Real Power Loss Minimization of AC/DC Hybrid Systems with Reactive Power Compensation by using Self Adaptive Firefly Algorithm

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Abstract – *This paper presents a Self Adaptive Firefly Algorithm (SFO) for the solution Real Power Loss (RPL) Minimization of AC/DC Hybrid Systems with Reactive Power Compensation .The DC links placed in the transmission system involve consumption of reactive power by the converters at both ends. The Reactive Power Flow can be manipulated based on the removing at the end bus it from the system .Optimal Power Flow (OPF) problem is formulated as a nonlinear constrained multiobjective optimization problem where different objectives and different constraints have been considered. Optimal Power Flow with Reactive Power Compensation is an important operational and planning problem in minimizing the RPL of the power systems. It presents simulation results of IEEE14 and 30 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

I. 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 problems of the present day stressed power systems are increased RPL, poor VP, unwanted loop flows and line overloads. The control of voltage level is accomplished by controlling the production, absorption and flow of reactive power at all levels in the system. The converters at the sending end of the DC links are in general nearer to the generators and get the required reactive power. But the converters at the receiving end are nearer to the loads of the existing systems and obtain reactive power through some other transmission lines connected to the end bus. The consumption of additional reactive power by the converters at the receiving end of DC link from the existing generators through some other transmission lines may deteriorate the system performances besides making additional reactive power burden to the existing generators.

In general, the reduction of Real Power Loss (RPL) is commonly used as the main objective for OPF problems. However, the other objectives, such as reduction of Fuel cost (FC), 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 and 30 bus systems.

II. Problem Formulation

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

$$x=[V_i^L, Q_j^G, P_s^G]$$
$$u=[P_k^G, V_j^G, T_v, Q_q^C, I_p^{dc}] \tag{4}$$

(5)

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

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

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

s_m = 1 for rectifier and -1 for inverter

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

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

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

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

The objective function $\Phi(x,u)$ can take different forms.

Minimization of Fuel Cost

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

Minimization of Real Power Loss

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

Enhancement of Voltage Stability

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

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

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

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

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

III. Equations and Units

The FO is a metaheuristic, nature-inspired, optimization algorithm which is based on the social flashing behavior of fireflies. After a sufficient amount of iterations, all fireflies converge to the best possible position on the search space [19].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 .

A. Representation of decision variables

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

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

B. 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

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

Where

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

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 .

C. Solution Process

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 i-th 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 j-th 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

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

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*

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

***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*

IV. Simulations

The PM is tested on IEEE 14 and 30 bus test systems. The fuel cost coefficients, lower and upper generation limits for these two test systems are taken from Ref. [21-23] and given in Tables A.1 and A.2 of the Appendix-A. In the analysis, one and two transmission lines are replaced by dc links for IEEE 14 and 30 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 2.20 GHz Intel core-i3 personal computer. The OPFDC problem is also solved using the PSO with a view of demonstrating the efficacy of the PM.

The optimal solution obtained by the PM and PSO for the test case for IEEE14 and 30 bus systems are given through Tables A.3 respectively in Appendix-A. The performances in terms of FC, PM and are compared with those of the PSO based algorithms for test Table 3 for IEEE 14 and 30 bus system respectively. The tables 3 also contain the base-case results, representing the performances before optimization. The transmission lines that are chosen for replacement by DC links in Table 2 for 14 and 30 bus systems The parameters chosen for the PA are given in Table 1.

Table 1 FA Parameter

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

Table 2 Transmission lines replaced by DC links

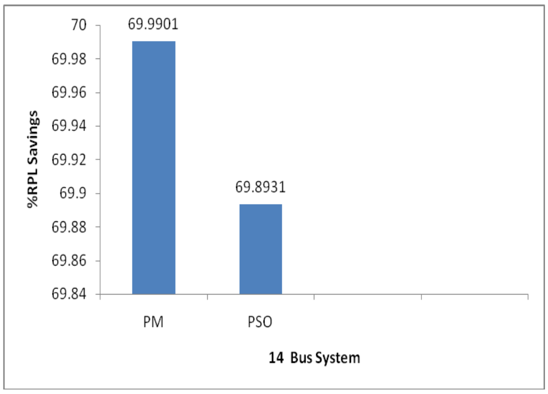
System	Line No
14 bus	9
30 bus	31 and 11

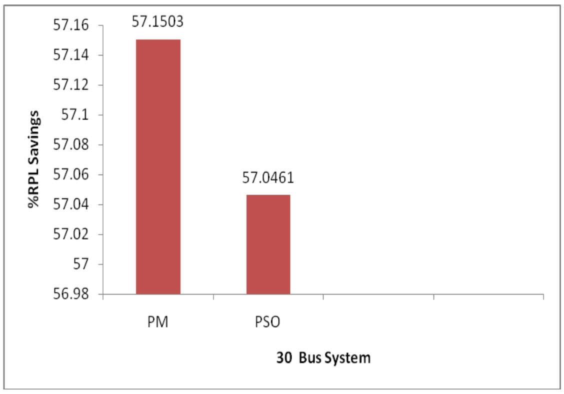
Table 3 Comparison of Performances for RPL

		Before Placement	**PM**	**PSO**
14	FC	834.6716	1022.2900	1022.2902
	RPL	8.9737	2.6930	2.7017
30	FC	813.6941	967.5238	967.1829
	RPL	7.0990	3.0419	3.0493

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 2.6930 and 2.7017 MW by the PM and PSO respectively for 14 bus system . Similarly, PM and PSO reduce the initial RPL of 7.0990 MW to 3.0419 and 3.0493 MW respectively for 30 bus system. 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 . It is to be noted that PM offers better control settings with optimal dc link parameters, resulting in lower RPL than those of PSO. The % RPL savings of PM are graphically compared with those of PSO in Figure 1 for all the test systems. It is seen from the figures that the %RPL savings of PM is greater than those of PSO. As minimization of FC are not considered as objectives in this case, the FC are away from the respective best values for all the test systems, while reducing the RPL.

Figure 1 Comparison of % RPL Savings





V. Conclusion

This paper shows the solution Real Power Loss Minimization of AC/DC Hybrid Systems with Reactive Power Compensation by using Self Adaptive Firefly Algorithm. 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. 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. The Proposed Method approach is tested on IEEE 14 and 30 bus test systems. 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 Generator Data for IEEE 14 bus test system

Bus	a	b	c	d	e	$P_j^{G(\min)}$	$P_j^{G(\max)}$	$Q_j^{G(\min)}$	$Q_j^{G(\max)}$
1	0.0016	2.00	150	0.063	50	50	300	-40	100
2	0.0100	2.50	25	0.098	40	20	80	-40	50
3	0.0625	1.00	0	0	0	15	50	0	40
6	0.00834	3.25	0	0	0	10	35	-6	24
8	0.025	3.00	0	0	0	10	30	-6	24

Table A.2 Generator Data for IEEE 30 bus test system

Bus	a	b	c	d	e	$P_j^{G(\min)}$	$P_j^{G(\max)}$	$Q_j^{G(\min)}$	$Q_j^{G(\max)}$
1	0.00375	2.00	0	0	0	50	200	-20	-250
2	0.01750	1.75	0	0	0	20	80	-20	100
5	0.06250	1.00	0	0	0	15	50	-15	80
8	0.00834	3.25	0	0	0	10	35	-15	60
11	0.02500	3.00	0	0	0	10	30	-10	50
13	0.02500	3.00	0	0	0	12	40	-15	60

Table A.3 Optimal Solution of PM for 14 bus and 30 bus system

	IEEE 14		IEEE 30	
	Before Placement	RPL	Before Placement	RPL
P^G	188.974 35.000 20.000 12.000 12.000	66.69303 5 80.000000 50.000000 35.000000 30.000000	138.539 57.560 24.560 35.000 17.930 16.910	51.44190 2 80.000000 50.000000 35.000000 30.000000 40.000000
V^G	1.060 1.045 1.010 1.070 1.090	1.100000 1.095827 1.076731 1.064582 1.081723	1.050 1.0338 1.0058 1.0230 1.0913 1.0883	1.100000 1.098881 1.081280 1.088537 1.048597 1.084278
T	0.978 0.969 0.932	1.042324 1.063676 0.967979	1.0155 0.9629 1.0129 0.9581	1.055620 1.007962 1.070347 1.009598
L_p^{dc}	---	9	---	31 11
I_p^{dc}	---	0.164998	---	0.100000 0.129758
α β_o γ		0.196857 0.078471 0.483875		0.023023 0.158179 0.521918

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