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Use of firefly algorithm for solving optimal power flow problem with static synchronous series compensator

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Abstract: This paper presents an efficient and reliable evolutionary based approach to solve the optimal power flow (OPF) problem in the presence of static synchronous series compensator (SSSC). The firefly algorithm (FFA) is developed by using principle of firefly swarm. The approach has been tested on IEEE 30- bus system with and without SSSC. The results show that FFA algorithm with SSSC gives better performance of the system. The results are promising and show the effectiveness and robustness of the approach.

Keywords: Optimal Power Flow, Optimization Methods, Power Systems, Firefly Algorithm, Static Synchronous Series Compensator.

I.INTRODUCTION

The electric power industry over the worldwide becoming complex day to day and continuous requirements are coming for stable, secured, controlled, economic and better quality power. The optimal power flow was first introduced by Carpenter in 1962.The goal of OPF is to find the optimal settings of a given power system network that optimize the system objective functions such as total generation cost, system loss, bus voltage deviation, emission of generating units, number of control actions and load shedding while satisfying its power flow equations, system security and equipment operating limits. Different control variables, some of which are generators real power outputs and voltages, transformer tap changing settings, phase shifters, switched capacitors and reactors are manipulated to achieve an optimal network setting based on the problem formulation.

OPF is a highly nonlinear and a multimodal optimization problem, i.e. there exist more than one local optimum. Hence, local optimization techniquesare not suitable for such problems. Moreover, there is no local criterion to decide whether a local solution is also the global solution. Therefore, conventional optimization methods that make use of derivatives and gradients arenot able to locate or identify the global optimum generally. On the other hand, many mathematical assumptions such as convex, analyticand differential objective functions have to be given to simplify the problem. However, the OPF problem is an optimization problem with non convex, non smooth, non differentiable objectivefunction. These properties have become more evident and dominant if the effects of valve point loading ofthermal generators and the nonlinear behaviour of electronic based devices such as FACTS are taking into consideration.

Traditionally, classical optimization methods were used to solve OPF problems. But, more recently due to incorporation of FACTS devices and deregulation of a power sector, the traditional concepts and practices of power systems are superimposed by an economic market management. These algorithms include traditional methods such as Newton's method [1], gradient method, linear programming[2],sequential unconstrained minimization techniquesas well as latest methods such as modified interior point method [3,4], analytic hierarchy process, particle swarm optimization[5] and genetic algorithms[6,7]. The performance of the proposed approach is sought and tested on the standard IEEE 30-bus test system. Obtained simulation results demonstrate that FFA provides very remarkable results for solving the OPF problem.

II.SSSC DEVICE MODEL

The basic scheme of SSSC is shown in Fig.1. The SSSC is a series compensation device of the FACTS family which has the voltage source converter (VSC) to control power flow in transmission lines and improve transient stability in power system[8].The SSSC controls the power flow in transmission lines by controlling the magnitude and phase angle of injected voltagev_{se} in series with the transmission line where SSSC is connected. The exchange of real and reactive power between SSSC and power system depends on the magnitude and phase displacement with respect to transmission line current [9].

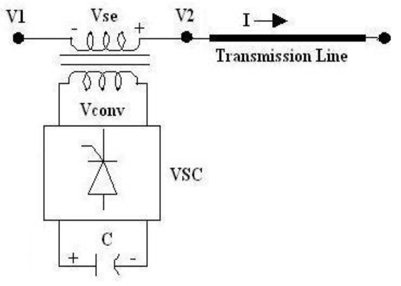

Fig.1.Basic scheme of SSSC

The SSSC can control the power flow through the transmission line by controlling the magnitude of v_{se} and injecting in quadrature with transmission line current I as mentioned in the following equations.

$$v_{se} = v_2 - v_1 = v_d + jv_q \quad (1)$$

$$v_d \approx 0 \quad (2)$$

$v_q > 0$: SSSC is capacitive(3)

$v_q < 0$: SSSC is inductive (4)

The magnitude of v_{se} is controlled through the changes in the amplitude modulation ratio(m_{se}) according to the following equation.

$$m_{se} = \sqrt{\frac{8v_{se}}{v_{dc}}} \quad (5)$$

III. OPF PROBLEM FORMULATION WITH SSSC

In an optimal power flow, the values of some or all of the control variables need to be found so as to optimize (minimize or maximize) a predefined objective function.The OPF problem is to optimize the steady state performance of a power system in terms of an objective function.

The OPF problem can be formulated as an optimization problem and is as follows:

$$\text{Min } F(P_g) = f(x,u) \quad (6)$$

subject to satisfaction of non linear equality constraints

$$g(x,u) = 0 \quad (7)$$

and non linear inequality constraints:

$$h(x,u) \leq 0 \quad (8)$$

$$u^{min} \leq u \leq u^{max} \quad (9)$$

$$x^{min} \leq x \leq x^{max} \quad (10)$$

$F(P_g)$is total cost function and is expressed as

$$F(P_g) = \sum_{i=1}^{N_g} (\alpha_i + \beta_i P_{g_i} + \gamma_i P_{g_i}{}^2) \ \$/h \qquad (11)$$

whereα_i, β_i, γ_i are costs co-efficient of generator at bus i. f(x, u) is the scalar objective function, g(x, u) represents nonlinear equality constraints (power flow equations) and h(x, u) is the nonlinear inequality constraints of vector arguments x, uincluding SSSC device constraints are restricted by their limits as follows

$$v_{se}^{min} \leq v_{se} \leq v_{se}^{max} \quad (12)$$

$$\theta_{se}^{min} \leq \theta_{se} \leq \theta_{se}^{max} \quad (13)$$

v_{se} and θ_{se} are the series voltage source magnitude and series voltage source angle respectively. The load of l^{th} transmission line is restricted by its limits are given as follows

$s_{tl} \leq s_{tl}^{max}$ tl=1,2,3……x_{tl}(14)$x_{tl}$is the number of transmission lines.

IV. FIREFLY ALGORITHM

Firefly algorithm [10] is a meta heuristic, nature-inspired optimization algorithm which is based on the social flashing behaviour of fireflies. It is based on the swarm behaviour such as fish, insects or bird schooling in nature. Although, the firefly algorithm has many similarities with other algorithms which are based on the so-called swarm intelligence such as the famous particle swarm optimization (PSO), artificial bee colony optimization (ABC) [11] and bacterial foraging algorithm(BFA). FFA is indeed much simpler both in concept and implementation. Its main advantage is that it uses mainly real random numbers and it is based on the global communication among the swarming particles called as fireflies.

A. Behaviour of Fireflies*:*

Fireflies or lightning bugs belong to a family of insects that are capable to produce natural light to attract a mate or prey. There are about two thousand firefly species which produce short and rhythmic flashes.The intensity (I) of flashes decreases as the distance (r) increases and thus most fireflies can communicate only up to several hundred meters. In the implementation of the algorithm, the flashing light is formulated in such a way that it gets associated with the objective function to be optimized.

In firefly algorithm, there are three idealized rules [12]:

- ➢ A firefly will be attracted by other fireflies regardless of their sex.
- ➢ Attractiveness is proportional to their brightness and decreases as the distance among them increases.
- ➢ The landscape of the objective function determines the brightness of a firefly.

B. Attractiveness and Light Intensity:

In the Firefly algorithm, there are two important issues: the variation of the light intensity and the formulation of the attractiveness. The light intensity varies according to the inverse square law i.e.

$$I(r) = \frac{i_s}{r^2} \quad (15)$$

Where I(r)is the light intensity at a distance r andi_s is the intensity at the source. When the medium is given, the light intensity can be determined as follows:

$$i = i_0 e^{-\gamma r} \quad (16)$$

To avoid the singularity at r=0, the equations can be approximated in the following Gaussian form:

$$i = i_0 e^{-\gamma r^2} \quad (17)$$

Fireflies attractiveness is proportional to the light intensity seen by adjacent fireflies and thus the attractiveness βof a firefly is determined by equation

$$\beta(r) = \beta_0 e^{-\gamma r^m} \ m \geq 1 \qquad (18)$$

Where $\beta_0$is the attractiveness at r=0

for a fixed γ, the characteristic length becomes

$$\tau = \gamma^{\frac{-1}{m}} \to 1 \ , m \to \infty \quad (19)$$

conversely, γcan be used as typical initial value for a specific length scale τ in an optimization problem and is given by

$$\gamma = \frac{1}{\tau^m} \qquad (20)$$

C. Distance:
The distance between any two fireflies i and j at x_i and x_j respectively the Cartesian distance is determined by equation

$$r_{i,j=} \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{i,k-} x_{j,k})^2} \qquad (21)$$

where $x_{i,k}$ is the k^{th} component of the spatial coordinate x_i of the i^{th} firefly and d is the number of dimensions.

D. Movement:
The movement of a firefly 'i'is attracted to another more attractive (brighter) firefly 'j' is determined by

$$x_i = x_i + \beta_0 e^{\gamma r_{i,j}^2} (x_j - x_i) + \alpha €_i (22)$$

where the second term is due to the attraction, while the third term is randomization with α being the randomization parameter and € being the vector of random numbers drawn from a Gaussian distribution. It is worth pointing out that a random walk partial towards the brighter fireflies and becomes a simple random walk if$\beta_0 = 0$.

E. Convergence:
For any large number of fireflies (n), if n>>m, where m is the number of local optima of an optimization problem, the convergence of the algorithm can be achieved. Here, the initial location of n fireflies isdistributed uniformly in the entire search space and as the iterations of the algorithm continue fireflies converge into all the local optimum. By comparing the best solutions among all these optima, the global optima is achieved. By adjusting parameters γ and α, the firefly algorithm can outperform than algorithm PSO. It can also find the global optima as well as the local optima simultaneously and effectively.

Brief procedure of FFA is as follows:

```
1. Objective function of f(x), where $x = (x_1, \dots\dots x_d)$
2. Generate initial population of fireflies;
3. Formulate light intensity I;
4. Define absorption coefficient $\gamma$;
5. While (t<Max Generation)
6. For i = 1 to n (all n fireflies);
7. For j=1 to n (all n fireflies)
8. If ($I_j > I_i$), move firefly i towards j;
9. End if
10. Evaluate new solutions and update light intensity;
11. End for j;
12. End for i;
13. Rank the fireflies and find the current best;
14. End while;
15. Post process results and visualization;
16. End procedure;
```

V. RESULTS

The FFA based method is tested on IEEE 30-bussystem. The FFA algorithm is applied to solve OPF problemwithout and with SSSC and case studies are taken as case 1 and case 2 respectively.Table I shows the FFA parameters.

TABLE I FFA Parameters

S.No.	Description	Values
1	Number of fireflies	25
2	Light absorption coefficient(γ)	1
3	Attractiveness coefficient(β_0)	1
4	Number of iterations	25

TABLE II Optimal settings of control variables for IEEE-30 bus test system

S.No.	Parameters	Case 1	Case 2
1	p_{g1}	168.845	161.380
2	p_{g2}	48.484	49.279
3	p_{g5}	20.591	21.260
4	p_{g8}	18.549	24.456
5	p_{g11}	19.475	16.455
6	p_{g13}	17.260	19.250
7	v_{g1}	1.017	1.042
8	v_{g2}	1.046	1.020
9	v_{g5}	0.990	0.990
10	v_{g8}	0.964	0.991
11	v_{g11}	1.037	1.040
12	v_{g13}	0.999	1.039
13	T_{6-9}	0.957	1.003
14	T_{6-10}	0.969	1.019
15	T_{4-12}	0.994	0.997
16	T_{28-27}	0.941	0.948
17	Q_{c10}	3.919	2.981
18	Q_{c12}	3.113	2.012
19	Q_{c15}	2.684	1.348
20	Q_{c17}	3.646	2.154
21	Q_{c20}	2.400	3.464
22	Q_{c21}	0.676	2.942
23	Q_{c23}	1.701	1.989
24	Q_{c24}	3.007	3.049
25	Q_{c29}	1.470	3.283
26	Total real power generation(MW)	293.207	292.162
27	Total Cost($/h)	807.972	806.329
28	Real power loss(MW)	9.807	8.762
29	Vse(p.u)	-	0.141
30	θse(deg)	-	87.443

By the observation of Table II andTable III,it clearly shows thattotal generation cost, real power losses are reducedand voltage profile is improved with SSSC compared to without SSSC using FFA algorithm.

Bus No.	Case 1		Case 2	
	Voltage magnitude (p.u)	Voltage angle (deg.)	Voltage magnitude (p.u)	Voltage angle (deg.)
1	1.017	0	1.039	0
2	0.999	-3.592	1.020	-3.246
3	0.988	-5.385	1.010	-4.952
4	0.981	-6.604	1.002	-6.066
5	0.989	-11.081	0.990	-10.048
6	0.972	-7.762	0.996	-7.155
7	0.971	-9.638	0.985	-8.889
8	0.964	-8.005	0.991	-7.309
9	1.012	-9.296	1.004	-8.819
10	0.999	-11.335	0.992	-10.741
11	1.037	-7.085	1.040	-6.941
12	1.013	-10.564	1.013	-9.884
13	1.046	-9.258	1.042	-8.423
14	0.999	-11.575	0.999	-10.906
15	0.996	-11.762	0.995	-11.088
16	1.000	-11.209	0.997	-10.536
17	0.996	-11.577	0.990	-10.948
18	0.986	-12.413	0.984	-11.791
19	0.983	-12.592	0.981	-12.001
20	0.988	-12.373	0.985	-11.797
21	0.987	-11.866	0.983	-11.301
22	0.988	-11.862	0.984	-11.290
23	0.987	-12.276	0.988	-11.656
24	0.980	-12.458	0.981	-11.887
25	0.987	-12.472	0.997	-11.934
26	0.969	-12.918	0.979	-12.371
27	1.000	-12.193	1.016	-11.669
28	0.965	-8.281	0.990	-7.655
29	0.984	-13.613	1.009	-13.167
30	0.970	-14.475	0.996	-13.890

TABLE III Bus voltages of IEEE -30 bus test system

The convergence characteristics are shown in Fig.2. and Fig.3.without and with SSSC using FFA algorithm respectively.The abscissa represents number of iterations and ordinate represents generation cost ($/h). From the characteristics it can be seen that the generation cost is reduced and convergence tendency is better with SSSC compared to without SSSC.

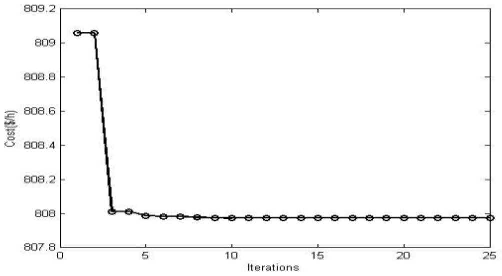

Fig.2 Convergence characteristics without SSSC

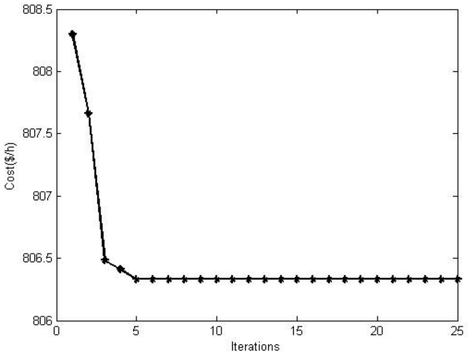

Fig. 3.Convergence characteristics with SSSC

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VI. CONCLUSION

This paper presents the meta heuristic method Firefly algorithm for solving OPF problem with SSSC. The approach is tested on IEEE- 30 bus system without and with SSSC. The total generation cost, losses, voltage profile and convergence tendency is better with SSSC compared to without SSSC. The case studies have shown that method is robust and can provide an optimal solution with fast computation time.

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