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VOLTAGE STABILITY ENHANCEMENT BY IGSA-FA HYBRID TECHNIQUE IMPLEMENTATION FOR OPTIMAL LOCATION OF TCSC

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Abstract

This paper proposes a hybrid technique for improving the voltage stability of a given system with optimal power flow solution using FACTS device installation. The hybrid technique is the combination of Improved Gravitational Search Algorithm (IGSA) and Firefly Algorithm (FA). The Thyristor Controlled Series Compensator (TCSC) device is utilized to evaluate the performance of the proposed algorithm by its optimal location and determining its capacity with optimized parameters. Therefore, the voltage stability is improved while satisfying a given set of operating and physical constraints and proposed technique is used to optimize the loading factor and apparent power flow index respectively. The algorithm is implemented in MATLAB working platform and the power flow security and voltage stability is evaluated with IEEE 30 bus transmission systems. Then, the total generated power, voltage stability, generation cost and TCSC cost are examined by changing the system load. The performance of the proposed method is perceived to be superior when compared with traditional Gravitational Search Algorithm and other techniques existing in literature.

Keywords: Apparent power flow index, Firefly Algorithm, IGSA, Optimal location, TCSC, Voltage stability.

1. Introduction

Diminishing cost functions like operating expenditures by accounting for equality and inequality constraints consolidates power flow with profitable dispatch leading to successful implementation of optimal power flow (OPF) [1]. The non-linear approach applying the Newton's method is one of the solution techniques

Nomenclatures

a_n, b_n, c_n	Fuel cost coefficients
$a_i^d(t)$	Acceleration of agents
C_{TCSC}	TCSC cost sizing, US$/KVAR
F_c	Fuel Cost, $/hr
h	Velocity coefficient
P_{gi}	Active power produced by i^{th} generator
$rand_i$	Uniform random number between 0 and 1
$S_{i,L}$	Power flow of i^{th} line at loading
$S_{i,max}$	Maximum power flow of the i^{th} line
$S_{i,n}$	Power flow of i^{th} line at normal situation
$S_{i,OPF}$	Power flow of the i^{th} line at OPF
t_o	Initial time, s
t_{max}	Maximum time, s
V_d	Voltage Variance
$V_i^d(t)$	Current velocity of the agents
$V_n^{\max}$	Maximum voltage at nth bus, V
$V_n^{\min}$	Minimum voltage at nth bus, V
X_{line}	Line reactance, Ω
X_{TCSC}	TCSC reactance, Ω

Greek Symbols

α	Maximum radius of the arbitrary step
β	Attractiveness of the fireflies
δ	Constant to evaluate gravitational constant
δ_{max}	Highest agent velocity
δ_{min}	Lowest agent velocity
η	Movement factor between 0 and 1

Abbreviations

API	Apparent Power Flow Index
GSA	Gravitational Search Algorithm
I	Light Intensity
IGSA	Improved Gravitational Search Algorithm
OPF	Optimal Power Flow
RBFNN	Radial Basic Function Neural Network
TCSC	Thyristor Controlled Series Compensator

of the OPF which appreciably addresses the marginal losses and is considered as comparatively sluggish method which is faced with the issue of handling large number of inequality constraints [2].

Transmission lines capacity and bus voltage limit are vital safety factors to carry out OPF in any power system [3]. The system being operational in normal state is equipped with security measures in order to discern that it is capable of resisting contingencies devoid of any limit contravention [4]. To ensure a consistent power system function, it is essential that the safety of the system is duly accounted for in the electrical energy system [5, 6].The traditional optimization methods do not offer flexibility to be applied to large practical systems as they cannot accommodate the non-linear characteristics and also generally address specific cases of OPF problem [7-9]. Also some of these methods suffer from the drawback of convergence characteristics being dependant on initial conditions thereby leading to infeasible solution in a practical domain. So, many metaheuristics search techniques have evolved over the years to solve OPF problem which is a complex constrained optimization problem. Some of the population based techniques effectively implemented to solve OPF problem are Genetic algorithm [10], Particle Swarm Optimization [11], Differential Evolution [12], Simulated Annealing [13] and Gravitational Search Algorithm [14].

The FACTS devices are excessively employed to effectively cut down the flows in heavily loaded lines, ultimately leading to enhanced loadability and reduced system damage by keeping under check the power flows in the system. Outstanding among the FACTS devices, the Thyristor Controlled Series Compensator (TCSC) is endowed with incredible application potential in precisely controlling the power flow on communication line, damping inter-area power oscillations, alleviating sub-synchronous resonance and stepping up transient solidity [15]. Thus, the conventional OPF algorithms are required to be modified for inclusion of FACTS devices and additional constraints like voltage stability retention coupled with OPF solution. Some of the work available in literature are hybrid Tabu Search and Simulated Annealing [16], dynamic strategy based fast decomposed GA [17] Symbiotic Organism Search algorithm [18] and Oppositional Krill Herd algorithm [19]. The OPF problem has been addressed triumphantly by diverse stochastic investigation methods with or without inclusion of FACTS devices [20-22]. The literature survey reflects that although numerous optimization methods have been developed and implemented however researchers are continuously striving to obtain better meta-heuristic techniques.

In this paper, an innovative hybrid approach based on GSA called IGSA along with Firefly Algorithm (IGSA-FA) is proposed to establish voltage stability with secured OPF solution by optimal TCSC location. The main advantage of this algorithm is search accuracy guided by gravitational constant and enhanced efficiency although it is memory-less. Further, the Firefly algorithm is an efficient choice for multi-objective problem in generating global optimization solution. The performance of the proposed algorithm is tested on IEEE 30 bus system and results are validated by comparing with those existing in literature. The simulation results generated also testifies the superiority of the algorithm in solving voltage stability based OPF problem.

The remainder of the document is organized as follows. Section 2 offers a detailed view of the problem formulation. The details about computational methods employed to fetch optimized results are explained in section 3. The results of power loss, generated power, generation cost, TCSC cost sizing and real power losses are observed in Section 4. The conclusion part of the document enriches the contents of Section 5.

2. TCSC Modelling and Problem Formulation

The TCSC is one of the most versatile and promising series FACTS controllers which houses sequences of compensating capacitors shunted by the thyristor controlled reactor. In this model, the controllable reactance is integrated in series to the transmission line and the line impedance is made adaptable such that, the apparent power going through the line is either perked up to the maximum or scaled down to the minimum depending on the loading condition. In Fig. 1, TCSC single line diagram model between buses i and j is illustrated. The OPF issue undertaken in the work is framed to cut down the fuel cost to the least in respect of the generation.

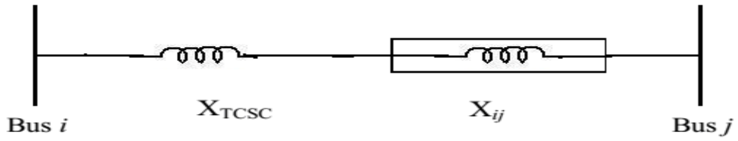


Fig. 1. Modelling of TCSC controller.

The objective function of fuel cost is incorporated with the inequality constraints of active power bounds of the generator. The quadratic equation of fuel cost is furnished by Eq. (1) give below:

Fuel cost, $F_c = \Sigma\left(a_n + b_n P_{gi} + c_n P_{gi}^2\right)\$/hr$ (1)

The equality and inequality constraints are employed for the investigation of the safety optimal power flow with the TCSC. The apparent power balancing conditions are deemed as the equality constraints. The generator real power, reactive power, voltage magnitude and TCSC reactance are taken as the inequality constraints. The voltage magnitude of the i^{th} buses and reactance bounds of the TCSC are expressed by the following equations:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (2)$$

$$-0.7X_{line} \le X_{TCSC} \le 0.2X_{line} \quad (3)$$

The underlying motive of the objective function is invested in ascertaining the optimal option of TCSC subject to the optimal power flow factors and security constraints. When the active and reactive powers of the loads are enhanced simultaneously, the loading factor becomes proportional. Hence, the values of loading factors are changed from the base case value to the maximum without infringing the equality and inequality constraints. For the purpose of placing the TCSC optimally, the optimal line power flow is deployed subject to the maximum power flow limit. With load variation, the line flow change of the system is assessed by means of newly defined parameter apparent power flow index, which is estimated by loading factor with OPF of the line and maximum flow limits of the line. The expression of apparent power flow index is furnished by Eq. (4) shown below:

Apparent power flow index,

$$API = \frac{S_{i,Opf}}{S_{i,\max}}\left(\frac{S_{i,L} - S_{i,n}}{S_{i,L} - S_{i,opf}}\right) \quad (4)$$

Estimation of API ascertains the optimal placement of TCSC as its maximum value at a bus indicates it to be a weak bus. Subsequently, TCSC capacity is evaluated in accordance with the voltage variance and the cost function. Hence, it is highly essential that these two parameters are kept to the least. In this regard, the objective function in Eq. (5) has the goal which requires both maximization and minimization of the objective function

$$O_b = \begin{cases} \max(API) \\ \min(V_d, C_{tcsc}) \end{cases} \tag{5}$$

The dependent parameters of the captioned equation are furnished as the input of the proposed technique so as to optimize the best parameters, based on which the optimal location and the capability of the TCSC are calculated.

3. Computational Methods for Optimal Location of TCSC

In this section, the optimal location and cost sizing of TCSC to improve voltage stability by using IGSA-FA algorithm is presented and comparative account of the results with traditional GSA and other hybrid techniques based on GSA validates that the best solution is yielded by IGSA with FA algorithm. The optimal location and the injected capacity of the TCSC depend on the security indexes called as the apparent power flow, voltage stability and cost function. Here, two phases are considered, and the first one is concerned with finding the optimal location and the second involves the injected capacity of TCSC and improving voltage profile respectively. Subsequently, the injection capacity of the TCSC is calculated by Eq. (2) and Eq. (3) through the security constraints. The IEEE standard bench mark 30 bus system is used for analysis and initially normal power flow and the stability conditions are determined and later the loading faults are introduced in the bus system. These two phases are solved by using proposed technique of IGSA-FA and the superiority of results obtained is verified by comparing it with the techniques of traditional GSA, Fuzzy based GSA, Radial Basis Neural Network (RBFNN) based GSA [23]. The detailed explanation of proposed technique of IGSA-FA is given in this section.

3.1. Gravitational search algorithm

The GSA has amazingly arrived on the arena as one of the stochastic search techniques rooted on Newtonian laws of gravity and mass interaction [24, 25]. In GSA, the efficiency of the agents is evaluated by their masses which are deemed as objectives. The gravitational forces of attraction between the objects trigger a complete motion towards the objects which possesses heavier masses. The heavier masses attain superior fitness values and the best solution is approached as against the lesser ones which signify the worst solution. However, in GSA technique, each and every mass has the position in the order such as inertial mass, active gravitational mass and passive gravitational mass. The mass position amounts to the solution of objective function and the fitness function employed is indicated by the gravitational and the initial masses [26].

However, traditional GSA method suffers from few demerits while searching for the best solution in the search space. If a proper tradeoff between exploration and exploitation fails, than it may either lead to premature convergence or may increase the time of convergence. Further, GSA has low convergence due to increased randomness associated with agent's velocity which is suitably curbed by various hybrid techniques being integrated with it.

3.2. Proposed method of improved GSA with firefly algorithm (IGSA with FA)

The hybrid technique as proposed in this paper to procure the best result is combination of the improved GSA (IGSA) and firefly algorithm (FA). IGSA-FA technique enhances the quality of the solution and ascertains fast convergence. The velocity of the agent is in the range between $-V_{max} \leq V_{i(t+1)}^{d} \leq V_{max}$ in the traditional GSA. This purposeless agent's adaption furnishes complication in the course of evaluation procedure, thereby turning out inaccurate solutions. In the novel technique proposed, the velocity and position of the agent search technique is enhanced based on the solution.

The velocity variation of the searching technique for the i^{th} agent, direction 'd' at time t+1 is expressed in Eq. (8)

$$V_{\max}^{d}(i) = V_{\max}^{0} * \psi_i \tag{8}$$

$$\text{where, } \psi_i = 1 - \left(\frac{(t_0)^h}{(t_{\max})^h} \right) \quad V_{\max}^{0} = \eta \times (\delta_{\max} - \delta_{\min}), \tag{9}$$

where, η represents the movement factor which has to be between $0 \leq \eta \leq 1$, δ_{max} and δ_{min} characterizes the highest and lowest agent position, h signifies the velocity coefficient, t_0 and t_{max} correspond to the initial and maximum time and $V_{max}^{d}(i)$ relates to the highest velocity. The position of the agent is adapted as per Eq. (10)

$$\delta_{\max} = \delta_i^d(t) + V_{\max}^{d}(i) \tag{10}$$

The termination procedure takes place after the best solutions are attained fulfilling the objective function based on the reduction of the fuel cost and the highest API. From the above process, the optimal location is identified and thereafter the TCSC is located in a suitable place. Then the selected real power settings are applied to the generator so that the secured OPF condition of the system is maintained by the TCSC.

The Firefly Algorithm represents a Meta heuristic, nature-inspired, optimisation technique which is dependent on the community flashing character of the fireflies, or the lighting bugs found mostly in the summer sky in the tropical temperature zones [27]. The attractiveness is in direct proportion to their brightness, and hence for any two flashing fireflies, the one with lesser brightness inches towards another with a greater brightness. As the attractiveness is directly proportional to the brightness, both these qualities tend to decline as their distance goes on increasing. If there is none which is brighter than a particular firefly, it moves discretely. The brightness or light intensity of a firefly is affected or decided by the landscape of the objective function to be optimised.

The firefly technique is employed to cut short the voltage variance and thereby increase the ability of the TCSC for preserving the voltage consistency of the transmission system. The variance in the normal voltage (V_n) and the fault time is effectively estimated. Here, the light intensity (I) is estimated, which is linked to the fitness function, which is deemed as the minimization of the voltage divergence between usual bus voltage and fault time bus voltage. The fitness function is estimated by the equations illustrated below.

$$I = F(X_i) = \min(V_d, \cos t) \tag{11}$$

where, $V_d = [V_n - V_i]_{i=1}^{N}$ (12)

where, i= 1, 2, ……N such that N represents the total number of transmission lines in the system, V_n is the bus voltage under normal condition and V_i is the voltage under fault/overload condition and verified with respect to V_{dmax}.

From the initial fitness value, the least minimum fitness is chosen and that gives quality of best solutions. The subsequent cycle of firefly commences with the generation of the new solution X_j with fitness function (F_j) estimated. At this juncture, we verify the condition (F_j<F_i), and if this stipulation is met, then the solution is shifted else, the attractiveness of the fireflies has to be revise and the fireflies will be shifted to their new location. The moving standard is either on arbitrary basis or in the direction of the better solution which is furnished as per Eq. (13) given below.

$$X_i^{t+1} = X_i^t + \beta\left(x_j - x_i\right) + \alpha\left(rand\left(\;\right) - \frac{1}{2}\right) \quad (13)$$

where α and β decide the step size in the direction of the optimal solution. Now, the attractiveness of fireflies is revised and the new solutions estimated. The overall working process of the proposed technique is illustrated in Fig. 2.

When the transmission line is overloaded, the optimal location of the TCSC is determined by the IGSA. Here, the maximum API bus is determined by the IGSA technique, and is identified as the most favourable location for fixing the TCSC. Depending on the affected parameters, the finest capacity of the TCSC is identified using the firefly algorithm. It is used to recover the normal operating condition and enhance the voltage stability. The overload of the transmission line is reduced after placing TCSC on the precise location. The line flow limit is employed to verify the violation of line limits after resolving the issue which exhibits the secured limits.

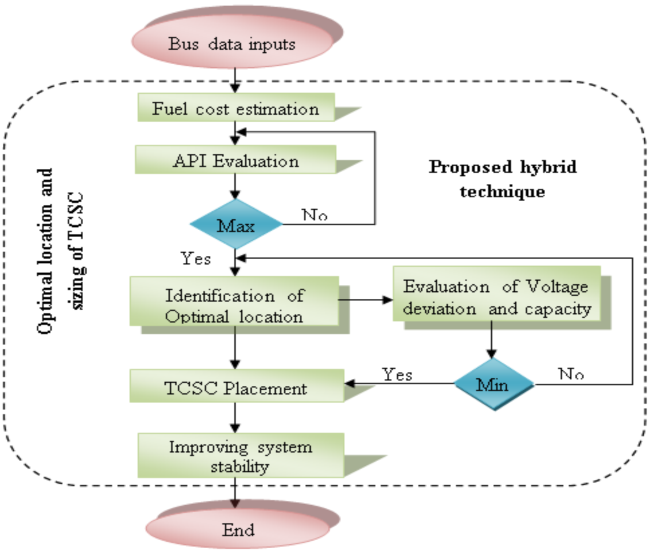


Fig. 2. Flowchart of proposed hybrid technique of IGSA-FA.

4. Results and Discussions

The work depicted in this paper has IGSA-FA being suitably deployed as a novel approach to attain two important aspect of revamped power system operation i.e. optimal load flow coupled with voltage stability. Further, the results are compared with GSA and the hybrid techniques of Fuzzy-GSA where velocity constraint is introduced which is predicted by fuzzy logic to reduce deviation of agents in search space and RBFNN-GSA where velocity constraint to substantially reduce deviation is predicted by Radial Basis Function Neural Network that accelerates the system performance. It is observed that the proposed method of IGSA and FA employed to ascertain the optimal location and sizing of TCSC device yields even superior results and their performances are evaluated by overloading transmission line. Further, the voltage deviation of the system is estimated. The proposed technique is applied to the IEEE standard bench mark 30 bus system and the bus data, line data and the limits of control variables are estimated from [28]. The fuel cost coefficient of the test system is referred from [29]. The Newton Raphson power flow method is effectively employed to calculate the power flow solution before and after setting TCSC.

The performance is evaluated by increasing the demand value of the load buses and the secured power flow is calculated by using the above mentioned methods. The comparison chart of individual relative error (%) for the existing methods with proposed method is illustrated in Fig. 3 and individual absolute error (%) for the existing methods with proposed method is tabulated in Table 1. From the results, it is evident that in each case secured power flow is determined and proposed method of IGSA-FA furnishes least power loss, improved voltage stability and cost values.

To establish superior performance of proposed method IGSA-FA and its comparison with the traditional GSA, Fuzzy-GSA and RBFNN-GSA, error calculation is done by individual relative error (%) and individual absolute error and the formulas for these statistical measurements are given below:

$$Individual\ relative\ error(\%) = \frac{(TCSC\ othercases - TCSC\ with\ IGSAFA)}{TCSC\ with\ IGSAFA} \times 100 \tag{14}$$

$$Individual\ absolute\ error = TCSC\ othercases - TCSC\ with\ IGSAFA \tag{15}$$

The optimal location of the TCSC in transmission line is obtained between 5 and 6 buses considering the implementation of each method and total generated power, power loss, generation cost and TCSC cost are tabulated in Tables 2 and 3.

From the comparison error chart, it is candidly established that TCSC installation has elevated the OPF and the proposed method performs effectively with TCSC installation thus locking secured power flow with minimum power loss and depreciated generation cost.

Table 1. Absolute error comparison of proposed method with existing methods.

Methods	**RBFNN based GSA**	**Fuzzy based GSA**	**GSA**	**Without TCSC**
Power	0	0.31602	0.16528	3.70501
Power loss	43.8921	99.9024	117.979	127.893
Cost of power	0.5834	1.10994	1.53769	1.24568

From the voltage profile analysis it is observed that at each bus voltage collapses at the load unbalanced condition, but at the same time the proposed method is used to enhance the voltage profile stable condition using the IGSA and FA. From bus 30 to (1, 2, 3) buses are analyzed to maintain the stability of the system. Table 2 establishes that the proposed techniques implementation ascertains minimum real power loss and minimum generation cost.

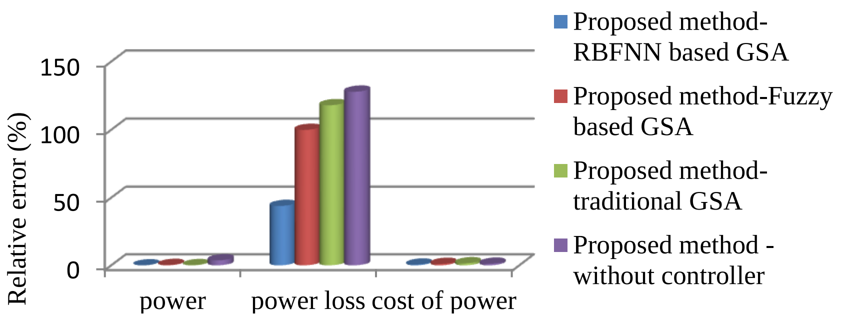
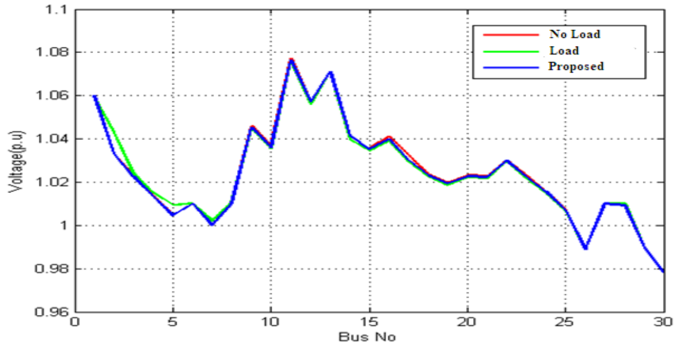


Fig. 3. Performance analysis of relative error using various methods.

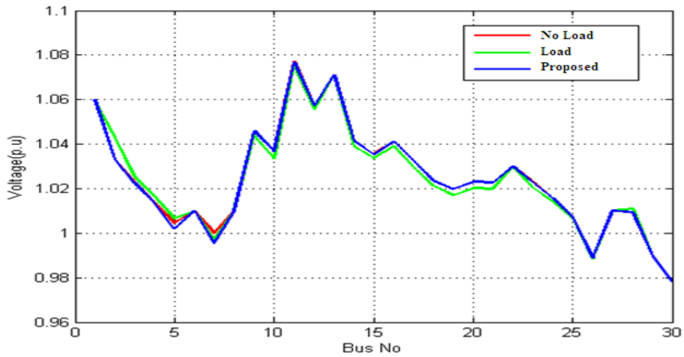
Table 2. Active power profile with respect to secured OPF.

Total active power generation in MW					
Loading Condition		**TCSC in line of between 5 and 6 buses with different method**			
		GSA	**Fuzzy based GSA**	**RBFNN based GSA**	**Proposed technique**
Prior to Loading	283.4	283.8684	282.5044	283.4	283.4
Loading without TCSC	293.9				
Total Real Power loss in MW					
Prior to Loading	6.8095	8.2651	7.5797	3.7917	2.6351
Loading without TCSC	8.641				
Total active power generation cost ($/hr)					
Prior to Loading	828.3393	812.6234	809.2	800.317	795.675
Loading without TCSC	810.2864				
TCSC cost ($/MVAR)		151.3658	148.2325	142.2168	138.4178

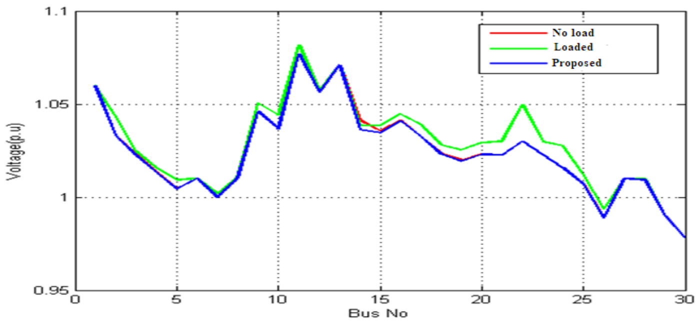
The voltage profile comparison analysis is carried out and illustrated in Fig. 4 to candidly depict that the proposed method effectively maintains the voltage level within the stability limit and reduces deviations, when compared with the other techniques. So, the proposed method effectively maintains the voltage profile within the mentioned limit (1.0-0.98 p.u.) even under heavy loading conditions. Fig. 5 gives a complete comparative account of voltage profile under various cases of no load condition, loaded case and with various hybrid techniques.



(a)



(b)



(c)

Fig. 4. Performances analysis of voltages with proposed method (a) buses 30-1, (b) buses 30-2 and (c) buses 30-3.

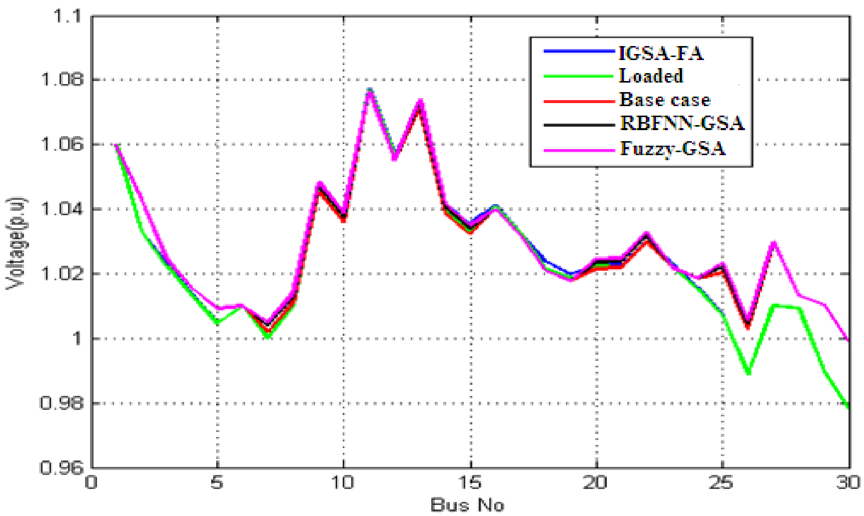


Fig. 5. Comparison analysis of bus voltage using various methods.

The TCSC cost sizing of proposed method, RBFNN based GSA, Fuzzy based GSA and GSA is 138.4178, 142.2168, 148.2325 and 151.3658 respectively. This clearly reveals that optimal location of TCSC in between buses 5 and 6 which were the two weak buses has enabled the system to establish secured OPF with reduced generation cost, diminished power losses and retention of voltage stability under loading conditions.

Table 3. Analysis of mean, standard deviation, minimum and maximum values for IEEE 30 bus system.

Parameters	Fuzzy- GSA	RBFNN- GSA	IGSA-FA
Mean	163.2929	162.2744	160.0731
Standard Deviation	0.8097	1.4992	1.2099
Min	162.0235	160.0517	158.0021
Max	164.9118	164.9975	161.9598

The convergence characteristics depicted in Fig. 6 candidly shows fast convergence of the proposed method. The processor configuration on which the algorithms are executed is: Intel (R) Core 2 duo CPU, 1.83 GHz, 2.99 GB RAM running on Windows XP and is coded in MAT LAB R2008b.The comparison of proposed IGSA-FA with various hybrid methods of Fuzzy-GSA, RBFNN-GSA enabled with TCSC installation further accelerate the system performance [23]. The proposed method is suitable for addressing multi-objective optimization. However, when applied online in large distribution network the algorithm will have to encounter several more conflicting objectives and hence the decision maker has to select an agreeable solution from a finite set by making compromises.

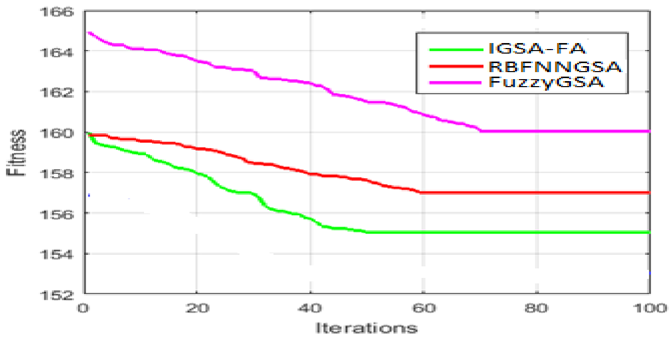


Fig. 6. Convergence characteristics of various techniques.

5. Conclusions

In this paper, a hybrid technique of IGSA-FA is proposed for reducing the voltage instability and improving the optimal power flow of the system under consideration. Some observations that can be concluded from the presented work:

- The OPF is attained with TCSC optimal placement using the proposed method and its effectiveness tested by comparison with existing methods. The total power generated by the system, power losses, generation cost, and line flow power are evaluated and compared with the proposed method.
- The power flow security of the proposed method is studied by line outage and it reduces the load power limits. From the analysis, it is observed that the results of line outage can ensure the power flow security by setting the installed TCSC. Therefore, by locating and sizing the TCSC optimally in the base case condition and loading conditions the secured power flow of the transmission system is active.
- Also, the voltage profiles are evaluated for maintaining the stability of the system. The proposed algorithm can be implemented in future for solving multi objective optimization problem and voltage constrained optimal power flow along with retaining system security. The algorithm is demonstrated to have fast convergence rate, more efficiency and stability in handling complex optimization problem.

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