International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 3 (2015) pp. 8091-8100

http://www.ripublication.com

# Loadability Enhancement of Security Constrained Power System Network with STATCOM using Firefly Algorithm

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## Abstract

In this paper, recently developed metaheuristic optimization technique FireFly Algorithm is used in determining the maximium loadability of the power system in real or / and reactive power loading conditions. The maximum loadability of the system is obtained by optimally placing a tuned STATCOM device in a security constrainted power system network. The critical buses where the STATCOM device need to be inserted is determined using Fast Voltage Stability Index. Numerical results are obtained for an IEEE 30 bus test system using Firefly and Real Coded Genetic algorithms. The results show that the usage of Firefly algorithm is efficient in increasing the stability of the power system.

**Keywords** STATCOM, Firefly algorithm, Fast Voltage Stability Index, Security Constrained Optimal Power Flow, Maximum loadability.

## Introduction

Power system networks are complex networks that run throughout the length and breath of a country. It comprises of generators, power transformers, transmission lines, active and passive loads, switchgear equipments and many more. It is an intricate task to maintain the system reliable under situations like overtraffic and blockouts while preserving their voltage and thermal stability. The usage of FACTS devices in the power network overcomes such critical situations and makes the network to perform better within safer limits. These FACTS devices balance the real and reactive powers in the network, decrease the losses and maintain the voltage and thermal stability[1].

The solution to an Optimal Power Flow problem provides the best operating conditions of the system under normal or critical conditions. Several traditional and intelligent optimization techniques have been used to obtain an optimal solution to various power flow problems by optimally placing the FACTS devices in the system [2-11].

Among various naturally inspired intelligent techniques, FireFly Algorithm (FFA) - a metaheuristic optimization technique, due to its capability and efficiency finds usage in various domains. This Firefly algorithm was developed by Xin-She Yang in the year 2007 at Cambridge University. In the field of power systems, it has been recently used in solving economic Emissions Load Dispatch (ELD) and OPF Problems [12-15]. This paper uses FFA in determining the maximum loadability of the power network in security constrained environment.

This paper comprises of seven sections. Introduction is dealt in this section followed by the description of implemented STATCOM model in section 2. The problem for the study is formulated in section 3. Section 4 describes the procedure for determining the critical buses using FAST Voltage Stability Index. Section 5 provides an overview of Firefly Algorithm and describes the algorithmic steps for implementing FFA in this work. The numerical results for an IEEE 30 bus system are presented and discussed in section 6 and section 7 concludes the benefits of STATCOM and FFA demonstrated in this study.

## Model of Statcom

The FACTS device most commonly used to regulate the voltage profiles of a system during loaded condition and to maintain the voltage stability within the limits is Static Synchronous Compensator, which is popularly called as STATCOM. It is a shunt connected voltage source converter that exchanges real and reactive powers with the power grid. Among several proposed steady state models, the power injection model [16 ] is used in this work.The model is shown in Figure below:

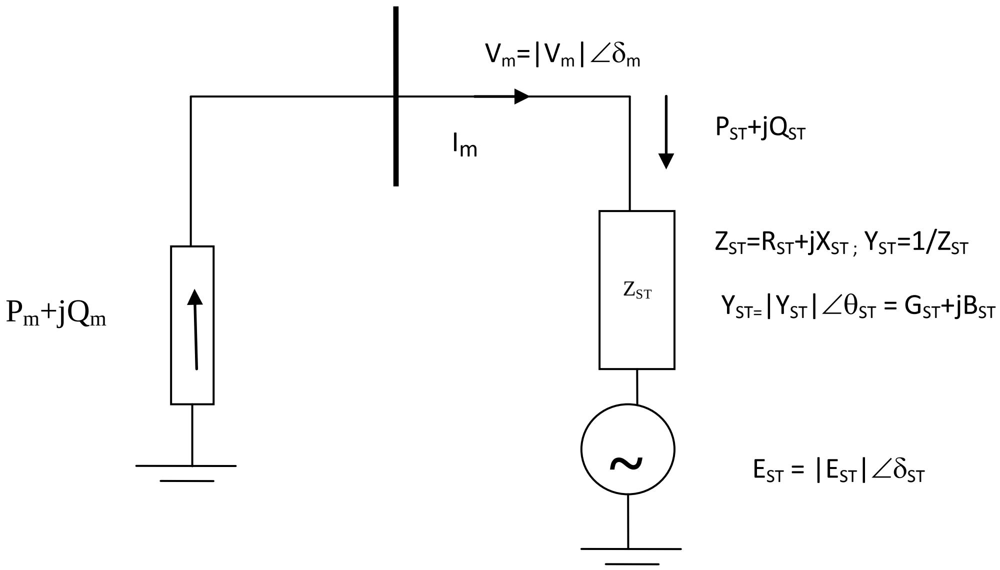


**Figure 1:** Power Injection model of STATCOM

The real and reactive powers of the bus to which the STATCOM is connected gets altered and are obtained as:

$$P_m = P_{ST} + \sum_{n=1}^{nb} |V_m||V_n||Y_{mn}|\cos(\delta_m - \delta_n - \theta_{mn}) \quad (1)$$

$$Q_m = Q_{ST} + \sum_{n=1}^{nb} |V_m||V_n||Y_{mn}|\sin(\delta_m - \delta_n - \theta_{mn}) \quad (2)$$

$$P_{ST} = G_{ST}|V_m|^2 - |V_m||E_{ST}||Y_{ST}|\cos(\delta_m - \delta_{ST} - \theta_{ST}) \quad (3)$$

$$Q_{ST} = -B_{ST}|V_m|^2 - |V_m||E_{ST}||Y_{ST}|\sin(\delta_m - \delta_{ST} - \theta_{ST}) \quad (4)$$

In this model, the Jacobian matrix of Newton Raphson method is slightly modified by including the new variables $|E_{ST}|$ and $\delta_{ST}$ that are introduced by STATCOM [16].

## Problem Formulation

Security Constrained Optimal Power Flow problem (SCOPF) is formulated to obtain the maximum loadability in a power system network. The solution to SCOPF problem is obtained by inserting an optimally tuned shunt connected FACTS device STATCOM in an optimal location in the power system network.

The objective function of the SCOPF, which involves the FACTS device is stated as:

Maximize $\lambda$ (5)

Subject to constraints

$$\sum_{j=1}^{NG} P_{Gj} = P_D + \sum_{n=1}^{nb} |V_m||V_n||Y_{mn}|\cos(\theta_{mn} - \delta_m + \delta_n) \quad (6)$$

$$\sum_{j=1}^{NG} Q_{Gj} = Q_D + \sum_{n=1}^{nb} |V_m||V_n||Y_{mn}|\sin(\theta_{mn} - \delta_m + \delta_n) \quad (7)$$

$$P_{Gj}^{\min} \le P_{Gj} \le P_{Gj}^{\max} \quad (8)$$

$$Q_{Gj}^{\min} \le Q_{Gj} \le Q_{Gj}^{\max} \quad (9)$$

$$V_m^{\min} \le V_m \le V_m^{\max} \quad (10)$$

$$x_{ST}^{\min} \le x_{ST} \le x_{ST}^{\max} \quad (11)$$

$$BOL = \begin{cases} 1 & ; if BL \le 100 \\ P1 & ; otherwise \end{cases} \quad (12)$$

$$VL = \begin{cases} 1 & ; 0.95 \le V \le 1.05 \\ P2 & ; otherwise \end{cases} \quad (13)$$

Where, $\lambda$ is load factor of the system; $P_{Gj}$ & $Q_{Gj}$ are $j^{th}$ generator's real and reactive powers; $P_D$ & $Q_D$ are total real and reactive power demands of the system; $V_m$ & $V_n$ are the voltages at buses m and n; NG is total number of generators and nb is total number of transmission lines in the power network; $Y_{mn}$ & $\theta_{mn}$ are magnitude and phase angle of admittance of the transmission line branch m-n; $\delta_m$ & $\delta_n$ are phase angles of the voltages at buses m and n respectively; $X_{ST}$ is the STATCOM's control parameter and it takes the value from 0.4 to 4; P1 & P2 are penalty factors; BOL is branch overloading index; BL is branch overloading; VL is voltage stability index.

## Fast Voltage Stability Index (FVSI)

The critical buses in loaded condition are determined using the equation (14). The two-bus system model is used to frame the equation [17].

$$FVSI_{m,n} = \frac{4z^2 Q_m}{v_m^2 x} \tag{14}$$

Where, m and n are sending and receiving end buses respectively, x and z denote the reactance and impedance of a line, $Q_m$ and $v_m$ are the reactive power and voltage of the sending end.

In reactive power loading conditions, the maximum loadability of each load bus is determined by conducting a power flow analysis using Newton Raphson method. The load buses are arranged in the ascending order of maximum loadability. The load bus that has minimum loadability in the series is treated as the most critical bus. The FVSI is very useful in deciding the location of the STATCOM device in the power network and the optimal location is determined using FFA.

## Overview of Firefly Algorithm

Firefly algorithm mimics the natural communicating behavior of fireflies using their rhythmic flashing lights. Brightness of the light is the important factor in attracting other fireflies and that brightness depends on the distance between the fireflies. The brightest firefly attracts other fireflies towards it.

The metaheuristic firefly algorithm is formulated to mimic the phenomenon of attraction among fireflies. In this, the control variables that decides the optimization of the objective function are formulated as fireflies. Attractiveness of a firefly and movement of fireflies towards brightest firefly can be mathematically modeled as follows:

The attractiveness of each firefly is determined using equation (15)

$$\beta = \beta_0 * \exp(-\gamma * d^2) \tag{15}$$

Where $\beta_0$ is firefly's initial attractiveness, $\beta$ is firefly's current attractiveness, $\gamma$ is absorption coefficient and d is distance between fireflies.

Cartesian equation is used to determine the distance between Brightest firefly and all other fireflies.

$$d_{p,q} = \|y_p - y_q\| = \sqrt{\sum_{i=1}^{n}\left(y_{p,i} - y_{q,i}\right)^2} \tag{16}$$

The new location of fireflies are determined using the equation (17).

$$y_p^{k+1} = y_p^k + \beta_0 * \exp(-\gamma * d^2) * (y_q^k - y_p^k) + \alpha * \varepsilon_p^k \tag{17}$$

Where α is randomizing coefficient and ε is the randomization vector.
The algorithm for implementation of FFA in OPF is described below:

1. Read the line data, bus data, generators' minimum and maximum real, reactive powers limits and thermal limits of transmission lines.
2. Set number of fireflies, size of a firefly (number of Control variables), buses' minimum and maximum voltage limits, loadability range and maximum number of iterations.
3. Randomly initialize the control variables within their limits.
4. Perform power flow analysis using Newton Raphson method implementing rescheduling of Generators' real and reactive powers.
5. Check for the voltage and thermal limits.
6. Repeat steps 3 - 5 until voltage and thermal limits are satisfied.
7. Determine the fitness function that acts as brightest firefly.
8. Calculate the distance of all fireflies from the brightest firefly using the equation (16)
9. Determine the attractiveness of all fireflies using the equation (15)
10. The movement of all fireflies towards brightest firefly is calculated using equation (17) and this provides a new set of control variables.
11. Repeat the steps 4 -10 till the maximum number of iterations.
12. Determine the optimal results.

## Results and Discussions

The proposed firefly algorithm is tested in an IEEE 30 bus system which comprises of 6 generators, 24 load buses and 41 transmission lines to determine the maximum loadability of the system for three different cases [18]. The three different cases are for (i) real power loading, (ii) reactive power loading and (iii) real and reactive power loading conditions.

The maximum loadability is obtained by optimally placing and tuning a STATCOM device along with the rescheduling of generators' to their maximum real and reactive power limits using FFA. Optimal power flow is conducted keeping all bus voltages and transmission lines' thermal levels within their limits. The control variables chosen in this work are Generators' voltages, real and reactive powers, location of STATCOM, control parameter of STATCOM and loadability of the system. Matlab coding is used to obtain the results. Results for maximum loadability of the system for the three different cases described above are obtained using FireFly Algorithm (FFA) and the results are compared with that of Real Coded Genectic Algorithm (RCGA).

The critical buses during loaded conditions are determined using FVSI and are tabulated in Table 1.

**Table 1:** Ranking of critical buses by FVSI

| **Critical Buses** | **Ranking** |
|---|---|
| 30 | 1 |
| 26 | 2 |
| 21 | 3 |
| 7 | 4 |
| 15 | 5 |

The size of population or number of fireflies chosen in RCGA/FFA is 100 and the number of generations/iterations is chosen as 200. The FFA parameter values are listed in Table 2.

**Table 2:** FFA Parameters

| **Parameters** | **FFA** |
|---|---|
| $\beta_0$ | 1.0 |
| $\gamma$ | 0.8 |
| $\alpha$ | 0.3 |
| $\varepsilon$ | (0 – 0.5) |

Table 3 briefs the results of maximum loadability for real, reactive and real & reactive loading conditions without and with STATCOM.

**Table 3:** Results for Maximum Loadablity

| **Cases** | **Maximum Loadability(%)** | | |
|---|---|---|---|
| | ***Without STATCOM*** | ***With STATCOM*** | |
| | | ***RCGA*** | ***FFA*** |
| Real Power loading | 143 | 146 | 147 |
| Reactive Power loading | 150 | 157 | 161 |
| Real and Reactive Power loading | 134 | 136 | 138 |

From the results in Table 3, it can be observed that the insertion of STATCOM at optimal location and optimally tuning its control variable $X_{ST}$ increases the loadability of the system. In real power loading and real & reactive power loading conditions, the loadablity has increased by 4%. In reactive power loading condition, the loadability has increased by 11%. The results show that the optimization using FFA increases the loadability of the system to a greater extent compared to RCGA. In FFA, the optimal location for STATCOM in reactive power loading was bus number 21 and the optimal value of $X_{ST}$ value was 3.6. In real and reactive power loading the STATCOM was located optimally at Bus No.15 with an optimal value of $X_{ST}$ as 0.75. Table 4 depicts the optimal control parameter values for real power loading conditions.

**Table 4:** Optimal Values of Control Variables for Real power loading

| **Control Variables** | **Optimal Value without STATCOM** | **Optimal Value with STATCOM using RCGA** | **Optimal Value WITH STATCOM using FFA** |
|---|---|---|---|
| $P_{G1}$ | 194.442 | 196.622 | 199.389 |
| $P_{G2}$ | 80 | 80 | 80 |
| $P_{G5}$ | 50 | 50 | 50 |
| $P_{G8}$ | 29.331 | 35 | 35 |
| $P_{G11}$ | 26.329 | 30 | 30 |
| $P_{G13}$ | 39.555 | 36.786 | 39.3215 |
| $V_1$ | 1.060 | 1.060 | 1.060 |
| $V_2$ | 1.047 | 1.034 | 1.104 |
| $V_5$ | 1.042 | 1.029 | 1.113 |
| $V_8$ | 1.016 | 1.018 | 1.106 |
| $V_{11}$ | 1.049 | 1.048 | 1.194 |
| $V_{13}$ | 1.038 | 1.038 | 1.261 |
| $Q_{G1}$ | 27.383 | 14.696 | -12.719 |
| $Q_{G2}$ | 64.050 | -8.469 | 53.538 |
| $Q_{G5}$ | 39.105 | 58.867 | 50.765 |
| $Q_{G8}$ | 8.138 | 50.647 | 54.237 |
| $Q_{G11}$ | -0.491 | 8.756 | 11.119 |
| $Q_{G13}$ | 0.604 | 1.106 | 6.292 |
| $\lambda$ | 1.43 | 1.46 | 1.47 |
| $X_{ST}$ | - | 0.605 | 0.88 |
| Location of STATCOM (BUS No) | - | 7 | 7 |

STATCOM is mainly used in power grids to enhance the voltage profiles of the buses and it plays an important role in maintaining the stability of the system in loaded conditions. Figure 2 shows the voltage profiles of an IEEE30 bus system with and without STATCOM device in 130% real power loading condition. From the results, it is observed that all the bus voltages are maintained above 1.0 P.U by inserting a STATCOM optimally at bus number 7 with an optimal $X_{ST}$ value of 0.67 calculated using FFA.

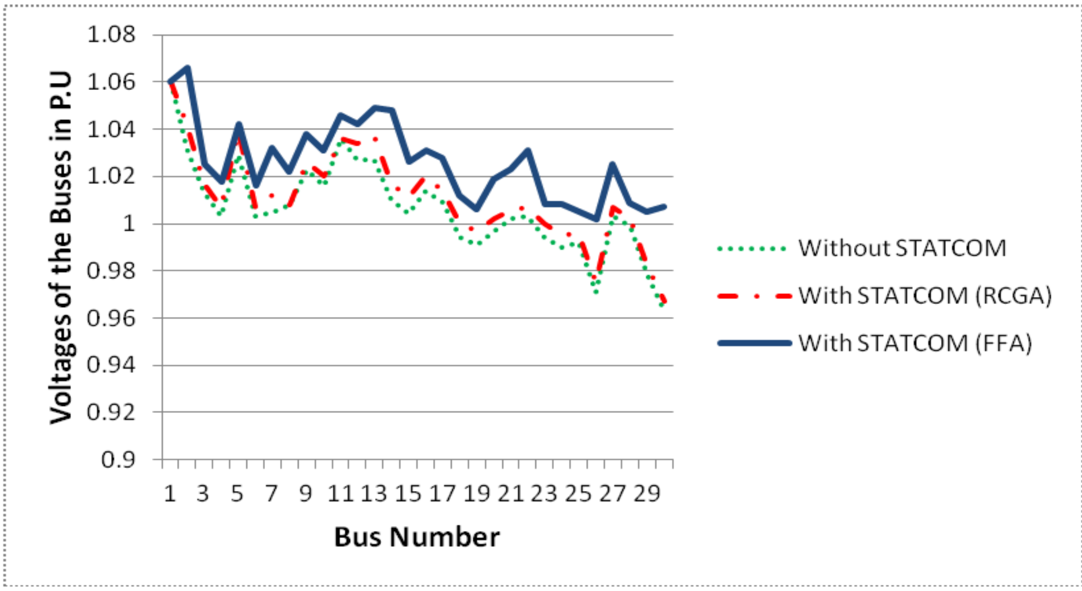


**Figure 2:** Voltages of Buses in IEEE 30 bus system for 130% real power loading

Analyzing the thermal limits of transmission lines, it is found that the branch 1-2 in IEEE 30 bus system gets overloaded first for any type of loading and is one of the factor that decides the maximum loadability of the security constrained system. The rated MVA rating of branch 1-2 is 130MVA. In the 130% of real power loading condition, introduction of STATCOM in the system reduces the MVA rating of branch 1-2 from 127.9MVA to 123.5MVA thereby increases the stability and security of the system.

## Conclusion

In this paper, a naturally inspired intelligent Firefly algorithm is used to insert an optimally tuned STATCOM device in an optimal position in the power system network. From the results, it can be concluded that Firefly algorithm is suitable for resolving OPF problems in a power system network. The comparison of results with that of RCGA shows that the FFA provides better global optimal solutions. The optimal insertion of STATCOM in the power network using FFA maintains the voltage profiles of all buses above 1 P.U. during loaded conditions. The thermal levels of all transmission lines are also decreased, thereby increasing the power transfer capability of the lines and eventually increasing the stability of the system. The application of FFA for the OPF problem studied in this paper can be extended to multi objective optimal power flow optimizations.

## Acknowledgements

The author expresses her sincere thanks to the Management of Sathyabama University for providing necessary facilities to carry out this research work.

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