OPTIMAL POWER FLOW SOLUTIONS USING FIREFLY ALGORITHM

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Abstract
Optimal power flow (OPF) is operation and control problem in electrical power system. In electrical power system problems are classified into two major division namely planning problem and operation problem. This OPF is required for the proper operation in economic aspects and security aspects. All operation problems are complex, multivariable in nature and have multiple local minima in a constraint solution space. OPF has discrete, continuous and complex variables and needs better mathematical approach to solve it. Conventional mathematical methods are gradient based and may struck in local minima near to initial starting point. To overcome this, in recent days intelligent algorithms are used to solve the OPF problem. In this paper Firefly algorithm is used to solve the OPF problem. Firefly algorithm (FA) mimics the insect firefly's intelligent technique to find optimal solution for engineering problems. For optimization flashing light is formulated based on objective function. Brightest firefly is the most optimal solution for the problem under consideration.
Keywords: OPF; firefly; intelligent alogorithm; operation problem; global solution.

I. INTRODUCTION

Carpentier introduced optimal power flow concept in 1962, then in 1968 Dommel and Tinney tried to find minimum generating cost and losses in the power system, using Newton's power flow, Lagrangian multipliers, gradient method and penalty method for soft limited inequality constraints [1]. Billinton and Sachdeva (1972) used NLP technique based on Powell and Fletcher algorithm for hydro thermal power plants. They considered Saskatchewan Power Corporation System and optimized for a real power generation for a combined hydro thermal plants and reactive power optimization for individual hydro and thermal systems [2]. Alsac and Stott (1973) improved the Dommenl and Tinney work by incorporating new constraints for steady-state security. He considered IEEE 30 bus test system to demonstrate his work, this test case become standard system for many research work and even for this reported research work. They analysed OPF, with and without outage condition and considering security in both case is presented in a neat way to understand in detail [3]. Barcelo et al. (1977) used Hessian matrix approximation based NLP for real time OPF. They have used sparse matrix technique to reduce memory. This technique is applied to practical system and results are compared to Newtons power flow solutions [4]. Housos and Irisarri (1982) used reduced Hessian matrix based on sparse technique and it is based on Darion-Fletcher-Powell (DFF) and Broyden-Fletcher-Goldfarb-Shanno (BFGS) methods. This approach is good for a small size power system and has convergence difficulties in large size power systems [5].

Anastasios G. Bakirtzis et al. (2002) used Enhanced Genetic Algorithm (EGA) to solve OPF. Objective function of OPF is converted into fitness function with little modification, as GA is suitable for maximization whereas OPF is a minimization problem. In addition to basic three operator of GA five more operators are introduced to enhance GA [6]. Irfan Mulyawan Malik and Dipti Srinivasan (2010) used GA to solve OPF for which they considered elitism and non uniform mutation rate [7]. Hongwen Yan and Xinran Li (2010) used improved DE algorithm to solve OPF. They used Monte Carlo method to improve DE algorithm [8] and used to solve stochastic optimal power flow [11]. Wilensky and Reisman (2006) explain fireflies natural behaviour of flashing lights which synchronous with other fireflies and converge to same rhythm. This convergence property inspires the authors to develop such a behaviour coordination model for optimization problem [9]. The two main mechanisms they modeled are phase-delay synchronization and phase-advance synchronization. Rhythmic flashing light of fireflies induce to develop firefly algorithm by Xin-She Yang at Cambridge University in 2007. Thousands of fireflies lives together and communicate them with flashing light. They communication has two fundamental functions they are attract prey and attract mating partner [10]. Communication is established based on frequency and duration of light. Mating partners produce synchronized flash lights which brings together for mating. Physics inverse square law states that intensity of light decreases with distance from the light source. This makes the visual of firefly light is limited to some distance. For optimization flashing light is formulated based on objective function [12]. Firefly algorithm finds global minima among the local minimum optimal solutions in the constraint solution space.

In this paper the IEEE 30 bus system is considered for the OPF problem. Firefly algorithm is implemented using MATLAB program and used to find OPF solutions for the considered IEEE 30 test case. The paper is organized as chapter 2 explains firefly algorithm, chapter 3 explain problem formulation, chapter 4 explains firefly algorithm implementation for OPF solution, chapter 5 explains simulation results and chapter 6 concludes the OPF solutions using firefly algorithm.

II. BASIC DESCRIPTION OF FIREFLY ALGORITHM (FA)

Firefly algorithm (FA) mimics firefly's intelligent technique to find optimal solution for engineering problems. For optimization flashing light is formulated based on objective function. Brightest firefly is the most optimal solution for the problem under consideration. A firefly is set of control variables of the problem considered. Brightness of the firefly is calculated by evaluating the objective function to be optimized. This algorithm may used for maximization or minimization problem. FA has idealization as compared to natural firefly, they are

- Firefly is unisex and attracted by another firefly in spite of sex
- Firefly moves towards brightest if no brighter one then firefly moves randomly in solution space
- Brightness of firefly is affected by problem nature

General form FA optimization is a maximization of objective function subjected to constraints. FA moves fireflies towards global optimal solution spot through iteration by iteration. A firefly is a set of control variable and its light intensity is objective function or fitness value of the firefly. The process of FA are create or initialize fireflies, find brightness of firefly, move each firefly towards brightest one, find global brightest to give optimal solution. General form of FA optimization is maximize objective function, subjected to equality function and inequality function as given below,

$$\text{Minimize } C_t = \sum_{i=1}^{NG} f_i(P_G) \ \$/\text{hr} \tag{1}$$

$$\text{Subject to:} \quad g(|V|, \delta)=0 \tag{2}$$

$$X_{min} \le X \le X_{max} \tag{3}$$

Where,
Ct is total generating cost in \$/hr
g(|V|, δ) is power flow balance equation
X is a set of control variable
Xmin, Xmax are min. and maximum value of control variable

III. OPF PROBLEM FORMULATION

In this research work quadratic cost minimization problem is considered, this objective is a function of real power generation and the general form is

$$\text{Minimize } C_t = \sum_{i=1}^{NG} \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \ \$/\text{hr}$$

Where,
NG is number of generators
Ct is total generating cost in United States Dollar (USD)/hr.

Optimization problem has a solution space which is bounded between many constraints, some constraints are equality constraints and other constraints are inequality constraints. Optimization technique has to find optimal solution in the constraint bound solution space.

A. Equality Constraints

Power balance equation gives equality constraint for OPF problem. This power balance equation is derived from load flow analysis which states, generation of real and reactive power should balance real and reactive power demand and losses. Sum of total real power generation is equal to sum of total real power demand and total real power losses, given as

$$\sum_{i=1}^{NG} P_{Gi} = P_D + P_L \quad (5)$$

Sum of total reactive power generation is equal to sum of total reactive power demand and total reactive power losses, given as

$$\sum_{i=1}^{NG} Q_{Gi} = Q_D + Q_L \quad (6)$$

The power flow equation of the power system network

$g(|v|, \delta) = 0$ (7)

Where,

P_{Gi}, Q_{Gi} – i^{th} generator real and reactive power generation

P_D, Q_D – total real and reactive power demand

P_L, Q_L – total real and reactive power loss

$g(|v|, \delta) = P_i(|v|, \delta) - P_i^{net}$ and $Q_i(|v|, \delta) - Q_i^{net}$

P_i, Q_i – calculated real and reactive power of bus-i

P_i^{net}, Q_i^{net} – specified real and reactive power of bus-i

$|v|$, δ – voltage magnitude and phase angle

B. Inequality Constraints

Optimal power flow problems' control variables and dependent variables has lower and upper limits and limits on power flow in the transmission lines form inequality constraints. Control variables of the problem are, real power generations, generator bus voltages and transformer tap positions, dependent variables of the problem are reactive power generation, load bus voltages and MVA flow in the transmission lines are stated as,

Generators has maximum and minimum limits for its real and reactive power generation form inequality constraint for ith generator is given as,

Pgimin ≤ Pgi ≤ Pgimax for i=1to NG (8)

Qgimin ≤ Qgi ≤ Qgimax for i=1to NG (9)

All bus voltages should be maintained within its minimum and maximum limits are stated as,

Vimin ≤ Vi ≤ Vimax for i=1to NB (10)

Transformer tap positions has minimum and maximum limits for its operation and stated as,

Timin ≤ Ti ≤ Timax for i=1to NT (11)

MVA flow in the transmission line should be less than its maximum limits and stated as,

MVAi ≤ MVAimax for i=1to Nbr (12)

Where,

Vi – ith bus voltage magnitude

Ti – ith transformer tap position

MVAi – ith transmission line MVA flow

NG – number of generators

NB – number of bus

NT – number of transformer

Nbr – number of branch / transmission line

IV. FIREFLY ALGORITHM IMPLEMENTATION FOR OPF

To optimize OPF problem the control variables, real power generation, generator bus voltages and transformer tap position are considered. The limits on these control variables form prime constraints in addition to power balance condition. Actual values of these control variables are used to form a firefly. These fireflies form population and initialized randomly from the solution space and then evolution is carried out using its brightness and distance from brightest firefly.

A. Encoding

Encoding is the process of converting set of control variables in OPF into firefly for optimization. Ability of FA is to operate on floating point and mixed integer makes ease of encoding. Final iteration of FA gives global bright firefly which is the optimal solution of OPF. For the evolution and better convergence fitness function is most important as follows.

B. Fitness Function

An appropriate fitness function (brightness) is vital for evolution and convergence of FA. It is an OPF objective functions and penalty functions if any. FA evaluates brightness for each firefly in the population. Objective function value for a firefly is called brightness of the firefly. FA makes a firefly to move towards brighter firefly in the population. Distance moved and brightness of each firefly is calculated and best firefly (global best) is calculated in the iteration. Improvement in solution is achieved iteration by iteration and final iteration provides global best optimal solution to OPF.

C. Attractiveness

Firefly moves towards more attractiveness. This attractiveness of considered firefly with others is calculated using the function. This attractiveness is decreases with increase in distance between fireflies. Main reasons for reduction in attractiveness are absorption factors in nature are implemented by using absorption coefficient. This function is monotonically decreasing function given below the equation (13).

$\beta = \beta 0 \exp(-\gamma\ r2)$ (13)

where,

β is attractiveness of a firefly

$\beta 0$ is initial attractiveness

γ is absorption coefficient

r is distance between fireflies

D. Distance

Distance between fireflies i and j is calculated using Cartesian distance as given below the equation (14)

$$r_{ij} = \| x_i - x_j \| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (14)$$

In 2-dimensional solution space the distance between i and j fireflies may calculated as follows the equation (15)

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (15)$$

E. Movement

Movement of ith firefly towards jth brighter firefly is based attractiveness and distance between them as given below

$$x_i^{k+1} = x_i^k + \beta_0 * \exp(-\gamma\ r^2) * (x_j^k - x_i^k) + \alpha * \varepsilon_i^k \quad (16)$$

Where the left side first term is initial position of ith firefly, second term gives attractiveness towards jth firefly and third term introduce random movement in ith firefly. Initial attractiveness $\beta 0$ is taken as 1.0; absorption coefficient γ is taken as 0.9. Randomizing coefficient α rang in between 0 and 1, in this work it is taken as 0.2; εi is randomization vector ranges from 0 to 0.5.

F. Stopping Criteria

Fireflies moves randomly and try to attract towards brighter firefly. FA improves problems' solution iteration by iteration and the iteration has to be stopped either the problem is converged or iteration reached its maximum value. Stopping of iteration is important to provide solution for time complexity. In this research work maximum number of 200 iterations is considered as stopping criteria.

G. ALGORITHM

Steps

FA algorithm for solving OPF is given below

Step 1: Firefly is a set of control variables in OPF

Step 2: Initialize fireflies in the population in solution space

Step 3: OPF objective function is used to find brightness of firefly

Step 4: Attractiveness of firefly with other fireflies is calculated

Step 5: Distance between fireflies is calculated

Step 6: firefly i is moved towards firefly j using equation (16)

Step 7: Rank the fireflies and find the current global best

Step 8: Repeat step 4 to step 7 till stopping criterion is satisfied

Step 9: Print the optimal result after stopping criterion is satisfied

V. SIMULATION RESULTS

To evaluate performance of developed algorithm in MATLAB software, bench mark test case IEEE 30 bus system is considered. Numerical result for IEEE 30 bus is presented and discussed in this chapter. The system has 6 generators include slack bus, hence 5-real power generation, 6 generator bus voltage magnitude and 4 transformer tap position are considered as control variables. Base MVA of the system is 100MVA.

The cost co-efficient used for the simulation is given in the table 1.

TABLE I. GENERATOR COST COEFFICIENTS FOR OPF

S. No	Bus No	Pmin (MW)	Pmax (MW)	α ($/hr)	β ($/ Mwhr)	γ ($/ Mw^2hr)
1	1	50	200	0	2	0.0038
2	2	20	80	0	1.75	0.0175
3	5	15	50	0	1	0.0625
4	8	10	35	0	3.25	0.0083
5	11	10	30	0	3	0.025
6	13	12	40	0	3	0.025

The limits on the control and dependent variables are given in the table 2. The limits are in per unit values of the respective variables.

TABLE II. LIMITS ON OTHER CONTROL AND DEPENDENT VARIABLES

Types of Variable	**Description**	**Lower Limit** (PU)	**Upper Limit** (PU)
Control	Transformer Tap Position	0.90	1.10
Control	PV bus voltage	0.95	1.05
Dependent	PQ bus voltage	0.95	1.05

Firefly Algorithm (FA) considers, 5 real power (PG), 6 generator bus voltages (VG), and 4 transformer tap position (T) are taken as a firefly. 80 fireflies are considered for the population, this population is initialized within the solution space. This population is evolving iteration by iteration to find global optimal solution. The maximum number of iteration it may evolve is taken as 200 iterations. The operators used in this algorithm are attractiveness, distance and movement towards brighter firefly. Quadratic cost function of OPF is used to calculate brightness of each firefly, attractiveness, distance and movement of considered firefly is calculated and updated for next generation. Initial attractiveness $\beta 0$ is taken as 1.0; absorption coefficient γ is taken as 0.9. Randomizing coefficient α rang in between 0 and 1, in this work it is taken as 0.2; εi is randomization vector ranges from 0 to 0.5.

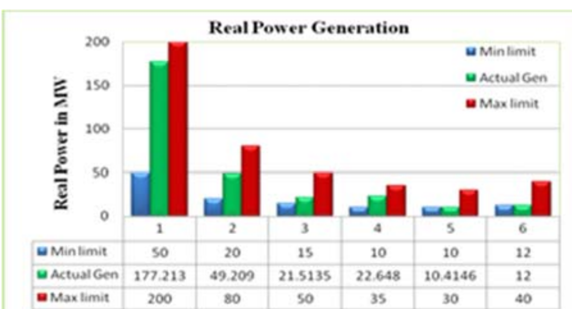

Fig. 1. Real Power Generation of all Generators

From the Figure 1 it is clear that the generation is within the boundary conditions. Slack generator contributes more for real power generation and 5th generator contribution is less as compared to others. Generators five and six are close to their minimum limit. Total real power generation is 292.9981 MW.

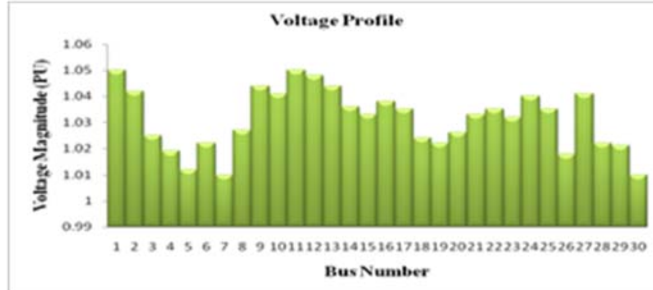

Fig. 2. Voltage Profile of 30 buses

Voltage control variables of generator bus voltages and dependent variables of load bus voltages are shown in Figure 2 all voltages are within limits. Increase in generator bus voltage will improve the overall voltage profile and less loss in the system but it is restricted to maximum limit of 1.05 PU.

Fig. 3. Transformer tap positions

The considered power system has four transformers and minimum limit of tap position is 0.90PU and maximum limit is 1.10 PU. The Figure 3 shows that all transformers tap position are within the limits.

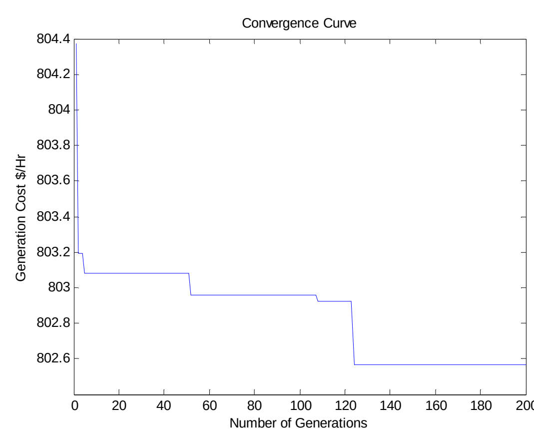

Fig. 4. Convergence Curve

FA iterated for 200 iterations as shown in Figure 4 and converged around 124th iteration. Generating cost for this generating pattern is 802.566 $/hr and real power loss is 9.5981 MW as given in Table 3

TABLE III. OPF RESULT OF FIREFLY ALGORITHM

Control Variables	Values
P_{g1} (MW)	177.213
P_{g2} (MW)	49.209
P_{g3} (MW)	21.5135
P_{g4} (MW)	22.648
P_{g5} (MW)	10.4146
P_{g6} (MW)	12
V_{g1} (pu)	1.05
V_{g2} (pu)	1.042
V_{g3} (pu)	1.012
V_{g4} (pu)	1.027
V_{g5} (pu)	1.05
V_{g6} (pu)	1.044
T_1 (pu)	0.932
T_2 (pu)	0.978
T_3 (pu)	0.969
T_4 (pu)	0.968
Tot. Gen. (MW)	292.9981
Loss (MW)	9.5981
Time (s)	517.1086
Cost ($/hr)	**802.566**

VI. CONCLUSION

Firefly algorithm is developed in MATLAB to solve optimal power flow problem in the electrical power system. Standard test case IEEE 30 bus system is considered to demonstrate the capability of the developed algorithm. For the objective of cost minimization quadratic cost function is considered. The results of the simulation are presented and prove the developed algorithm gives minimum generating cost. The algorithm makes continuous tuning of the optimal result and the iteration versus objective function is also presented in the paper. In the future extension work, the developed algorithm may used to solve large power system and real time Indian power system. The algorithm results may compare to other latest algorithms to prove its capability.

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