Optimal Power Flow with DC Link Placement Problem by using Self Adaptive Firefly Algorithm

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Abstract – This paper presents a Self Adaptive Firefly Algorithm (SFO) for the solution of the Optimal Power Flow (OPF) with DC Link Placement Problem. OPF problem is formulated as a nonlinear constrained multiobjective optimization problem where different objectives and different constraints have been considered. Optimal Power Flow is an important operational and planning problem in minimizing the chosen objective functions of the power systems. The recent developments in power electronics have enabled introduction of dc links in the AC power systems with a view of making the operation more flexible, secure and economical. This paper formulates a new OPF to embrace dc link equations and presents a heuristic optimization technique, inspired by the behavior of fireflies, for solving the problem. The solution process involves AC/DC power flow and uses a self adaptive technique so as to avoid landing at the suboptimal solutions. It presents simulation results of IEEE test systems with a view of demonstrating its effectiveness.

Keywords: optimal power flow, AC/DC power flow, firefly optimization, valve point effect

Nomenclature

a_j b_j c_j	fuel cost coefficients of the j-th generator
d_j e_j	coefficients of valve point effects of the j-th generator
FO	firefly optimization
f_i	i-th firefly
$G_{mn} + jB_{mn}$	real and imaginary terms of bus admittance matrix corresponding to m-th row and n -th column
g_{mn}	conductance of the transmission line connected between buses m and n
h_m	converter transformer tap at bus-m
I_p^{dc}	dc current at p-th dc link
L_i	VSI at load bus-i
LI_i	light intensity of the i-th firefly
nd	number of decision variables
nf	number of fireflies in the population
nl	number of lines
$nobj$	number of objectives
P_s^G	real power generation at slack bus
P_w^{ac}	active power transmitted from the ac system into the dc system at bus-w
P_m^G and Q_m^G	real and reactive power generation at m-th bus respectively
P_m^D and Q_m^D	real and reactive power demand at m-th bus respectively
P_m^{dc}	dc link power at bus-m
Q_q^C	reactive power injection by q-th shunt compensator
Q_w^{ac}	reactive power consumed by the dc link transformer and converter at bus-w
r_{ij}	Cartesian distance between the i-th and j-th firefly
R_{mn}^{dc}	dc resistance of the link between buses m and n
S_{Li}	loading of i-th transmission line
t	iteration counter
T_v	tap setting of v-th transformer
V_i	voltage at i-th bus
V_j^G	voltage magnitude at j-th generator bus

V_i^L	voltage magnitude at i-th load bus
V_m^{dc}	dc link voltage at bus-m
V_w^{ac}	ac voltage at bus-w
X_m^c	commutating reactance of converter and/or leakage reactance of transformer at bus-m
$\Phi(x,u)$	objective function to be minimized
Φ^A	augmented objective function
δ_{mn}	voltage angle difference between buses m and n
φ_m	voltage angle at bus-m taking transformer secondary current as the reference
θ_m	converter angle of converter at bus-m
λ	penalty factors
α	Random movement factor
$\beta_{i,j}$	attractiveness between the i-th and j-th firefly
β_o and γ	maximum attractiveness and light intensity absorption coefficient respectively
Ω	a set of load buses
Π	a set of generator buses
Ψ	a set of PV buses
$\Im$	a set of DC links
$\Re$	a set of tap changing transformers
$\aleph$	a set of shunt compensators
M	a set of lines, whose S_{Li} violates the respective limit
superscript 'min' & 'max'	lower and upper limits respectively
superscript "limit"	lower/upper limit of the respective variable

1. Introduction

The optimal power flow (OPF) has been widely used in power system operation and planning since its introduction by Carpenter in 1962 [1]. The OPF determines optimal settings for certain power system control variables by optimizing a few selected objective functions while satisfying a set of equality and inequality constraints for given settings of loads and system parameters. The control variables include generator active powers, generator bus voltages, transformer tap ratios and the reactive power generation of shunt compensators. In general, the total fuel cost (FC) is commonly used as the main objective for OPF problems. However, the other objectives, such as reduction of real power loss (RPL), improvement of the voltage profile (VP) and enhancement of the voltage stability (VS) can also be included, as it has progressively become easy to formulate and solve large-scaled complex problems with the advancement in computing technologies. The equality constraints are the power flow balance equations, while the inequality constraints are the limits on the control variables and the operating limits of the power system dependent variables.

The recent developments in power electronics have introduced DC transmission links in the existing AC transmission systems with a view of achieving the benefits of reduced network loss, lower number of power conductors, increased stability, enhanced security, etc. They are often considered for transmission of bulk power via long distances. The attributes of DC transmission links include low capacitance, low average transmission cost in long distances, ability to prevent cascaded outages in AC systems, rapid adjustments for direct power flow controls, ability to improve the stability of AC systems, mitigation of transmission congestion, enhancement of transmission capacity, rapid frequency control following a loss of generation, ability to damp out regional power oscillations following major contingencies and offering major economic incentives for supplying loads. Flexible and fast DC controls provide efficient and desirable performance for a wide range of AC systems. The existing OPF problem can be modified to handle AC/DC systems [2-3]. The resulting optimization problem, designated as OPF with DC links (OPFDC), is a large scale, non-linear non-convex and multimodal optimization problem with continuous and discrete control variables. The existence of nonlinear power flow constraints and the DC link equations make the problem non-convex even in the absence of discrete control variables [4].

In the recent decades, numerous mathematical programming techniques such as gradient method [1], linear programming [5], nonlinear programming [6], interior point method [7] and quadratic programming [8] with various degrees of near-optimality, efficiency, ability to handle difficult constraints and heuristics, have been widely applied in solving the OPF problems. Although many of these techniques have excellent convergence characteristics, they have severe limitations in handling non-linear and discontinuous objectives and constraints. The gradient method suffer from the difficulty in handling inequality constraints; and the linear programming requires the objective and constraint functions to be linearized during optimization, which may lead to the loss of accuracy. Besides they may converge to local solution instead of global ones, when the initial guess is in the neighborhood of a local solution. Thus there is always a need for simple and efficient solution methods for obtaining global optimal solution for the OPF problems.

Apart from the above methods, another class of numerical techniques called evolutionary search algorithms such as genetic algorithm (GA) [9], evolutionary programming [10], particle swarm optimization (PSO) [11], differential evolution [12], frog leaping [13], harmony search optimization (HSO) [14], gravitational search [15], clonal search [16], artificial bee colony [17] and teaching-learning [18] have been widely applied in solving the OPF problems. Having in common processes of natural evolution, these algorithms share many similarities; each maintains a population of solutions that are evolved through random alterations and selection. The differences between these procedures lie in the techniques they utilize to encode candidates, the type of alterations they use to create new solutions, and the mechanism they employ for selecting the new parents. These algorithms have yielded satisfactory results across a great variety of power system problems. The main difficulty is their sensitivity to the choice of the parameters, such as the crossover and mutation probabilities in GA and the inertia weight, acceleration coefficients and velocity limits in PSO.

Recently, firefly optimization (FO) has been suggested by Dr. Xin-She Yang for solving optimization problems [19]. It is inspired by the light attenuation over the distance and fireflies' mutual attraction rather than the phenomenon of the fireflies' light flashing. In this approach, each problem solution is represented by a firefly, which tries to move to a greater light source, than its own. It has been applied to a variety of engineering optimization problems and found to yield satisfactory results. However, the choice of FO parameters is important in obtaining good convergence and global optimal solution.

This paper formulates the problem of OPFDC, suggests a solution methodology involving a self adaptive FO (SFO) with a view of obtaining the global best solution and demonstrates its performance through simulation results on the modified IEEE 14, 30 and 57 bus systems.

2. Problem Formulation

The exercise is to identify the optimal control parameters such as generator active powers, generator bus voltages, transformer tap ratios and the reactive power generation of shunt compensators, besides determining the DC control parameters. The formation of the problem involves both the AC and DC sets of equations. The AC set of equations are the standard AC power balance equations whereas the DC set equations represent power, current and voltage balance equations at both DC and AC terminal buses of DC links. Moreover the DC link can be operated in different modes such as constant current, constant power, etc [8]. In this formulation, DC links with constant current control are considered. The OPFDC problem is formulated as a constrained nonlinear optimization problem through combining the standard OPF problem and the DC link equations as

$$\text{Minimize} \quad \Phi(x,u) \tag{1}$$

Subject to

$$b(x,u) = 0 \tag{2}$$

$$g(x,u) \le 0 \tag{3}$$

Where

$$x = [V_i^L, Q_j^G, P_s^G] \tag{4}$$

$$u = [P_k^G, V_j^G, T_v, Q_q^C, I_p^{dc}] \tag{5}$$

$$b(x,u) = \begin{Bmatrix} P_m^G - P_m^D - V_m \sum_{n\in\{\Omega,\Pi\}} V_n (G_{mn}\cos\delta_{mn} + B_{mn}\sin\delta_{mn}) = 0 \\ Q_m^G - Q_m^D - V_m \sum_{n\in\{\Omega,\Pi\}} V_n (G_{mn}\sin\delta_{mn} - B_{mn}\cos\delta_{mn}) = 0 \\ h(x,u) = 0 \end{Bmatrix} \tag{6}$$

$$g(x,u) = \begin{Bmatrix} P_k^{G(\min)} \le P_k^G \le P_k^{G(\max)} \\ Q_j^{G(\min)} \le Q_j^G \le Q_j^{G(\max)} \\ Q_q^{C(\min)} \le Q_q^C \le Q_q^{C(\max)} \\ T_v^{\min} \le T_v \le T_v^{\max} \\ V_j^{G(\min)} \le V_j^G \le V_j^{G(\max)} \\ V_i^{L(\min)} \le V_i^L \le V_i^{L(\max)} \\ I_p^{dc(\min)} \le I_p^{dc} \le I_p^{dc(\max)} \\ |S_{Li}| \le S_{Li}^{\max} \end{Bmatrix} \tag{7}$$

$$h(x,u) = \begin{Bmatrix} V_m^{dc} - s_m c_2 h_m V_w^{ac} \cos\theta_m + s_m c_3 X_m^c I_m^{dc} = 0 \\ V_m^{dc} - 0.995 s_m c_2 h_m V_w^{ac} \cos\varphi_m = 0 \\ Q_w^{ac} - V_w^{ac} c_2 h_m I_m^{dc} \sin\varphi_m = 0 \\ P_w^{ac} - V_w^{ac} c_2 h_m I_m^{dc} \cos\varphi_m = 0 \\ P_m^{dc} - V_m^{dc} I_m^{dc} = 0 \\ I_m^{dc} - \left(V_m^{dc} - V_n^{dc}\right)/R_{mn}^{dc} = 0 \\ V_m^{dc} - V_n^{dc} - I_m^{dc} R_{mn}^{dc} = 0 \end{Bmatrix} \tag{8}$$

s_m = 1 for rectifier and -1 for inverter

$c_2 = 3\sqrt{2}/\pi$ $\qquad$ $c_3 = 3/\pi$

$i \in \Omega$ $j \in \Pi$

$k \in \Psi$ $v \in \Re$

$p \in \Im$ $q \in \aleph$

The objective function $\Phi(x,u)$ can take different forms. Seven different cases involving FC, RPL, VP and VS, which are calculated from the power flow solution, are considered in tailoring the objectives in this paper.

Case-1: Minimization of Fuel Cost

$$\text{Minimize} \quad \Phi_1(x,u) = \sum_{j \in \Pi} a_j \, P_j^{G^2} + b_j \, P_j^G + c_j + \left| d_j \sin(e_j (P_j^G(\min) - P_j^G)) \right| \tag{9}$$

Case-2: Minimization of Real Power Loss

$$\text{Minimize} \quad \Phi_2(x,u) = \sum_{w=1}^{nl} g_{mn} \left(|V_m|^2 + |V_n|^2 - 2\,|V_m|\,|V_n| \cos\delta_{mn} \right) \tag{10}$$

Case-3: Enhancement of Voltage Stability

The VS can be enhanced by minimizing the Largest value of VS index (LVSI) of load buses [20] as

$$\text{Minimize} \quad \Phi_3(x,u) = \max\{L_i; i \in \Omega\} \tag{11}$$

$$\text{Where} \quad L_i = \left| 1 - \sum_{j=\Pi} F_{ji} \frac{V_j}{V_i} \right| \tag{12}$$

The multi-objective OPFDC problem is tailored by combining several objectives through weight factors so as to optimize all the objectives simultaneously.

$$\text{Minimize} \quad \Phi(x,u) = \sum_{i=1}^{nobj} w_i \, \Phi_i \tag{13}$$

The different cases comprising several objectives considered in this paper are:

Case-4 : FC and RPL
Case-5 : FC and VS
Case-6 : RPL and VS
Case-7 : FC, RPL and VS

3. Equations and Units

The FO is a metaheuristic, nature-inspired, optimization algorithm which is based on the social flashing behavior of fireflies. FO initially produces a swarm of fireflies located randomly in the search space. In each iterative step, the positions of the fireflies are updated based on the brightness and the relative attractiveness of each firefly. After a sufficient amount of iterations, all fireflies converge to the best possible position on the search space [19]. The self-adaptive control of the parameters α_i, β_o and γ during the search process effectively leads the algorithm to land at the global best solution with minimum computational effort. The proposed method (PM) involves representation of problem variables that include the control variables and self-adaptive parameters, α_i, β_{oi} and γ_i; and the formation of a light intensity function, LI.

3.1 Representation of decision variables

The converters at both ends of the DC links draw lagging reactive power and pose a burden to the existing power system. If Q_q^C of shunt compensators are taken as decision variables, the optimization algorithm will adjust them to settle at their respective maximum limit in order to supply the reactive power requirements of the DC link converters. So Q_q^C of shunt compensators are not treated as variables in the PM and set to supply reactive power at their respective capacities. The decision variables in the PM thus comprises real power generation at PV buses, voltage magnitudes at generator buses, transformer tap settings, DC link currents, α, β_o and γ. Each firefly in the PM is defined to denote these decision variables in vector form as

$$f = [P_k^G, V_j^G, T_v, I_p^{dc}, L_{p,} \alpha, \beta_o, \gamma]; \quad j \in \Pi \quad k \in \Psi \quad v \in \Re \quad p \in \Im \tag{14}$$

3.2 Intensity Function

The SFO searches for optimal solution by maximizing a light intensity function, denoted by LI, which is formulated from the objective function of Eq. (1) and the penalty terms representing the limit violation of the dependant variables such as reactive power generation at generator buses, voltage magnitude at load buses and real power generation at slack bus. The LI can be built as

$$\text{Maximize} \quad LI = \frac{1}{1+\Phi^A} \tag{15}$$

Where

$$\Phi^A = \Phi(x,u) + \lambda_V \sum_{i \in \Omega} \left(V_i^L - V_i^{\text{limit}}\right)^2 + \lambda_Q \sum_{i \in \Pi} \left(Q_i^G - Q_i^{\text{limit}}\right)^2 + \lambda_P \left(P_s^G - P_s^{\text{limit}}\right)^2 + \lambda_S \sum_{i \in \mathrm{M}} \left(S_{Li} - S_{Li}^{max}\right)^2 \tag{16}$$

The power system is altered through setting the control parameters of $\{P_k^G, V_j^G, T \text{ and } I_p^{dc}\}$ for each firefly. The AC/DC power flow is then run with a view of computing the objective function $\Phi(x,u)$ and the light intensity function LI.

3.3 Solution Process

An initial swarm of fireflies is obtained by generating random values within their respective limits to every individual in the swarm. The LI is calculated by considering the values of each firefly and the movements of all fireflies are performed with a view of maximizing the LI till the number of iterations reaches a maximum specified number of iterations $Iter^{\max}$. The pseudo code of the PM is as follows.

Read *the Power System Data*
Choose *the parameters,* nf *and* $Iter^{\max}$.
Generate *the initial population of fireflies*
Set *the iteration counter* $t = 0$
while *(termination requirements are not met) do*
for $i = 1 : nf$

- *Set the control parameters according to* i*-th firefly values*
- *Obtain the values for* α_i, β_o and γ *from the firefly*
- *Run AC/DC power flow*
- *Evaluate the augmented objective function* Φ^A *and light intensity function* LI_i *using Eqs. 16 and 15 respectively*

for $j = 1 : nf$

- *Set the control parameters according to* j*-th firefly values*
- *Obtain the values for* α_i, β_o and γ *from the firefly*
- *Run AC/DC power flow*
- *Evaluate the augmented objective function* Φ^A *and light intensity function* LI_j *using Eqs. 16 and 15 respectively*

if $LI_i < LI_j$

Compute $r_{i,j} = \left\| f_i - f_j \right\| = \sqrt{\sum_{k=1}^{nd} \left(f_i^k - f_j^k \right)^2}$

Evaluate $\beta_{i,j} = \beta_{o,i} \exp\left(-\gamma_i \, r_{i,j}^2 \right)$

Move i*-th firefly towards* j*-th firefly through*

$$f_i(t) = f_i(t-1) + \beta_{i,j}\left(f_j(t-1) - f_i(t-1) \right) + \alpha\left(rand - 0.5 \right)$$

end*-(if)*
end*-(*j*)*
end*-(*i*)*
Rank the fireflies and find the current best.
end*-(while)*
Choose *the best firefly possessing the largest* LI_i *in the population as the optimal solution*

4. Simulations

The PM is tested on IEEE 14, 30 and 57 bus test systems. The fuel cost coefficients, lower and upper generation limits for these two test systems are taken from Ref. [21-23]. The DC link data are given in Table A.1 of the Appendix-A. The lower and upper voltage limits for both load and generator buses are taken as 0.95 and 1.1 per units for 14 and 30 bus system, while for 57 bus systems they are taken as 0.94 and 1.1 per units. In the analysis, one ,two and three transmission lines are replaced by dc links for IEEE 14, 30 and 57 bus systems respectively. In addition, the initial generations at PV buses are modified with a view making all the generations to share the load demand besides setting them within their respective limits and given along with results. The sequential AC/DC power flow involving NR technique is used during the optimization process [4]. Programs are developed in Matlab 7.5 and executed on a 2.67 GHz Intel core-i5 personal computer. The OPFDC problem is also solved using the PSO and HSO with a view of demonstrating the efficacy of the PM.

The optimal solution obtained by the PM, PSO and HSO for all the test cases for IEEE14,30 and 57 bus systems are given through Tables B.1,B.2 and B.3 respectively in Appendix-B. The performances in terms of FC, RPL, LVSI and lower and upper VM at load buses of PM and are compared with those of the PSO and HSO based algorithms for test cases 1-7 in Tables 2, 3, 4,5,6,7 and 8 for IEEE 14, 30 and 57 bus system respectively. The tables 2, 3 and 4 also contain the base-case results, representing the performances before optimization. The parameters chosen for the PA are given in Table 1.

Table 1 FA Parameter

Parameter	Value
nf	30
$Iter^{\max}$	300

Table 2 Comparison of Performances for case 1

		Before Placement	Case-1		
			PM	**PSO**	**HSO**
14	FC	834.6716	816.8550	819.1639	818.0184
	RPL	8.9737	6.8716	7.3627	7.1733
	NVSI	0.3724	0.3730	0.3906	0.3732
	LVSI	0.0750	0.0763	0.0797	0.0772
30	FC	813.6941	793.0635	795.0379	794.7864
	RPL	7.0990	6.7575	7.3043	6.9238
	NVSI	1.6705	1.7003	1.6962	1.7332
	LVSI	0.1336	0.1368	0.1231	0.1422
57	FC	4556.5930	3804.9280	3806.4773	3806.2054
	RPL	28.8037	29.2642	29.3098	29.3097
	NVSI	5.7914	5.4953	5.6427	5.6452
	LVSI	0.2887	0.2468	0.2418	0.2421

Table 3 Comparison of Performances for case 2

		Before Placement	Case-2		
			PM	**PSO**	**HSO**
14	FC	834.6716	1021.1331	1009.2404	1017.5986
	RPL	8.9737	2.1736	2.3655	2.2420
	NVSI	0.3724	0.3656	0.3352	0.3717
	LVSI	0.0750	0.0802	0.0731	0.0813
30	FC	813.6941	959.1382	965.2581	950.0422
	RPL	7.0990	1.9884	2.0908	2.0763
	NVSI	1.6705	1.5395	1.6844	1.5518
	LVSI	0.1336	0.1237	0.1353	0.1236
57	FC	4556.5930	5624.3810	5604.0332	5608.8455
	RPL	28.8037	12.2914	12.5085	12.4250
	NVSI	5.7914	5.9910	5.9952	5.9869
	LVSI	0.2887	0.2949	0.2950	0.2945

Table 4 Comparison of Performances for case 3

		Before Placement	Case-3		
			PM	**PSO**	**HSO**
14	FC	834.6716	870.1265	885.1147	881.7622
	RPL	8.9737	7.5491	6.0318	7.2336
	NVSI	0.3724	0.2716	0.2821	0.2778
	LVSI	0.0750	0.0556	0.0588	0.0563
30	FC	813.6941	889.1098	892.1391	894.0747
	RPL	7.0990	12.3872	13.5682	13.3393
	NVSI	1.6705	1.1149	1.1100	1.1135
	LVSI	0.1336	0.1056	0.1126	0.1111
57	FC	4556.5930	3978.3335	5623.5418	3983.9945
	RPL	28.8037	32.6007	35.5571	34.2063
	NVSI	5.7914	4.7538	4.7361	4.6879
	LVSI	0.2887	0.1975	0.2355	0.2015

Table 5 Comparison of Performances for case 4

		Case-4		
		PM	**PSO**	**HSO**
14	FC	947.7844	915.3126	954.3711
	RPL	2.7438	2.9657	2.7984
	NVSI	0.3736	0.3530	0.3776
	LVSI	0.0791	0.0739	0.0809
30	FC	902.1639	893.1067	937.6718
	RPL	2.2671	2.3259	2.1054
	NVSI	1.5068	1.5096	1.5206
	LVSI	0.1209	0.1210	0.1220
57	FC	5602.9113	5603.4333	5623.0357
	RPL	12.4601	12.5156	12.3009
	NVSI	5.9870	5.9952	5.9917
	LVSI	0.2945	0.2950	0.2949

Table 6 Comparison of Performances for case 5

		Case-5		
		PM	**PSO**	**HSO**
14	FC	868.7187	845.1958	867.0520
	RPL	6.0611	8.7675	7.4832
	NVSI	0.3057	0.2912	0.2724
	LVSI	0.0659	0.0599	0.0557
30	FC	806.3870	835.6746	892.8385
	RPL	8.5556	12.7478	13.6669
	NVSI	1.2777	1.1341	1.1245
	LVSI	0.0902	0.0979	0.1126
57	FC	3974.9678	3964.7235	3959.4764
	RPL	32.2904	32.4012	35.0916
	NVSI	4.7604	4.7606	4.7134
	LVSI	0.1980	0.1975	0.2085

Table 7 Comparison of Performances for case 6

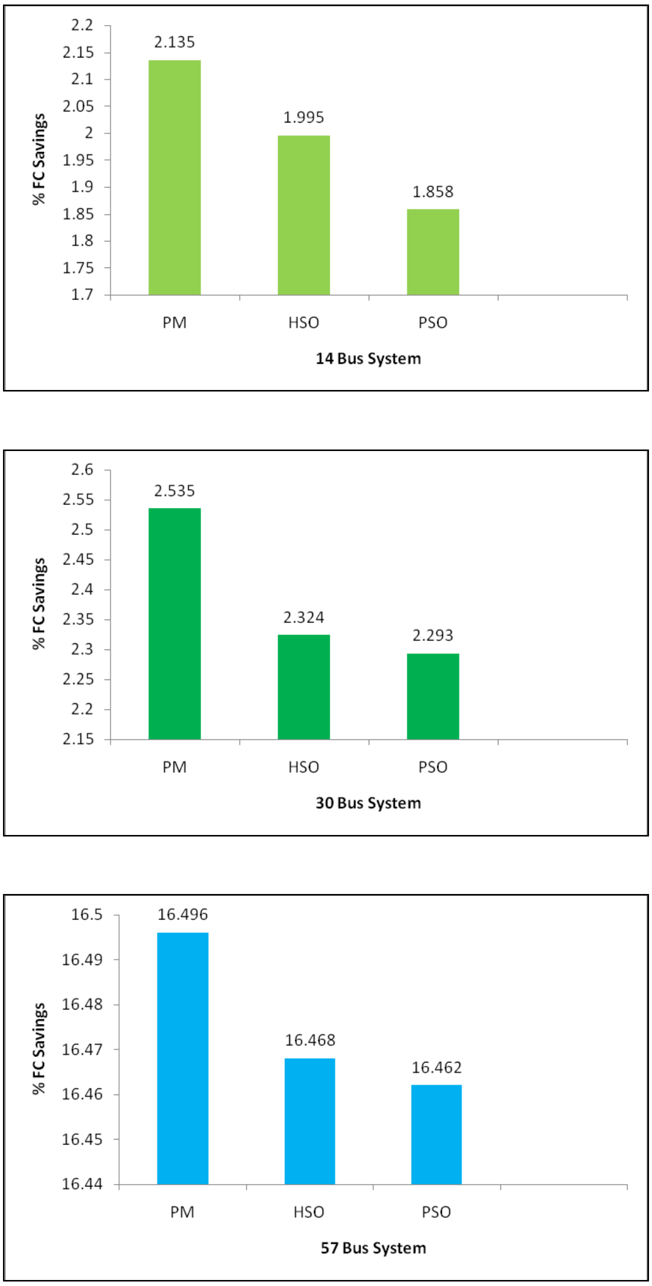
		Case-6		
		PM	**PSO**	**HSO**
14	FC	1009.3476	977.3259	1019.2049
	RPL	2.4128	2.6365	2.2531
	NVSI	0.3085	0.2998	0.3584
	LVSI	0.0674	0.0652	0.0790
30	FC	953.5531	956.9661	957.6956
	RPL	2.0911	2.1042	1.9936
	NVSI	1.4446	1.4648	1.5271
	LVSI	0.1144	0.1154	0.1225
57	FC	5608.4559	5603.5714	5624.6388
	RPL	12.4252	12.5151	12.2938
	NVSI	5.9867	5.9950	5.9908
	LVSI	0.2945	0.2950	0.2949

Table 8 Comparison of Performances for case 7

		Case-7		
		PM	**PSO**	**HSO**
14	FC	911.6855	905.6309	986.2700
	RPL	3.0644	4.7199	2.5900
	NVSI	0.3188	0.2913	0.3465
	LVSI	0.0665	0.0627	0.0761
30	FC	919.0106	888.4618	928.8309
	RPL	2.1731	2.4057	2.1852
	NVSI	1.4758	1.4520	1.5107
	LVSI	0.1175	0.1150	0.1211
57	FC	5602.6780	5571.4384	5617.0429
	RPL	12.4318	12.6676	12.3197
	NVSI	5.9834	5.9929	5.9884
	LVSI	0.2943	0.2950	0.2947

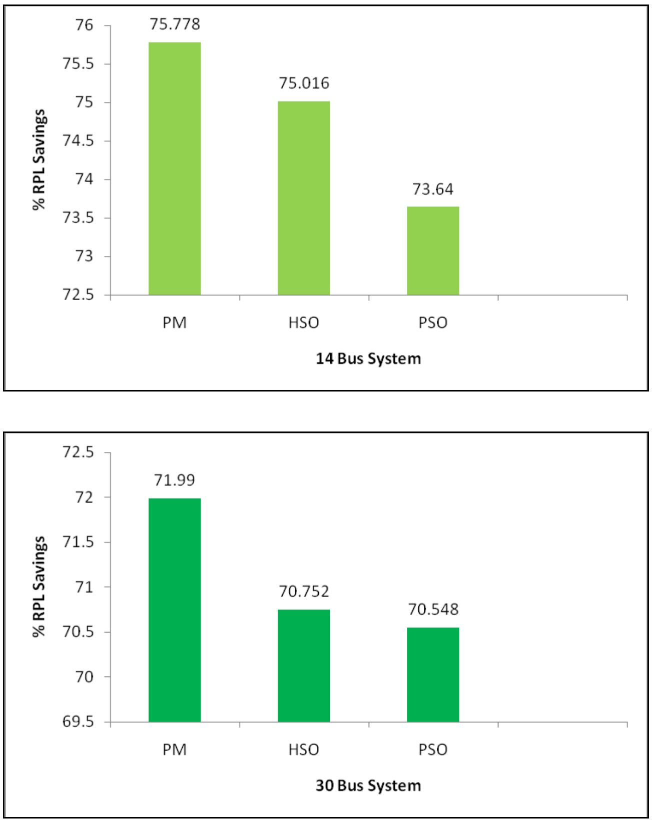
Case-1: The objective in this case is the minimization of the FC. It is observed from Table 2 In case of 14 bus system the initial FC of 834.6716 $/h is reduced to 816.8550, 819.1639 and 818.0184 $/h by the PM, PSO and HSO respectively.In case of 30 bus system the initial FC of 813.6941 $/h is reduced to793.0635 $/h , 795.0379$/h and 794.7864$/h by the PM , PSO ,HSO respectively.In case of 57 bus system the initial FC of 4556.5930 $/h is reduced to 3804.9280, 3806.4773 and 3806.2054 $/h by the PM, PSO and HSO respectively. It is very clear from the results that the PM offers best possible control settings with optimal dc link parameters, which minimize the FC to the lowest possible value, when compared with those of PSO and HSO. It is to be noted that PM offers better control settings with optimal dc link parameters, resulting in lower FC than those of PSO and HSO. The % FC savings of PM is graphically compared with those of PSO and HSO in Figure 1 for all the test systems. It is seen from the figures that the %FC savings of PM is greater than those of PSO and HSO. As minimization of RPL and LVSI are not considered as objectives in this case, the RPL and LVSI are away from the respective best values for all the test systems, while reducing the FC.

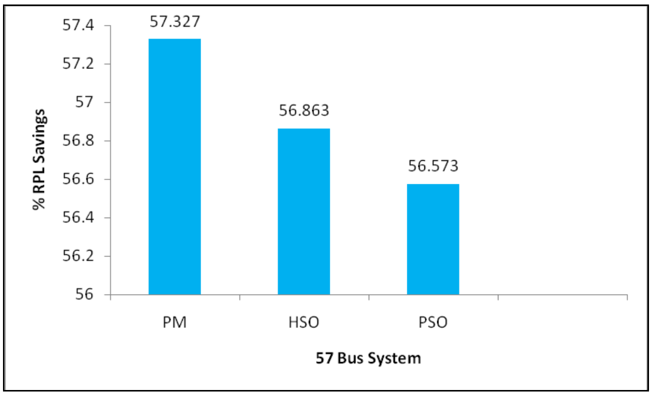
Figure 1 Comparison of % FC Savings



Case-2: The minimization of the RPL is considered as the objective in this case. It is observed from Table 3 that the initial RPL of 8.9737 MW is reduced to 2.1736, 2.3655 and 2.2420MW by the PM, PSO and HSO respectively for 14 bus system . Similarly, PM, PSO and HSO reduce the initial RPL of 7.0990 MW to 1.9884, 2.0908 and 2.0763 MW respectively for 30 bus system. In case of 57 bus system, the initial RPL of of 28.8037 MW is reduced to 12.2914, 12.5085 and 12.4250 MW by the PM, PSO and HSO respectively. It is very clear from the results that the offers best possible control settings with optimal dc link parameters, which minimize the RPL to the lowest possible value, when compared with those of PSO and HSO. It is to be noted that PM offers better control settings with optimal dc link parameters, resulting in lower RPL than those of PSO and HSO. The % RPL savings of PM are graphically compared with those of PSO and HSO in Figure 2 for all the test systems. It is seen from the figures that the %RPL savings of PM is greater than those of PSO and HSO. As minimization of FC and LVSI are not considered as objectives in this case, the FC and LVSI are away from the respective best values for all the test systems, while reducing the RPL.

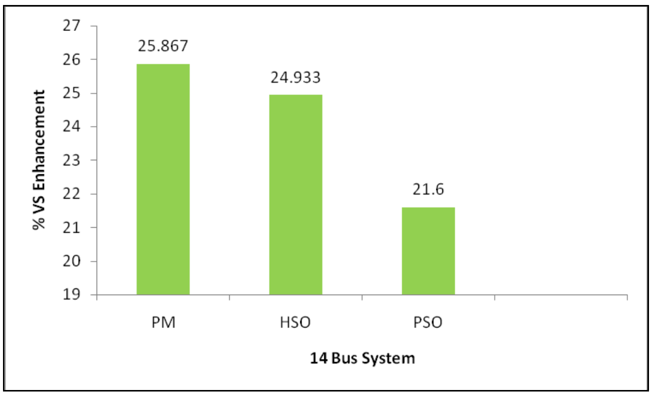
Figure 2 Comparison of % RPL Savings

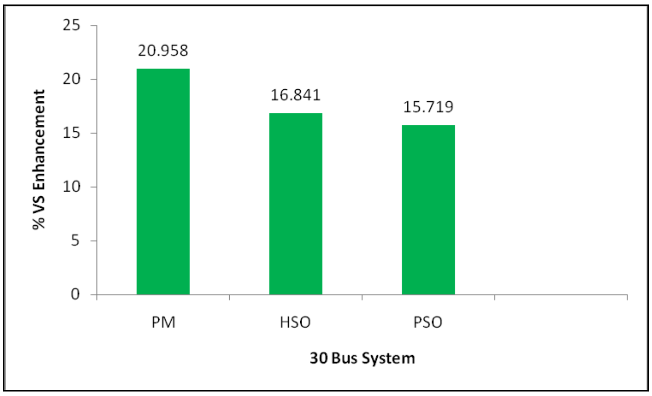


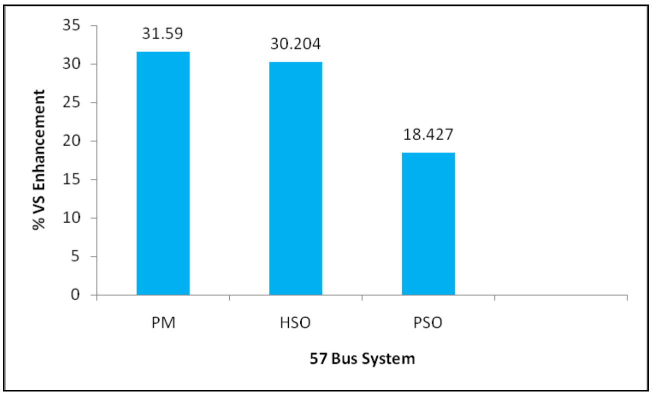


Case-3: The objective in this case is the enhancement of VS through minimizing of the LVSI. It is observed from Table 4 that the PM and reduce the LVSI from 0.0750 to 0.0556 but the PSO and HSO are able to reduce the LVSI to 0.0588 and 0.0563 respectively for 14 bus system. Similarly, PM, PSO and HSO reduce the initial LVSI of 0.1336 to 0.1056, 0.1126 and 0.1111 respectively for 30 bus system. In case of 57 bus system the initial LVSI of 0.2887 is reduced to 0.1975, 0.2355 and 0.2015 respectively for PM, PSO and HSO. It is very clear from the results that the PM offers best possible control settings with optimal dc link parameters, which minimize the LVSI to the lowest possible value, when compared with those of PSO and HSO. It is to be noted that PM offers better control settings with optimal dc link parameters, resulting in lower LVSI than those of PSO and HSO. The %VS enhancements of PM is graphically compared with those of PSO and HSO in Figure 3 for all the test systems. It is seen from the figures that the %VS enhancements of PM are greater than those of PSO and HSO. As minimization of FC and LVSI are not considered as objectives in this case, the FC and RPL are away from the respective best values for all the test systems, while enhancing the VS.

Figure 3 Comparison of % VS Enhancement







Cases-4-7: The performances in terms of FC, RPL and LVSI of PM are compared with those of the PSO and HSO based algorithms for test cases 4-7 in Tables 5,6,7 and 8 for 14, 30 and 57 bus systems. It is seen from the results of cases 4-7 that the PM and as well as the PSO and HSO offer a compromised solution, which lies in between the respective best and worst objective function values obtained in cases-1-3 in Tables 2, 3 and 4 for 14, 30 and 57 bus systems . While analyzing the performances, it can be observed that if one performance among the chosen objectives decreases, the other increases due to the conflicting nature of the objectives and vice-versa. The quality of the compromised solutions cannot be estimated as it depends on the weight values assigned to the individual objectives and the range of the each objective function values. It is known that another compromised solution can be obtained by simply changing the weight parameter of each objective. The lower and upper load bus voltages of all the cases of the PM for 14,30 and 57 bus systems. It is seen from that the PM adjust all the bus voltages to lie within the respective lower and upper limits for all the test cases, thereby ensuring acceptable voltage profile.

5. Conclusion

The study of OPF is an important analysis in power system operational planning. A self adaptive FO strategy for multi-objective OPF problem for AC/DC systems is suggested with a with a view to prevent sub-optimal solutions. FO is a biology inspired and population-based stochastic optimization technique and a worthy competitor to its better known siblings. The FO is a meta heuristic, nature-inspired, optimization algorithm which is based on the social flashing behavior of fireflies. It is inspired by the light attenuation over the distance and fireflies' mutual attraction rather than the phenomenon of the fireflies' light flashing. The solutions are treated as fireflies and adjusted depending on the light intensities, light attenuation and mutual attraction between fireflies to find the best solution. The algorithm uses sequential AC/DC load flow involving NR technique for computing the objective function during search and is able to offer the global best solution. The results on OPF problem project the ability of the proposed strategy to produce the global best solution involving lower computational burden. It has been chartered that the new approach for solving OPF will go a long way in serving as a useful tool in load dispatch centre.

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Appendix-A

Table A.1 DC link data

Specified Parameters	DC Link-1	DC Link-2	DC Link-3
V_1^{dc}	1.2860	1.2795	1.2855
θ_1 (deg)	12.50	12.25	12.00
θ_2 (deg)	22.60	22.55	22.50
R_{12}^{dc}	0.0137	0.0140	0.0135
X_1^c	0.10	0.09	0.11
X_2^c	0.07	0.05	0.08

Appendix-B

Table B.1 Optimal Solution of PM for 14 bus system

	Before Placement	**Case-1 FC**	**Case-2 Loss**	**Case-3 VS**	**Case-4 FC+Loss**	**Case-5 FC+VS**	**Case-6 Loss+VS**	**Case-7 FC+Loss+VS**
P^G	188.974 35.000 20.000 12.000 12.000	210.733450 20.000000 15.118302 10.019869 10.000000	66.181388 80.000000 49.998971 34.993869 29.999329	151.830156 49.231391 15.000000 26.973942 23.513634	105.834019 62.777672 46.109299 19.937808 27.085047	147.735915 53.062716 24.458871 14.768706 25.034876	74.104840 80.000000 50.000000 27.878990 29.428933	131.331742 41.524629 44.955984 23.458288 20.793724
V^G	1.060 1.045 1.010 1.070 1.090	1.069161 1.043032 1.014153 0.994000 1.017539	1.056867 1.047690 1.029105 0.988988 1.015985	1.099635 1.050647 1.029409 1.100000 1.099963	1.044593 1.041066 1.026746 0.994212 1.023732	1.091324 1.049293 1.001035 1.071346 1.043298	1.067152 1.060629 1.060420 1.089940 1.088957	1.091382 1.078034 1.059272 1.085826 1.100000
T	0.978 0.969 0.932	1.025943 1.073938 0.915559	1.064377 1.087629 0.996035	0.918225 0.900549 0.900000	1.035505 1.086717 0.968433	0.936764 0.952542 0.953878	0.951748 1.002307 1.073886	0.981478 0.981654 0.986315
L_p^{dc}		4	3	3	4	3	3	4

I_p^{dc}		0.838623	0.459927	0.926372	0.620555	0.656816	0.509991	0.653579
α β_o γ		0.007783 0.072105 0.267120	0.002791 0.003213 0.548396	0.000000 0.516342 0.400630	0.208434 0.161304 0.638686	0.002643 0.537369 0.666158	0.237196 0.788217 0.337759	0.150939 0.508943 1.000000

Table B.2 Optimal Solution of PM for 30 bus system

	Before Placement	Case-1 FC	Case-2 Loss	Case-3 VS	Case-4 FC+Loss	Case-5 FC+VS	Case-6 Loss+VS	Case-7 FC+Loss+VS
P^G	138.539 57.560 24.560 35.000 17.930 16.910	174.944247 48.652195 19.876890 20.906853 13.777302 12.000000	52.696639 80.000000 50.000000 35.000000 29.941086 37.750696	103.738056 69.211222 37.775641 28.168481 29.533785 27.359983	70.706910 77.163266 40.717049 35.000000 29.999952 32.079902	164.766936 49.296177 21.305315 16.474191 17.524022 22.588923	55.204116 80.000000 49.990690 34.978338 29.950810 35.367098	64.771872 78.975469 43.716864 34.991697 29.950594 33.166586
V^G	1.050 1.0338 1.0058 1.0230 1.0913 1.0883	1.094227 1.073754 1.045982 1.053184 1.047144 1.027020	1.040723 1.034281 1.028374 1.029432 1.058506 1.091412	1.097603 1.087875 1.080962 0.992195 1.099353 1.100000	1.050052 1.040514 1.035081 1.036931 1.074994 1.100000	1.097561 1.064849 1.021384 1.016703 1.100000 1.089828	1.050375 1.042880 1.038306 1.048003 1.067826 1.099983	1.051325 1.041919 1.036970 1.042823 1.074918 1.100000
T	1.0155 0.9629 1.0129 0.9581	1.001013 0.957654 0.964426 0.992747	0.970070 0.908277 0.956721 0.931851	0.997415 0.914201 0.937592 0.901773	0.965348 0.915511 0.955867 0.929937	0.902190 1.007465 0.966054 0.900000	0.966076 0.902782 0.951842 0.908955	0.964268 0.908863 0.953140 0.918456
L_p^{dc}		19 5	6 5	40 6	6 5	40 6	6 5	6 5
I_p^{dc}		0.100000 0.709581	0.299405 0.404416	0.942904 0.893428	0.308093 0.476039	0.398782 0.647717	0.413631 0.369248	0.350325 0.444987
α β_o γ		0.023427 0.161088 0.911664	0.015049 0.022465 0.795699	0.066007 0.675989 0.568635	0.000022 0.044214 0.840239	0.113671 0.466584 0.738745	0.000987 0.056747 0.829070	0.000007 0.044965 0.836589

Table B.3 Optimal Solution of PM for 57 bus system

	Before Placement	Case-1 FC	Case-2 Loss	Case-3 VS	Case-4 FC+Loss	Case-5 FC+VS	Case-6 Loss+VS	Case-7 FC+Loss+VS
P^G	359.604	466.005027	191.212952	481.365554	196.594040	475.837525	195.041655	196.585219
	35.000	10.000000	35.068426	13.248550	35.149319	12.984918	35.176877	34.954744
	40.000	20.196948	120.870500	20.053114	119.804310	20.043638	119.855804	119.504138
	50.000	10.000000	79.907321	16.317664	78.787579	16.601963	78.998061	78.877063
	450.000	546.485116	354.570714	469.279363	351.966482	472.830219	352.803256	351.961830
	35.000	10.904419	71.461467	26.577605	71.094921	26.071680	71.349560	71.348845
	310.000	216.472717	410.000000	256.558869	409.863462	258.720494	409.999941	410.000000
V^G	1.040	1.082904	1.024419	1.085417	1.027114	1.085972	1.026913	1.027132
	1.010	1.059186	1.016029	1.065668	1.018348	1.064979	1.018187	1.018269
	0.985	1.038370	1.004480	1.031301	1.005578	1.030829	1.005646	1.005511
	0.980	1.049558	0.979654	1.068073	0.978594	1.067293	0.978796	0.978809
	1.005	1.080490	0.972008	1.099404	0.971978	1.098717	0.972168	0.972330
	0.980	1.050122	0.940000	1.070943	0.940000	1.070846	0.940000	0.940000
	1.015	1.061587	0.975962	1.082914	0.975903	1.081879	0.975770	0.975992
T	0.970	1.003470	1.006550	0.965470	1.006205	0.964539	1.006097	1.006201
	0.978	0.950842	0.954902	0.953478	0.955821	0.952676	0.955850	0.955533
	0.967	0.969376	0.971420	1.024039	0.970947	1.025316	0.971208	0.971164
	0.940	0.973098	0.926888	0.932489	0.925481	0.933161	0.925821	0.925440
	0.930	0.998557	1.080731	0.994692	1.081305	0.995297	1.081583	1.081655
	0.955	0.998947	1.028700	0.949368	1.029748	0.949043	1.029611	1.029434
	0.958	0.923363	0.913920	0.955539	0.914497	0.955498	0.914210	0.914163
	0.895	0.912036	0.938048	0.916195	0.937631	0.915053	0.937509	0.937997
	0.900	0.933716	0.963918	0.957031	0.965540	0.957533	0.965505	0.965379
	0.955	0.951818	0.948894	0.933485	0.950017	0.933801	0.949809	0.949620
	1.043	0.920700	0.905176	0.910612	0.903411	0.910595	0.903787	0.903585
	1.000	0.968237	0.918820	0.985511	0.920487	0.985058	0.920213	0.919815
	1.000	0.906064	0.900402	0.922799	0.900302	0.924044	0.900359	0.900221
	1.043	0.948665	0.930586	0.955566	0.930808	0.955427	0.930563	0.930443
	0.975	0.904008	0.990745	0.980007	0.990449	0.978924	0.990562	0.990647
	0.980	1.055723	0.948844	1.037508	0.948073	1.038728	0.948001	0.948055
	0.958	1.060418	0.901064	1.091368	0.900058	1.092459	0.900140	0.900118
L_p^{dc}		64	16	62	16	62	16	16
		39	12	38	12	38	12	12
		16	8	3	8	3	8	8
I_p^{dc}		0.154155	0.252855	0.102875	0.242724	0.103010	0.244914	0.245017
		0.303355	0.188265	0.290310	0.186725	0.287063	0.186252	0.187306
		0.736719	0.891663	0.905660	0.891326	0.903752	0.889992	0.890771
α		0.043981	0.000307	0.008307	0.000820	0.012970	0.000001	0.000369
β_o		0.276637	0.300090	0.227654	0.299711	0.232029	0.301355	0.300562
γ		0.424006	0.275040	0.292366	0.278560	0.298667	0.278415	0.278221

References

[1] Carpentier, J, “Contribution a l’Etude du Dispatching Economique,” Bulletin de la Societe Francaise des Electriciens, vol. 3, pp.431-474, 1962.

[2] Cong Ji, Zhi-nong Wei, Guo-qiang Sun, Yong-hui Sun, “AC-DC Decoupling Algorithm of Optimal Power Flow with HVDC System,” Applied Mechanics and Materials, vol.457, pp.1107-1112, 2014.

[3] Wang Feng , Le Anh Tuan, Lina Bertling Tjernberg, Anders Mannikoff and Anders Bergman, “A New Approach for Benefit Evaluation of Multiterminal VSC–HVDC Using a Proposed Mixed AC/DC Optimal Power Flow,” IEEE Trans. on Power Delivery, vol.29, no.1, 432-443, 2014.

[4] J.Arrillaga, C.RArnold and B.J.Harker, “Computer Modeling of Electrical power systems,” John Wiley & sons Ltd, pp.168-185, 1983.

[5] K. Mangoli, and K.Y. Lee, “Optimal real and reactive power control using linear programming, Electrical Power System Research,” vol.26, no.1, pp.1-10, 1993.

[6] O.Alsac,and B. Scott, “Optimal load flow with steady state security, IEEE Transactions on power Apparatus and systems,” vol.PAS, pp.745-751, 1974.

[7] Momoh JA and Zhu JZ, “Improved interior point method for OPF problems,” IEEE Trans Power Syst., vol.14, no.3, pp.1114–20, 1999.

[8] Burchett RC, Happ HH and Vierath DR, “Quadratically convergent optimal power flow,” IEEE Trans Power Apparatus Syst., vol.103, pp.3267–76, 1984.

[9] Abdel-Fattah Attia, Yusuf A.Al-Turki and Abdullah M.Abusorrah, “Optimal power flow using adapted genetic algorithm with adjusting population size,” Electric Power Components and Systems, vol.40, pp.1285-99, 2012.

[10] Sood YR, “Evolutionary programming based optimal power flow and its validation for deregulated power system analysis,” Int J Electr Power Energy Syst, vol.29, no. 1, pp.65-75, 2007.

[11] Mahmood Joorabian and Ehsan Afzalan, “Optimal power flow under both normal and contingent operation conditions using the hybrid fuzzy particle swarm optimisation and Nelder–Mead algorithm (HFPSO–NM),” Applied Soft Computing, vol.14, pp.623–633, 2014.

[12] A.V.Naresh babu, T. Ramana and S.Sivanagaraju, “Analysis of optimal power flow problem based on two stage initialization algorithm,” Int J Electr Power Energy Syst., vol.55, pp.91-99, 2014.

[13] Niknam T, Narimani MR, Jabbari M and Malekpour AR, “A modified shuffle frog leaping algorithm for multi-objective optimal power flow,” Energy, vol.36, pp.6420-32, 2011.

[14] Sivasubramani.S and Swarup.KS, “Multi-objective harmony search algorithm for optimal power flow problem,“ Int J Electr Power Energy Syst., vol.33, no.3, pp.745–52, 2011.

[15] Duman S, Güvenç U, Sönmez Y and Yörükeren N, “Optimal power flow using gravitational search algorithm,” Energy Convers Manage, vol.59, pp.86-95, 2012.

[16] B.Srinivasa Rao and K. Vaisakh, “Multi-objective adaptive clonal selection algorithm for solving environmental/economic diaptch and OPF problems with load uncertainty,” Electrical Power and Energy Systems, vol.53, pp.390-408, 2013.

[17] M. Rezaei Adaryani and A. Karami, “Artificial bee colony algorithm for solving multi-objective optimal power flow problem, Electrical Power and Energy Systems,” vol.53, pp. 219-230, 2013.

[18] Mojtaba Ghasemi, Sahand Ghavidel, Mohsen Gitizadeh and Ebrahim Akbari, “An improved teaching-learning-based optimization algorithm using Levy mutation strategy for non-smooth optimal power flow,” Electrical Power and Energy Systems, vol.65, pp.375-384, 2015.

[19] X. S. Yang, “Firefly algorithms for multimodal optimization,” in Proceedings of the Stochastic Algorithms: Foundations and Applications of Lecture Notes in Computing Sciences, Springer, Sapporo, Japan, vol.5792, pp. 178-178, 2009.

[20] P. Kessel and H. Glavitsch, “Estimating the voltage stability of a power system,” IEEE Trans. Power Deliver, vol.1, no.3, pp.346-54, 2000.

[21] Tahir Nadeem Malika, Azzam ul Asarb, Mudasser F. Wynec and Shakil Akhtar, “A new hybrid approach for the solution of nonconvex economic dispatch problem with valve-point effects,” Electric Power Systems Research, vol.80, pp.1128-1136, 2010.

[22] Jason Yuryevich and Kit Po Wong, “Evolutionary programming based optimal power flow,” IEEE Trans. on Power Systems, vol.14, no.4, pp.1245-1257, 1999.

[23] S. Prabhakar Karthikeyan, K. Palanisamy, C. Rani, I. Jacob Raglend and DP. Kothari, “Security

constrained unit commitment problem with operational, power flow and environmental constraints," WSEAS Trans. on Power Systems, vol.4, no.2, pp.53-56, 2009.