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Adaptive Firefly Algorithm based OPF for AC/DC Systems

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Abstract – Optimal Power Flow (OPF) 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

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

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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 30, 57 and 118 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

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

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

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

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

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

s_m = 1 for rectifier and -1 for inverter

$$\begin{array}{ll} c_2 = 3\sqrt{2}/\pi & c_3 = 3/\pi \\ i \in \Omega & j \in \Pi \\ k \in \Psi & v \in \Re \\ p \in \Im & q \in \aleph \end{array}$$

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

$$\text{Minimize} \quad \Phi_1(x,u) = \sum_{j \in \Pi} a_j\, P_j^{G2} + b_j\, P_j^G + c_j + \left| d_j \sin(e_j (P_j^G(\min) - P_j^G)) \right| \tag{9}$$

Case-2: Minimization of real power loss

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

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

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

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

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

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

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 $\left\{ P_k^G, V_j^G, T \text{ and } I_p^{dc} \right\}$ 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 $\alpha_i$, $\beta_o$ and $\gamma$ from the firefly
            •Run AC/DC power flow
            •Evaluate the augmented objective function $\Phi^A$ 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 $\alpha_i$, $\beta_o$ and $\gamma$ from the firefly
            •Run AC/DC power flow
            •Evaluate the augmented objective function $\Phi^A$ and light intensity function $LI_i$ 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 30, 57 and 118 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 30 bus system, while for 57 and 118 bus systems they are taken as 0.94 and 1.1 per units. In the analysis, two, three and five transmission lines, as listed in Table 1, are replaced by dc links for IEEE-30, -57 and -118 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.

Table 1 Transmission lines replaced by DC links

System	Line No
30 bus	31 and 11
57 bus	3, 40 and 70
118 bus	18, 29, 43, 72 and 85

Table 2 Comparison of Performances for 30 bus system

		Performance		
		FC	RPL	LVSI
Test Cases	Before Placement	813.6941	7.0990	0.1336
	PM	800.9169	9.1340	0.1243
Case-1	PSO	802.2393	8.7274	0.1344
	HSO	801.0114	9.0058	0.1252
	PM	964.5326	3.2066	0.1277
Case-2	PSO	959.8069	3.4543	0.1233
	HSO	961.2365	3.2552	0.1281
	PM	849.7093	6.2549	0.1210
Case-3	PSO	817.2031	9.2432	0.1225
	HSO	821.5187	7.0845	0.1212
	PM	916.7663	3.7880	0.1277
Case-4	PSO	892.0969	4.2629	0.1312
	HSO	953.0426	3.2372	0.1266
	PM	816.4639	8.0069	0.1176
Case-5	PSO	808.0260	9.5656	0.1166
	HSO	807.4715	9.3716	0.1218
	PM	961.4487	3.7099	0.1178
Case-6	PSO	910.9013	4.0731	0.1255
	HSO	961.5347	3.2086	0.1253
	PM	917.5211	3.8004	0.1285
Case-7	PSO	926.8445	4.0007	0.1206
	HSO	949.4676	3.2893	0.1247

The optimal solution obtained by the PM, PSO and HSO for all the test cases for 30 and 57 bus systems are given through Tables B.1 and B.2 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 and 4 for 30, 57 and 118 bus system respectively. The tables 2, 3 and 4 also contain the base-case results, representing the performances before optimization.

Case-1: The objective in this case is the minimization of the FC. It is observed from Table 2 that the PM reduce the FC from 813.6941 \$/h to 800.9169 \$/h but the PSO and HSO are able to reduce the FC to 802.2393 and 801.0114 \$/h respectively for 30 bus system. In case of 57 bus

Table 3 Comparison of Performances for 57 bus system

		Performance		
		FC	RPL	LVSI
Test Cases	Before Placement	4556.593	28.8037	0.2887
	PM	3812.631	30.8391	0.2493
Case-1	PSO	3813.615	30.8404	0.2493
	HSO	3812.969	30.8351	0.2494
	PM	5836.861	13.6551	0.2999
Case-2	PSO	5970.491	14.3978	0.2813
	HSO	5906.710	13.9190	0.3294
	PM	5894.334	31.0756	0.2405
Case-3	PSO	5613.787	31.7592	0.2406
	HSO	5279.057	31.0144	0.2408
	PM	3838.220	14.5926	0.2881
Case-4	PSO	3838.774	14.7483	0.2793
	HSO	3825.421	15.9785	0.3006
	PM	3843.149	31.0393	0.2414
Case-5	PSO	3899.978	31.0129	0.2399
	HSO	3844.151	31.0600	0.2408
	PM	4713.910	15.4013	0.2851
Case-6	PSO	4713.959	14.6794	0.2747
	HSO	4860.220	15.3695	0.2944
	PM	4440.248	16.3199	0.2866
Case-7	PSO	4568.978	16.4968	0.2612
	HSO	4756.115	14.9878	0.2809

Table 4. Comparison of Performances for 118 bus system

		Performance		
		FC	RPL	LVSI
Test Cases	Before Placement	145520.36	197.28	0.3714
	PM	129660.92	203.57	0.3768
Case-1	PSO	129915.47	201.34	0.3762
	HSO	129872.99	207.56	0.3758
	PM	148723.65	93.73	0.3718
Case-2	PSO	148325.57	96.15	0.3723
	HSO	149246.72	95.02	0.3721
	PM	148563.27	108.56	0.3153
Case-3	PSO	148642.45	104.25	0.3169
	HSO	148710.67	103.79	0.3158
	PM	130653.72	97.44	0.3784
Case-4	PSO	130713.62	100.37	0.3781
	HSO	130696.28	99.48	0.3779
	PM	130714.53	112.35	0.3247
Case-5	PSO	131053.58	114.57	0.3261
	HSO	130978.47	114.02	0.3258
	PM	146102.86	96.57	0.3184
Case-6	PSO	146428.52	98.53	0.3207
	HSO	146384.83	98.27	0.3197
	PM	131758.52	101.35	0.3283
Case-7	PSO	131937.24	103.27	0.3296
	HSO	131874.35	102.35	0.3291

system from Table 3, the initial FC of 4556.5930 $/h is reduced to 3812.6312, 3813.6148 and 3812.9687 $/h by the PM, PSO and HSO respectively. Similarly for 118 bus system, the initial FC of 145520.36 $/h is reduced to 129660.92, 129915.47 and 129872.99 $/h by the PM, PSO and HSO respectively as given in Table 4. 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 Fig. 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.

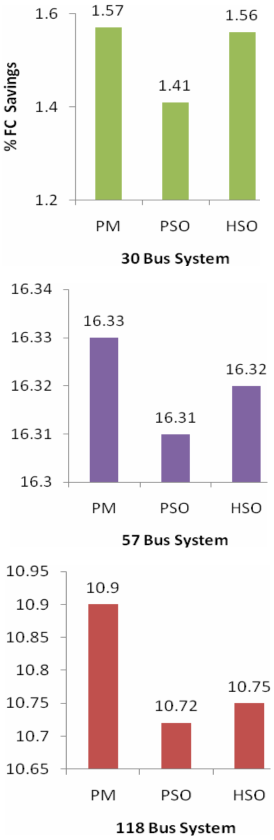


Fig. 1 Comparison of % FC Savings

Case-2: The minimization of the RPL is considered as the objective in this case. It is observed from Table 2 that the initial RPL of 7.0990 MW is reduced to 3.2066, 3.4543 and 3.2552 MW by the PM, PSO and HSO respectively. Similarly, PM, PSO and HSO reduce the initial RPL of 28.8037 MW to 13.6551, 14.3978 and 13.9190 MW respectively for 57 bus system, as given in Table 3. In case of 118 bus system, the initial RPL of of 197.28 MW is reduced to 93.73, 96.15 and 95.02 MW by the PM, PSO and HSO respectively, as indicated in Table 4. 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

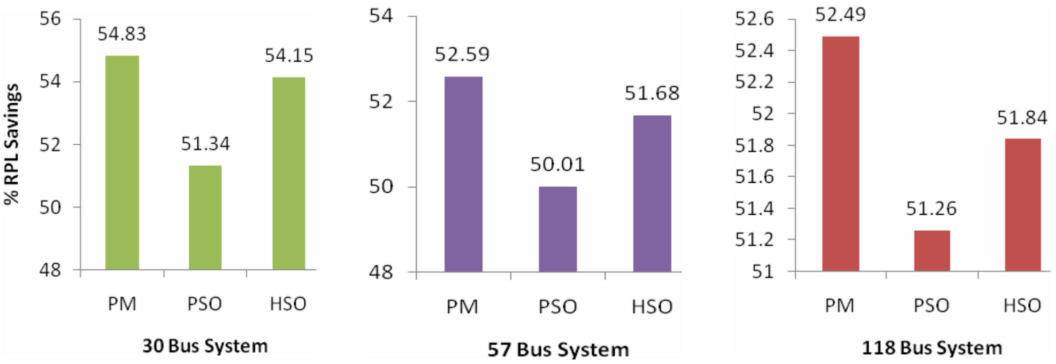


Fig. 2 Comparison of % RPL Savings

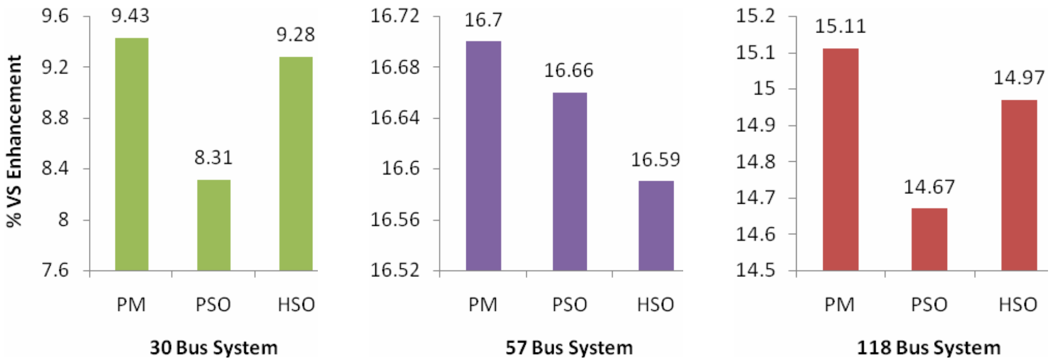


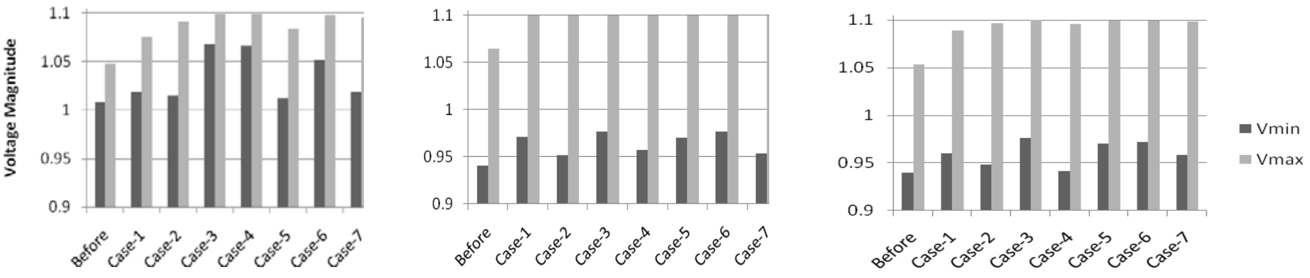
Fig. 3 Comparison of % VS enhancement

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 Fig. 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.

Case-3: The objective in this case is the enhancement of VS through minimizing of the LVSI. It is observed from Table 2 that the PM and reduce the LVSI from 0.1336 to 0.1210 but the PSO and HSO are able to reduce the LVSI to 0.1225 and 0.1212 respectively for 30 bus system. Similarly, PM, PSO and HSO reduce the initial LVSI of 0.2887 to 0.2405, 0.2406 and 0.2408 respectively for 57 bus system, as indicated in Table 3. In case of 118 bus system, it can be noticed from Table 4 that the initial LVSI of 0.3714 is reduced to 0.3153, 0.3169 and 0.3158 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 Fig. 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.

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 2, 3 and 4 for 30 57 and 118 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. 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 are graphically displayed in Fig. 4 for 30, 57 and 118 bus systems. It is seen from these figures that the PM adjust all the bus voltages to lie within the respective lower



(a) 30 bus system

(b) 57 bus system

(c) 118 bus system

Fig. 4 Lower and upper VMs

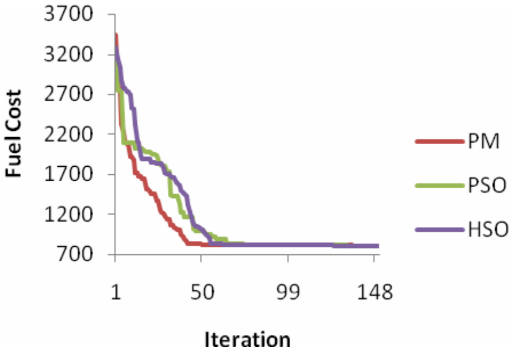


Fig. 5 Convergence characteristics for case-1 of 30 bus system

and upper limits for all the test cases, thereby ensuring acceptable voltage profile.

The HSO generates a new harmony, while SFO and PSO produce as many off-springs as the population size in each iteration. Therefore, 25 iterations of HSO is considered to be equivalent to one iteration of SFO and PSO while studying the convergence of the algorithms. The convergence characteristic that represents the variation of FC against the number of iterations of the PM, PSO and HSO based approaches for case-1 of 30 bus system are shown in Fig. 5. The figure indicates that the PM quickly converge to the final solution in less than 45 iterations, while PSO and HSO requires around 70 and 55 iterations respectively. It is very clear that the PM is able to converge to the global best solution at lower number of iterations than those of the existing PSO and HSO based approaches.

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.

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 -throw 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

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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 30 bus system

	Before Placement	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7
P^G	138.539	178.064323	52.796728	131.476641	55.397969	81.335840	146.900619	74.143608
	57.560	47.466625	79.965824	45.633739	80.000000	60.826550	51.680809	68.906581
	24.560	20.405339	49.844248	44.390933	50.000000	50.000000	28.724112	47.129888
	35.000	20.130264	35.000000	34.765747	35.000000	31.996396	27.408494	33.990142
	17.930	13.383317	29.937031	12.418082	28.536885	28.139547	24.692874	29.903181
	16.910	13.084119	39.062809	20.969743	38.175007	34.889661	12.000000	33.127016
V^G	1.050	1.100000	1.100000	1.100000	1.069732	1.100000	1.094930	1.100000
	1.0338	1.091551	1.099774	1.100000	1.060919	1.096768	1.100000	1.099333
	1.0058	1.056305	1.081769	1.097819	1.064468	1.071394	1.080284	1.091662
	1.0230	1.063844	1.083251	1.084018	1.059686	1.072214	1.054954	1.100000
	1.0913	1.096334	1.077662	1.100000	1.095302	1.065116	1.092843	1.100000
	1.0883	1.063539	1.069471	1.096295	1.041255	1.073724	1.100000	1.079686
T	1.0155	1.050779	0.974191	0.999605	0.933751	0.985710	0.950904	0.982273
	0.9629	1.036759	1.003529	0.900000	0.995479	1.007358	0.900000	0.948778
	1.0129	1.015330	1.043921	0.923743	0.937536	1.019973	0.945822	1.033166
	0.9581	0.944747	0.982242	0.935543	0.900000	0.980294	0.913437	0.995742
I_p^{dc}	---	0.100000	0.100000	0.100000	0.100000	0.106859	0.140955	0.100000
		0.153938	0.117831	0.402257	0.100000	0.102443	0.368676	0.227715
α	---	0.091040	0.056672	0.109252	0.035958	0.091379	0.143410	0.247872
β_o		0.312221	0.438668	0.193211	0.303786	0.298941	0.919629	0.091451
γ		0.422947	0.227145	0.401566	0.737609	0.196008	0.660245	0.810787

Table B.2 Optimal Solution of PM for 57 bus system

	Before Placement	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7
P^G	359.604	519.317660	180.106003	517.314279	277.866865	516.935265	145.867994	248.451452
	35.000	10.984094	98.124032	11.763549	46.947926	12.168421	100.000000	21.836335
	40.000	20.589175	108.330829	23.345949	57.943161	23.241054	106.574634	69.877960
	50.000	10.000000	78.903313	10.000000	36.894345	10.103117	79.226449	22.184646
	450.000	421.710545	347.353389	416.991084	415.587596	416.278143	387.077868	466.546834
	35.000	10.057234	41.637522	11.117625	37.656326	11.339254	45.091977	27.304052
	310.000	288.980413	410.000000	291.306813	394.223722	291.810348	401.553698	410.000000
V^G	1.040	1.099930	1.100000	1.099995	1.093501	1.092513	1.100000	1.096543
	1.010	1.078623	1.098094	1.076398	1.088257	1.079780	1.076371	1.074816
	0.985	1.041352	1.089791	1.045814	1.076845	1.058066	1.045660	1.066064
	0.980	1.068560	1.038896	1.071450	1.045400	1.037708	1.070695	1.059009
	1.005	1.096553	1.056014	1.100000	1.064364	1.066170	1.099466	1.084761
	0.980	1.066448	1.047110	1.071687	1.045595	1.050399	1.071271	1.060828
	1.015	1.089045	1.081363	1.097247	1.072378	1.075969	1.096660	1.083498
T	0.970	0.972566	0.994283	0.977174	0.997159	0.957996	0.976832	0.996842
	0.978	0.937914	1.057814	0.940165	1.070380	0.977396	0.939393	0.988159
	0.967	1.032290	1.058955	1.036216	1.066606	1.033448	1.035756	1.043240
	0.940	0.933183	0.948598	0.926714	0.939476	0.957945	0.927588	0.976469
	0.930	0.968978	0.991870	0.965789	1.002102	0.983325	0.965668	0.982630
	0.955	0.912231	0.973075	0.916255	0.971646	0.940302	0.915824	0.908471
	0.958	0.963084	0.933622	0.959022	0.924916	0.928776	0.959181	0.937040
	0.895	0.930335	1.006298	0.927873	1.015430	0.975179	0.928423	1.023941
	0.900	0.940620	1.053674	0.937665	1.056381	1.010163	0.938388	1.025899
	0.955	0.957185	0.945325	0.946250	0.939785	0.937395	0.947079	0.949442
	1.043	0.925605	0.975890	0.928620	0.962781	0.948913	0.928347	0.954857
	1.000	0.991164	0.955087	0.985362	0.961334	0.960411	0.984791	0.959156
	1.000	0.900486	0.927028	0.900000	0.919000	0.932952	0.900228	0.929930
	1.043	0.950854	0.900000	0.947135	0.900000	0.955115	0.947166	0.929276
	0.975	0.990757	1.046828	0.994174	1.048959	1.010494	0.993299	1.075797
	0.980	1.035101	1.002468	1.035098	1.008199	1.018277	1.034597	0.970133
	0.958	1.083610	1.038464	1.082474	1.036079	1.069099	1.082035	1.088742
I_p^{dc}	---	0.188877	0.148225	0.196563	0.202357	0.121530	0.197716	0.123502
		0.255297	0.148854	0.273098	0.200523	0.188788	0.270058	0.195786
		0.821478	0.273290	0.836736	0.285289	0.551962	0.833835	0.399285
α	---	0.002354	0.212126	0.005014	0.199820	0.026129	0.000817	0.369302
β_o		0.258030	0.734888	0.242716	0.736803	0.489168	0.247775	0.448558
γ		0.315299	0.567873	0.322099	0.620231	0.315388	0.321627	0.459627