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Biobjective Optimal Reactive Power Flow using Chemical Reaction based Optimization

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ABSTRACT

The optimal reactive power flow (ORPF) helps to effectively utilize the existing reactive power source with a view to minimize the network loss and improve voltage profile. The chemical reaction optimization (CRO), inspired from the interactions of molecules in a chemical reaction to reach a low energy stable state and searches for optimal solution through reactions involving the on-wall ineffective collisions, decomposition, inter-molecular ineffective collision and synthesis. This paper attempts to develop a global best solution method that simultaneously minimizes the network loss and enhances the voltage profile for ORPF using CRO. The results of IEEE 30 bus system are presented to demonstrate its performance.

NOMENCLATURE

CRO	chemical reaction optimization
DE	differential evolution
ORPF	optimal reactive power flow
$G_{ij} + jBij$	real and imaginary terms of bus admittance matrix corresponding to k-th row and -j-th column
g_{ij}	conductance of the transmission line connected between buses -i and j
$g(x,u)$	equality constraint
$h(x,u)$	inequality constraint
$J(x,u)$	objective function
KE	kinetic energy
NVD	net voltage deviations
nc	number of shunt reactive power compensators
n	number of decision variables
$nobj$	number of objectives
ng	number of generators

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nt	number of transformers
PE	potential energy
PM	proposed method
PS	population size
Q_{Gi}	reactive power generation at bus-i
Q_{Ci}	reactive power injection by i-th shunt compensator
RPL	real power loss
T_i	tap settings of i-th transformer
VP	voltage profile
V_i	voltage at i-th bus
$V_{Li}^{\lim it}$	limit violated voltage magnitude at i-th load bus
$Q_{Gi}^{\lim it}$	limit violated reactive power generation at i-th PV bus
V_{Gi}	voltage magnitude at i-th generator bus
V_{Li}	voltage magnitude at i-th load bus
x	vector of dependant variables
u	vector of control or independent variables
λ_1 and λ_2	weight factors
λ_V and λ_Q	penalty factors
ω_i	structure of i-th molecule
$\Im$	a set of transmission lines
Φ	a set of load buses
Ω	a set of generator buses
superscript $\min$ and $\max$	lower and upper limits respectively

INTRODUCTION

Optimal Reactive Power Flow (ORPF) attempts to minimize the real power loss (RPL) via the optimal adjustment of the power system control variables, while at the same time satisfying various equality and inequality constraints. 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 problem control variables comprise the generator bus voltages, the transformer tap settings, and the reactive power of shunt compensators, while the problem dependent variables contain the load bus voltages, the generator reactive powers, and the line flows. Generally ORPF problem is a large scale highly constrained nonconvex and multimodal optimization problem (Alsac, O. and B. Scott, 1974; Lee, K.Y., *et al*., 1985).

Several traditional optimization techniques such as gradient method (Alsac, O. and B. Scott, 1974; Lee, K.Y., *et al*., 1985), Newton method (Monticelli, A., *et al*., 1987), linear programming (Deeb, N. and S.M. Shahidehpur, 1990; Hobson, 1980; Lee, K.Y., *et al*., 1984; Mangoli, M.K. and K.Y. Lee, 1993), interior point method (Momoh, J.A., *et al*., 1994) and non linear programming (Wu, Y.C., *et al*., 1994) have been applied to solve the ORPF problem. These methods have severe limitations in handling non-linear and discontinuous objectives and constraints. Besides, these classical optimization techniques involving derivatives and gradients may not be able to determine the global optimum. Thus there is a need for evolving simple and effective methods for obtaining global optimal solution for the ORPF problem.

Metaheuristic methods such as genetic algorithm (GA) (Wu, Q.H., *et al*., 1998; Durairaj, S., *et al*., 2005; Yan, W., *et al*., 2006), evolutionary programming (Lai, L.L. and J.T. Ma, 1997), particle swarm optimization (PSO) (Mahadevan, K. and P.S. Kannan, 2010), differential evolution (DE) (Vaisaka, K. and P. Kanta Rao, 2008; Chung, Y., *et al*., 2010; Abou El Ela, A.A., *et al*., 2011), seeker optimization algorithm (Dai, B., W. Chen, 2009) and biogeography based optimization (BBO) (Bhattacharya and K.P. Chattopadhyay, 2010) have been recently applied in solving the ORPF problems. These algorithms have found extensive applications in solving complex optimization problems, when the classical optimization technique cannot be applied. These approaches are more likely to converge towards the global solution because they simultaneously evaluate many points in the search space and do not require assuming that the search space is differentiable or continuous.

More recently, a Chemical Reaction Optimization (CRO), a population based stochastic optimization technique inspired from the process of chemical reactions, has been suggested for solving combinatorial optimization problems in discrete domains by Lam *et al*. (2010). A modified version of CRO, named as real coded CRO, to handle problems in both continuous and discrete domains, has been outlined in (Lam Albert, Y.S., *et al*., 2012). The CRO has been applied to a variety of optimization problems (Kuntal Bhattacharjee, *et al*., 2014; Xu, J., *et al*., 2011; Yu, J.J.Q., *et al*., 2011) that includes economic emission load dispatch (Kuntal Bhattacharjee, *et al*., 2014) and found to yield satisfactory results.

Though ORPF attempts to minimize the network loss, there is a need for better voltage profile from consumer point of view. This paper thus focuses in developing a solution method that simultaneously minimizes the network loss and enhances the voltage profile. It formulates the ORPF as a biobjective optimization problem and then builds a CRO based methodology for obtaining the global best solution. The results of IEEE 30 bus system are presented to demonstrate the effectiveness of the developed strategy.

CRO:

In chemical reactions, the molecules of initial reactants, possessing high-energy unstable states, undergo a sequence of collisions either with walls of the container or with other molecules, pass through some energy barriers and become final products by releasing energy. The final products generally have less energy, thereby making them more stable than the reactants. This phenomenon of driving the molecules from high-energy unstable states to low-energy stable states by chemical reaction can be related to the process of minimising the objective function value in optimization problems through adjusting the control variables. Inspired from this relation, CRO algorithm for solving multimodal optimization problems has been developed by Lam *et al*. (Lam AYS, Li VOK, 2010; Lam Albert, Y.S., *et al*., 2012). In CRO algorithm, each solution point in the problem space is represented by a molecule, which composes several atoms and involves two kinds of energies, the potential energy (PE) and the kinetic energy (KE). Each molecule therefore contains a profile of several properties such as ω, PE and KE. The PE represents the problem objective function for each solution point ω as

Minimize $PE_i = f(\omega_i)$ (1)

When the algorithm evolves, the molecules adjust their structure through a sequence of collisions among molecules to possess lower PE and KE and the removed energy is stored in a central energy buffer. Molecules collide either with each other or with the walls of the container, resulting in an internal change of molecules. There are four types of elementary reactions implemented in CRO, namely, on-wall ineffective collision, decomposition, inter-molecular ineffective collision, and synthesis. These reactions explore the solution space in search of optimal solution.

An initial set of molecules with size equal to PS is then randomly generated in the solution space. Their initial PEs are determined by their corresponding objective function values. In each iteration, there is one elementary reaction taking place, which is probabilistically chosen by generating a random number. The molecule with lowest PE is recorded and the iterative process is continued until the stopping criterion is met. After convergence, the molecule with the lowest PE is considered as the optimal solution. The detailed pseudo code is available in Ref. (Lam AYS, Li VOK, 2010).

Problem Formulation:

The ORPF problem is formulated as a biobjective optimization problem with several equality and inequality constraints as

Minimize $J(x,u) = \lambda_1 \; RPL + \lambda_2 \; NVD$ (2)

Subject to

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

$$h(x,u) \le 0 \tag{4}$$

Where

$$RPL = \sum_{k \in \Im} g_{ij} \left(\left|V_i\right|^2 + \left|V_j\right|^2 - 2\left|V_i\right| \left|V_j\right| \cos\delta_{ij} \right) \tag{5}$$

$$NVD = \sum_{j \in \Phi} \left|V_j - 1\right| \tag{6}$$

x is the vector of dependant variables consisting of load bus voltage magnitudes, reactive power generation at generator buses and real power generation at slack bus. u is the vector of control or independent variables comprising of generator bus voltage magnitudes, transformer tap settings and output of reactive shunt compensators. The equality constraints $g(x,u)$ are the sets of non-linear power flow equations that govern the power system

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{nb} V_j \left(G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right) = 0 \quad (7)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{nb} V_j \left(G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \right) = 0 \quad (8)$$

The equality constraints $h(x,u)$ represent the operating limits on reactive power generations, transformer tap settings and voltage magnitudes.

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (9)$$

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max} \quad (10)$$

$$T_i^{\min} \le T_i \le T_i^{\max} \quad (11)$$

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \quad (12)$$

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} \quad (13)$$

Proposed Method:

The proposed method involves representation of problem variables and the formation of appropriate PE function.

Representation of Control Variables:

In CRO, a solution is represented by a molecular structure- ω_i. In the proposed method, each molecular structure ω_i is defined to denote the control variables of voltage magnitude at generator buses, transformer tap positions and reactive power of shunt compensators in vector form as

$$\omega_i = [V_{G1}, V_{G2}, \cdots, V_{Gng}, T_1, T_2, \cdots, T_{nt}, Q_{C1}, Q_{C2}, \cdots, Q_{Cnc}] \quad (14)$$

Formation of PE Function:

The proposed method searches for optimal solution by minimizing a PE function, which is formulated from the objective function and the penalty terms representing the limit violation of the dependant variables such as reactive power generation at PV buses and voltage magnitude at load buses. The PE function is built as

$$PE = J(x,u) + \lambda_V \sum_{i \in \Phi} \left(V_{Li} - V_{Li}^{\lim it} \right)^2 + \lambda_Q \sum_{i \in \Omega} \left(Q_{Gi} - Q_{Gi}^{\lim it} \right)^2 \quad (15)$$

Where

$$V_{Li}^{\lim it} = \begin{cases} V_{Li}^{\min} & \text{if } V_{Li} < V_{Li}^{\min} \\ V_{Li}^{\max} & \text{if } V_{Li} > V_{Li}^{\max} \\ V_{Li} & \text{else} \end{cases} \quad (16)$$

$$Q_{Gi}^{\lim it} = \begin{cases} Q_{Gi}^{\min} & \text{if } Q_{Gi} < Q_{Gi}^{\min} \\ Q_{Gi}^{\max} & \text{if } Q_{Gi} > Q_{Gi}^{\max} \\ Q_{Gi} & \text{else} \end{cases} \quad (17)$$

Solution Process:

The population containing molecules is initialized by random values within the respective control variable limits. The ACRO search process is performed through chemical reactions involving the on-wall ineffective collisions, decomposition, inter-molecular ineffective collision and synthesis, after evaluating the PE values. The molecule with lowest PE is recorded and the iterative process is continued till convergence. The algorithmic steps are summarized below:

1. Read the ORPF problem data
2. Choose CRO parameters
3. Randomly generate molecules to form the initial population and initialize KE of all molecules
4. Probabilistically choose any one of the reaction process of on-wall ineffective collision, decomposition, inter-molecular ineffective collision and synthesis.
5. Randomly select a molecule or molecules depending on the chosen reaction process.
6. Set the control parameters based on the values of molecule, perform load flow, evaluate the RPL and NVD and then compute PE .
7. Modify the molecules according to the chosen reaction process.
8. Repeat the steps 4-7 till convergence.
9. The molecule with lowest PE is the optimal solution
10. Stop

Simulations:

The PM is tested on IEEE 30 bus test system, whose data have been taken from Ref. (Lee, K.Y., *et al*., 1985). The IEEE 30 bus system comprises 6 generators at buses 1, 2, 5, 8, 11 and 13 and four tap changing transformers at lines 6-9, 6-10, 4-12 and 28-27. The adjustable shunt reactive power sources are connected at buses 10, 12, 17, 20, 21, 23, 24 and 29 for reactive power control. The net power demand of the system is 2.834 per unit on 100 MVA base. The lower and upper voltage limits for both generator and load buses are taken as 0.95 and 1.1 per unit respectively. NR technique (Tinney, W.F. and C.E. Hart, 1967) is used to carry out the load flow during the optimization process. The optimal solution obtained by the proposed method is compared with that of the DE (Abou El Ela, A.A., *et al*., 2011) based method in Table 1. It is very clear from the table that the PM is able to reduce the both the RPL and NVD lower than that of the DE. The voltage magnitudes of all load buses of the PM are graphically compared with that of the base-case voltages in Fig.1. It clearly indicates that the PM offer better voltage profile and they lie in-between the lower and upper limits. It can also be observed that all the bus voltages are very closer to the nominal bus voltage of 1.0 per unit.

Table 1: Comparison of Results

Control Variables	Base Case	PM	DE [17]
V_{G1}	1.05	1.03489	1.0993
V_{G2}	1.04	1.02579	1.0967
V_{G5}	1.01	1.00509	1.0990
V_{G8}	1.01	1.00133	1.0346
V_{G11}	1.05	0.97899	1.0993
V_{G13}	1.05	1.01399	0.9517
T_{6-9}	1.078	0.99265	0.9038
T_{6-10}	1.069	0.90694	0.9029
T_{4-12}	1.032	0.98852	0.9002
T_{28-27}	1.068	0.97083	0.9360
Q_{C10}	0.0	0.05000	0.00685
Q_{C12}	0.0	0.04892	0.04716
Q_{C15}	0.0	0.04982	0.04493
Q_{C17}	0.0	0.01978	0.04510
Q_{C20}	0.0	0.04997	0.04477

Q_{C21}	0.0	0.04994	0.04608
Q_{C23}	0.0	0.04982	0.03881
Q_{C24}	0.0	0.04999	0.04285
Q_{C29}	0.0	0.02858	0.03254
RPL	0.05812	0.05271	0.07073
NVD	1.1283	0.10636	1.4191

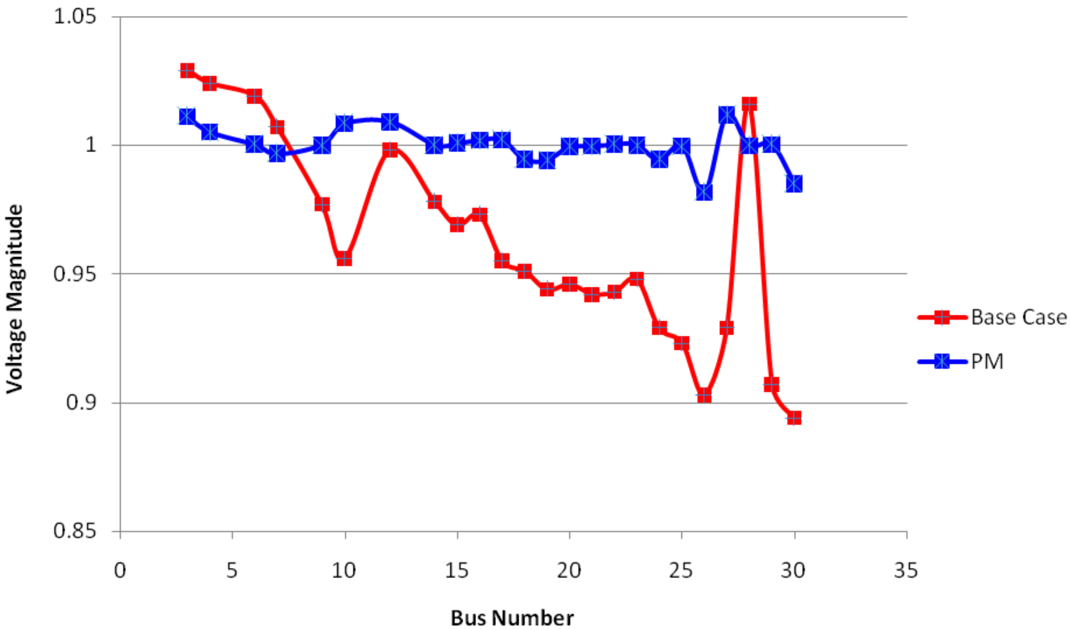

Fig. 1: Plot of voltage profile

Conclusion:

CRO is a population based stochastic optimization technique, inspired from the process of chemical reactions, for solving multimodal optimization problems. ORPF is a complex optimization problem determines the values for system control variables that minimize the RPL, while at the same time satisfying various equality and inequality constraints. The problem is formulated as a biobjective optimization problem of simultaneously minimizing both the RPL and NVD. A CRO based solution methodology is developed for the biobjective ORPF problem. The PM attempts to efficiently search the solution space, avoid the local trap and enhance the convergence. The results of IEEE 30 bus test system project the ability of the PM in obtaining the global best solution. Besides the PM offers a better VP that lies nearer to the nominal bus voltage of 1.0 per unit. The PM for solving ORPF will go a long way in serving as a constructive tool in load dispatch centre.

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