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Optimal allocation of FACTS devices based on heuristic approach considering ATC along with device cost and voltage variations

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ABSTRACT:
Voltage stability is one of the significant aspect in steady state operation of power systems. The optimal reactive power requirement behind it is the guiding philosophy to have stable voltage in power system. As it is known that the conventional generation provides active power, but it fails to provide reactive power. Thus, the absence of the reactive power affects the performance of system; and as by general phenomenon it can solved by optimally allocating the flexible alternating current transmission system (FACTS) devices in transmission system. This proposes an optimal allocation of FACTS devices to have increased voltage stability at optimal cost of FACTS devices; together with enhancing the Available Transfer Capability (ATC) in the system. The allocated FACTS device improves the voltage profile, ATC at optimal cost, solved by using heuristic based on salp swarm optimization algorithm. The relevant comparisons made in this work shows the superiority of proposed approach over the other methods.

Keywords: Voltage stability, Available Transfer Capability (ATC)**,** Flexible alternating current transmission system (FACTS),

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I. INTRODUCTION

Voltage stability is one of the key issue in operation and control of power systems. The ever-increasing loads, together with the increasing environmental consciousness among the public and also persistent economic aspects made the normal operation even more sensitive and complicated. With the above aspects, the voltage control in align with changing loads lead to voltage security problem, that makes the voltage close to its operating limits. The academicians as well as the practicing power engineers have taken it to the extent to model it with relevant modes of system thereby to attain the real time operating scenario [1, 2]. In order to maintain the system security (together with voltage), it is utmost essential to operate the system within the specific margins of power flows in the line. This margins provide the operating limits that are calculated from offline studies by simulating the interconnected system on any simulation platform. The system operators in the control centres operate the system within this limits for secure operation of entire system. Hence, it can be concluded that the relevant models are to be formulated and offline studies has to be performed on the concerned system to ensure better security in its real time operation [3].

The voltage collapse is also a significant threat to all the levels of voltages that exists in the power network, starting from generation, distribution, and transmission systems, also in industrial environments as well. This is well characterized by loss of stable voltage operating point for given loading condition and also by the deterioration of voltage levels within the vicinity of electrical interconnecting point that is currently experiencing the voltage collapse. The voltage stability improvement methodologies as stated earlier are prematurely possible in all variants of power system networks and also the voltage stability can be enhanced during the design as well as the operation phases of the system [4, 5].

But alternatively, FACTS devices can provide distinct advantages with the same objectives that can met without any major changes in the network. The inherent advantages that would follow by incorporating FACTS devices include decrease in investment on transmission network, enhanced system security and network reliability, increased power transfer capability in the network and all together an overall enhancement of quality of power delivered at the receiving end [6]. To be specific this studies are more focused to operate the device well within the operating limits. The performed studies must compare and contrast all the available FACTS devices in terms of individual voltage stability margin it can provide in the system, at the outlay of performance with ATC, voltage stability and device costs were analyzed in this work.

Here in this work the ATC is evaluated using continuation power flow along with Real Code genetic algorithm for optimal allocation of SVC and TCSC considering the voltage profile and the thermal limits. The proposed method is tested on IEEE -14 and 24-bus reliability test network [7]. In this paper, by placing the FACTS devices the ATC is increased by using TCSC with fast algorithm and the applied method is tested on IEEE 30 bus system [8]. In this work the FACTS such as TCSC and SVC is placed in the system to increase the total transfer capability and it is observed that the TCSC is superior than SVC [9]. In this paper novel method is used for ATC calculation using the active power distribution factor that is based on exact circle equation without considering the thermal limits and is tested on IEEE 30 bus network [10]. A hybrid neural and bees algorithm is used to evaluate the ATC by optimal placement of UPFC FACTS controller, the proposed method shows significant reduction in losses and improvement in ATC [11].

In this work the ATC is evaluated using continuation power flow along with Cat swarm optimization for optimal allocation of SVC and TCSC considering the voltage profile and the thermal limits. The proposed method is tested on IEEE -14 and 24-bus test network [12]. The author has proposed a novel method for ATC calculation by using fuzzy modelling for large power system and it is tested on IEEE -24 bus test network [13].To evaluate the ATC and voltage stability the author has proposed the sensitivity approach by optimally placing the FACTS devices. The proposed approach is simulated in the power world simulator [14].

II. SIGNIFICANCE OF AVAILABLE TRANSFER CAPABILITY:

The transfer capability refers to the existing not utilized transfer capability that is available for making transactions with the participants with market. It is accurate and can be estimated which includes margins for transmission, this remails as the key factor for congestion management and planning of transmission system. The placement and location of optimal size of FACTS device is to increase the ATC of network. As network voltage variation is considered as one of the objective, the FACTS device in the lines will ensure the increase of ATC across the lines and hence the less congestion in the system. Hence for this two reasons the voltage variations and ATC has been considered as objectives in the formulated problem. Also, the FACTS device cost is also taken into consideration, such that the allocation is made at the significant reduction in cost together with the network transfer capability and voltage variation.

The ATC can be explained through the algebraic equation as given below:

ATC=TTC-TRM-CBM-ETC

Where, TTC is Total Transfer Capability, TRM is Transfer Reliability Margin, CBM is Capacity Benefit Margin and ETC is Existing Transmission Commitments,

The evaluation of ATC for given configuration with transaction as depicted by the sensitivity imposed on the system with other variables of interest.

The corresponding value of ac power transfer distribution factors (ACPTDFs) for determination of static ATC greater precisely is obtained from the following equation as given below in Eqn. (1).

$$ACPTDF_{ij,mn} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \quad \dots, \frac{\partial P_{ij}}{\partial \delta_n}, \frac{\partial P_{ij}}{\partial V_{g+1}} \quad \dots, \frac{\partial P_{ij}}{\partial V_n}\right] [J]^{-1} \begin{bmatrix} 0 \\ . \\ . \\ . \\ +1 \\ 0 \\ . \\ . \\ . \\ -1 \\ 0 \end{bmatrix} \quad (1)$$

III. MODELLING OF FACTS DEVICES:

In the proposed approach, three types of FACTS controllers are used, they are one shunt compensator (SVC) and the series compensator (TCSC) and finally the series-shunt compensator (UPFC); has been used. The mathematical modelling of above mentioned three devices is given below

3.1 Modelling of SVC

To regulate the voltage at any bus the SVC can be employed. This devices topology is simple with a fixed capacitor in parallel with the reactor controlled by a thyristor. By nature, SVC perform as reactive power generating or absorbing device to improve the voltage profile in the power system network [15].

According to Fig. 1, the actual current drawn by the SVC is

$$I_{SVC} = jB_{SVC}V_k \quad (2)$$

The reactive power injected at bus k is given as

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} \quad (3)$$

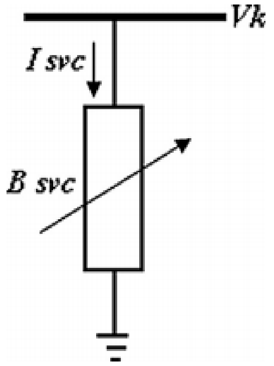


Figure 1 Equivalent Circuit of SVC

3.2 Modelling of TCSC

TCSC is usually a series reactance which is used to control the amount of real power within the limits [15]. The TCSC model with changing reactance X_{TCSC} is given Fig. 2

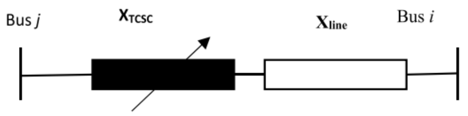


Figure 2 Equivalent Circuit of TCSC

The admittance matrix of the variable TCSC compensator is given equation by

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} jB_{ii} & jB_{ij} \\ jB_{ji} & jB_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (4)$$

For capacitive operation, the equations has

$$B_{ii} = B_{jj} = \frac{1}{X_{TCSC}} \quad (5)$$

$$B_{ij} = B_{ji} = -\frac{1}{X_{TCSC}} \quad (6)$$

For inductive operation, equations signs will be changed.

3.3 Modelling of UPFC

The Unified Power Flow controller (UPFC) is series-shunt controller, and the corresponding equivalent is shown in Fig. 3. The synchronous sources as depicted in the figure, depict the basic Fourier voltage-series components within the UPFC as given in [15, 16].

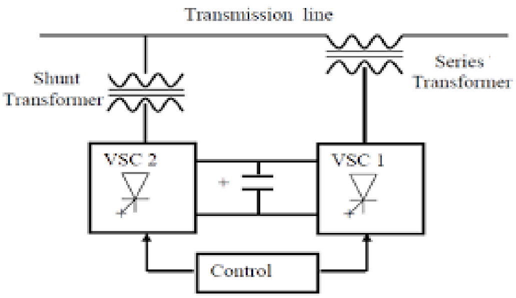


Figure 3 Equivalent Circuit of UPFC

The expression for complex form of voltage sources in UPFC in terms of voltage limits and phase angles are as given below:

$$V_{eR} = E_{eR}(\cos\delta_{eR} + j\sin\delta_{eR}) \quad (7)$$

Where the E_{eR} and θ_{eR} are the voltage limits ($E_{eR\,min} \leq E_{eR} \leq E_{eR\,max}$) and phase angles ($0 \leq \delta_{eR} \leq 2\pi$) of shunt compensation

$$V_{cR} = E_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \quad (8)$$

Where the E_{cR} and θ_{cR} are the voltage limits ($E_{cR\,min} \leq E_{cR} \leq E_{cR\,max}$) and phase angles ($0 \leq \delta_{cR} \leq 2\pi$) of series compensation

IV. DESCRIPTION OF MSSA METHOD

The recently proposed SSA algorithm is considered for optimization with single and multiple objectives with same algorithm i.e., Multi-objective Salp Swarm Algorithm MSSA [17]. Recently, this algorithm has been well received by the researches in various domains, and especially in energy systems, many works has been reported in the literature [18-21]. With this, the authors are much inspired to implement and test this algorithm for the formulated problem in this work. In the literature, mathematical models of behaviour of swarming are very limited [22-23].

Furthermore, no significant mathematical pattern of the salp swarms is available for the optimization problems, even though bee, ants and fish swarms have been commonly modelled and used to solve problems with optimisation. The very first model of salp chains for optimisation problems involving the swarming and evolution of salps for the subsequent iterations are discussed here.

The population is first divided into two classes, leaders and followers, in order to mathematically model the salp chains. The chief is the salp on the front of the chain while the remaining salps are known as followers. Similar to other techniques, salp positions are defined as n-dimensional search areas, where for any given problem n is the number of variables. The swarm guides swarm, and the search follows each other, and the search engines are followed (and the leader is indirectly). The salp locations are stored in matrix, and later retrieved for subsequent iterations.

V. PROBLEM FORMULATION

Here in this work, the diverse objectives were considered for determining the optimal allocation of various FACTS devices that are considered. The objective functions include the FACTS device cost, voltage variation and ATC that are optimized with respect to system/apparatus operational constraints that are modelled as follows:

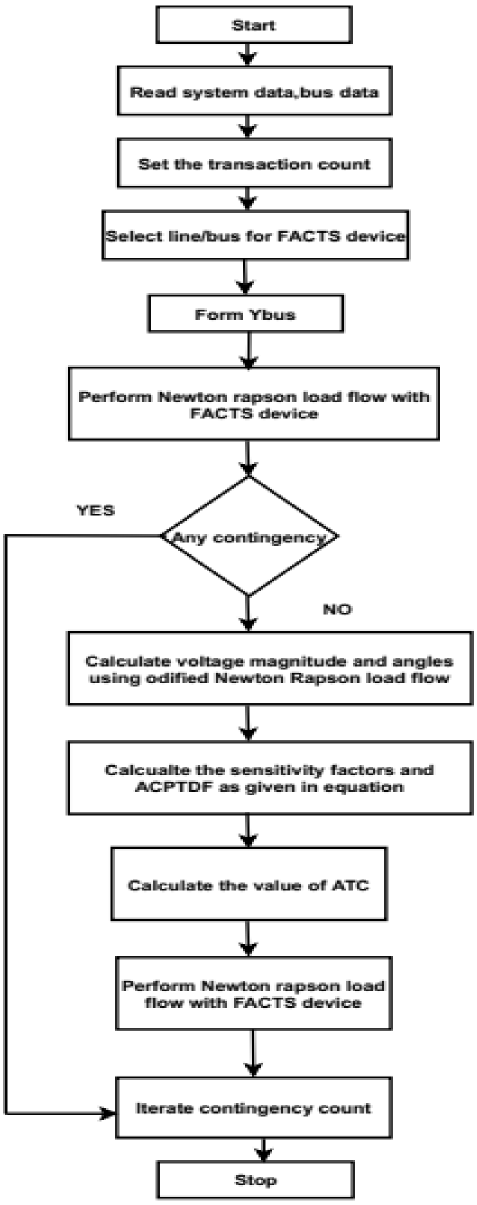


Figure 4 Procedure for evaluating ATC for given configuration and placement of individual FACTS device

5.1 Objective functions

a. Minimization of FACTS Investment cost

The investment cost of individual FACTS devices are modelled as quadratic equations as function of its capacity for different FACTS devices [24] as given below in Eq. (9) to (11).

$$Cost_{SVC} = 0.0003s^2 - 0.3051s + 127.38 \qquad (9)$$

$$Cost_{TCSC} = 0.0015s^2 - 0.7130s + 153.75 \qquad (10)$$

$$Cost_{UPFC} = 0.0003s^2 - 0.2691s + 188.22 \qquad (11)$$

$Cost_{SVC}$ is the cost of SVC device expressed in US \$/KVar, $Cost_{TCSC}$ is the cost of TCSC device expressed in US \$/KVar and $Cost_{UPFC}$ is the cost of TCSC device expressed in US \$/KVar.

As with the corresponding equations, it can be inferred that cost of UPFC is far superior when compared to SVC device. These cost functions were taken for corresponding sub-cases for individual optimization of sizing the respective FACTS device.

b. Minimization of voltage variation (MVV):

The minimization of variations in voltage is taken as another objective, where the voltage profile is brought near to unity, such that the effective square of the difference between bus voltages to unity must be reduced. The corresponding objective can be mathematically expressed as given below in Eq. (12).

$$Voltage\ variation = \sum_{i=1}^{N_b} (1 - V_i)^2 \qquad (12)$$

c. Maximization of Available Transfer Capacity (ATC):

As the last objective ATC is considered because the installed capacity will be reduced and gives flexibility to change the system. It can be modelled mathematically by the following equation.

$$P_{ij,mn}^{max} = \begin{cases} \dfrac{Limit_{ij}^{max} - P_{ij}}{ACPTDF_{ij,mn}} & ; ACPTDF_{ij,mn} > 0 \\ \infty\ (infinite) & ; ACPTDF_{ij,mn} = 0 \\ \dfrac{-Limit_{ij}^{max} - P_{ij}}{ACPTDF_{ij,mn}} & ; ACPTDF_{ij,mn} < 0 \end{cases} \qquad (13)$$

$$ATC_{mn} = min\{P_{ij,mn}^{max}\ ij \in N_b\} \qquad (14)$$

5.2 Constraints:

i. Load flow equations

The Newton-Rapson method to solve the load flow equations were found to be more efficient due to its quadratic convergence characteristics; and hence applied for large power system networks. The net power injection at any bus i can be expressed in admittance form as follows [15]

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{j=1}^{N_b} Y_{ij} V_j \qquad (15)$$

Where P_i and Q_i are the real and reactive power injections at bus i; with I_i being the current entering into bus i having voltage V_i.Assume the network has N_b number of buses. Now expressing the voltage and admittance in their polar form results in the following expressions for P_i and Q_i respectively.

$$P_i = \sum_{j=1}^{N_b} |V_i||V_j||Y_{ij}|\, cos(\emptyset_{ij} + \delta_j - \delta_i) \qquad (16)$$

$$Q_i = -\sum_{j=1}^{N_b} |V_i||V_j||Y_{ij}|\, sin(\emptyset_{ij} + \delta_j - \delta_i) \qquad (17)$$

The above equations of P_i and Q_i represent a set of nonlinear simultaneous algebraic equations at each bus in the network, that are to be satisfied for steady state operation of system.

ii. Generation and load balance:

As a result of above, the net power balance in both real and reactive power must be satisfied with regard to the operational point of system. The corresponding balance in powers can be expressed as given in Eq. (18) and (19).

$$\sum_{i=1}^{N_g} \mathrm{P}_{Gi} - \sum_{j=1}^{N_b} P_{Li} - \mathrm{P}_{LOSS} = 0 \qquad (18)$$

$$\sum_{i=1}^{N_g} Q_{Gi} - \sum_{j=1}^{N_b} Q_{Li} - Q_{LOSS} = 0 \qquad (19)$$

iii. Power generation limits:

The operational generation from each generator must be within the corresponding limits of the generator, and the respective limits for generations for each generator can be expressed as given in Eq. (20)

$$\mathrm{P}_{\mathrm{Gi}min} \le \mathrm{P}_{\mathrm{Gi}} \le \mathrm{P}_{\mathrm{Gi}max} \; i = 1,2, \ldots \ldots N_g \quad (20)$$

iv. Operational limits of FACTS devices

The operating limits of SVC is given as

$$Q_{SVC,min} \le Q_{SVC} \le Q_{SVC,max} \qquad (21)$$

The operating limits of TCSC is given as

$$X_{TCSC,min} \le X_{TCSC} < X_{TCSC,max} \qquad (22)$$

Where $X_L$reactance of transmission line in p.u; and X_{TCSC} is the additional reactance due to placing TCSC in the line. Similarly, the operating limits of UPFC is given as

$$Q_{UPFC,,min} \le Q_{SVC} \le Q_{UPFC,max} \qquad (23)$$

v. Voltage limits

The bus voltages in the networks should be constrained to operate within the minimum and maximum values as given below in Eqn. (24).

$$V_{i,min} < V_i < V_{i,max} \; i \in N_{line} \qquad (24)$$

vi. Line current limits

The line flows must be within the thermal limits of the conductor, the corresponding limiting constraint must be satisfied as given below in Eqn. (25).

$$I_{L,j} < I_{j,max} \; j \in N_{line} \qquad (25)$$

VI. PROPOSED METHODOLOGY FOR CALCULATING THE ATC WITH OPTIMAL ALLOCATION OF FACTS DEVICES:

The calculation of ATC is made according to the procedure as depicted in Fig. 4. At first the load flow subroutine is defined for evaluating the steady state behaviour of interconnected network with FACTS device. The ATC values were calculated for various configurations with FACTS being placed at different locations to find the optimal location and rating as well. The combinations were implemented according to the MSSA algorithm, to find the optimal location of FACTS devices. The SVC, TCSC and UPFC devices were taken into consideration as discussed earlier.

In this work, the MSSA algorithm is used for optimizing the size and location in order to minimize the real power loss and to improve voltage profile by placing the FACTS devices. The proposed method is tested and implemented on MATLAB 2020, 12 GB RAM, i5 processor personal computer. The IEEE 30 bus system [25] comprises of 6 generators with 24 loads, 4 transformers inter-connected with 41 transmission lines. In the same way, the IEEE 57-bus system [26] comprises of only 4 generating units with the 3 synchronous compensation systems, having the 50 loads inter-connected by 80 transmission lines and 06 tap changing transformers. In this work, the SVC is varied from$\boldsymbol{-100\ to\ 100\ MVAR}$, TCSC is varied from$\boldsymbol{-0.8X_L}$ **to** $\boldsymbol{0.2X_L}$, where $\boldsymbol{X_L}$is the reactance of the transmission line in p.u; and lastly the UPFC is varied from $\boldsymbol{2\ to\ 10\ MVAR\ and\ 30}$ **to** $\boldsymbol{350\ MVAR}$ for IEEE 30 and 57 bus system respectively.

VII. RESULTS & DISCUSSION

The following are the simulation case studies performed on the test systems by considering one device at a time as given below for both of the 30-bus and 57-bus systems.

Case 1: 30-bus system
Case 1a: Allocation of SVC
Case 1b: Allocation of TCSC
Case 1c: Allocation of UPFC

Case 2: 57-bus system
Case 2a: Allocation of SVC
Case 2b: Allocation of TCSC
Case 2c: Allocation of UPFC

The above combinations were simulated on MATLAB with relevant subroutines defined for individual load flow evaluations for each of FACTS devices and the corresponding conditionals for taking care of constraints as listed in the corresponding Section-5.2. All the above subcases were separately simulated considering one FACTS device at a time. The simulation results for individual device is given in Table 1, 2 and 3 respectively, that has been evaluated for other two of the optimization techniques i.e., MSSA, MOPSO and NSGA-II. All the objectives including the ATC has been evaluated and has been tabulated at each FACTS device in the corresponding tables. In order to show the significance of proposed approach to obtaining the feasible solution, it has been compared with other approaches as well.

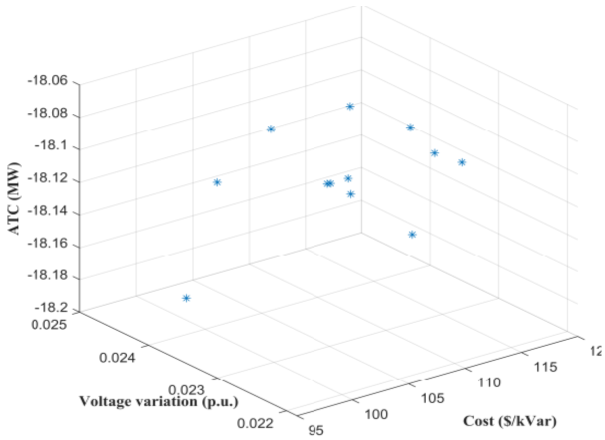
From the obtained pareto fronts for individual device for 30 bus system as shown in Fig. 5 (a), 5 (c) and 5 (e) for SVC, TCSC and UPFC, similarly for 57 bus system Fig. 5 (b), 5 (d) and 5 (f) respectively. It is seen that the solution space is highly constrained and hence the objective space is also confined to limited region as shown in corresponding figures. The voltage profiles obtained for each of the device allocated for each of method is also given in Fig. 6 obtained for 30 bus system and in Fig. 7 for 57 bus system better understanding. From the obtained profiles it is seen that the proposed MSSA approach has resulted in better convergence than other methods used for comparison.

Table 1: Objective function values with allocation of SVC

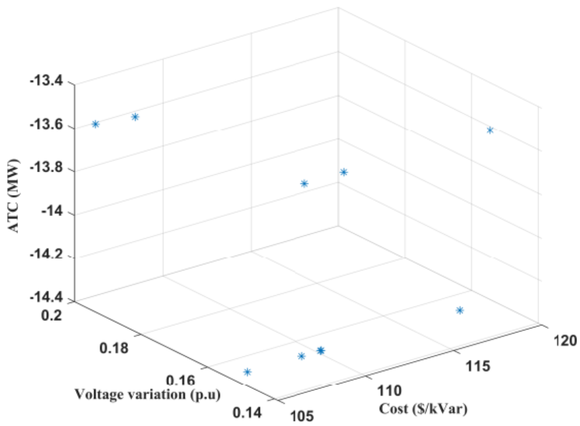
System	Method	Cost ($/Mvar)	MVV (p.u.)	ATC (MW)	Location	Rating
IEEE 30 bus system	MSSA	99.87	0.024252	18.1857	1	+100
	MOPSO	99.89	0.023804	18.1052	17	+100
	NSGA-II	117.06	0.024684	18.1102	17	35
IEEE 57 bus system	MSSA	108.09	0.148028	14.3333	27	68
	MOPSO	117.06	0.138918	13.4334	28	35
	NSGA-II	109.16	0.148028	14.3333	27	64

Table 2: Objective function values with allocation of TCSC

System	Method	Cost ($/Mvar)	MVV (p.u.)	ATC (MW)	Line number	Rating
IEEE 30 bus system	MSSA	153.44	0.247555	18.2025	33	-0.42556
	MOPSO	153.59	0.246666	19.3742	8	-0.21081
	NSGA-II	153.59	0.256988	22.5687	9	-0.21993
IEEE 57 bus system	MSSA	152.97	0.428858	13.2014	19	-1.08466
	MOPSO	153.10	0.432935	13.6924	26	-0.90275
	NSGA-II	153.13	0.420445	13.3933	30	-0.86586



5(a)



5(b)

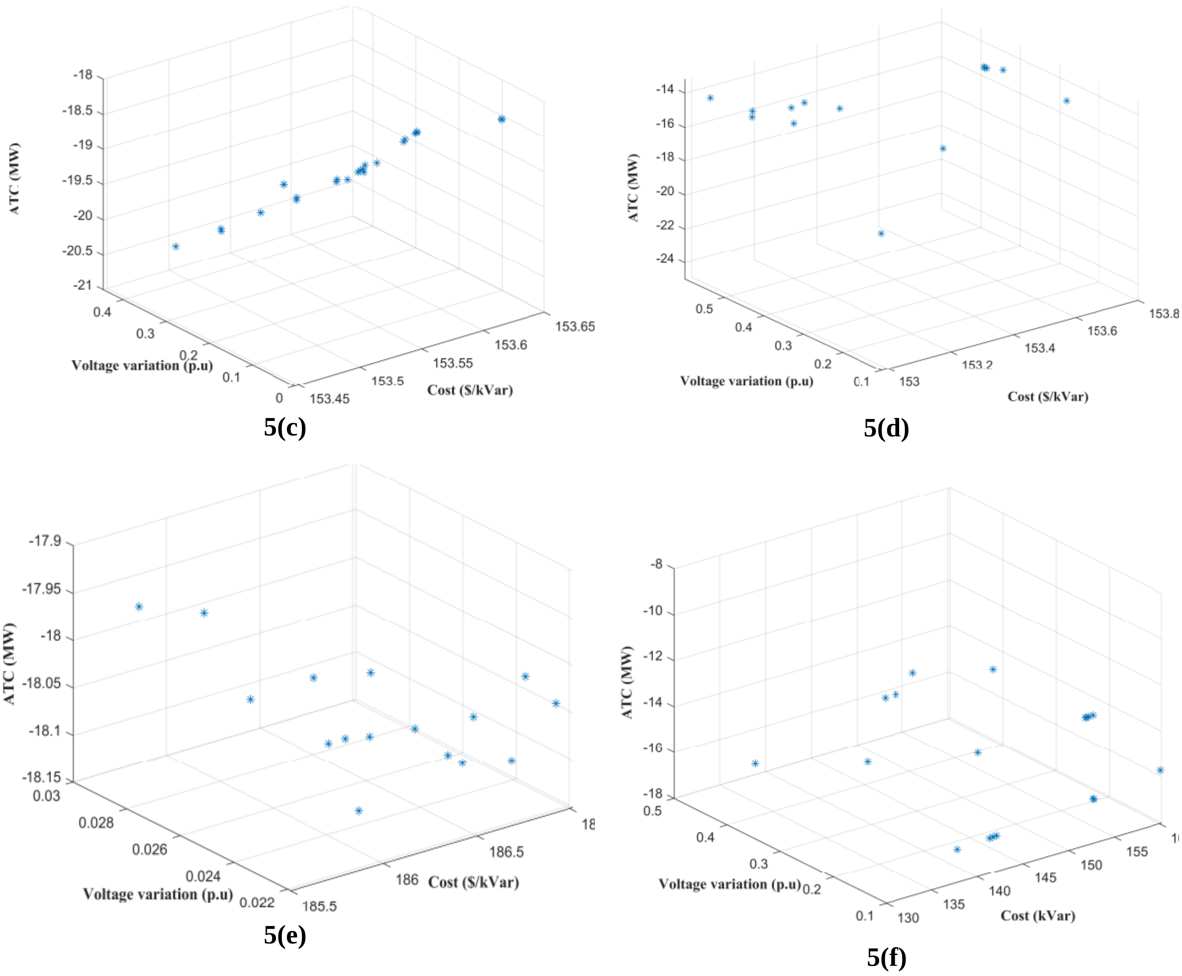


Fig. 5 Pareto fronts obtained by proposed method for IEEE 30 and 57 bus systems

Now, the similar implementation was carried out on other larger system, namely 57-bus system. Even though the loading levels are similar to the earlier system, the nature of system so diverse when compared to the former. Hence to test the validity of proposed approach this system has been selected. A separate subroutine for this system is defined and the corresponding subroutines for each device is simulation and the obtained solutions are tabulated in Table 1, 2 and 3 for all the approaches separately; the corresponding pareto's were shown in Fig. 5 (b), 5 (d) and 5 (f) respectively.

The solutions depicted for such larger system has comparatively larger ratings of FACTS device irrespective of loading conditions. The same tendency was witnessed in other approach as well. This confirms that the proposed approach is compatible for any system irrespective of loading level and diverse nature of geographical spread. The ATC obtained can still be enhanced if the cost is not considered as one of objective, but the cost factor is not enhancing the ATC beyond a certain value as it has to strive for minimum cost as possible. From the obtained pareto fronts of both the test systems it can be concluded that the objective space so constrained depending on the operating region and rating specifications of the considered FACTS device. Hence, in this work such highly constrained problem has been considered and solution approach was proposed and compared.

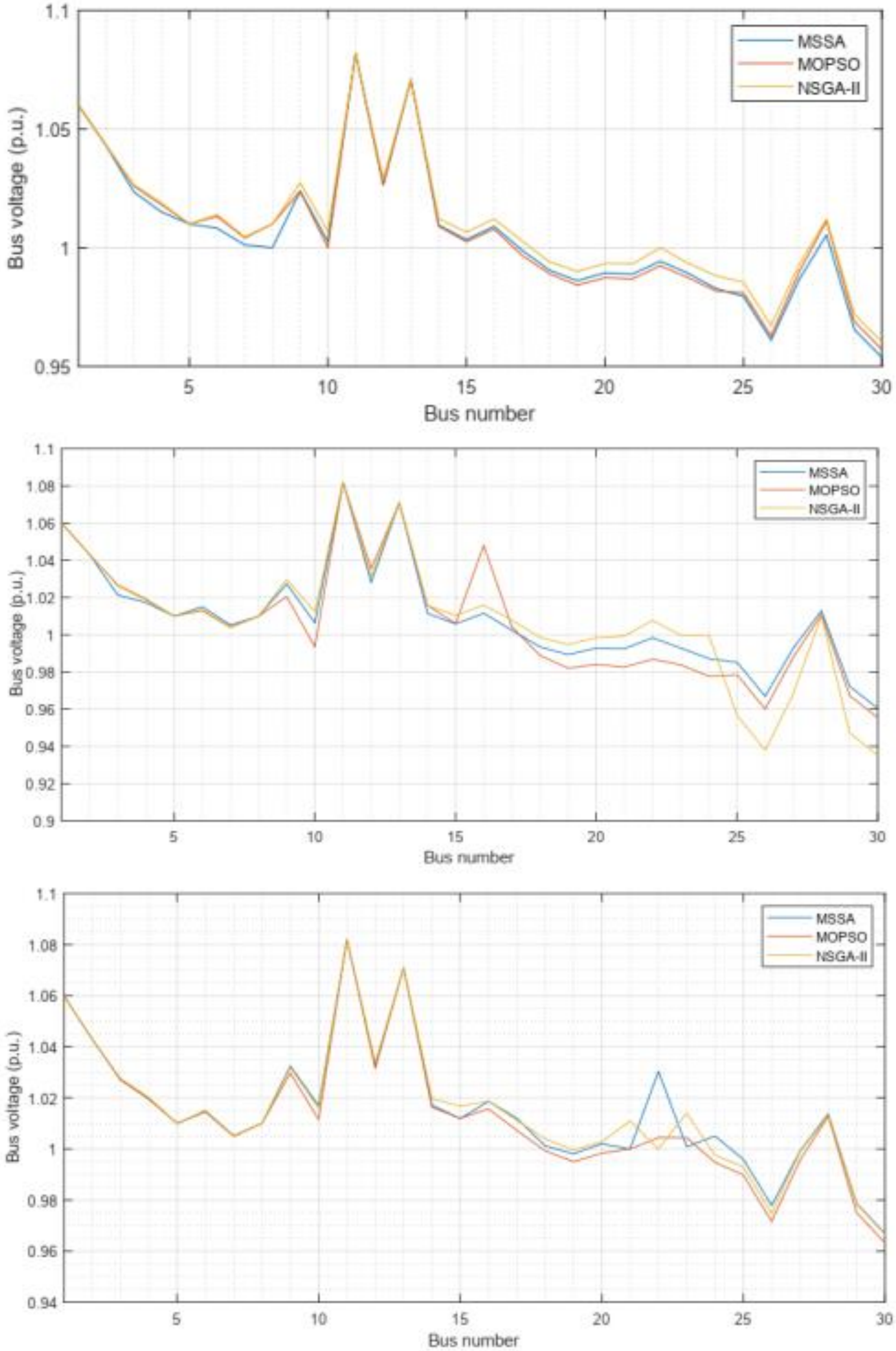


Fig. 6 Voltage profiles for SVC, TCSC and UPFC for IEEE 30 bus network

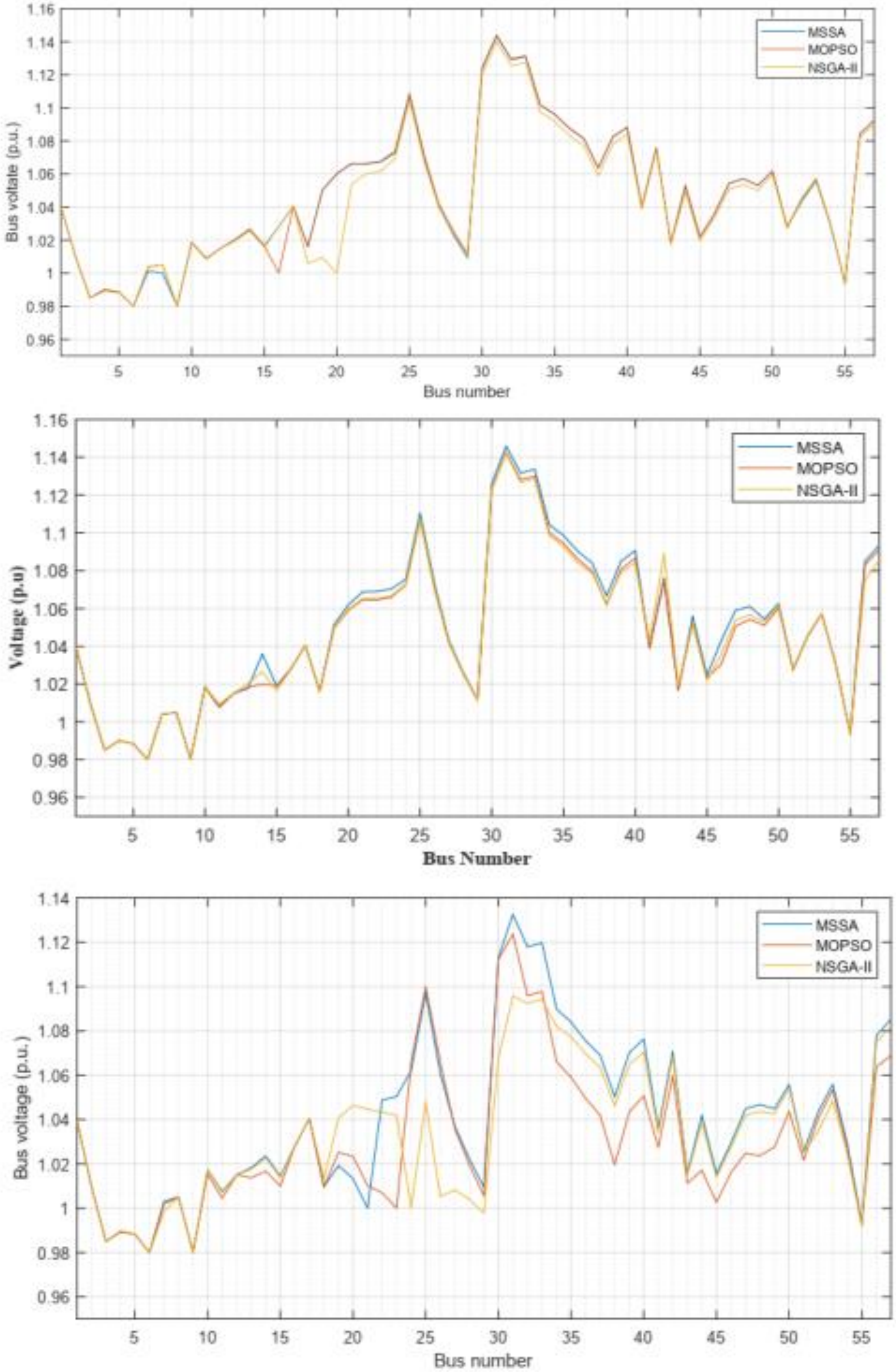


Fig. 7 Voltage profiles for SVC, TCSC and UPFC for IEEE 57 bus network

Table 3: Objective function values with allocation of UPFC

System	Method	Cost ($/Mvar)	MVV (p.u.)	ATC (MW)	Line number	Rating
IEEE 30 bus system	MSSA	185.75	0.026767	17.9383	12	10
	MOPSO	186.24	0.022383	17.0287	35	7
	NSGA-II	186.87	0.076896	17.6587	30	12
IEEE 57 bus system	MSSA	145.16	0.158885	17.5224	34	208
	MOPSO	145.44	0.157122	17.4804	32	206
	NSGA-II	153.80	0.118188	16.4142	34	154

VIII. CONCLUSION

In this work the optimal allocation of SVC, TCSC and UPFC were made by optimizing the FACTS device cost and voltage variation together with the ATC into consideration. Here a multi-objective problem has been formulated with network operational constraints along with the FACTS device constraints, such that optimal sizing and placement of various devices considered in the network has been made. The ATC has been considered as one of objective such that the FACTS devices has been placed at feasible locations where it is causing optimal allowable power flow happening in the network. Here, the formulated problem has been proposed to solve using the heuristic MSSA approach, and also its superiority has been tested by other approaches that has been implemented on two test networks namely, 30 and 57 bus systems, respectively. The methodology handled in this work is also found to be scalable for any network of interest.

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