Real Power Loss Minimization of AC/DC Hybrid Systems with Reactive Power Compensation by using Teaching Learning based Optimization Algorithm

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Abstract – *This Paper Presents a Teaching Learning based Optimization (TLBO) Algorithm for the Solution Real Power Loss (RPL) Minimization of AC/DC Hybrid Systems with Reactive Power Compensation . The objectives is to minimize the Real power Loss of generating units with optimal setting of control variables without violating inequality constraints and satisfying equality constraints. 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) is an important operational and planning problem in minimizing the chosen objectives of the power system. The recent developments in power electronics allow replacing the existing transmission lines by DC links with a view of making the operation more flexible, secure and economical. The solution process involves sequential NR based AC/DC power flow. It presents simulation results of two IEEE 14 and 30 bus test systems with a view of demonstrating its effectiveness.*

Keywords: *optimal power flow, AC/DC power flow, teaching-learning based optimization ,valve point effect.*

NOMENCLATURE

$a_j\ b_j\ c_j$	fuel cost coefficients of the j-th generator
$b(x,u)$	equality constraints
$d_j\ e_j$	coefficients of valve point effects of the j-th generator
FC	fuel cost
F_q	performance, indicating the fitness, of the q-th student
$g(x,u)$	inequality constraint
$G_{mn} + jB_{mn}$	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
gp_s	grade points
HSO	harmony search optimization
$h(x,u)$	DC link equations
h_m	converter transformer tap at bus-m
I_m^{dc}	injected DC current at bus-m
I_p^{dc}	DC current at p-th DC link
$Iter^{\max}$	maximum number of iterations for convergence check.
LVSI	Largest VSI
L_i	VSI at load bus-i
L_p^{dc}	location of p-th DC link
ng	number of generators
nt	number of transformers
ns	number of students
nl	number of lines
$nobj$	number of objectives
OPF	optimal power flow
OPFDC	OPF with DC link placement problem
PSO	particle swarm optimization
PM	proposed method

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_j^0	base case real power generation at j-th PV bus
P_s^{limit}	limit violated real power generation at slack generator
P_m^{dc}	DC link power at bus-m
Q_i^G	reactive power generation by i-th generator
Q_q^C	reactive power injection by q-th shunt compensator
Q_i^{limit}	limit violated reactive power generation at i-th generator bus
Q_w^{ac}	reactive power consumed by the DC link transformer and converter at bus-w
RPL	real power loss
R_{mn}^{dc}	DC resistance of the link between buses m and n
S_{Li}	loading of i-th transmission line
$S_{Li}^{\max}$	limit for loading of i-th transmission line
$S^{j\,k\;ave}$	mean grade of the j-th subject at k-th iteration
$S_{teacher}^{j\,k}$	grade point of the j-th subject of the teacher at k-th iteration
TLO	teaching learning based optimization
t	iteration counter
t_f	teaching factor, which decides the value of mean to be changed and can be either 1 or 2
T_v	tap setting of v-th transformer
VP	voltage profile
VS	voltage stability
VSI	voltage stability index
V_i	voltage at i-th bus
V_i^{limit}	limit violated voltage magnitude at i-th load 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 the converter at bus-m
λ	penalty factors
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
$\Delta S^{j\,k}$	difference between the grade point of the teacher and the mean grade point of the subject
superscript "min" & "max"	lower and upper limits respectively

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 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.

While most of the existing DC links are designed for point to point transmissions, the multi-terminal DC system operation has become a reality and its usage is expected to increase in future with a view of making the operation more flexible, secure and economical. The realization of multi-terminal DC systems cannot be done at once but can be executed through replacing the existing AC transmission lines by DC links over a period of time.

It is to be noted that such modernization through heuristic replacement of AC lines by DC links in the system may not be optimal and may not ensure enhanced system performance. The decision as to which of the transmission lines is to be replaced by DC links and their parameters, besides determining the optimal settings for control parameters, is of great significance in achieving the desired performances. The problem of replacing the transmission lines by DC links may be represented as “DC link placement problem”. There is thus a need for extending the OPF problem to embrace the problem of placing the DC links in the existing power systems. The resulting optimization problem, designated as OPF with DC link placement problem (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 [2-6].

In the recent decades, numerous mathematical programming techniques such as gradient method [1], linear programming [7,8], nonlinear programming [9,10], interior point method [11-13] and quadratic programming [14] 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 suffers 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 [15-18], evolutionary programming [19-21], particle swarm optimization (PSO) [22-24], differential evolution [25-28], frog leaping [29], harmony search optimization (HSO) [30], gravitational search [31], clonal search [32], artificial bee colony [33] and teaching-learning [34] 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 temperature in SA, the crossover and mutation probabilities in GA and the inertia weight, acceleration coefficients and velocity limits in PSO.

Recently, teaching learning based optimization (TLO) has been suggested for solving optimization problems [35,36]. It is inspired from teaching-learning process in class rooms. It mimics the behavior of the students in improving their performance through gaining the knowledge from the teacher and interacting with other students. It has been applied to a variety of power system problems [37-39] and found to yield satisfactory results.

This paper formulates the problem of OPFDC, suggests a solution methodology involving TLO with a view of obtaining the global best solution and demonstrates its performance through simulation results on IEEE 14 and 30 bus systems.

II. TEACHING LEARNING BASED OPTIMIZATION

TLBO, inspired from teaching–learning process in class rooms, is suggested for solving multimodal optimization problems.

Teaching Phase: The teaching phase represents the global search property of the TLBO algorithm. In the light of the fact that the students will gain knowledge according to the quality of the teaching delivered by a teacher and the quality of the students present in the class, the mean grade point of the subject increases and the difference between the grade point of the teacher and the mean grade point of the subject is expressed as

$$\Delta S^{j\,k} = rand(0,1) \times \left(S^{j\,k}_{teacher} - t_f \; S^{j\,k\,ave} \right) \tag{1}$$

Where

$S^{j\,k\,ave}$ is the mean grade of the j-th subject at k-th iteration and computed by

$$S^{j\,k\,ave} = \frac{1}{nS} \sum_{i=1}^{nS} S_i^{j\,k} \tag{2}$$

(2) $S^{j\,k}_{teacher}$ is the grade point of the j-th subject of the teacher at k-th iteration

t_f is the teaching factor, which decides the value of mean to be changed and can be either 1 or 2, evaluated by

$$t_f = round([1 + rand\,(0,1)\{2-1\}] \tag{3}$$

The new grade point of the j-th subject of the i-th student, as a result of teaching, is mathematically modeled by

$$S_i^{j\,k+1} = S_i^{j\,k} + \Delta S^{j} \tag{4}$$

The grade points of all the students at the teachers phase are further improved by the learner phase.

Learning Phase: The learner phase stands for the local search process of the TLBO algorithm. In this phase, the students enrich their knowledge by interaction among themselves, which helps in improving their performances. In this phase, a student randomly chooses another student for interaction and enriches the knowledge through learning if the other student has more knowledge than him or her. The influence on the grade points due to the interaction of p-th student with q-th student may be mathematically expressed as follows:

$$S_p^{j\,k+1} = \begin{cases} S_p^{j\,k} + rand \times \left(S_p^{j\,k} - S_q^{j\,k} \right) & if \;\; F_p > F_q \\ S_p^{j\,k} + rand \times \left(S_q^{j\,k} - S_p^{j\,k} \right) & otherwise \end{cases}$$

(5) (5)

F_p and F_q are the performance, indicating the fitness, of the p-th and q-th student respectively. The algorithm of the TLO is narrated below.

III. 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 [4-6]. 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 set of equations as

Minimize $\Phi(x,u)$ (6)

Subject to

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

$$g(x,u)\le 0 \quad (8)$$

Where

$x=[V_i^L, Q_j^G, P_s^G]$, the vector of dependant variables (9)

$u=[P_k^G, V_j^G, T_v, Q_q^C, L_p^{dc}, I_p^{dc}]$, the vector of control or independent variables (10)

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

, the equality constraints (11)

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

the inequality constraints (12)

$$h(x,u)=\begin{Bmatrix} V_m^{dc}-smc_2\,h_m\,V_w^{ac}\cos\theta_m+s_m\,c_3\,X_m^c\,I_m^{dc}=0 \\ V_m^{dc}-0.995c_2\,h_m\,V_w^{ac}\cos\varphi_m=0 \\ Q_w^{ac}-V_w^{ac}\,c_2\,h_m\,I_m^{dc}\sin\varphi_m=0 \\ P_w^{ac}-V_w^{ac}\,c_2\,h_m\,I_m^{dc}\cos\varphi_m=0 \\ P_m^{dc}-V_m^{dc}\,I_m^{dc}=0 \\ I_m^{dc}-\left(V_m^{dc}-V_n^{dc}\right)/R_{mn}^{dc}=0 \\ V_m^{dc}-V_n^{dc}-I_m^{dc}\,R_{mn}^{dc}=0 \end{Bmatrix}$$

, the DC link equations (13)

s_m = 1 for rectifier and -1 for inverter

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

$c_3=3/\pi$

$i\in\Omega$, a set of load buses

$j\in\Pi$, a set of generator buses

$k\in\Psi$, a set of PV buses

$v\in\Re$, a set of tap changing transformers

$p\in\Im$, a set of DC links

$q\in\aleph$, a set of shunt compensators

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

Minimization of Fuel Cost

Minimize

$$\Phi_1(x,u)=\sum_{j\in\Pi}a_j\,P_j^{G^2}+b_j\,P_j^G+c_j+\left|d_j\sin(e_j(P_j^G(\min)-P_j^G))\right| \quad (14)$$

Minimization of Real Power Loss

Minimize

$$\Phi_2(x,u)=\sum_{w=1}^{nl}g_{mn}\left(|V_m|^2+|V_n|^2-2|V_m||V_n|\cos\delta_{mn}\right) \quad (15)$$

Enhancement of Voltage Stability

The VS can be enhanced by minimizing the largest value of VS index (VSI) of load buses [40] as

Minimize

$$\Phi_3(x,u)=\max\{L_i;\,i\in\Omega\} \quad (16)$$

Where $L_i=\left|1-\sum_{j=\Pi}F_{ji}\frac{V_j}{V_i}\right|$ (17)

The values of F_{ji} are obtained from the bus admittance matrix.

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

Minimize $\Phi(x,u) = \sum_{i=1}^{nobj} w_i \ \Phi_i$ (18)

Where the weights w that indicate the relative significance among the chosen objectives, are small positive real values, whose sum is usually set as one.

IV. PROPOSED ALGORITHM

The proposed TLO based method involves representation of problem variables and the formation of a performance function.

A. 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. S denotes the grade points of each student in the PM and represents the control variables in vector form as:

$$S = [P_k^G, V_j^G, T_v, \ I_p^{dc}]; \quad j \in \Pi \quad k \in \Psi \quad v \in \Re \quad p \in \Im \qquad (19)$$

B. Performance Function

The TLO searches for optimal solution by maximizing a fitness function, denoted by F, which is formulated from the objective function of Eq. (10) 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. F can be built as

$$Max \quad F = \frac{1}{1+\Phi^A} \qquad (20)$$

Where

$$\Phi^A = \Phi(x,u) + \lambda_V \sum_{i\in\Omega}\left(V_i^L - V_i^{\text{limit}}\right)^2 + \lambda_Q \sum_{i\in\Pi}\left(Q_i^G - Q_i^{\text{limit}}\right)^2 + \lambda_P\left(P_s^G - P_s^{\text{limit}}\right)^2 + \lambda_S \sum_{i\in M}\left(S_{Li} - S_{Li}^{max}\right)^2 \qquad (21)$$

$$V_i^{\text{limit}} = \begin{cases} V_i^{L(\min)} & if \ V_i^L < V_i^{L(\min)} \\ V_i^{L(\max)} & if \ V_i^L > V_i^{L(\max)} \\ V_i^L & else \end{cases}$$

(22)

$$Q_i^{\text{limit}} = \begin{cases} Q_i^{G(\min)} & if \ Q_i^G < Q_i^{G(\min)} \\ Q_i^{G(\max)} & if \ Q_i^G > Q_i^{G(\max)} \\ Q_i^G & else \end{cases} \qquad (23)$$

$$P_s^{\text{limit}} = \begin{cases} P_s^{G(\min)} & if \ P_s^G < P_s^{G(\min)} \\ P_s^{G(\max)} & if \ P_s^G > P_s^{G(\max)} \\ P_s^G & else \end{cases} \qquad (24)$$

The power system is altered through replacing the transmission lines of L_p^{dc} with DC currents of I_p^{dc} and setting the control parameters of $\{P_k^G, V_j^G \text{ and } T\}$ for each student. The AC/DC power flow is then run with a view of computing the objective function $\Phi(x,u)$ and the performance function F.

C. Repair Mechanism

It is undesirable to choose a transmission line for replacement by two or more DC links. During the iterative process, there is a possibility that a solution point may contain same line numbers in L_p^{dc} of the student for placing two or more DC links. If this happens, it may be corrected by the following repair mechanism.

Alter any one line number by generating a random number to represent another line.

Repeat the above step till no two numbers in L_p^{dc} are the same.

D.Stopping Criterion

The process of generating new population can be terminated either after a fixed number of iterations or after some number of iterations when there has been no increase in the fitness function value.

E. Solution Process

An initial population of students is obtained by generating random values within their respective limits to every individual in the population. The fitness F is calculated by considering gp_s of each student; and the teaching and learning phases are performed for all the students in the population with a view of maximizing their performances. The iterative process is continued till convergence. The pseudo code of the PM is presented below

Read *the Power System Data*
Cho Choose *the number of students in the population,* ns *and* $Iter^{max}$ *for convergence check.*
Generate *the initial population of students*
Set *the iteration counter* $t=0$
while *(termination requirements are not met) do*
  for $i=1:ns$
- *Repair the* i*-th student*
- *Replace the transmission lines by DC links and set the control parameters according to* i*-th student values*
- *Run AC/DC power flow*
- *Evaluate the augmented objective function* Φ^A *and performance function* F_i *using Eqs. 21 and 20 respectively*

  end-*(*i*)*
Choose *the best student possessing the largest* F_i *in the population as the teacher*
Evaluate *the mean grade point for each subject by Eq. (2)*
Perform *the Teaching phase to modify the grade points of each student by Eq. (4)*
Perform *the Learning phase to update the grade points of each student by Eq. (5)*
  end-*(while)*
Choose *the best student with highest* F_i *in the population as the optimal solution*

V. SIMULATIONS

The PM is tested on IEEE 14 and 30 bus test systems, whose data have been taken from Ref. [41]. The fuel cost coefficients, lower and upper generation limits for these two test systems are taken from Ref. [42-44] and given in Tables A.1 and A.2 of the Appendix-A. In addition, the initial generations at PV buses are altered to lie within the respective lower and upper limits as given in the Tables A-1andA-2 of Appendix-A. The sequential AC/DC power flow involving NR technique is used during the optimization process [4-6]. 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 HSO with a view of demonstrating the efficacy of the PM.

The optimal solution obtained by the PM and HSO for test case for 14 and 30 bus systems are given through Table A.3 respectively in Appendix-A. The performances in terms of FC of PM compared with the HSO based algorithms for the test Table 3 . The table 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 TLBO Parameter

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

Table 2 Transmission lines replaced by DC links

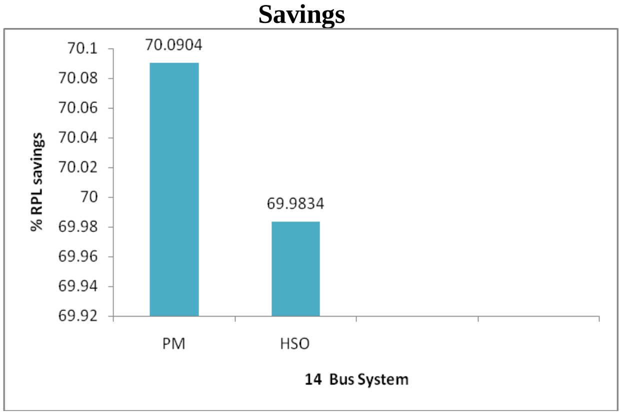
System	Line No
14 bus	9
30 bus	31 and 11

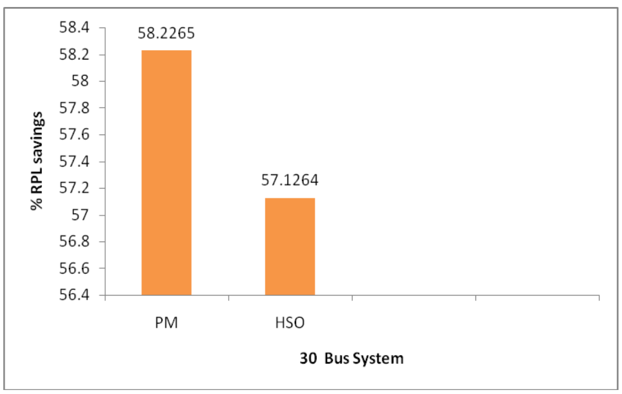
Table 3 Comparison of Performances for RPL

		Before Placement	**PM**	**HSO**
14	FC	834.6716	1022.2792	1022.2903
	RPL	8.9737	2.6840	2.6936
30	FC	813.6941	967.3416	967.4712
	RPL	7.0990	2.9655	3.0436

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 2.6840 and 2.6936 MW by the PM and HSO respectively for 14 bus system . Similarly, PM and HSO reduce the initial RPL of 7.0990 MW to 2.9655 and 3.0436 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 HSO . It is to be noted that PM offers better control settings with optimal dc link parameters, resulting in lower RPL than those of HSO. The % RPL savings of PM are graphically compared with those of HSO 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





VI. CONCLUSION

The study of OPF is an important analysis in power system operational planning. A multi-objective OPF with DC link placement problem is formulated and a TLO based solution strategy for the developed problem is suggested with a view to obtain the global best solution. This paper shows the Real Power Loss Minimization of AC/DC Hybrid Systems with Reactive Power Compensation. The solutions are treated as grade points of students and the best student in the population is considered as the teacher. The grade points are adjusted towards the best solution point based on the teaching and learning process. The algorithm uses sequential AC/DC load flow involving NR technique for computing the objective function during search. The Proposed Method approach is tested on IEEE 14 and 30 bus test systems. The results on the test systems 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 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	66.684032 80.000000 50.000000 35.000000 30.000000	138.539 57.560 24.560 35.000 17.930 16.910	51.365529 80.000000 50.000000 35.000000 30.000000 40.000000
V^G	1.060 1.045 1.010 1.070 1.090	1.100000 1.100000 1.082114 1.088746 1.092364	1.050 1.0338 1.0058 1.0230 1.0913 1.0883	1.100000 1.098027 1.078146 1.086575 1.087217 1.099333
T	0.978 0.969 0.932	1.005506 1.044602 0.982939	1.0155 0.9629 1.0129 0.9581	1.024026 0.990483 0.999349 0.972067
L_p^{dc}	---	9	---	31 11
I_p^{dc}	---	0.150796	---	0.100000 0.124734

REFERENCES

[1] Carpentier, J. (1962). Contribution a l'Etude du Dispatching Economique', Bulletin de la Societe Francaise des Electriciens, 3: 431-474

[2] Momoh. J.A., El-Hawary. M.E and Adapa. R. (1999). "*A review of selected optimal power flow literature to 1993 Part I: Nonlinear and quadratic programming approaches*". IEEE Trans. on Power Systems, 14: 96–104

[3] Momoh. J.A., El-Hawary. M.E and Adapa. R. (1999). "*A review of selected optimal power flow literature to 1993 Part II: Newton, linear programming and interior point methods*". IEEE Trans. on Power Systems, 14: 105-111

[4] T.K.Nagsarkar, M.S.Sukhija, "*Power system analysis"*, Oxford university press. **(2007)**

[5] J.Arrillaga,N.R.Watson, "*Computer modelling of Electrical power systems*", John wiley & sons Ltd. **(2013)**

[6] J.Arrillaga, C.RArnold, B.J.Harker, "*Computer modelling of Electrical power systems*", John wiley & sons Ltd. **(1983)**

[7] K.Y. Lee, Y.M. Park, and J.L.Oritz. (1984). "*Fuel-cost minimization for both real and reactive power dispatches*", IEE Proceedings C. 131(3): 85-93.

[8] K. Mangoli, and K.Y. Lee. (1993). "*Optimal real and reactive power control using linear programming"*, Electrical Power System Research. 26(1): 1-10.

[9] Dommel. H and Tinny. W (1968). "*Optimal power flow solution, IEEE Trans*". Power Appar. Syst., PAS-87(10) :1866–1876

[10] O.Alsac,and B. Scott. (1974). "*Optimal load flow with steady state security*", IEEE Transactions on power Apparatus and systems. PAS: 745-751.

[11] Wei H, Sasaki H, Kubokawa J and Yokoyama R. (1998). "*An interior point nonlinear programming for optimal power flow problems with a novel structure data*". IEEE Trans Power Syst., 13: 870–877.

[12] Yan X and Quantana VH. (1999). "*Improving an interior point based OPF by dynamic adjustments of step sizes and tolerances*". IEEE Trans Power Syst., 14(2): 709–17.

[13] Momoh JA and Zhu JZ. (1999). "*Improved interior point method for OPF problems*". IEEE Trans Power Syst., 14(3): 1114–20.

[14] Burchett RC, Happ HH and Vierath DR. (1984). "*Quadratically convergent optimal power flow*". IEEE Trans Power Apparatus Syst., 103: 3267–76.

[15] Lai LL and Ma JT. (1997). "*Improved genetic algorithms for optimal power flow under both normal and contingent operation states*". Int J Elercr Power Energy Syst., 19(5): 287-92.

[16] Sailaja Kumari M and Maheswarapu S. (2010). "*Enhanced genetic algorithm based computation technique for multi-objective optimal power flow*". Int J Electr Power Energy Syst., 32(6): 736-42.

[17] Kılıç, U, Ayan. K. (2013). "*Optimal power flow solution of two terminal HVDC systems using genetic algorithm"*, Electrical Engineering 96(1): 65-77.

[18] Kılıç. U, Ayan. K, Arifoğlu. U. (2014). "*Optimizing reactive power flow of HVDC systems using genetic algorithm*", International Journal of Electrical Power and Energy Systems 55: 1-12.

[19] Yuryevich J and Wong KP. (1999). "*Evolutionary based optimal power flow algorithm*". IEEE Trans Power Syst., 14(4):1245-50.

[20] Ongsakul. W and Tantimaporn. T. (2006). "*Optimal powers flow by improved evolutionary programming*"', Electr. Power Comp. Syst., 34(1): 79-95.

[21] Sood YR. (2007). "*Evolutionary programming based optimal power flow and its validation for deregulated power system analysis*". Int J Electr Power Energy Syst, 29(1): 65-75.

[22] Abido, M.A. (2002). "*Optimal power flow using particle swarm optimization*"', Proc. Int. J. Electr. Power Energy Syst., 24(7): 563–571

[23] Onate Yumbla. P.E., Ramirez. J.M and Coello Coello. C.A. (2008). "*Optimal power flow subject to security constraints solved with a particle swarm optimizer"*', IEEE Trans. Power Syst., 23 (1), 33-40.

[24] Kim JY, Mun KJ, Kim HS and Park JH. (2011). "*Optimal power system operation using parallel processing system and PSO algorithm*". Int J Electr Power Energy Syst., 33(8): 1457-61.

[25] Sayah. S and Zehar. K. (2008). "*Modified differential evolution algorithm for optimal power flow with non-smooth cost functions*", Int. J. Energy Convers. Manage., 49 (11): 3036-3042

[26] Abido. M.A and Al-Ali. N.A. "*Multi-objective differential evolution for optimal power flow, Int. Conf. on Power Engineering*", Energy and Electrical Drives, POWERENG 2009, Lisbon, Portugal, 18–20 March 2009: 101–106.

[27] Abou El Ela, A.A., Abido, M.A. (2010). "*Optimal power flow using differential evolution algorithm*", Electr. Power Syst. Res., 80 (7): 878–885

[28] A.V.Naresh babu, T. Ramana and S.Sivanagaraju. (2014). "*Analysis of optimal power flow problem based on two stage initialization algorithm",* Int J Electr Power Energy Syst., 55: 91-99.

[29] Niknam T, Narimani MR, Jabbari M and Malekpour AR. (2011). "*A modified shuffle frog leaping algorithm for multi-objective optimal power flow"*. Energy, 36: 6420–32.

[30] Sivasubramani S and Swarup KS. (2011). "*Multi-objective harmony search algorithm for optimal power flow problem*". Int J Electr Power Energy Syst., 33(3): 745–52.

[31] Duman S, Güvenç U, Sönmez Y and Yörükeren N. (2012). "*Optimal power flow using gravitational search algorithm. Energy Convers Manage"*, 59: 86-95.

[32] B.Srinivasa Rao and K. Vaisakh. (2013). "*Multi-objective adaptive clonal selection algorithm for solving environmental/economic diaptch and OPF problems with load uncertainty*", Electrical Power and Energy Systems, 53: 390-408.

[33] M. Rezaei Adaryani and A. Karami. (2013). "*Artificial bee colony algorithm for solving multi-objective optimal power flow problem*", Electrical Power and Energy Systems, 53: 219-230.

[34] Amin Shabanpour-Haghighi, Ali Reza Seifi and Taher Niknam. (2014). "*A modified teaching-learning based optimization for multi-objective optimal power flow problem*", Energy Convers Manage, 27: 597-607.

[35] Rao, R.V., Savsani, V.J. and Vakharia, D.P. (2012). "*Teaching-learning-based optimization: A novel optimization method for continuous non-linear large scale problems*". Information Sciences, 183 (1): 1-15.

[36] Rao, R.V., Savsani, V.J. and Vakharia, D.P. (2011). "*Teaching-learning-based optimization: A novel method for constrained mechanical design optimization problems*". Computer-Aided Design, 43 (3): 303-315.

[37] M.R. Nayak, C.K. Nayak and P.K. Rout. (2012). "*Application of Multi-Objective Teaching Learning based Optimization Algorithm to Optimal Power Flow Problem*", Procedia Technology, DOI:10.1016/j.protcy.2012.10.031, vol.6: 255–264

[38] Provas Kumar Roy, Ranadhir Sarkar. (2014). "*Solution of unit commitment problem using quasi-oppositional teaching learning based algorithm*", Electrical Power & Energy Systems, Vol. 60: 96-106

[39] H.R.E.H. Bouchekara, M.A. Abido, M. Boucherm. (2014). "*Optimal power flow using Teaching-Learning-Based Optimization technique"*, Electric Power Systems Research, Vol. 114: 49-59.

[40] P. Kessel and H. Glavitsch. (2000). "*Estimating the voltage stability of a power system*", IEEE Trans. Power Deliver, 1(3): 346-54.

[41] Test Systems Archive, Available at http://www.ee.washington.edu/research/pstca/ (Accessed December 2012).

[42] Tahir Nadeem Malika, Azzam ul Asarb, Mudasser F. Wynec and, Shakil Akhtar. (2010). "*A new hybrid approach for the solution of nonconvex economic dispatch problem with valve-point effects*", Electric Power Systems Research, 80: 1128–1136

[43] Jason Yuryevich and Kit Po Wong. (1999). "*Evolutionary programming based optimal power flow*", IEEE Trans. on Power Systems, 14(4): 1245-1257.

[44] S. Prabhakar Karthikeyan, K. Palanisamy, C. Rani, I. Jacob Raglend and DP. Kothari. (2009). "*Security constrained unit commitment problem with operational, power flow and environmental constraints*", WSEAS Trans". on Power Systems. 4(2): 53-56.