

# Firefly Algorithm in Determining Maximum Load Utilization Point and Its Enhancement through Optimal Placement of FACTS Device

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## Abstract

In a Power System, load is the most uncertain and extremely time varying unit. Hence it is important to determine the system's supreme acceptable loadability limit called maximum loadability point to accommodate the sudden variation of load demand. Nowadays the enhancement of the maximum loadability point is essential to meet the rapid growth of load demand by improvising the system's load utilization capacity. Flexible AC Transmission system devices (FACTS) with their speed and flexibility will play a key role in enhancing the controllability and power transfer capability of the system. Considering the theme of FACTS devices in the loadability limit enhancement, in this paper maximum loadability limit determination and its enhancement are prepared with the help of swarm intelligence based meta-heuristic Firefly Algorithm(FFA) by finding the optimal loading factor for each load and optimally placing the SVC (Shunt Compensation) and TCSC (Series Compensation) FACTS devices in the system. To illuminate the effectiveness of FACTS devices in the loadability enhancement, the line contingency scenario is also concerned in the study. The study of FACTS based maximum system load utilization acceptability point determination is demonstrated with the help of modified IEEE 30 bus, IEEE 57 Bus and IEEE 118 Bus test systems. The results of FACTS devices involvement in determining the maximum loading point enhance the load utilization point in normal state and also help to overcome the system violation in transmission line contingency state. Also the firefly algorithm in determining the maximum loadability point provides better search capability with faster convergence rate compared to that of Particle swarm optimization (PSO) and Differential evolution algorithm.

## Keywords

FACTS, Maximum Loadability, Firefly Algorithm (FFA)

## 1. Introduction

In present days, the growing nations face the challenges of electrical power demand increasing in rocketing speed, mushrooming of ill-type load such as heaters, air conditioners and some type of motors, which have negative exponential load characteristics and sudden block out due to voltage collapse. The increasing power demand is not answered by expansion of power generating plant and transmission unit since it not only requires huge capital investment but also considers the socio-economic and environmental factors. The solution to the above problem is hidden in finding the answer of maximum loadability limit of the power system. The maximum loadability limit is the point where the system can able to accommodate the utmost total system loading value without violating system constraints such as voltage limit of the buses, real and reactive power limit of generator, transmission line power transfer limit. Since the control variables of the power system have a mixture of discrete and continuous variables, the maximum loadability limit determination problem has been formulated as a non-linear optimization problem. In the beginning stage of the maximum loadability point determination, mathematical iterative optimization techniques such as i) continuation power flow method (CPF); ii) sequential quadratic programming (SQP); iii) interior point method (IP); and iv) repetitive power flow solution have been utilized more. Most of the authors in their literature utilize the continuation power flow (CPF) technique proposed by Ajarapu and Christy [1]. But the difficulties in the CPF method are complex mathematical formulations or convergence problems if the system is already near the maximum loading limit and fails to give the accurate result if the step length is high. The Interior Point (IP) algorithm [2], Sequential Quadratic Programming (SQP) algorithm [3], and repetitive power flow solution [4] were also used for loadability problem. These three algorithms have limitation in handling the mixture of continuous and discrete variable, large sets of equality and inequality conditions and also having limitations in starting and terminating conditions as the number of system variable increases. Hence the conventional optimization methods are not able to locate global optimum, and can only lead to a local optimum and sometimes results in divergence.

In early 2000, evolutionary/meta-heuristic computing techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Evolutionary Programming (EP) have emerged as very powerful general purpose solution tools for solving the complex power system problems. Basically, these meta-heuristics search techniques are capable of finding the optimum solution of a problem irrespective of the number of control variables and also effective in handling the mixture of continuous and discrete variables. Among the above mentioned meta-heuristic algorithm, the particle swarm optimization (PSO) technique [5] generates high quality solutions for the power system problem within short calculation time and has more global searching ability at the beginning of the run and a local search near the end of the run. Many researchers used hybrid PSO [6] [7], multi-agent PSO [8], CAPSO algorithm [9] technique to improve the efficiency in searching the optimal loading point. The above PSO algorithms have to maintain a lot of algorithmic control parameters to achieve the better search path in determining best loading point. To reduce the algorithmic control parameters handling complexity, a simple and few control parameters based Evolutionary Differential evolution algorithm [10] has practiced widely. Though DE provides more precise and faster convergence rate in obtaining the optimum point, the probability of getting the nearest optimal point is very less. Premature convergence is a most frequent happening in DE. Recent year's revolutionary hybrid process of combining the advantages of two meta-heuristic algorithms in determining the optimal solution has been practised more in many applications. In literature [11], the above revolutionary way of combining DE and PSO has been used in determining the maximum loadability point. Here the search capability of DE is improved by the PSO but has high complexity in algorithmic structure and in algorithmic control parameters. In the last decade due to the lot of research work in meta-heuristics algorithm, many new algorithm's like Firefly algorithm, Bat Algorithm, Cuckoo search, Teachers Learning based optimization Algorithm etc. have been emerged and providing strong potential in solving the engineering optimization problem with limited control variables and better search capability. Among them Firefly algorithm [12]-[14] shows more efficient in handling multimodal optimization problem with their fastest search capability and also maintain better exploration balance against exploitation.

The rise of load demand in the current electricity scenario may increase the stress of transmission system which in turn may lead to the chance of the transmission line outage. The Maximum loading point determination considering the above scenario is effectively handled with the inclusion of FACTS devices in the system. FACTS devices helps in controlling the real and reactive power flow of the transmission system and voltage support in the system [15] which in turn enhances the maximum acceptable loading point at normal condition

and also helps in regaining the system stability at line contingency state. Few researchers [16]-[19] determine the maximum loadability point of the system by optimally determining the loading value of each load and its enhancement by optimally placing and settings the FACTS devices at normal conditions.

In this paper, maximum loadability determination and its enhancement at normal and transmission line outage condition with the FACTS devices such as SVC and TCSC is experimented and the results are analyzed with the help of modified IEEE 30 Bus, IEEE 57 Bus and 118 Bus systems. Firefly Algorithm optimization tool is used to determine the maximum loading point by finding the optimal loading value of each load and also by finding the optimal placement and settings of TCSC and SVC in each Bus system without violating the system constraints.

## 2. Maximum Loading Point Determination

Maximum loading value of the system is the boundary of the system load where all the system parameters such as Bus voltage, real and reactive power of the generator, power flow of the transmission line can be accommodated within their limits. The maximization of system load is achieved by optimizing the loading factor of each load. Hence the above is considered as an optimization problem and its mathematical problem formulation is described in below section

### 2.1. Mathematical Problem Formulation for Finding Optimal Loadability Point Determination

The main objective of our paper is to maximize the total real power load of the system without violating the system's equality and inequality constraints such as power balance, voltage limit, generation real and reactive power limit and line flow limit. This can be mathematically formulated as below

$$\text{Objective Function F1} = \text{Maximum} \left( \sum_{i=1}^{N_{bus}} RPL_{newi} \right) \quad (1)$$

where

$$RPL_{newi} = RPL_{oldi} (1 + \lambda_i),$$

$$N_{Bus} = \text{Total number of load connected buses,}$$

$$\lambda_i = \text{Total number of load connected buses,}$$

$$RPL_{newi} = \text{new real power load value of the } i^{\text{th}} \text{ bus in p.u,}$$

$$RPL_{oldi} = \text{Initial real power load value of the } i^{\text{th}} \text{ bus in p.u.}$$

Subject to the

#### 1. Equality constraints of Power balance Equation

$$0 = P_{Gi} - P_{Di} - V_i \sum V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i), \quad i \in (N_{pq} + N_{pv}) \quad (2)$$

$$0 = Q_{Gi} - Q_{Di} - V_i \sum V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i), \quad i \in N_{pq} \quad (3)$$

where

$$P_{Gi} \text{ is the real power value of the } i^{\text{th}} \text{ Generator Bus in p.u,}$$

$$P_{Di} \text{ is the real power value of the } i^{\text{th}} \text{ Load Bus in p.u,}$$

$$Q_{Gi} \text{ is the reactive power value of the } i^{\text{th}} \text{ Generator Bus in p.u,}$$

$$Q_{Di} \text{ is the reactive power value of the } i^{\text{th}} \text{ Load Bus in p.u,}$$

$$V_i \text{ is the Voltage Magnitude value of the } i^{\text{th}} \text{ Bus in p.u,}$$

$$V_j \text{ is the Voltage Magnitude value of the } j^{\text{th}} \text{ Bus in p.u,}$$

$$Y_{ij} \text{ is the Magnitude of the admittance connected between the } i^{\text{th}} \text{ and } j^{\text{th}} \text{ Bus in p.u,}$$

$$\theta_{ij} \text{ is the Angle of the admittance connected between the } i^{\text{th}} \text{ and } j^{\text{th}} \text{ Bus in p.u,}$$

$$\delta_j \text{ is the Angle of the voltage in } j^{\text{th}} \text{ Bus in p.u,}$$

$$\delta_i \text{ is the Angle of the voltage in } i^{\text{th}} \text{ Bus in p.u,}$$

$$N_{pq} \text{ is the total number of Load Bus,}$$

$$N_{pv} \text{ is the total number of Generator Bus.}$$

## 2. Inequality Constraints

$$V_{i \min} \leq V_i \leq V_{i \max} \quad (4)$$

$$QG_{i \min} \leq QG_i \leq QG_{i \max} \quad (5)$$

$$PG_{i \min} \leq PG_i \leq PG_{i \max} \quad (6)$$

$$PL_i \leq PL_{i \max} \quad (7)$$

$$\lambda_{i \min} \leq \lambda_i \leq \lambda_{i \max}, i \in N_L (\lambda_{i \min}, \lambda_{i \max}) \mathcal{E}(0,1) \quad (8)$$

where

$PL_i$  is the Maximum allowable power flow of the  $i^{\text{th}}$  transmission line in p.u,

$\lambda_i$  is the Loading factor of  $i^{\text{th}}$  Load,

$N_L$  is the total Number of Loads.

### 2.2. FACTS in Maximum Loading Point Determination

FACTS devices have the flexible and rapid control capability of various system parameters in a power system network [15]. Real and reactive power flow of the transmission system and voltage of each bus are main among the system parameters in the network. In this paper, combined contribution of FACTS devices such as thyristor control static compensator (TCSC) and Static VAR Compensator (SVC) has been utilized to achieve the Maximum loadability point enhancement at Normal and line contingency state. The TCSC has been modelled as a variable reactance inserted in a transmission line and SVC has been modelled as a reactive source added at the sending end of the transmission line. Depending upon the position and settings of TCSC and SVC, the loadability limit of the system get varied. Hence the placement and settings of FACTS devices are also considered as a control variable in determining the maximum loadability point. The above also included in the mathematical formulation of determining maximum load utilization point by randomly generating the transmission line number along with the loading factor. The settings of TCSC and SVC data are extracted from the literature [18]. Hence in the above mathematical formulation, Facts Devices inequality constraints are also considered for the maximum loadability limit enhancement. This can be given as follows

$$Q_{SVCmin} \leq Q_{SVC} \leq Q_{SVCmax} \text{ MVAR, } (Q_{SVCmin}, Q_{SVCmax}) \mathcal{E}(200, -200) \quad (9)$$

$$X_{Tescmlmax} X_L \leq X_{TCSC} \leq X_{Tescmlmin} X_L \text{ p.u, } (X_{Tescmlmax}, X_{Tescmlmin}) \mathcal{E}(0.8, -0.2) \quad (10)$$

where

$Q_{SVC}$  is the reactive power injected in the bus by Placing SVC,

$X_{TCSC}$  is the reactance added to the Transmission Line by placing TCSC,

$X_{Tescmlmax}$  and  $X_{Tescmlmin}$  is the maximum and minimum line reactance multiplier added to the line reactance  $X_L$ .

### 3. Firefly Algorithm (FFA) for the Maximum Loading Point Determination

Firefly algorithm was developed by Xin-She Yang [12] and it is based on idealized behaviour of the flashing characteristics of fireflies. Nature based algorithms are highly effective and efficient to solve difficult optimization problems. FFA is nature inspired algorithm and gaining popularity recently for solving nonlinear optimization problems technique [13]. For simplicity, we can summarize the flashing characteristics of the FFA as the following three rules: i) All fireflies are unisex, so that one firefly is attracted to other fireflies regardless of their sex; ii) Attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less bright one will move towards the brighter one; iii) The attractiveness is proportional to the brightness and they both decrease as their distance increases. If no one is brighter than a particular firefly, it will move randomly. The brightness of a firefly is affected or determined by the landscape of the objective function to be optimized. The movement of a firefly “ $i$ ” is attracted to another more attractive (brighter) firefly “ $j$ ” is determined by

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_j - x_i) + \alpha_i \epsilon_i^t \quad (11)$$

In the Equation (11) the second term gives the attractiveness of a firefly which varies with the light intensity/brightness seen by adjacent fireflies and the distance between themselves and  $\beta_0$  is the attraction parameter when the distance is zero. The parameter  $\gamma$  which characterizes the variation of the attractiveness is the light absorption coefficient and is crucial to determine the speed of convergence of the algorithm. In theory,  $\gamma$  could take any value in the set between 0 to infinity. On the other hand, if  $\gamma = 0$ , the attraction is constant. If  $\beta_0 = 0$ , it becomes a simple random walk. So, here the value of  $\gamma$  and  $\beta_0$  was selected by conducting trail and test method. The distance between any two fireflies  $i$  and  $j$  at  $x_i$  and  $x_j$  can be the Cartesian distance  $r_{ij} = \|x_i - x_j\|_2$ . Third term is randomization with  $\alpha_t$  being the randomization parameter, and  $\epsilon_t^i$  is a vector of random numbers drawn from a Gaussian distribution or uniform distribution at time  $t$  ( $\epsilon^t \in (0,1)$ ). Here  $\alpha_t$  essentially control the randomness (or, to some extent, the diversity of solutions), we can tune this parameter during iterations so that it can vary with the iteration counter  $t$ . So a good way to express  $\alpha_t$  is to use  $\alpha_t = \alpha_0 \delta^t$ , where  $\delta^t$  is ( $0 < \delta < 1$ ) and  $\delta$  is essentially a cooling factor. Here we use  $\delta = 0.95$  to  $0.97$  and  $\alpha_0 = 0.01 L$  where  $L$  is the scaling parameter depend on the problem. In this work, we use  $L$  as 10. Artificial diversification is also applied in the Firefly population to avoid premature convergence, which corresponds to a local optimum. In this work, random movement of firefly is used by simple mutation method like that of used in Genetic Algorithm. In this work, it is assumed that for a given firefly  $x$ , if the dimension  $O_k$  is selected, then the resulting dimension will be selected using the equation.

$$O_k = a_k + (b_k - a_k) \times rand \quad (12)$$

where

$a_k$  and  $b_k$  are lower and upper bands of  $O_k$ ,

$rand$  is a uniform random number chosen in the range of  $(0, 1)$ .

#### Structure of Firefly Algorithm (FFA):

1. Initialize the objective function  $f(x)$  as given in the section 2.1
2. Initialize a population of fireflies  $X(x_1, x_2, \dots, x_{NF})$  with the population size of  $NF \times N$ . Where  $NF$  is the Number of fireflies as 50 and  $N$  is the Dimension size depends on the number of loads available to the test systems and a FACTS device such as SVC and TCSC Location and ratings
3. The light absorption coefficient  $\gamma$  is defined as random search between 0 to 10 and the attraction parameter  $\beta_0$  value as one
4. While ( $t \leq \text{Max Generation}$ )
5. For  $I = 1:n$  (all  $n$  fireflies)
6. For  $j = 1:i$
7. Light Intensity  $I_i$  of each firefly  $x_i$  is determined by the objective function  $f(x_i)$
8. If ( $I_i > I_j$ )
9. Move firefly  $i$  towards  $j$  in all the dimensions as per the Equation (11)
10. Else
11. Move firefly  $i$  randomly by creating a new dimension as per the Equation (12)
12. End if
13. Evaluate newly created firefly Light Intensity and update the Light Intensity solutions
14. End for  $j$
15. End for  $i$
16. Rank the fireflies based on its Light Intensity
17. Extract the Local best firefly of each population
18. End While
19. Obtain the global best firefly from all the Local best firefly

## 4. Results and Discussion

Three standard IEEE Bus systems such as modified IEEE 30 Bus system, IEEE 57 Bus and IEEE 118 Bus system [7] [8] has been used to exhibit the proposed theme of Firefly based maximum loadability enhancement. In this paper, three strategies have been adopted in sequence to achieve the proposed theme. The three Strategies are as follows:

Strategy1: Determination of maximum loadability point using Firefly Algorithm and its result comparison with the other Meta-heuristic Algorithmic results.

Strategy2: FACTS devices Involvement in the Enhancement of maximum loadability point.

Strategy3: Maximum loadability point determination in Line Contingency.

The detailed study of these three strategies has been given below. The FFA Programs were developed and tested using the MATLAB 7.0 Software Packages with the support of MATPOWER simulation software package [20].

#### 4.1. Strategy 1: Maximum Loading Point Determination Using FFA

The total initial (Base case) real power load of 1.892 Per Unit, 12.508 Per Unit and 42.42 Per Unit has been utilized in the modified IEEE-30 bus, IEEE-57 bus and IEEE-118 bus test system respectively. In this strategy, the maximum loading point is determined by finding the optimal incremental loading factor from each initial real power load using Firefly algorithm as mentioned in the section. Here the incremental load has been assumed to be at unity power factor. This strategic implementation result of modified IEEE-30 bus, IEEE-57 bus and IEEE-118 bus test system have been recorded and emphasized in Table 1, Table 3 and Table 6 respectively by comparing the results of the other literature.

In Table 1, the fourth row shows the FFA algorithm based maximum loadability point of modified IEEE 30 Bus system. The number of loading factors of this system is 20. To highlight the value of the FFA, the results has been compared with the results of DE and DE-PSO from the literature [11] given in the second and third row of Table 1 respectively. It is inferred from Table 1 that the percentage of total incremental real power load of the FFA is better compared to that of DE and DEPSO. The Critical voltage of the Bus system shows that the maximum loadability point is calculated without the violation of voltage limits. The statistical measures of meta-heuristic algorithm such as mean, best, standard deviation are recorded in Table 2 by conducting 20 different trials. The low standard deviation around the high mean value of FFA shows the better quality and robustness of the FFA compared to that of DE and DE-PSO. The statistical analysis clearly depicts that FFA provides greater amount of balance between exploitation and exploration process.

To check the performance consistency of the FFA, higher order systems such as IEEE 57 Bus system having 42 loading factor and IEEE 118 Bus system having 99 loading factor has been used for implementation and the implemented results are recorded in Table 3 and Table 6 respectively. The IEEE 57 Bus system FFA results are compared with the PSO and HPSO algorithm results given in the literature [7] and the IEEE 118 results are

**Table 1.** FFA based maximum loadability comparison result of IEEE 30 Bus system.

Algorithm	Maximum Loadability in p.u	Critical Voltage	Total Incremental System Load from Base Case in %	Optimal SVC Bus No.	Optimal TCSC Line	SVC in MW	$X_{TCSC}$ in p.u
Base Case	1.892	0.961 @ 8bus	-	-	-	-	-
DE [11]	2.6709	Not Mentioned	41.16807	-	-	-	-
DEPSO [11]	2.6974	0.9499 @ 8bus	42.5687	-	-	-	-
FFA without FACTS	2.7208	0.9501 @ 8bus	43.8089	-	-	-	-
FFA with FACTS	2.8461	0.9501 @ 8bus	50.42957	1	[1 3]	14.0863 (Inductive Mode)	0.073 (Capacitive Mode)

**Table 2.** Statistical performance comparison of FFA for IEEE 33 Bus system.

Method	Worst	Mean	Best	Standard Deviation	No of Iteration
DE	2.5813	2.6334	2.6709	0.0234	15
DE-PSO	2.642	2.6759	2.6974	0.02149	12
FFA	2.710249	2.7198	2.720865439	0.0031	15

compared with the DE and DEPSO algorithm results given in the literature [11]. From the results in **Table 3** and **Table 6** it is inferred that the FFA's maximum loadability point and its percentage increment from the base value has better value with that of other compared algorithm. The statistical analysis results of the both system by conducting 20 independent trials are recorded in **Table 4** and **Table 5**. It is evident from the statistical tab that the FFA provides better consistency results in terms of quality and iteration convergence.

#### 4.2. Strategy 2: FACTS Devices Involvement in the Enhancement of Maximum Loadability Point

In this strategy, the enhancement of system's maximum load utilization is achieved by involving the FACTS devices such as TCSC and SVC united. The combined TCSC and SVC regulates the active and reactive power control and also the voltage magnitude control by means of shunt and series compensation. Hence the optimal placement and settings of FACTS devices such as TCSC and SVC along with the optimal loading factor for each load helps to increase the systems loadability limit. The above objective has been achieved using the FFA by solving the formulation mentioned in the section 2 along with the FACTS devices setting constraints. The FFA with FACTS devices strategy has been implemented using three test systems and the results are recorded in the fifth row of **Table 1**, **Table 3** and **Table 6**.

In the modified IEEE 30 bus test system, the TCSC has been placed on the transmission line connected between bus no.1 and bus no.3 with the  $X_{TCSC}$  of 0.073 p.u added to the line. Here TCSC operates in the capacitive mode that decrease the net reactance of the line in turn increases the real power capacity of the line. Similarly the SVC is connected to the bus no.1 with the size of 14.0863 MVAR. Here SVC operates in the inductive mode to control bus reactive power within the limits to increase power transfer capacity. The above combined TCSC and SVC placement in enhancement of load value is shown in **Figure 1** by comparing the load value of

**Table 3.** FFA based maximum loadability comparison result of IEEE 57 Bus system.

Algorithm	Maximum Loadability in p.u	Critical Voltage	Total Incremental System Load from Base Case in %	Optimal SVC Bus No.	Optimal TCSC Line	SVC in MVAR	$X_{TCSC}$ in p.u
Base Case	12.508	0.936 @ 31bus		-	-	-	-
PSO [7]	14.039	Not Mentioned	12.2401	-	-	-	-
HPSO [7]	14.062	Not Mentioned	12.4240	-	-	-	-
FFA without FACTS	14.134	0.9221 @ 31bus	12.9996	-	-	-	-
FFA with FACTS	14.301	0.9340 @ 31bus	14.3348	44	[44 45]	25.715 (Capacitive Mode)	0.0045 (Inductive Mode)

**Table 4.** Statistical performance comparison of FFA for IEEE 57 Bus system.

Method	Worst	Mean	Best	Standard Deviation	No of Iteration
PSO	13.8	14.0296	14.039	0.0278	39
HPSO	13.92	14.0555	14.062	0.0211	29
FFA	14.04369	14.1218	14.13427	0.015	21

**Table 5.** Statistical performance comparison of FFA for IEEE 118 Bus system.

Method	Worst	Mean	Best	SD	No of Iteration
DE	54.4993	56.2432	56.6212	0.6999	18
DE-PSO	56.2189	56.4966	57.0156	0.27	15
FFA	56.18822	57.2121	57.32037904	0.1935	22

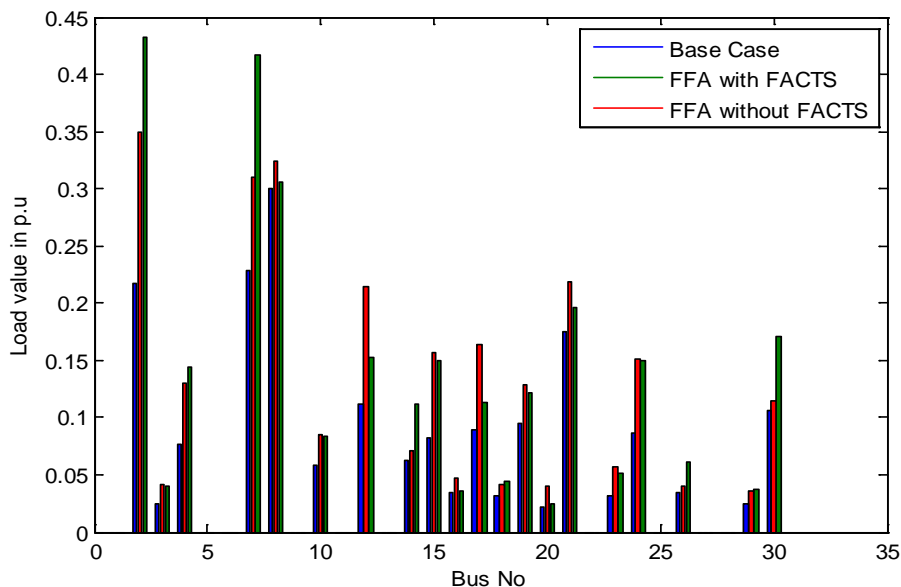


Figure 1. Modified IEEE 30 Bus system load value comparison.

Table 6. FFA based maximum loadability comparison result of IEEE 118 Bus system.

Algorithm	Maximum Loadability in p.u	Critical Voltage	Total Incremental System Load from Base Case in %	Optimal SVC Bus No.	Optimal TCSC Line	SVC in MVAR	$X_{TCSC}$ in p.u
Base Case	42.42	0.946 @ 53bus	-	-	-	-	-
DE [11]	56.6212	Not Mentioned	33.4776	-	-	-	-
DEPSO [11]	57.076	Not Mentioned	34.5497	-	-	-	-
FFA without FACTS	57.32	0.9397 @ 53bus	35.1249	-	-	-	-
FFA with FACTS	57.57	0.9412 @ 53bus	35.7142	79	[79 80]	19.086 (Inductive Mode)	0.03930 (Capacitive Mode)

FFA without FACTS and base case. By comparing fourth and fifth row of Table 1 it is inferred that the FFA with maximum loading point increased with percentage of 6.6206 from the FFA without FACTS.

The Convergence Graph of FFA with FACTS and without FACTS has been shown in Figure 2 for the Modified IEEE 30 Bus system.

In IEEE 57 Bus system, the SVC has been placed on the bus no.44 with the size of 25.715 MVAR. Here the SVC operates in capacitive mode it increases the voltage level of the Bus system which in turn increases the power flow capacity of transmission line. The above voltage level enhancement is shown in Figure 3 by comparing the voltage level of each bus in the FFA with FACTS and without FACTS devices.

The increase in the voltage level of the bus may affect the power flow controllability of the system in turn affects the loading capacity of the load. The power flow controllability of the system is maintained by the placement of TCSC at the transmission line connected between the bus no.44 and bus no.45. Figure 4 shows that the each load value of the system based on the FFA with FACTS devices has been compared with the FFA without FACTS and base case. From the recorded value in the fourth and fifth row of Table 3 it is concluded that FFA with FACTS devices based total load value of the system has 1.3352 percentages more than the FFA without FACTS device.

The convergence graph of FFA with FACTS and without FACTS has been shown in Figure 5 for the Modified IEEE 57 Bus system.

In the IEEE 118 Bus system, the SVC has been placed on the bus no. 79 and TCSC has been placed on the



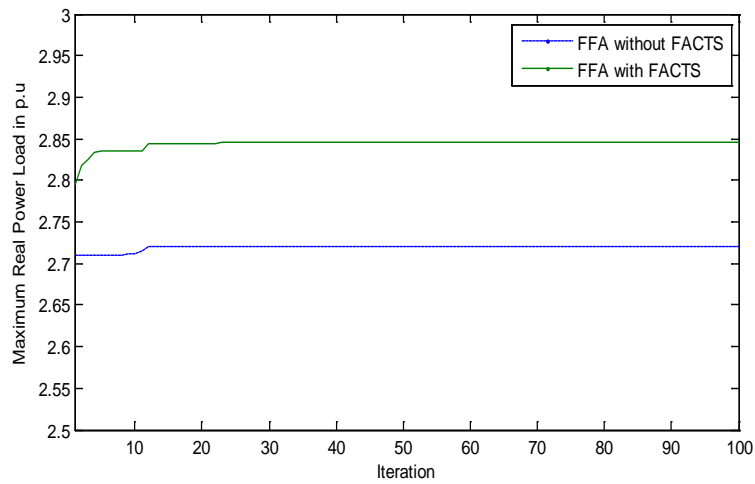


Figure 2. FFA convergence graph of IEEE 30 Bus system.

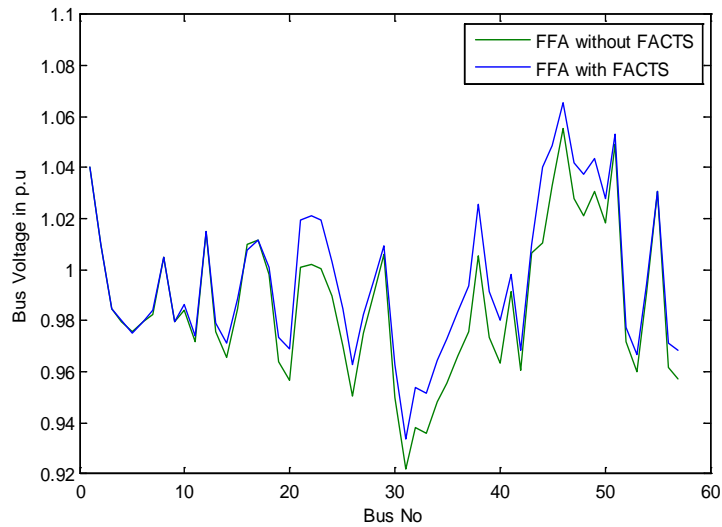


Figure 3. FFA based IEEE 57 bus voltage comparison.

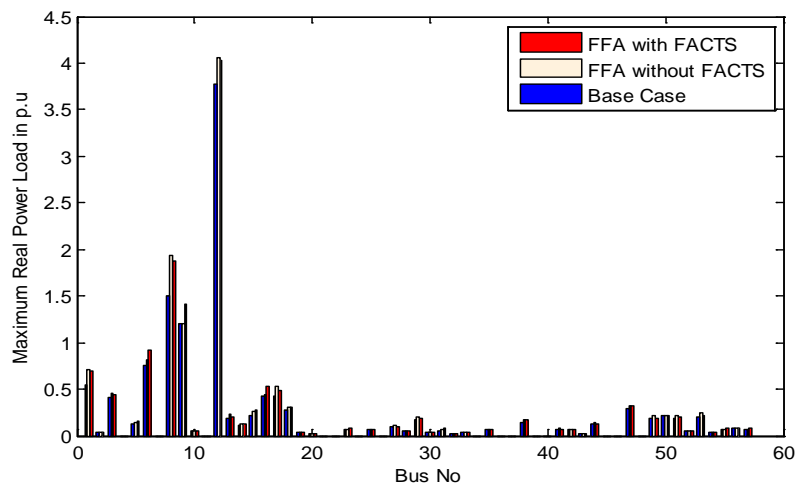
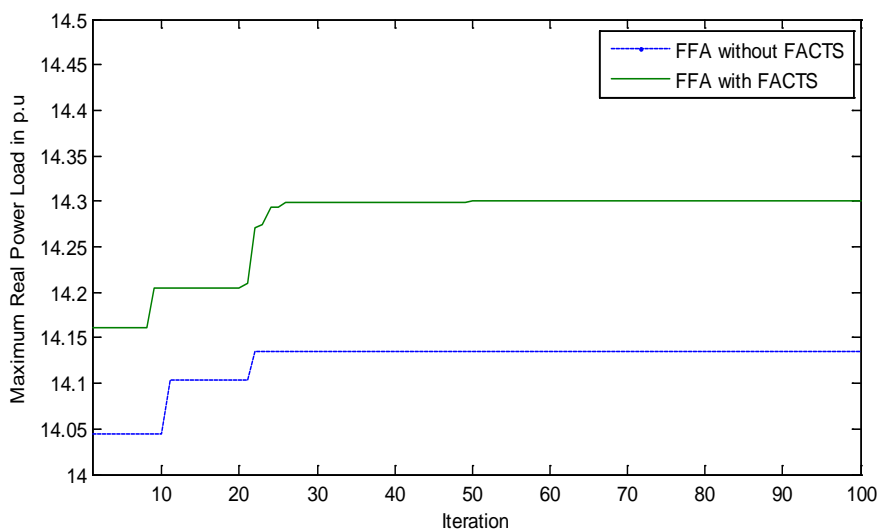


Figure 4. IEEE 57 Bus system load value comparison.



**Figure 5.** FFA convergence graph of IEEE 57 Bus systems.

transmission line connected between the bus no.79 and bus no.80. Here the SVC operates in inductive mode and TCSC operates in capacitive mode. Each load value of the system using FFA with FACTS has been compared with the base case and FFA without FACTS and it is shown in **Figure 6**. Total load utilization capacity of the system using FFA with FACTS is increased to 0.584 percentages than the FFA without FACTS as per inference from the fourth and fifth row of **Table 3**.

The Convergence Graph of FFA with FACTS and without FACTS has been shown in **Figure 7** for the Modified IEEE 118 Bus system respectively.

#### 4.3. Strategy3: Effectiveness of FACTS Devices in Severe Line Contingency

In a power system, the contingencies may be due to the outage of transmission lines or generators. Since in a practical power system, the possibility of transmission line outage is very high compared to that of generator outage hence it is necessary to calculate the maximum loadability point at a transmission line contingency. Considering the above subject matter, system's maximum loadability point is determined by creating a transmission line outage for each test systems in this strategy.

Consider a transmission line connected between bus no.19 and bus no. 20 in modified IEEE 30 Bus system has been assumed to be tripped. The tripped transmission line outage decreases the voltage level to 0.9492 p.u and 0.9384 p.u at bus no. 18 and bus no. 19 respectively. The decreased voltages violate the system since the minimum system bus voltage limit is 0.95 p.u. FFA based optimal placement of SVC on bus no.15 with the size of 17.4309 MW and TCSC operates in the inductive mode with the  $X_{TCSC}$  of 0.0123 p.u added to the transmission line connected between bus no. 15 and bus no.18 provide the solutions to determine the maximum loadability point by limiting all the bus voltage within the limits of 0.95 and 1.05 p.u. The above is illustrated in the comparison voltage graph between base case and FFA with FACTS in the contingency state shown in **Figure 8**. The maximum loading point of 2.714p.u is obtained at the assumed line outage and it is recorded in the first row of **Table 7**.

In IEEE 57 Bus system, a transmission line between bus no.9 and bus no.12 has been assumed to be tripped. The above line outage increases the reactive power of generator bus no. 9 to 17.4693 MVAR in the base case. Here the system gets violated since the reactive power maximum limit of generator bus no. 9 is 9MVAR.The FFA based optimal placement of SVC on bus no 24 and TCSC on the transmission line connected between bus no 24 and bus no 26 provide the solution to determine the maximum loadability point by limiting the generator bus no. 9 reactive power to 8.4413 MVAR and also the other system control variables within the limit. Here the SVC operates in capacitive mode with the size of 58.5261 MVAR and TCSC operates in inductive mode with the  $X_{TCSC}$  of 0.0084 p.u added to the line. The maximum loading point of 14.1135 p.u is obtained at the assumed line outage and it is recorded in the second row of **Table 7**. The voltage graph of the IEEE 57 Bus system at

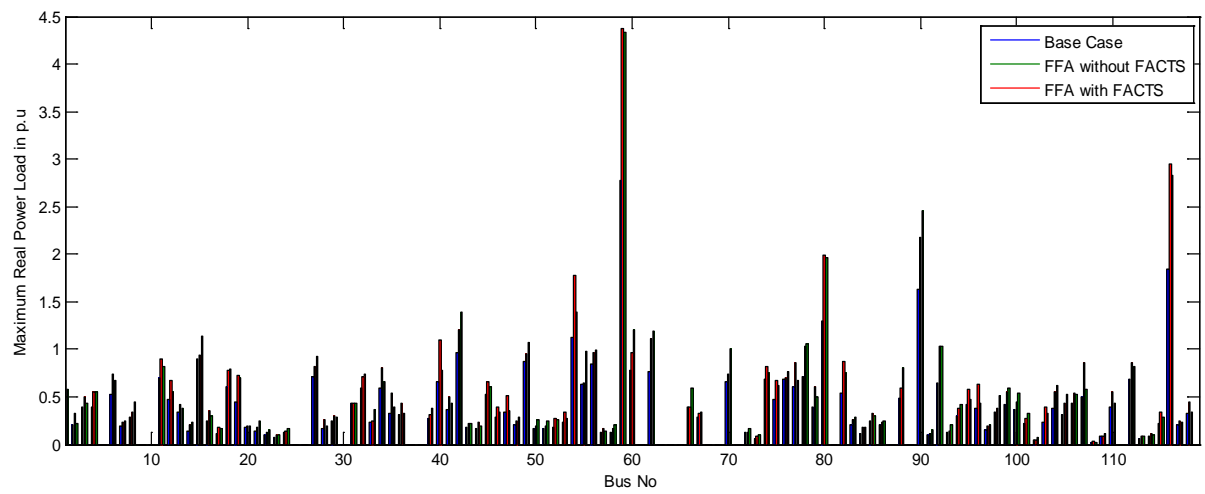


Figure 6. IEEE 118 Bus system load value comparison.

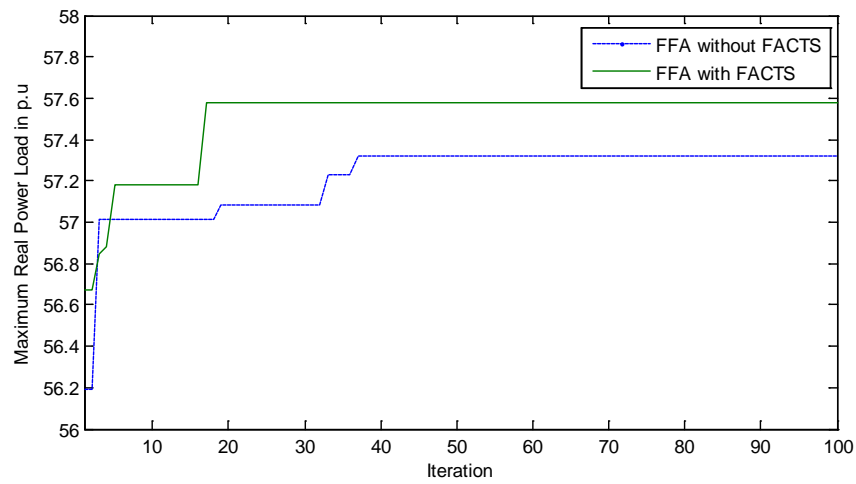


Figure 7. FFA convergence graph of IEEE 118 Bus systems.

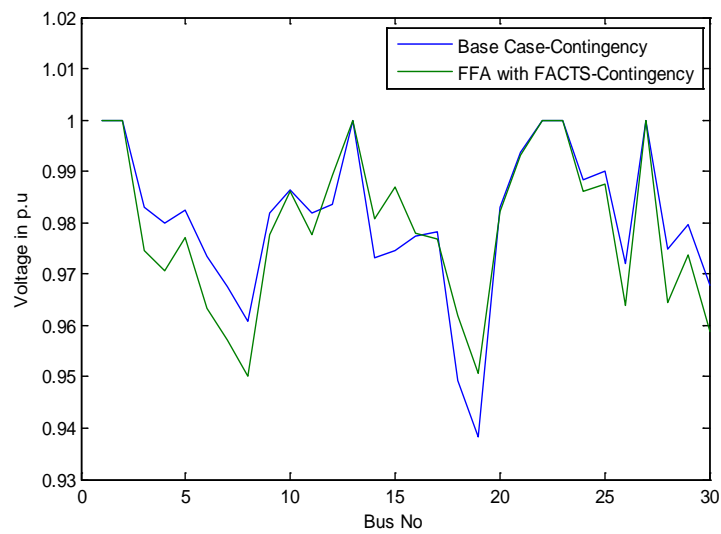
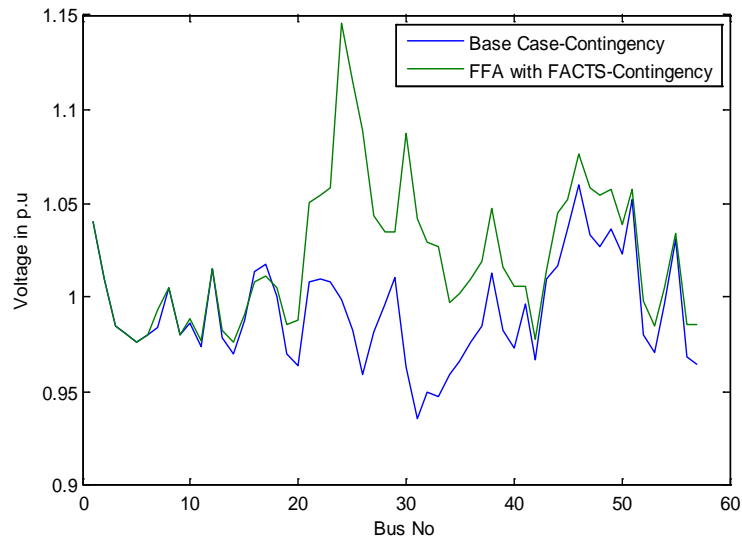


Figure 8. FFA based IEEE 30 bus voltage comparison in the contingency state.

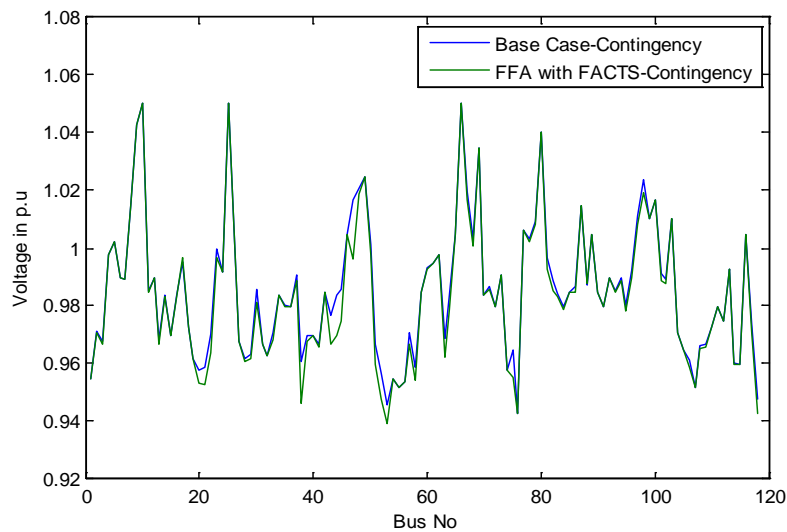
the base case line outage and the FFA with FACTS based line outage is shown in **Figure 9**. From **Figure 9** it is inferred that the optimal placement of FACTS increases the voltage profile of almost all the Bus system at the line outage.

Similar like modified IEEE 30 Bus system and IEEE 57 system, a transmission line between bus no. 69 and bus no. 75 has been assumed to be tripped in IEEE 118 Bus system. The tripped transmission line outage causes the system violation since the reactive power of the bus no.32 is increased to 17.5 MVAR compared to the maximum limit of 17 MVAR at bus no. 32. This reactive power violation has been brought into control by optimally placing the SVC at bus no.17 with the size of 29.4520MVAR and TCSC operates in the inductive mode with the  $X_{TCSC}$  of 0.0080 p.u added to the transmission line connected between bus no. 17 and bus no. 113 provide the solutions to determine the maximum loadability point by limiting the reactive power at bus no. 32 as 3.9 MVAR and other system limits. The maximum loading point of 54.512 p.u is obtained at the assumed line outage and it is recorded in the third row of **Table 7**. The voltage graph of the IEEE 118 Bus system at the base case line outage and the FFA with FACTS based line outage is shown in **Figure 10**.

The loading value of each bus in the three test system using FFA based optimal placement of FACTS devices in the contingency state has given in **Figure 11**.



**Figure 9.** FFA based IEEE 57 bus voltage comparison in the contingency state.



**Figure 10.** FFA based IEEE 118 bus voltage comparison in the contingency state.

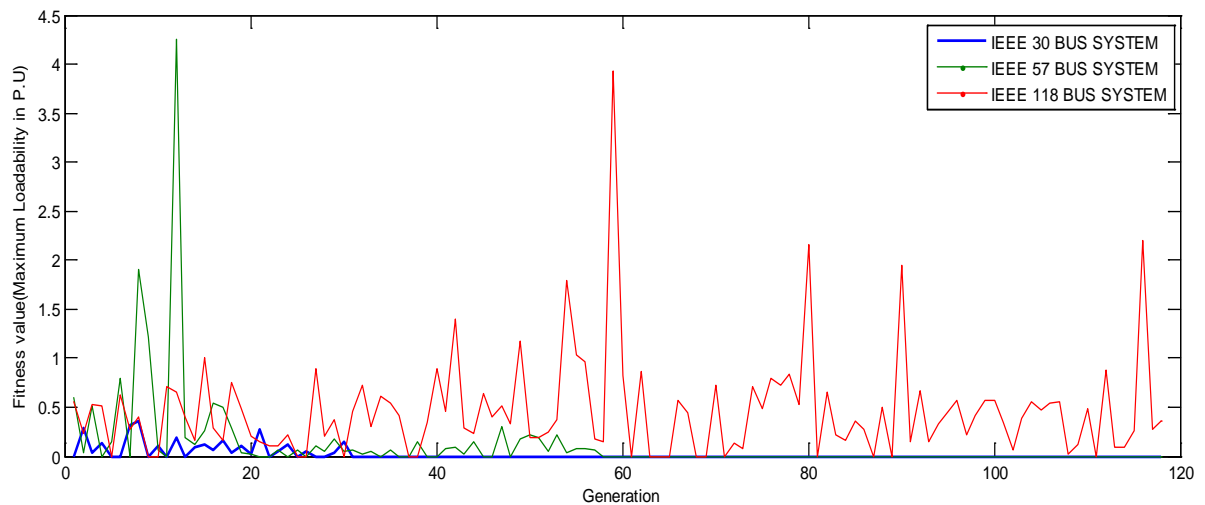


Figure 11. FFA with FACTS based load bus value of the test system in the contingency state.

Table 7. FFA with FACTS based maximum loading point in a line contingency state.

FFA With SVC and TCSC at a Line Contingency State	Transmission Line Outage [Sending Receiving End Bus]	Maximum Loadability in p.u	Critical Voltage in p.u @ bus	Optimal SVC Bus No.	Optimal TCSC Line	SVC in MVAR	$X_{TCSC}$ in p.u
IEEE 30 Bus System	[18 19]	2.714	0.9501 @ 8	15	[15 18]	17.4309	0.0123
IEEE 57 Bus System	[9 12]	14.11	0.9758 @ 1	24	[24 26]	58.5261	0.0084
IEEE 118 Bus System	[69 75]	54.512	0.9392 @ 53	17	[17 113]	29.4520	0.0080

## 5. Conclusion

In this work, maximum loadability point determination using Firefly Algorithm is implemented in modified IEEE 30 Bus system, IEEE 57 Bus System and IEEE 118 Bus system. The results of Firefly algorithm provides better maximum loading point compared to the other evolutionary algorithm. It is evident from the convergence characteristics that the FFA provides better balance between the exploration and exploitation process at the faster convergence rate. The FACTS devices involvement of TCSC and SVC in determining the maximum loading point enhances the load utilization point in normal state and also helps to overcome the system violation in transmission line contingency state. Overall, the firefly algorithm in determining the maximum loadability point and its enhancement with the help of FACTS provides better search capability and also enriches the system load utilization capacity by maintaining the system security level.

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