power has increased, but the reactive power has been relatively less absorbed than the reference [3].

B. OPTIMAL LOAD FLOW BY WHALE ALGORITHM METHOD IN RESTRUCTURED POWER SYSTEMS WITH TCSC

The objective function of optimal load flow is to minimize the total production costs of the production units and, as a result, reduce the price of electricity in the electricity market. Optimal load flow constraints are generation and transmission constraints and FACTS devices. Wall's algorithm is proposed along with an effective fitness function to consider the objective function and all equality and inequality constraints, and how to implement it to solve the optimal load flow problem is stated. Newton-Raphson load flow is formulated in the presence of FACTS tools for use in optimal load flow. Finally, the proposed method is applied on the test system and its results are expressed [14].

1) OBJECTIVE FUNCTION OF MODIFIED OPF

It includes three objective functions as follows:

a) The cost of power generation of generators: [15]

$$\mathrm{f}_1(\mathrm{X}) = \sum_{i=1}^{NG} \mathrm{f}_i(\mathrm{P}_{gi}) = \sum_{i=1}^{NG} \mathrm{a}_i + \mathrm{b}_i\mathrm{P}_{gi} + \mathrm{c}_i(\mathrm{P}_{gi})^2 \tag{23}$$

where,

fi(Pgi) is the cost of producing power P by the i-th generator and is considered as a quadratic function of the production rate of that unit.

a, b, c are the constant coefficients of the quadratic function or the unit cost curve for generator i that can be achieved. NG is the number of generators.

b) Transmission losses:

$$f_2(X) = P_L = \sum_{i=1}^{NL} G_K\left[V_i^2 + V_j^2 - 2V_iV_j cos\left(\delta_i - \delta_j\right)\right] \tag{24}$$

TABLE 14. Load flow results in the proposed comprehensive model.

	Without Facts devices		With UPFC		With HVDC		Proposed model		Percentage of improvement compared to base
	voltage	angle	voltage	angle	voltage	angle	voltage	angle	-
North	1/ 050 pu/10kV	0/ 00 deg	1/ 050 pu/10kV	0/ 00 deg	1/ 050 pu/10kV	0/ 00deg	1/ 050pu/10kV	0/ 00deg	0%
South	1/ 00 pu/10kV	-3/ 66 deg	1/ 015 pu/10kV	-2/ 75 deg	1/ 032 pu/10kV	-3/ 94 deg	1/045 pu/10kV	-5/ 75deg	4.29%
Lake	1/ 00 pu/10kV	-5/ 71 deg	1/ 030 pu/10kV	-8/ 65 deg	1/ 011 pu/10kV	-4/ 55 deg	1/040 pu/10kV	-10/ 65deg	3.81%
Main	0/ 998 pu/10kV	-6/ 10 deg	1/ 00 pu/10kV	-5/ 45 deg	1/ 00 pu/10kV	-8/ 00 deg	1.00 pu/10kV	-9/ 45deg	0.19%
Elm	0/ 986 pu/10kV	-7/ 09 deg	0/ 981 pu/10kV	-4/ 23 deg	0/ 980 pu/10kV	-7/ 92 deg	1.001 pu/10kV	-9/ 23deg	1.43%
PG1	131/ 40MW		131/68MW		131/ 91MW		157/ 90MW		15.46%
PG2	40/ 00MW		40/ 00MW		40/ 00MW		40/ 00MW		0%
QG1	89/ 02MVAR		88/ 32MVAR		85/ 06MVAR		90/92 Mvar		1.27%
QG2	-61/ 01MVAR		-72/ 02MVAR		-71/ 98MVAR		-66/36 Mvar		-3.57%
P3-4	22/ 41MW		40/ 31MW		38/ 37MW		41/ 99MW		-
P4-3	22/36 MW		30/ 35MW		40/ 00MW		48/11 MW		-
Q3-4	1/ 56MVAR		5/ 65MVAR		3/ 62MVAR		8/92 Mvar		-
Q4-3	1/71 MVAR		13/ 85MVAR		2/ 36MVAR		11/99Mvar		-
Total losses	6/40MW		6/85MW		6/92MW		6/ 40MW		-

TABLE 15. The results of load flow in the proposed models in defferent references for the 5-BUS system.

	REF[5] WITH SVC		REF[3]WITH HVDC		REF[12] WITH HVDC		REF[21] WITH TCSC		Proposed model		Percentage of improvement compared to base
	voltage	angle	voltage	angle	voltage	angle	voltage	angle	voltage	angle	-
North	1/ 06 p.u	0/ 00 deg	1/1p.u	0/00	1/ 1p.u	0/ 00deg	1/ 09p.u	0/ 00deg	1/ 050 pu/10kV	0/ 00deg	0.95%
South	1/ 00 p.u	-2/ 05 deg	1/ 0949 p.u	-	1/ 1p.u	-1/318deg	1/ 1p.u	-1/ 303deg	1/045 pu/10kV	-5/ 75deg	1.89%
Lake	1/ 00 p.u	-4/ 83 deg	1/ 0667 p.u	-	1/ 071p.u	-3/ 472deg	1/ 078p.u	-3/ 6222 deg	1/040pu/10 kV	-10/65deg	3.21%
Main	0/ 994 p.u	-5/ 11 deg	1/ 0775 p.u	-	1/ 075p.u	-3/ 901deg	1/ 077p.u	-3/ 846deg	1.00 pu/10kV	-9/45deg	0.38%
Elm	0/ 975 p.u	-5/ 80 deg	1/ 0725 p.u	-	1/ 071p.u	-4/ 447deg	1/ 072p.u	-4/ 417deg	1.001 pu/10kV	-9/23deg	0.47
PG1	131/ 06MW		80/ 12MW		87/ 960MW		80/ 15MW		157/ 90MW		15.46%
PG2	40/ 00MW		87/ 95MW		80/ 135MW		87/ 89MW		40/ 00MW		0%
QG1	85/ 34MVAR		-13/ 76MVAR		20/ 292MVAR		0/ 29MVAR		90/92 Mvar		1.27%
QG2	-77/ 07MVAR		9/ 03MVAR		3/ 150MVAR		14/ 40MVAR		-66/36 Mvar		-3.57%
P3-4	19/ 65MW		14/ 996MW		13/ 71MW		14/ 97MW		41/ 99MW		-
P4-3	19/ 59MW		14/ 999MW		13/ 71MW		14/ 95MW		48/11 MW		-
Q3-4	11/ 19MVAR		4/ 07MVAR		3/ 895MVAR		-4/ 37MVAR		8/92 Mvar		-
Q4-3	13/ 02MVAR		2/ 79MVAR		2/ 3MVAR		-2/ 12MVAR		11/ 99Mvar		-

where,

Vi, series voltage of the i-th FACTS devices.

Vj, shunt voltage of i-th FACTS devices,

Gk, conductance of respective buses

NL, number of transmission lines.

δi, δj, angles at the ith and the jth bus, respectively

TABLE 16. The results of load flow in the proposed models in defferent references for the 39-bus system.

	Ref [3]	Ref [22]	proposed Model39-bus		Ref [3]	Ref [22]	proposed Model 39-bus
Pg1	2.35847	3.49000	3.99	V11	1.0647	1.048	1.055
Pg2	5.30634	5.97331	6.70	V12	0.9863	1.066	1.044
Pg3	6.75987	7.00000	7.71	V13	1.0581	1.048	1.059
Pg4	6.62081	5.45566	6.98	V14	1.0524	1.044	1.060
Pg5	5.06120	5.47801	5.53	V15	1.0364	1.028	1.047
Pg6	6.70167	4.00000	5.97	V16	1.0411	1.033	1.048
Pg7	5.88666	5.34792	6.35	V17	1.0520	1.042	1.055
Pg8	5.63718	6.50000	6.60	V18	1.0493	1.037	1.059
Pg9	8.39473	8.74932	9.00	V19	1.0291	1.014	1.050
Pg10	10.30272	11.00000	11.01	V20	1.0701	1.044	1.055
qg1	-1.47115	-2.04424	-2.01	V21	1.0269	1.026	1.042
qg2	4.48391	3.75206	4.46	V22	1.0273	1.030	1.030
qg3	0.57159	1.42014	1.78	V23	1.0409	1.032	1.031
qg4	2.11010	-0.13930	2.11	V24	1.0457	1.039	1.051
qg5	-1.02441	0.52513	1.00	V25	1.0532	1.047	1.059
qg6	-1.43144	-0.30549	-2.60	V26	1.0892	1.083	1.060
qg7	2.64157	1.00298	2.01	V27	1.0690	1.061	1.058
qg8	-1.47291	-0.24810	-1.00	V28	1.0956	1.094	1.055
qg9	-1.04856	-0.81278	-1.18	V29	1.0889	1.089	1.060
qg10	-1.59251	-2.10976	-1.50	V30	1.0744	1.060	1.059
V1	1.0643	1.027	1.060	V31	1.0857	1.069	1.048
V2	1.0409	1.023	1.041	V32	1.0731	1.068	1.060
V3	1.0460	1.029	1.052	V33	1.0703	1.071	1.048
V4	1.0417	1.022	1.060	V34	1.0056	1.098	1.019
V5	1.0647	1.041	1.056	V35	1.0706	1.100	1.057
V6	1.0700	1.046	1.058	V36	1.0493	1.040	1.058
V7	1.0611	1.035	1.060	V37	1.0014	1.065	1.047
V8	1.0602	1.034	1.049	V38	1.0500	1.100	1.052
V9	1.0914	1.051	1.060	V39	1.0546	1.006	1.046
V10	1.0624	1.051	1.058	-	-	-	-

c) Improvement of voltage deviation:

The total voltage difference in all the buses of the system is with the nominal voltage.

$$f_3(X) = VDI = \sum_{i=1}^{NT} |V_i - V_{Ni}| \tag{25}$$

2) EQUALITY CONSTRAINTS

$$g_i(X) = \left|P^{ex}_{se_i} - P^{ex}_{sh_i}\right| = 0 \quad i = 1.2\ldots.N \tag{26}$$

$P^{ex}_{se_i}$ is the exchanged power of the i-th FACTS devices through the series devices and $P^{ex}_{sh_i}$ is the exchanged power of the i-th FACTS devices through the shunt device. Since FACTS devices themselves do not produce active power, the net power exchanged through their series and shunt equivalent sources must be zero. Here we ignore all losses of FACTS devices and transmission system.

Usually, power flow equations are used as equality constraints [18].

$$P_i(V.\theta) = P_{gi} - P_{di} = \sum_{j=1}^{nb} V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij})$$
$$Q_i(V.\theta) = Q_{gi} - Q_{di} = \sum_{j=1}^{nb} V_i V_j \left(g_{ij}\sin\theta_{ij} + b_{ij}\cos\theta_{ij}\right) \tag{27}$$

where,

Pgi,	active power generated in the i-th bus.
Pdi,	active power consumed (load) in the i-th bus
n,	number of system buses.

d) Inequality constraints:

The limitations of the transitive power ranges of the lines and the active power ranges of the generator are the reference and are:

$$\begin{aligned} h_i(X) &= \left|P_{Line_i}\right| - P^{max}_{Line_i} \le 0 \quad i = 1.2\ldots.NL \\ h_{NL+1}(X) &= P_{g1} - P^{max}_{g1} \le 0 \\ h_{NL+2}(X) &= P^{min}_{g1} - P_{g1} \le 0 \end{aligned} \tag{28}$$

where,

P_{Linei},	active power transmitted of the i-th line.
P^{max}_{linei},	The maximum active power transmitted of the i-th line.
$Pg1$,	active power produced by base generator.
P^{max}_{g1}, P^{min}_{g1},	the minimum and maximum power generated of the base generator, respectively.

Finding an optimal solution for one of the objectives that can be considered an optimal solution for all the objective functions is a very difficult and most likely impossible task. Fuzzy

TABLE 17. **The results of load flow (9 bus).**

	REF [26] WITH HVDC		REF[3]WITH HVDC		REF[4] WITH HVDC		UPFC-HVDC Model for 9-bus WSCC system	
	voltage	angle	voltage	angle	voltage	angle	voltage	angle
1	1.040 p.u	0.00 deg	0.941 p.u	-	1.063640 p.u	-	1.060 p.u	0.00 deg
2	1.025 p.u	8.32 deg	1.010 p.u	-	1.083900 p.u	-	1.041 p.u	8.12 deg
3	1.025 p.u	2.93 deg	1.012p.u	-	1.061280 p.u	-	1.055 p.u	3.91 deg
4	1.067 p.u	-2.10 deg	1.036 p.u	-	1.047477 p.u	-	1.037 p.u	-5.06 deg
5	1.030 p.u	-4.05deg	0.919 p.u	-	0.924871 p.u	-	1.040 p.u	-8.33 deg
6	1.103 p.u	-6.33 deg	1.025 p.u	-	1.034400 p.u	-	1.030 p.u	-8.83 deg
7	1.038 p.u	2.83 deg	1.037 p.u	-	1.047932 p.u	-	1.051 p.u	5.41 deg
8	1.032 p.u	-0.43 deg	1.028 p.u	-	1.034598 p.u	-	1.044 p.u	-4.79 deg
9	1.053 p.u	0.28 deg	1.045 p.u	-	1.046922 p.u	-	1.057 p.u	5.91 deg
PG1	70.806 MW		1.07118		0.96905		115.11 MW	
PG2	163.00 MW		1.13236		1.22509		98.94 MW	
PG3	85.00 MW		0.98724		1.02942		103.71 MW	
QG1	-48.116 MVAR		0.20760		0.01092		-25.77 MVAR	
QG2	-13.313 MVAR		0.58083		0.70183		-20.38 MVAR	
QG3	-27.00 MVAR		-0.10439		-0.13526		-28.07 MVAR	
P5-4	(P6-4) -58.59 MW		0.7103		0.136019		-78.89 MW	
P4-5	(P4-6) 58.63 MW		0.7107		0.136029		70.67 MW	
Q5-4	(Q6-4) 18.57 MVAR		0.1804		0.026697		27.72 MVAR	
Q4-5	(Q4-6) 18.86 MVAR		0.1635		0.024080		32.33 MVAR	
PG1	70.806 MW		1.07118		0.96905		115.11 MW	
PG2	163.00 MW		1.13236		1.22509		98.94 MW	
PG3	85.00 MW		0.98724		1.02942		103.71 MW	

membership functions is the method used to solve the mentioned problem. These membership functions determine the satisfaction direction for all the defined objective functions and it is based on the possibility of finding the best acceptable solution among the Pareto optimal solutions. Fuzzy sets are defined by equations that are common to membership functions. These functions express the degree of membership in fuzzy sets using values from zero to one. A membership value of zero refers to incompatibility with fuzzy sets, while a value of one means complete compatibility. In other words, the numerical value of membership refers to the degree of satisfaction of each objective function of the answer of the problem.

$$\mu\left(\mathrm{F_i}\right)=\begin{cases}1 & \text{if } \rightarrow \mathrm{F_i}\leq \mathrm{F_i^{min}}\\ \dfrac{\mathrm{F_i^{max}}-\mathrm{F_i}}{\mathrm{F_i^{max}}-\mathrm{F_i^{min}}} & \text{if } \rightarrow \mathrm{F_i^{min}}\leq \mathrm{F_i}\leq \mathrm{F_i^{max}}\\ 0 & \text{if } \rightarrow \mathrm{F_i}\geq \mathrm{F_i^{max}}\end{cases} \tag{29}$$

where,

$\mathrm{F_i^{min}}$, $\mathrm{F_i^{max}}$ are the minimum and maximum values of the ith objective function, respectively.

To obtain the minimum value of each objective function, we consider and minimize it individually. But to obtain the minimum and maximum values, we multiply the values of the objective functions by a fixed number. For example, here we triple that by doing this we create an upper bound for the objective functions when the multi-objective optimization operation is executed, that is, $\mathrm{F_i^{max}}= 3\mathrm{F_i^{min}}$.

The value of the membership function refers to how much it produces the answer of the i-th objective function, i.e. Fi. So, the best solution is selected by the max-min fuzzy theorem.

$$\mu_{Bestsolution} = MAX\, \min\left[\mu\left(F_j\right)\right]^k \tag{30}$$

where,

J, represents the number of objectives to be minimized. K is the number of Pareto optimal solutions obtained. At first, for each solution, the minimum membership value for all objectives is considered, that all the objectives of the problem must be more satisfied with the objective function than this minimum value, then, for K the answer with acceptable values of K, the best answer is determined based on the highest membership value for these K values. For a multi-objective optimization problem, the answer X1 dominates X2 if the following two conditions are met:

$$\begin{aligned}&\forall i\in\left\{1,2,\ldots,\mathrm{N_{obj}}\right\}:\mathrm{F_i(x_1)}\leq\mathrm{F_i(x_2)}\\ &\exists j\in\left\{1,2,\ldots,\mathrm{N_{obj}}\right\}:\mathrm{F_j(x_1)}<\mathrm{F_j(x_2)}\end{aligned} \tag{31}$$

x_1 is Pareto optimal if it is not dominated by another solution in the search space. Now, to implement the whale algorithm, we act as follows. First, we form a population of whale that include control variables and are selected within their allowed range. Then, for each whale, we calculate the state

TABLE 18. Optimal load flow without FACTS by WOA.

Mode 1 Without SVC-TCSC-HVDC devices	
PG1	82.6750
PG2	85.6136
Cost ($/h)	809.0865

variables (voltage angles of the buses) using the direct load flow solution. Then, using the load flow results, we calculate the active power generated by the reference bus and the transitive power of the lines and the exchanged power of the series and shunt sources of FACTS devices. Now we can calculate all the equality constraints and inequality constraints and the objective function (f(X)) and get the value of the Lagrange function (L(X)) for each whale, and finally calculate the merit of each whale. Then we continue the whale algorithm until we reach the appropriate convergence and finally we choose the one that has the best fitness and introduce the variables values of active power the corresponding generators as the most optimal generators production values. According to the whale optimization algorithm (WOA), every whale or solution must have two values, the first value is the position of the whale, which we specify in the code with the Position variable. The second value is the degree of conformity or merit of each whale, which we have shown with cost. Now we want to evaluate the degree of merit or conformity of this created whale, for this we have used a function called cost Function which calculates the degree of merit. The result of optimization using the WOA algorithm method in the presence of the proposed model is shown in Fig. 29.

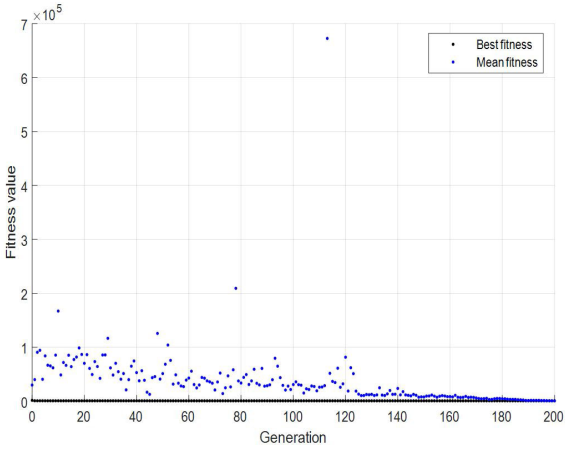

FIGURE 29. The result of optimization using the WOA algorithm method in the presence of the proposed model.

3) IMPLEMENTATION OF THE PROPOSED METHODS (OBJECTIVE FUNCTION SEPARATELY)

1) Minimizing the fuel cost of generators in the power system
2) Minimizing active power transmission losses
3) Improvement of system buses voltage deviation

TABLE 19. Optimal load flow with FACTS by WOA.

Mode 2 With SVC-TCSC-HVDC devices	
PG1	84.6116
PG2	83.3651
Cost($/h)	748.01

TABLE 20. Optimal load flow with FACTS by WOA.

Mode 1 Without SVC-TCSC-HVDC devices	
PG1	48.1784
PG2	120.000
Losses (MW)	3.1798

TABLE 21. Optimal load flow with FACTS by WOA.

Mode 2 With SVC-TCSC-HVDC devices	
PG1	47.1352
PG2	121.5500
Losses (MW)	2.8124

TABLE 22. Optimal load flow with FACTS by WOA.

Mode 1 Without SVC-TCSC-HVDC devices	
PG1	48.7068
PG2	119.9993
Voltage deviation (PU)	0.0495

TABLE 23. Optimal load flow with FACTS by WOA.

Mode 2 With SVC-TCSC-HVDC devices	
PG1	48.7068
PG2	119.9908
Voltage deviation (PU)	0.0401

4) IMPLEMENTATION OF THE PROPOSED METHODS (MULTI-OBBJECTIVE FUNCTION)

When the objective functions were examined separately according to Table 18-23, after the simulation according to the obtained results, we observed that all three objective functions were minimized as much as possible, but in the simultaneous examination of all three objective functions (F(x)) = F1+F2+F3) because during the optimization process these functions affect each other and the objective of the algorithm is to simultaneously minimize all these objective functions, we will see that the obtained results are far worse than the case where the objective functions are were examined separately according to Table 24 and 25, which means that the algorithm has converged to a greater value than the mode of examining the functions separately.

TABLE 24. Optimal load flow without FACTS by WOA.

Mode 1 Without SVC-TCSC-HVDC devices	
PG1	60/8295
PG2	109/2201
Cost ($/h)	818/0496
Losses (MW)	5/0496
Voltage deviation (PU)	0/0700

TABLE 25. Optimal load flow without FACTS by WOA.

Mode 2 With SVC-TCSC-HVDC devices	
PG1	85.8796
PG2	84.0023
Cost ($/h)	794.9692
Losses (MW)	4.8819
Voltage deviation (PU)	0.0700

TABLE 26. Comparison of the proposed algorithm (WOA) with other optimization algorithms.

Parameters	GA In [4]	BSA In [3]	PSO In [12]	ABC In [24]	proposed algorithm (WOA)
Pg1	0.794997	0.80006	0.80135	0/797	0.846116
Pg2	0.885547	0.88054	0.87960	0/882	0.833651
V1	1.099632	1.1000	1.109	-	1.0000
V2	1.094199	1.0950	1.100	-	1.0000
Cost	748.0335	748.0225	748.451	748/15	748.01
Losses	3.0544	-	3.168	-	2.9767
CPU Time	6.76	1.73	-	1.90	1.40

5) COMPARISON OF PROPOSED WOA ALGORITHM WITH OTHER OPTIMIZATION ALGORITHMS

The WOA algorithm is used to minimize the objective function of fuel cost of power system generators, network losses and voltage deviation of loads in optimal load flow in the presence of FACTS devices. In this article, a comparison has been made to minimize the fuel cost of generators in the standard system (Table 26). Because the comparison should be made under the exact same conditions and network, the references mostly focus on 5-bus or 33-bus, which is examined in this article, 30-bus, and in the different references, they mostly only checked the fuel cost and there was no comparison for voltage deviation. (The same population and the same number of repetitions are important in algorithms for comparison).

The voltage range of buses containing generators is as follows:

$$0.95\text{P.U.} \leq V \leq 1.1\text{P.U.}$$

And the voltage range of load buses:

$$0.95\text{P.U.} \leq V \leq 1.06\text{P.U.}$$

The results of the comparison have been examined in terms of generators' production power, losses and cost, and the duration of the algorithm execution. It should be noted that algorithms other than WOA have not been simulated in this article and their results have been extracted from different sources for comparison. On the other hand, according to the results of the system, the fuel cost has more changes before and after the installation of FACTS devices, but the other two objective functions do not change much and change to a lesser extent.

VIII. CONCLUSION

In many countries, increasing the power transfer capacity and controlling the power flow in transmission lines is of vital importance. Especially in restructured environments where the production situation and load centers can change quickly, adding new lines to respond to the increase in demand is limited due to environmental and economic constraints. FACTS devices help to respond to these needs in the existing transmission system. In this article, the main goal is to determine the optimal location and parameters of FACTS devices in transmission networks with the aim of reducing power losses and improving network loadability, which is the improvement of static voltage stability, under normal and emergency conditions. For this purpose, three algorithms SPEA, HSA and ED have been used. This problem was studied in two technical and economic approaches and its results were presented. For this purpose, first, the problem of locating in peak load conditions of the network was done separately and then simultaneously in the technical approach. In this approach, regardless of the rate of equipment used, attention was paid only to the improvement of the target functions, and the equipment was installed in a place and with a capacity that could have the greatest impact on the improvement of the target functions. In each case, the optimal location and capacity of TCSC were determined and the results were reported. Next, in the economic approach, the cost of installing the equipment in question was also included in the optimization problem. In this approach, the profit from TCSC installation is considered as the objective function of the problem, and the best place and capacity of the equipment was determined in order to achieve the maximum amount of profit. In this approach, first the simulations were carried out as a single target and then as two targets at the same time and the results were reported. As it is clear from the results of the simulations, in the technical approach, in order to achieve the lowest amount of losses in the IEEE standard 30 bus network by installing the equipment, TCSC should be installed in line number 15 between buses 4 and 12. The best amount of reactance compensation of this line was about 79.90% of the line reactance, as a result of which the network power loss was reduced by about 4.17%. Also, in the continuation of the simulations, the best place and capacity to install TCSC in the network was determined in order to improve the network load. As a result of this simulation, the best location of line 36 between buses 27 and 28 was determined and the best amount of reactance compensation for this line was also 80% of the line reactance. As a result of this compensation, the

TABLE 27. Maximum capacity of ieee standard 30-BUS network lines.

Line No.	From Bus	To Bus	R	X	Y/2	PMAX(MW)	Line No.	From Bus	To Bus	R	X	Y/2	PMAX(MW)
1	1	2	0.02	0.06	0.015	130	22	15	18	0.11	0.22	0	16
2	1	3	0.05	0.19	0.01	130	23	18	19	0.06	0.13	0	16
3	2	4	0.06	0.17	0.01	65	24	19	20	0.03	0.07	0	32
4	3	4	0.01	0.04	0	130	25	10	20	0.09	0.21	0	32
5	2	5	0.05	0.2	0.01	130	26	10	17	0.03	0.08	0	32
6	2	6	0.06	0.18	0.01	65	27	10	21	0.03	0.07	0	32
7	4	6	0.01	0.04	0	90	28	10	22	0.07	0.15	0	32
8	5	7	0.05	0.12	0.005	70	29	21	22	0.01	0.02	0	32
9	6	7	0.03	0.08	0.005	130	30	15	23	0.1	0.2	0	16
10	6	8	0.01	0.04	0	32	31	22	24	0.12	0.18	0	16
11	6	9	0	0.21	0	65	32	23	24	0.13	0.27	0	16
12	6	10	0	0.56	0	32	33	24	25	0.19	0.33	0	16
13	9	11	0	0.21	0	65	34	25	26	0.25	0.38	0	16
14	9	10	0	0.11	0	65	35	25	27	0.11	0.21	0	16
15	4	12	0	0.26	0	65	36	28	27	0	0.4	0	65
16	12	13	0	0.14	0	65	37	27	29	0.22	0.42	0	16
17	12	14	0.12	0.26	0	32	38	27	30	0.32	0.6	0	16
18	12	15	0.07	0.13	0	32	39	29	30	0.24	0.45	0	16
19	12	16	0.09	0.2	0	32	40	8	28	0.06	0.2	0.01	32
20	14	15	0.22	0.2	0	16	41	6	28	0.02	0.06	0.005	32
21	16	17	0.08	0.19	0	16	-		-	-	-	-	-

TABLE 28. Load characteristics of the studied network (30-BUS).

Bus no.	Pg (MW)	Qd (MVAr)	Pd (MW)	Bus no.	Pg (MW)	Qd (MVAr)	Pd (MW)	Bus no.	Pg (MW)	Qd (MVAr)	Pd (MW)
1	50	0	0	11	0	0	0	21	0	11.2	17.5
2	60.97	12.7	21.7	12	0	7.5	11.2	22	26.91	0	0
3	0	1.2	2.4	13	21.59	0	0	23	19.2	1.6	3.2
4	0	1.6	7.6	14	0	1.6	6.2	24	0	6.7	8.7
5	0	19	94.2	15	0	2.5	8.2	25	0	0	0
6	0	0	0	16	0	1.8	3.5	26	0	2.3	3.5
7	0	10.9	22.8	17	0	5.8	9	27	37	0	0
8	0	30	30	18	0	0.9	3.2	28	0	0	0
9	0	0	0	19	0	3.4	9.5	29	0	0.9	2.4
10	0	2	5.8	20	0	0.7	2.2	30	0	1.9	10.6

load index value of the network improved by 23.02%. In the economic approach, the best place of line 36 with the optimal capacity of 79.32%, capacitive to obtain the maximum profit in order to reduce power losses and improve the load ability of the network,after the installation of TCSC, the values of 0.0414 p.u. in order to reduce the power losses and 3.7411 p.u.were obtained in order to improve network loadability. In these two simulations, the amount of profit obtained from TCSC installation was equal to 662,730,000 and 667,550,000 dollars, respectively. Next, the optimal location of TCSC under single line contingency, and generator emergency exit conditions has been done. Outage of line number 25 is considered for line outage scenario and also fourth generator is considered for out of operation. According to the simulation results, it can be seen that the objective function has a good convergence process and finally reaches the value of 43.97. In this case, two numbers of TCSC have been used, and their optimal location is lines number 28 and 40, each with a value of 0.5pu compared to the impedance of the entire line. According to the results, it is observed that the final value of the objective function converges to 38.63. The optimal value of TCSC is equal to 0.5pu compared to the lines corresponding to them and their optimal location is lines number 7 and 41. Also, a new comprehensive modeling of simultaneous use of SVC-TCSC-HVDC devices including SVC as parallel compensator, TCSC as series compensator, and HVDC connection by applying Newton-Raphson power flow on this comprehensive model in a network an experiment was conducted. To solve constrained optimization problems such as the OPF problem in power systems in this paper, cost function-based methods are the most popular approaches. However, since the cost function approach is generic and applicable to any type of constraint, their performance is not always satisfactory and consistent. In order to solve these problems, a constraint management strategy has been developed from the WOA method to solve the OPF problem according to the characteristics of the WOA. The results obtained in the numerical studies section show that in general, FACTS tools in the network can reduce losses and increase the total transmission capability. But the noteworthy point is that using FACTS tools in combination can have a better effect on network efficiency. In fact, the use of devices with series and parallel branches in a combined manner has a good effect on the network operation. In fact, by supplying reactive power locally, UPFC has been able to reduce the flow of lines and therefore reduce losses. The results of this part show that the use of UPFC in the network has freed up the capacity of the network lines and therefore the network load ability has increased. Considering that in this article, in the placement of TCSC in order to reduce power losses and improve network load ability, network uncertainties are not considered, it is suggested that in order to more realistically consider the conditions of the power system, load uncertainty and production should also be considered.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

ABBREVIATION

ABC	Artificial bee colony
BSOA	Brain storm optimization algorithm
CP	Custom power
COA	Chaotic optimization algorithm
CPPS	Cyber-physical power system
CSA	Cuckoo search algorithm
D-FACTS	Distributed flexible ac transmission system
DG	Distributed generator
D-STATCOM	Distributed synchronous static compensators
DSA	Distribution system automation
DQLF	Decoupled quadratic load flow.
D-SSSC	Distributed static synchronous series compensator
DPSO	Discrete particle swarm optimization
DEA	Differential evolution algorithm
EGA	Enhanced genetic algorithm
GUPFC	Generalized unified power flow controller
GSA	Gravitational search algorithm
IOT	Internet of things
IOE	Internet of energy
IoCP	Internet of cyber-physical thing
ICT	Information and communication technology
IPFC	Interline power flow controller
JBMFO	Jaya blended moth flame optimization
LOSF	Line outage sensitivity factor
LFDC	Local fuzzy based damping controller
MOBBO	Multi-objective biogeography-based optimization
MOEPSO	Multi-objective evolutionary particle swarm
NSHFABC	Non-dominated sorting hybrid fruit fly-based
OPF	Optimal power flow
OA	Optimal allocation
OF	Objective function
PMU	Phasor measurement unit
PST	Phase shifting transformer
POC	Power oscillation controller
RES	Renewable energy sources
SSA	Salp swarm algorithm
SM	Solution methods
SCADA	Supervisory control and data acquisition
SFOA	Sunflower optimization algorithm
SSSC	Static synchronous series compensator
SVC	Static Var compensator
STATCOM	Static Synchronous compensator
TCSC	Thyristor controlled series compensators
TCR	Thyristor controlled reactor
TSSA	Tabu search and simulated annealing (hybrid)

TLBO	Teaching learning based optimization
TSC	Thyristor switched capacitor-
TSR	Thyristor switched reactor
VSC	Voltage source converter

APPENDIX (TABLE 27)

Line number one is connected from the bus 1 to the bus 2 and the maximum capacity of passing through it is equal to 130 MW. In fact, the first column indicates the number of the line, the second and third columns indicate the initial and final buses of the line respectively, and the last column indicates the maximum load ability of the line.

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