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Optimal placement of FACTS devices using optimization techniques: A review

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Abstract Modern power system is dealt with overloading problem especially transmission network which works on their maximum limit. Today's power system network tends to become unstable and prone to collapse due to disturbances. Flexible AC Transmission system (FACTS) provides solution to problems like line overloading, voltage stability, losses, power flow etc. FACTS can play important role in improving static and dynamic performance of power system. FACTS devices need high initial investment. Therefore, FACTS location, type and their rating are vital and should be optimized to place in the network for maximum benefit. In this paper, different optimization methods like Particle Swarm Optimization (PSO), Genetic Algorithm (GA) etc. are discussed and compared for optimal location, type and rating of devices. FACTS devices such as Thyristor Controlled Series Compensator (TCSC), Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are considered here. Mentioned FACTS controllers effects on different IEEE bus network parameters like generation cost, active power loss, voltage stability etc. have been analyzed and compared among the devices.

1. Introduction

Today's power system becomes more complex interconnected system due to alarming increase in load demand and dynamic load pattern which affect severely on transmission lines. They are operating either overloaded or under loaded. The uneven load distribution affects voltage profile and makes system voltage security vulnerable to the fault. It becomes difficult to maintain power system security and reliability. Conventional approach of add new transmission lines in the system and build new power generation facilities is bound with certain factors such as technical and economical bounds. So the best and necessary solution left is to make optimal use of existing generation and transmission network. FACTS controllers are the best and effective alternative for power system performance improvement like voltage security, transfer capability and reduction in losses etc. instead of making complex new transmission corridor. These devices can be connected in series, shunt, series-series and series-shunt. It is important to decide FACTS devices type according to the purpose of need. For voltage control at the point, shunt controllers are desirable and power flow in the line can be controlled through series controllers [1].

In 1999, Hingorani and Gyugyi introduced the concept of FACTS. Modulation and alteration of line power flow becomes accurate, fast and precise manner is attainable with FACTS concept [2]. The core of FACTS controllers is basic power electronics devices. FACTS devices applications include enhancement of transmission lines power transfer capacity and regulate different parameters in transmission network such as current, impedance, phase angle and voltage. Power flow can be made flexible or controllable using these devices. FACTS devices helps to increase loadability of the network through reduction of power flow in overloaded lines and line losses also reduced [3].FACTS devices effectively tackle the problem of voltage collapse and system security. These devices help in the problem of Congestion management. System accommodated the changes easily with FACTS devices [4].

Optimal location and settings of FACTS controllers play an important role for enhancement of system performance and economic benefits. In the past, several approaches are proposed by researchers to work out the problem of optimal location of FACTS devices. Common techniques of placement of devices are categorized into analytical, linear programming and heuristic search methods. The problem of optimal location is considered as combinatorial analysis and heuristic search methods are best tools for such problems as they are robust, fast and best suited for real problems of the power system. Common heuristic search methods proposed for optimal placement in research are Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO), Harmony Search Algorithm (HSA), and Ant Colony Optimization (ACO) [5].

In this paper, different optimization approaches especially heuristic approach for different parameters and their results are reviewed and compared. Literature regarding optimal location and ratings of SVC, TCSC and STATCOM using optimization technique especially GA are reviewed. Different objective functions and bus networks are considered and separately each FACTS devices effects on certain parameters of bus network such as generation cost, losses, voltage profile etc. are represented in tabular form. Comparison of different FACTS devices on the ground of parameters affected like reduction in active losses, improvement in voltage profile, minimization of cost etc. This paper compares different search techniques and review of recent techniques in literature and show effectiveness of individual FACTS devices for various parameters for a given bus network.This paper has following sections: II. FACTS devices and their mathematical models, III. Recent optimization techniques, IV. FACTS Applications using GA, V. Conclusion, VI. Research Scope.

2. Recent Optimization Techniques

2.1 Particle Swarm Optimization(PSO)

PSO method was introduced in 1995 by Dr. Kennedy and Eberhart. PSO is motivated by swarm intelligence like fish school and bird flocks etc. In birds, social interaction with each other and with environment to search the food is the basis of PSO. In PSO, compared to GA few parameters need to be changed and it is easy to implement. PSO has been used to loading of branch and voltage stability maximization and minimization of losses on IEEE 30 bus network using TCSC and SVC together at optimal location. In [6], Result of PSO method has been compared with Evolutionary Programming (EP) and it was concluded that loading factor (182%) increased more with minimum number of FACTS devices in PSO as compared to EP. PSO is faster than EP.

Kavitha et al. in [7] presented the comparison of WIPSO (improved weight PSO), BBO (Biogeography optimization) and PSO methods for number of FACTS devices, optimal location, type, rating of SVC and TCSC. Objective functions which consist of load voltage deviation, cost and line loadings are considered. Implementation has been done on IEEE 30, 57 and 14 bus systems. Analysis of result shows that WIPSO performs better than PSO and BBO perform best compared to WIPSO and PSO. SVC and TCSC optimally placed together gives better voltage profile security compared to when placed individually.

PSO is more popular compared to other due to its advantages such as easy implementation, low computational time, robustness and rapid convergence. Comparison of PSO with different methods through pie chart shown in Figure 1 [8].

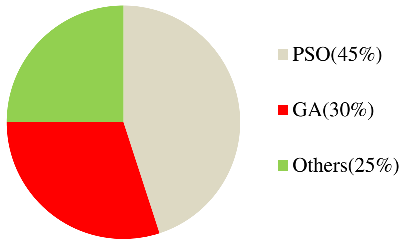

Figure 1. Pie chart showing use of methods

Inkollu et al. in [9], proposed new technique which is a hybrid of PSO and Gravitational Search Algorithm (GSA). PSO has been used for optimizing the gravitational constant of GSA to improve its search performance and it has been used to find the optimal location and rating of FACTS devices. Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC) is considered. The objective function has been made on the basis of voltage collapse and power loss. Technique has been implemented on IEEE 30 bus network. Comparison made between PSO-GSA and GA-GSA technique and it has been observed that computation time is less in former technique.Venkatesh et al. in [10], presented PSO method used for optimal location of FACTS controller for enhancing the Available Transfer Capability (ATC) of the system. FACTS devices considered are SSSC, STATCOM, UPFC on six bus network.

2.2 Genetic Algorithm
It is a natural genetic based evolutionary technique inspired by Darwin theory of survival of fittest. It comprises three operators: selection, crossover and mutation applied at each iteration.Adebayo et al. presented new method called Network Structural Characteristics Techniques (NSCT) to search optimal location of FACTS controllers such as TCSC and UPFC and compared it with GA. Both methods are implemented on IEEE 14 bus network. Generation and devices cost function minimization has been taken as the objective. It has been observed from simulation that NSCT is more superior than GA due to less time consumption and no iteration for searching optimal location of FACTS controllers. Total computational time for GA is 6.73 sec and for NSCT is 1.23 sec [11].

Khandani et al. proposed hybrid of GA and Sequential Quadratic Programming (SQP) to find optimal location of SVC and solution of Optimal Power Flow problem for enhancement of TTC. GA method is relatively slow but does not depend on initial point while SQP depends on initial point and cannot handle discrete variables, hybrid model takes advantage of both. This hybrid method has been implemented on IEEE 5 bus system. It has been shown that SVC at position 2 is the optimal place for enhancement of TTC.[12]

Rashed et al. discussed the enhancement of loadability of the system by optimally placed multiple TCSC in the system with the help of PSO and GA. Minimizing investment cost of devices taken as objective function with voltage limits and thermal limits of lines as constraint. IEEE 6 and 14 bus networks are used for simulation results. In 6 bus network, active power flow in line by installing 3 TCSC's optimally improves 39% with GA and 43% with PSO. Similarly, in 14 bus network, with 5 TCSC, 20% improvement with GA and 29% with PSO. Maximum loadability increase in 6 and 14 bus system are 15% and 22% respectively. By the comparison of two methods, it has been shown that PSO is faster than GA. It is found that TCSC is the one of most effective device to increase the system loadability [13].

2.3 Brainstorm Optimization Algorithm (BSOA)
BSOA technique was proposed by Shi in 2011 and its idea comes from brainstorming procedure in human species. BSOA development based on the notion that human beings are considered most intellect creatures

so algorithm motivated by their approach of problem solving is considered best over algorithms inspired by ants, birds, bees etc. it contains four operations: initialization, clustering, cluster center perturbation, individual perturbation.

A. R. Jordehi in [14] presented BSOA approach with eight other approaches i.e. PSO, GA, Simulated Annealing (SA), Backtracking Search Algorithm (BSA), DE, hybrid of Genetic Algorithm and Pattern Search (GA–PS), Asexual Reproduction Optimization (ARO) and GSA are used for optimal allocation of FACTS controllers such as SVC and TCSC on IEEE 57 bus network and comparisons are made. BSOA emerged best among other techniques to minimize power loss and voltage deviation of the system. In context of TCSC, it has been observed that the main work of TCSC helps to control power flow but also shows the effectiveness to enhance voltage security of the network.

2.4 Gravitational Search Algorithm (GSA)
GSA is a meta-heuristic technique developed in 2011 based upon Newton's law of gravity and motion. In this technique, each agent is associated with mass. Agent with heaviest mass among other attract low mass agents according to the Newton law of gravitation and the position of heaviest mass agent considered as optimal solution in the search area.

Bhattacharyya et al. in [15] applied GSA method for optimal placement of SVC and TCSC to increase the system loadability and power transfer capability of generators. The proposed approach is compared with DE, PSO and GA. The techniques are applied on IEEE 57 and 30 bus network. It has been shown that GSA is most effective in minimizing operating cost and active power loss compared to others.

2.5 Adaptive Evolutionary Algorithm (AEA)
Evolutionary methods are potent algorithms for multi-objective optimization problem where optimal solutions can be found in one simulation run. EA's does not required problem information that is being solved unlike classical methods [16].

The main challenge evolutionary method is dealt with maintaining its population diversity to avoid premature convergence. The proposed AEA method in [17] provides control of population diversity to prevent premature convergence and maintain the global search. In the paper, AEA method performance compared with PSO, SA and EA on the basis of L-index, voltage deviation, and reactive power loss. AEA emerged superior compared to other methods on IEEE 57 bus network and it outperforms for voltage deviation minimization in IEEE 14 bus system. It was shown that AEA is better than standard EA.

2.6 Moth Flame Algorithm (MFA)
MFA technique is proposed by Seyedali Mirjalili, inspired by moth navigation in environment called transverse orientation. In night, moth travel in straight direction by maintaining specific angle with moon for long distances but these insects trapped in circular or spiral paths around artificial lights. Mathematical modeling of this travelling behavior is done for optimization.

M. Ebeed et al. in [18] presented MFA method for optimal setting of STATCOM for voltage profile and stability improvement and loss minimization. Comparison of MFO with PSO has been done and validated on IEEE 30 bus network. MFA emerged more superior than PSO in stabilizing voltage deviation and minimize power losses with STATCOM like power loss minimized by 6 and 4 percent respectively by MFO and PSO respectively. It has been shown that STATCOM is effective for voltage profile improvement and loss minimization.

2.7 Imperialistic Competitive Algorithm (ICA)
Atashpaz-Gargari and C. Lucas developed novel meta-heuristic technique ICA which is motivated by the imperialism and socio-political development of human beings. Each candidate is treated as country and become either a colony or an imperialist.

A. R. Jordehi in [19] discussed TCSC and Thyristor Control Phase Shifting Transformer (TCPST) optimal placement by ICA on IEEE 14 bus system.

ICA outperforms some state of art methods like Evolutionary Programming (EP), Artificial Bee Colony (ABC), Bat Swarm Optimization (BSO), GSA. It has been shown that FACTS devices installation made the system secure at the time of contingencies and load growth with ICA.

2.8 Adaptive Cuckoo Search Algorithm (ACSA)

Suash Deb and Xin-She Yang introduced meta-heuristic CSA technique in 2009 inspired from search method of cuckoo bird species for laying eggs. Cuckoo bird lays eggs on other birds nest and they search the nest through levy flights or random walks. Mathematical modeling including step size parameter and probability inspired from above behavior leads to CSA. In ACSA, only step size parameter is removed for search of next nest instead value of best nest updated based on current best nest.

Taleb et al. proposed ACSA for the optimal location of TCSC in IEEE 9 bus network for minimum bus bar voltage and minimizing active and reactive power loss. Evaluation of result of ACSA with PSO and GA has been done. It has been found out that minimum bus voltage reduced by 0.62% in comparison of PSO and GA. Overall active and reactive power loss is more reduced than PSO and GA [20].

3. FACTS applications using GA

In this section, overview of FACTS devices optimal placement, type and size using Genetic Algorithm with consideration of various objective functions (single and multi-objective) with different equality/inequality constraints are analyzed and study the effect of FACTS on different parameters of power system. The device considered mainly is SVC and TCSC. Table.1 and Table.2 shows Multi and single objective function optimization using GA with different bus system.

In [21], [23, [26], [30], [35] from table.1 and [38], [43], [46], [49] from table.2, it is inferred that TCSC has been used to enhance the performance of system by affecting various parameters like reducing generation cost, reducing active and reactive power loss, improving voltage stability by decreasing L-index, improving total transfer Capability (TTC), controlling the active power flow, enhancement of stability margin (SM) etc. It is found in [26], that cost of 10 MVAR TCSC installed in IEEE 30 bus network for voltage stability and reduction in losses is 1,53,000 US$. Similarly for 13 MVAR, cost of TCSC is 1,881,500 US$.

In [22], [24], [32], [36], [39], it is observed that SVC has been used to reduce generation cost reduction, active and reactive power loss reduction. STATCOM has been used in [40], [48], [50] for improvement in voltage stability, loadability and in loss reduction. It is seen in [48] that 60 MVAR STATCOM cost 10.8 million US$ in IEEE 14 bus network for improving voltage security.

It is observed from [44], that active power loss increases when SVC and TCSC are used together in IEEE 30 bus network but reactive power loss decreases significantly. In [37], it has been concluded that TCSC is more effective than SVC for enhancing the voltage stability of the 14 bus power system and generation cost reduction is nearly same in both the cases. It is inferred from [29] and [31] that active power loss reduces more in case of SVC than TCSC for IEEE 5 bus system and TCSC is more effective to reduce reactive power loss in IEEE 30 bus system. TCSC is best suited FACTS device among other for loadability enhancement.

In single type optimization, it has been shown that TCSC is the most effective device over Thyristor Controlled Phase Shifting Transformer (TCPST) and Thyristor Controlled Variable Reactor (TCVR) for enhancement of system loadability. TCSC drives the power in other direction to reduce loading on the line. [25].Nireekshana et al. shown that TCSC is better than SVC for ATC enhancement when the same bus–to–bus transactions are chosen [47].Karami et al shown the cost benefit analysis of STATCOM in which active power losses reduction saves 80 million$ and this study shows that tradeoff between STATCOM initial cost and saving from losses gives benefit of 69.3 million $.[50].Rashed et al presented Differential Evolution (DE) technique and compared it with GA. DE technique has superiority over GA in some features like high quality solution, stable convergence etc. [46].

Table 1. Multi-objective optimization

Objective functions	Multi-objective function	Equality/Inequality Constraints	Test Bus and Optimal location	Rating of device	Parameters affected
Investment cost function $C_1(f)$= depends on type of FACTS device **Bid function** $C_2(P_G) = P_{min}^T P_G$ [21]	Total cost function $C_T=C_1(f)+C_2(P_G)$ Overall obj. function m-C_{Total} m= 4000 US$/hour to convert obj. function into max. one	Equality const. E(f,g)= 0 Inequality const. $B_1(f)<b_1$, $B_2(g)<b_2$	*10 bus system* TCSC between bus 4-5	capacitive 70% of X_{line}	Generation cost reduced from 1117.75 to 915.90 US$/hour
For real power loss $F_1(u,v) = \sum_{k=1}^{NTL}[g_k[v_i^2 + v_j^2 - 2v_iv_j\cos(\delta_i - \delta_j)]$ **For voltage deviation** $F_2(u,v) = \sum_{k=1}^{NL}\|(v_k - v_k^{ref})\|$ **For SVC size** $F_3(SVC\ size) =$ Rating of SVC in p.u. [22]	F(u,v) = $F_1(u,v)+F_2(u,v)$ $+F_3(SVC\ size)$	Equality Const. $P_{Gi} - P_{Di} - P(V,\delta) = 0$ $Q_{Gi} - Q_{Di} - Q(V,\delta) = 0$ Inequality Const. $Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}$	*30 bus system* SVC at bus 30 (for LO 36) 28(for LO 5) 28(for LO 15) LO = line outage	capacitive 11.04 MVAR Inductive 1.55 MVAR Inductive 15.42 MVAR	
Total cost function $C_T=C_1(f)+C_2(P_G)$ $C_1(f)$= FACTS cost function $C_2(P_G)$= generation cost function [23]	Fitness= $\frac{1}{C_T+W(\sum_i^N P_{Gi}-P_{Di}-P_{Li})}$	Equality const. E(f,g)= 0 Inequality const. $B_1(f)<b_1$, $B_2(g)<b_2$	*9 bus system* TCSC 5th bus OL TL 3 TL 4 9th bus OL TL 2 OL=overloading	(In MVAR) 10.166 17.977 62.989	
For real power losses $O_1 = \sum_{l=1}^{b}[(v_i^2 + v_j^2 - 2v_iv_j\cos(\delta_i - \delta_j)]y_{ij}cos\theta_{ij}$ **For voltage deviation** $O_2 = \sum_{i=1}^{n}(u_{iref} - u_i/u_{iref})^2$ **For installation cost** $O_3 = 0.0003Q^2 - 0.3051Q + 127.38$	$f(x) = 0.4\frac{O_i}{\sum \Delta loss_{base}} + 0.4\frac{O_2}{\sum \Delta v_{base}} + 0.2\frac{O_3}{C_{max}} - \xi\sum_{i=1}^{nr} bal_i - \varsigma\sum_{k=1}^{n} thermal_k - \varrho\sum_{k=1}^{n} voltage_k$ S_l=power of line l U_i=voltage of bus i	Equality Const. $P_{Gi} - P_{Di} - P(V,\delta) = 0$ $Q_{Gi} - Q_{Di} - Q(V,\delta) = 0$ Inequality Const. $S_l \le S_l^{max}$ $U_{imin} \le U_{nom} \le U_{imax}$	*13 bus system* SVC at 10th bus	143 MVAr	Loss drop from 25.886 to 22.432

[24]					
For BL $Ovl_{line} = e^{\lambda_{out}(100-BL)}$, >100% loading 1, < 100% loading **For BVL** $Vtg_{bus} =$ 1, 0.95 < Vt < 1 $e^{\lambda_{vtg}(\|(1-VL)-0.05\|)}$, otherwise BL= branch loading BVL= bus voltage loading [25]	Obj= $\prod_{line} Ovl_{line} + \prod_{bus} Vtg_{bus}$ λ_{out} and λ_{vtg} are coefficients to adjust slope of the exponentials	Equality Const. $P_{Gi} - P_{Di} - P(V,\delta) = 0$ $Q_{Gi} - Q_{Di} - Q(V,\delta) = 0$ Inequality Const. $S_l \leq S_l^{max}$ $U_{imin} \leq U_{nom} \leq U_{imax}$	*118 bus system* TCSC at branch 5-8 23-24 92-100 SVC at branch 43-44 95-96		15 devices used ,TCSC emerged as most efficient device for loadability enhancement
Reactive power loss $f_i(x)=\sum_{i=1}^{N_{line}} Q_{iloss}$ **Voltage stability margin (L index)** $f_2(x)= max(L_j)$ **Cost of FACTS controllers** $f_3(x)= C_{upfc}+C_{tcpst}+C_{tcsc}$ [26]	Min f(x)= $[f_i(x),f_2(x),f_3(x)]$	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$ $\sum_{i=1}^{N_{bus}} Q_G - Q_D - Q_L = 0$ Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $S_{ij}<S_{ijmax}$ $V_{imin}<V_i<V_{imax}$ $\delta_{imin}<\delta<\delta_{imax}$	*30 bus system* For TCSC line 10-22 line 10-20	(In MVAR) 1 13	L index drop to 0.072 from 0.136 Q_{loss} reduced to 17 from 22MVAR Cost of 10 MVAR TCSC 153000 US$ 13 MVAR 1881500 US$
Generation cost function $C_{Gi}(P_G)=a_{Gi}+b_{Gi}P_G+C_{Gi}P_G^2$ **Cost of FACTS controllers** $C_2(f)= C_{svc}+C_{upfc}+C_{tcsc}$ [27]	objective function= min $[C_{total}=C_{Gi}(P_G)+ C_2(f)]$	Equality const. E(f,g)= 0 Inequality const. (power flow eqn.) $B_1(f)<b_1$, $B_2(g)<b_2$	*30 bus system* Bus 2 load increment SVC at line 36 Bus 15 load increment TCSC at line 10	73.38 MVAR 72.90 MVAR	System cost in SVC case 881.87 $/hr System cost in TCSC case 849.41 $/hr
Fuel cost $C_{Gi}(P_G)=a_{Gi}+b_{Gi}P_G+C_{Gi}P_G^2$ **Power loss** $P_{loss} = \sum_{j=1}^{m} loss_j$ [28]	Obj. function F(x,u) = min.$(C_{Gi}(P_G)+P_{loss})$	Equality const. (active and reactive power balance) g(x,u)= 0 Inequality const $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $S_{ij}<S_{ijmax}$ $V_{imin}<V_i<V_{imax}$ $-0.5X_L \leq X_{TCSC} \leq 0.5X_L$	*30 bus system* For TCSC Line 27 for minimum cost between line 12 & 14 for min. loss For SVC Bus 24 for min. cost Bus8 for min. loss	capacitive 30.6% X_{line} inductive 29% X_{line} 4.2 MVAR 50 MVAR	In TCSC and SVC case, Loss reduced from 2.01 to 1.953 MW and 1.934 MW respectively Fuel cost reduced from 576.60 to 575.99 and 575.94($/hr) respectively

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VSI (L index) $L_j = \left\lvert 1-\sum_{i=1}^{g} F_{ji}\frac{V_i}{V_j}\right\rvert$ **FACTS cost fn.** $C_{tcsc}=0.015s^2-0.7130s+153.75$(US$/kvar) $C_{svc}=0.0003s^2-0.3051s+127.38$(US$/kvar) [29]	Fitness fn = a_1*(max L_j) + a_2*(cost fn) + a_3* (losses) $a_1 = 2.78$ $a_2 = 0.1$ $a_3 = 2.05$ VSI = voltage stability index	Equality const. $S^k(\lvert V\rvert^k,\theta,u^k)=0$ Inequality const. $h^k((\lvert V\rvert^k,\theta,u^k)\le 0$	*30 bus system* TCSC Bus 2-4 SVC Bus 18	 13 MVA 97.18 MVA	In TCSC and SVC case, loss reduced from 28.36 to 24.91 MVA and 26.3 MVA respectively Overall cost 9197500 US$ and 4521600 US$ respectively
Cost function $g_1=\sum_{i=1}^{t} f_i(S_i)$ **Line flow limits** $g_2=\prod_{i=1}^{l} f_2^k(p_i)$ **Active power losses** $g_3=p_{sl}=\mathrm{Re}\{V_{sl}[\sum Y_{sli}.V_i]^*\}$ g_4= ATC= TTC-ETC [30]	Objective function= min(g_1,g_2,g_3,g_4) TTC calculated by RPF method in which maximize λ ATC= available transfer capability TTC = total transfer capability ETC= existing transfer commitment	Equality const. $S^k(\lvert V\rvert^k,\theta,u^k)=0$ Inequality const. $h^k((\lvert V\rvert^k,\theta,u^k)\le 0$ u is control variables	*30 bus system* TCSC Line 2-6 Line 27-28	 19.097 MVAR 10.327 MVAR	Loss reduced from 3.006 to 2.231 MW TTC increase from 70.25 to 86.85 MW
Generation cost function $C_{Gi}(P_G)=a_{Gi}+b_{Gi}P_G+C_{Gi}P_G^2$ **Benefit function** $B_{Dj}(P_D)=d_{Dj}P_D-e_{Dj}P_D^2$ [31]	Objective fn max($\sum_{i=1}^{N_D} B_{Dj}(P_D) - \sum_{i=1}^{N_G} C_{Gi}(P_G) + cost(FACTS)$) N_D= no. of loads N_G=no. of generators	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$ Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$	*5 bus system* TCSC bus 3-5 For SVC 3rd bus		In TCSC and SVC case, losses reduced from 21.95 to 20.303 MW and 19.81 MW respectively Generation cost reduced from 6126.50 to 6095.20 and 6078.6 US$/hr respectively
Generation cost function $C_{Gi}(P_G)=a_{Gi}+b_{Gi}P_G+C_{Gi}P_G^2$ **FACTS devices cost functions** $C_{svc}=0.0003s^2-0.3051s+127.38$(US$/kvar) [32]	Min F = min($C_{Gi}(P_G)+C_{svc}(g)$)	Power flow equations E(f,g)= 0 Inequality const. $B_1(f)<b_1$, $B_2(g)<b_2$	*14 bus system* SVC at bus 5 *30 bus system* SVC at bus 5	 51.31 MVAR 136.973 MVAR	Fuel cost reduced to 829.93 US$/hr
Generation cost function $C_{Gi}(P_G)=a_{Gi}+b_{Gi}P_G+C_{Gi}P_G^2$ **FACTS devices cost functions** $C_{tcsc}=0.015s^2-0.7130s+153.75$(US$/kvar) $C_{svc}=0.0003s^2-0.3051s+127.38$(US$/kvar) [33]	Total cost function $C_T = C(f) + C_{Gi}(P_G)$ Overall obj. function = m-C_{Total} m= 4000 US$/hour to convert obj. function into max. one	Equality const. E(f,g)= 0 Inequality const $B_1(f)<b_1$, $B_2(g)<b_2$	*14 bus system* For SVC 5 -6 bus For TCSC 2 -5 bus	 10.5 MVAR Capacitive 22%X_{line}	

Voltage stability index (VSI) $F_1 = L_{max}$ $\lvert L_j \rvert = \left\lvert 1 - \frac{\sum i\epsilon\alpha_G C_{ij} V_i}{V_j} \right\rvert j\varepsilon\alpha_L$ **Generation cost function** $F_2 = C_{Gi}(P_G) = a_{Gi} + b_{Gi}P_G + c_{Gi}P_G^2$ **For real power loss** $F_3 = \sum_{k=1}^{NTL}[g_k[v_i^2 + v_j^2 - 2v_iv_j\cos(\delta_i - \delta_j)]$ [34]	$F = h_1F_1 + h_2F_2 + h_3F_3$ $h_1 + h_2 + h_3 = 1$ $h_1 = 0.35$ $h_2 = 0.3$ $h_3 = 0.35$	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$ Inequality const. $P_{Gimin} < P_{Gi} < P_{Gimax}$	*14 bus system* For SVC Bus 4 For TCSC 9-14 bus	 18.94 MVAR 23% X_{line}	In SVC and TCSC case, VSI reduced from 0.0783 to 0.0772 and 0.0732 respectively Loss reduced by 0.0946 and 2.0378 MW respectively Generation cost reduced by 0.5611 and 0.2278 $/hour respectively
Generation cost function $C_{Gi}(P_G) = a_{Gi} + b_{Gi}P_G + C_{Gi}P_G^2$ **Benefit function** $B_{Dj}(P_D) = d_{Dj}P_D - e_{Dj}P_D^2$ [35]	Objective fn $min\ [\ \sum_{i=1}^{N_G} C_{Gi}(P_G) - \sum_{i=1}^{N_D} B_{Dj}(P_D) + cost(FACTS)]$ N_D= no. of loads N_G=no. of generators	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$ Inequality const. $P_{Gimin} < P_{Gi} < P_{Gimax}$ $Q_{Gimin} < Q_{Gi} < Q_{Gimax}$ $S_{ij} < S_{ijmax}$ $V_{imin} < V_i < V_{imax}$ $X_{tcscmin} < X < X_{tcscmax}$	*14 bus system* For TCSC Between 6-13 bus	23.98 % X_{line}	Generation cost reduced from 1407.154 to 1344.47 $/hr
Generation cost function $C_{Gi}(P_G) = a_{Gi} + b_{Gi}P_G + C_{Gi}P_G^2$ **FACTS device cost function** $C_{svc} = 0.0003s^2 - 0.3051s + 127.38$(US$/kvar) [36]	Overall obj. function $\min(C_T)$ $= C(f) + C_{Gi}(P_G)$	Equality const.(active and reactive power balance) E(f,g)= 0 Inequality const. (power flow eqn.) $B_1(f) < b_1,\ B_2(g) < b_2$	*14 bus system* SVC at 5th bus	 51.66 MVAR	Fuel cost 1064 $/hour
System security $F_t = \sum_{l=1}^{a} w_1 \left(\frac{s_l}{s_{lmax}}\right)^{2q} + \sum_{m=1}^{b} w_m \left(\frac{V_{mref} - V_m}{V_{mref}}\right)^{2r}$ $F_e = C_{svc} + C_{tcsc}$ [37]	Fitness fn = Min F(x) = [$F_t(x)$, $F_e(x)$]	Equality Const. E(f, g) = 0 Inequality const. $B(f) > b_1,\ B(f) < b_2$ f = variables of FACTS devices g = power systems operating state	*14 bus system* TCSC Bus 9-14 SVC Bus 7-9	 Capacitive 0.996 MVAR 22.91 MVAR	

Table 2. Single objective optimization

Objective functions	Equality/Inequality Constraint	Test bus and Optimal location	Rating	Parameters affected
Obj. fcn = max $\boldsymbol{\lambda}$ $\boldsymbol{\lambda}$ is system loading factor [38]	Equality const. $P_{gi}–P_{di}$ - ∑ | V_i |* | V_j | * (G_{ij} $\cos\delta_{ij}$ + B_{ij} $\sin\delta_{ij}$) = 0 $Q_{gi}–Q_{di}$ - ∑| V_i |*| V_j |* (G_{ij} $\sin\delta_{ij}$ – B_{ij} $\cos\delta_{ij}$) = 0 Inequality const. $V_{imin}<V_i<V_{imax}$ $- 0.5 * X_{line} < X_{TCSC} < 0.5 * X_{line}$	*4 bus sytem* TCSC at line 3	Capacitive 23% X_{line}	TTC improved from 489.6 to 813.6 MW
Susceptance equation $B^{i+1}_{SVC} = B^{i}_{SVC}+(\Delta B_{SVC}/B_{SVC})B^{i}_{SVC}$ [39]	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$ Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $S_{ij}<S_{ijmax}$ $V_{imin}<V_i<V_{imax}$ $X_{tcscmin}<X<X_{tcscmax}$	*9 bus system* SVC at 9th bus(NL) *30 bus system* SVC at 1st bus(NL) NL= normal loading	B = 46.77 siemens B = 9.6 siemens	Q loss reduced from 79.55 to 4.73 Q loss reduced from 68.68 to 19.79
$P_{li} = \boldsymbol{\lambda}P_{0li}$ & $Q_{li} = \boldsymbol{\lambda}Q_{0li}$ $P_{gi} = \boldsymbol{\lambda}P_{0gi}$ Obj.fcn= max($\boldsymbol{\lambda}$) $\boldsymbol{\lambda}$ is system loading factor [40]	Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $S_{ij}<S_{ijmax}$ $\|V_{bi}\| \leq 0.05$	*57 bus system* STATCOM with SMES At Bus 38	Capacitive 67.528 MVAR	$\boldsymbol{\lambda}$ improved 14% Loss reduced by 12 MW
For voltage stability $\sum abs\|v_i - v_{refi}\|^3$ [41]	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$	*68 bus system* For SVC 40 49 50	(in MVAR) 145 150 150	
Obj. = Maximize λ λ= system loading margin [42]	Equality const. $\sum_{i=1}^{N_{bus}} P_G - P_D - P_L = 0$	*14 bus system* For SVC at bus 9 *30 bus sytem* For SVC at bus 30		λ improved from 3.9752 to 4.11 λ improved from 3.01 to 3.30
min F = $\sum_{k=1}^{nl} Q_{lk} + \sum_{k=1}^{nl} P_{lk} + \sum_{n=1}^{ng} Q_{gn}$ [43]	Equality const. $P_{gi}–P_{di}$ - ∑ | V_i |* | V_j | * (G_{ij} $\cos\delta_{ij}$ + B_{ij} $\sin\delta_{ij}$) = 0 $Q_{gi}–Q_{di}$ - ∑| V_i |*| V_j |* (G_{ij} $\sin\delta_{ij}$ – B_{ij} $\cos\delta_{ij}$) = 0 Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$	*30 bus sytem* TCSC at Line 2 Line 3 Line 6	capacitive 40% X_{line} inductive 16.7 X_{line} Capacitive 2.8% X_{line}	Active flow Increase by 10 MW Decrease by 3 MW Increase by 0.64 MW

	$X_{mintcsc}<X<X_{maxtcsc}$ $V_{imin}<V_i<V_{imax}$ $\delta_{min}<X<\delta_{max}$			
Min(f,u) = $P_L(V,\delta,S)= \sum_{i=1}^{N}[P_{Lt} \times E_{loss} \times \Delta T - C_{in}]$ [44]	E(b,v)= 0 $B_1(s)<b_1,\ B_2(v)<b_2$	*30 bus system* For SVC Bus 24^{th} For SVC and TCSC together at bus 24^{th} and line 1-3 respectively	25 MVAR 25 MVAR & $53.99X_{line}$	**SVC case** Real loss reduced from 17.869 to 17.695 MW & Q loss reduced from 24.862 to 22.3 MVAR **TCSC and SVC** Real loss reduced from 17.869 to 17.979 MW & Q loss reduced from 24.862 to 14.145 MVAR
OVL(k)=1, if $S_{pq}<S_{pqmax}$ $e^{\lambda\left\|1-\frac{\|S_{pq(k)}\|}{S_{pqmax(k)}}\right\|}$, if $S_{pq}>S_{pqmax}$ [45]	Inequality const. $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $S_{ij}<S_{ijmax}$ $V_{imin}<V_i<V_{imax}$	*30 bus system* TCSC at line 11 SVC at bus 22	Capacitive $32.12X_{line}$ 19.28 MVAR	29% reduction in losses
Real power loss minF = $\sum_{k=1}^{ntl} P_{lk}$ [46]	Equality const. $P_{gi}-P_{di}-\sum_{j=1}^{n} V_iV_jY_{ij}(x_{tcsc})\cos(\delta_{ij}+\gamma_j-\gamma_i)=0$ $Q_{gi}-Q_{di}-\sum_{j=1}^{n} V_iV_jY_{ij}(x_{tcsc})\sin(\delta_{ij}+\gamma_j-\gamma_i)=0$ Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $V_{imin}<V_i<V_{imax}$ $\delta_{ijmin} \le \delta_{ij} \le \delta_{ijmax}$	*3 bus system* TCSC bus 1-3 *5 bus system* TCSC bus 1-2 *14 bus system* TCSC bus 2-3	Capacitive 2.20% X_{line} Capacitive 0.1% X_{line} Capacitive 4.2% X_{line}	
Obj. = max ATC ATC = TTC-TRM-(ETC+CBM) ATC= available transfer capability TTC = total transfer capability ETC= existing transfer commitment [47]	Equality const. $\sum_{i=1}^{N} P_{Gi} - P_D - P_{Loss}=0$ Inequality const. $P_{Gimin}<P_{Gi}<P_{Gimax}$ $Q_{Gimin}<Q_{Gi}<Q_{Gimax}$ $V_{imin}<V_i<V_{imax}$ CBM= capacity benefit margin TRM= transmission reliability margin (TRM),	*14 bus system* TCSC at line 9 SVC at bus 10 *30 bus system* TCSC at line 28 SVC at bus 20	Capacitive $8.8\%X_{line}$ 8.1 MVAR Capacitive $1.03\%X_{line}$ 9.9 MVAR	ATC increase by15.5 by 7 by 40 by 20

Z =MANP×VANP MANP=$\frac{1}{n}\sum_{j=1}^{n} NP_j$ VANP= $\sqrt{\frac{1}{n}\sum_{j=1}^{n}(NP_j - MANP)^2}$ Z= objective function NP= nodal price of active power VANP= variance of nodal price [48]	Equality const. G(X,P,Q) =0 Inequality const. H(X,P,Q)<0	*14 bus system* STATCOM at line 5 *30 bus system* STATCOM at line 15 *118 bus system* STATCOM at line 35	30.02 MVAR capacitive 28.75 MVAR capacitive 27.92 MVAR capacitive	**14 bus case** Fuel cost reduced from 1265643 to 12644.53 \$/hr **30 bus case** Fuel cost reduced from 14444.88 to 14278.6 \$/hr **118 bus case** Fuel cost reduced from 83311.63 to 83189.6 \$/hr
J= $\sum\left\|V_j - V_{jref.}\right\|^2$+ (1-SM)+$n_f$ [49]	Equality const. $\sum_{i=1}^{N} P_{Gi} - P_D$-$P_{Loss}$=0 Inequality const. X_{min}<X<X_{max} 0.95<V_{bus}<1.05	*AEP 14 bus system* TCSC between bus 1-2 1-5 2-3	 Capacitive 1.7 X_{line} 11.91X_{line} 8.53 X_{line}	SM increase from 0.1166 to 0.2188 SM= security margin
Max F(u) = ($\boldsymbol{\lambda}$-$\boldsymbol{\lambda}_0$) $\boldsymbol{\lambda}$ = distance between operating and collapse point.[50]	Equality const. f(x, $\boldsymbol{\lambda}$, p) = 0 $D_x^T F(x, \lambda, p_0)w = 0$ D_x^T = jacobian matrix	*14 bus system* STATCOM line 9-14	 60 MVAR	Increase voltage security by 44.2 MW Loss reduced by 50.83 MW 10.8 million \$ investment cost

4. Conclusion

In this paper, recent optimization techniques are discussed such as Particle Swarm Optimization (PSO), Genetic Algorithm, Brainstorm Optimization Algorithm (BSOA), Gravitational Search Algorithm (GSA), Adaptive Evolutionary Algorithm (AEA), Moth Flame Algorithm (MFA), Imperialistic Competitive Algorithm (ICA), Adaptive Cuckoo Search Algorithm (ACSA) and compared among each other. It has been observed that recent methods are generally inspired by human behavior like BSOA, ICA etc and show good performance to solve practical problems. They outperformed conventional heuristic methods like GA and PSO in speed.

The other part of the paper presents analytical review on optimal location of FACTS devices mainly SVC, TCSC and STATCOM. Different bus system and objective function for various parameters optimization has been studied e.g. for minimization of generation cost, active power losses and investment cost of FACTS and regarding voltage stability.

Power system parameters changes with and without FACTS devices has also been considered. It can be concluded that FACTS devices enhance system performance and maintain system security at the time of contingencies. This paper will be helpful for choosing specific type of FACTS devices on the basis of different objective.

5. Future Scope

It has been observed that hybrid optimization techniques are more effective, robust and fast to search the particular solution. More work can be done to develop the hybrid optimization technique from recent methods.

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