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Full Length Article

Optimizing real power loss and voltage stability limit of a large transmission network using firefly algorithm

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ABSTRACT

This paper proposes a Firefly algorithm based technique to optimize the control variables for simultaneous optimization of real power loss and voltage stability limit of the transmission system. Mathematically, this issue can be formulated as nonlinear equality and inequality constrained optimization problem with an objective function integrating both real power loss and voltage stability limit. Transformers taps, unified power flow controller and its parameters have been included as control variables in the problem formulation. The effectiveness of the proposed algorithm has been tested on New England 39-bus system. Simulation results obtained with the proposed algorithm are compared with the real coded genetic algorithm for single objective of real power loss minimization and multi-objective of real power loss minimization and voltage stability limit maximization. Also, a classical optimization method known as interior point successive linear programming technique is considered here to compare the results of firefly algorithm for single objective of real power loss minimization. Simulation results confirm the potentiality of the proposed algorithm in solving optimization problems.

1. Introduction

In recent years, the Optimal Power Flow (OPF) has become an essential tool in power systems planning, operation and control for both integrated and deregulated power industries. OPF is stated as a nonlinear, nonconvex, static optimization problem with both discrete and continuous variables. The OPF problem solution aims to optimize certain objective functions like Real Power Loss (RPL) through optimal adjustment of various control variables, while satisfying both equality and inequality constraints. RPL minimization, generation cost minimization and voltage stability enhancement are the different objectives of OPF problem. The mathematical formulation of OPF problem was firstly presented by Dommel and Tinny [1] and then the issue has been handled by several researchers. In the literature, there are many conventional techniques such as Newton based programming method [2], Linear programming method [3] and recently Interior point method [4] to solve the OPF problem.

With the development of Flexible AC transmission Systems (FACTS) technology, there is a possibility of controlling power flow to improve power system performance without generation rescheduling and topology changes. Among all the FACTS controllers, Unified Power Flow Controller (UPFC) is a popular device that provides flexibility in OPF by means of shunt and series compensation [5,6]. Glanzman and Anderson [7] coordinated several FACTS devices to avoid congestion, to provide secure transmission with reduced RPL. But, it is a well known fact that a secure operation of power system is not possible unless the optimization problem takes into account the system voltage security in its solution. Continuation Power Flow (CPF), a powerful tool, gives the information about the percentage of overloading capability of the system without voltage collapse [8]. In Reference [9], Milano et al. successfully included CPF problem into an OPF problem to address simultaneously both the security and the voltage collapse issues. voltage stability limit (VSL) is defined as the maximum percentage overloading (λ_{max}) capability the system can withstand without voltage collapse, which is considered as another objective function along with the RPL minimization, thereby redefining the task as multi-objective optimization problem. The difficulty with the traditional techniques lies in the fact that they are more sensitive to initial points due to non monotonic solution surface and so not able to find the global optimum. To overcome the restrictions of traditional algorithms, meta-heuristic algorithms have been applied to work out OPF problems. Recently, nature inspired meta-heuristic algorithms show a powerful and efficient performance for dealing with high dimension nonlinear OPF problems. In all meta-heuristic search techniques, much effort has been devoted to make an appropriate trade-off between exploration and

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exploitation in searching for the optimal solutions. Many meta-heuristic algorithms have been applied to solve OPF problems, such as Particle Swarm Optimization (PSO) [10], Tabu Search (TS) algorithm [11], Bacteria Foraging Algorithm (BFA) [12], Differential Evolution (DE) algorithm [13], and Gravitational Search Algorithm (GSA) [14]. More recently, harmony search algorithm [15,16], Krill Herd (KH) algorithm [17–22] and monarch butterfly optimization [23] perform powerfully and efficiently in solving highly non linear optimization problems.

In the present paper, a meta-heuristic algorithm known as FA is employed to solve the combined OPF and CPF problem of RPL minimization and VSL maximization. The FA is developed by "Xin-She Yang" [24–32] based on the flashing behavior of the fireflies which are available in nature. A comprehensive review of FA and its merits and demerits is given in Reference [27]. In Reference [33], the authors have applied FA to solve Economic Load Dispatch Problem (ELDP) and recently it has been applied to solve OPF problem, incorporating Thyristor Controlled Series Capacitor (TCSC) to enhance power transfer capability of transmission line [34]. In this work, the control variables like transformer tap positions, UPFC location and its variables are optimized with the FA to optimize the single objective function of RPL minimization and multi-Objective of RPL minimization and VSL maximization, keeping all the variables within the limits. For both cases of single and multiple objectives, the optimization is carried out in three ways. First, only transformer taps are optimized, second UPFC location and its variables are only optimized with fixed optimized tap positions, and finally both the transformer taps and UPFC variables are simultaneously optimized. New England 39-bus system is considered as the test system for simulation purpose. The simulation results are compared with the results of IPSLP method and RCGA method to show the potentiality of the proposed algorithm.

The structure of this paper is organized as follows. Section 2 presents the mathematical formulations of single and multi-objective optimization problems along with principle of operation of UPFC. Section 3 describes global numerical optimization, the FA. The RCGA method is presented in section 4. Section 5 describes IPSLP technique. In section 6, the results of the proposed FA are compared with the results of RCGA and IPSLP methods. Finally, section 7 provides the conclusion and points out the path of the future work.

2. Statement of the problem

Problem: To solve single objective function problem of RPL minimization and multi-objective function problem of RPL minimization and maximization of VSL of the New England 39 bus test systems, connected with UPFC by using IPSLP, RCGA and FA. Here, both sequential and simultaneous allocation of transformer taps and UPFC are carried out for comparison.

2.1. Problem formulation of OPF

Mathematically, OPF problem of RPL minimization can be formulated as follows:

$$\begin{aligned}&\text{Minimize } F(x,u)\\&\text{Subject to } g(x,u)=0\\&h(x,u)\le 0\end{aligned} \quad (1)$$

F(x, u) is the fitness function equating to the RPL of the test system. g*(x, u)* is a set of non linear equality constraints to represent power flow, and *h(x, u)* is a set of nonlinear inequality constraints i.e., bus voltages, transformer tap setting values, line MVA limits, etc. Vector *x* consists of state variables or dependent variables and vector u consists of independent variables or control variables. In this research work, the control variables are transformer tap values, which can vary in between 0.85 and 1.15 in step of 0.05, series injected voltage magnitude (V_{se}) of UPFC with the ranges [0, 0.3 p.u.] and series injected voltage phase angle (δ_{se}) of UPFC with the range [0,2π]. All these control variables are optimized with IPSLP, RCGA and FA to minimize the RPL of the test system. Here, the minimum and the maximum voltages of load buses are considered as 0.9 p.u. and 1.1 p.u. for the test system.

2.2. OPF formulation considering with VSL

The single objective function could be extended further with the inclusion of VSL, results a new fitness function. The VSL can be calculated through continuation power flow (CPF) technique which introduces load parameter (λ) stated as the percentage increase of load and generation from its base value. The resulting load and generation equations in terms of the load parameter are given as follows:

$$P_{Li}=P_{Li0}(1+\lambda) \quad (2)$$

$$Q_{Li}=Q_{Li0}(1+\lambda) \quad (3)$$

$$P_{Gi}=P_{Gi0}(1+\lambda) \quad (4)$$

The load parameter (λ) can be increased until the system soon reaches the edge of instability, which is also called as notch point (NP) of the P–V curve. So the maximum value of the load parameter (λ_{max}) is known as voltage stability limit (VSL). The objective is to

$$\begin{aligned}&\text{Optimize } F(x,u,\lambda_{max})\\&\text{Subject to } g(x,u)=0\\&h(x,u)\le 0\end{aligned} \quad (5)$$

Since both the RPL and voltage stability limits are in different range of values, the fitness function is formulated as a weighted sum. The reciprocal of VSL is sum to original cost function and overall cost function can be minimized. The fitness function to be optimized now can be represented as follows:

$$F(x,u,\lambda_{max})=W1*G(x,u)+W2*V(\lambda_{max}) \quad (6)$$

$$\text{where } G(x,u)=RPL$$

$$V(\lambda_{max})=1/\lambda_{max}=VSL$$

W1 is the weight adjustment for RPL and W2 is the weight adjustment for VSL. Ideally, W1 and W2 are adjusted so that the weighted values of RPL and VSL are similar in value. To find out this critical point in the system, the process of CPF [8] is carried out for each solution generated. The load is increased in steps, and for each increment, the values are calculated by the process of prediction and correction.

2.3. Unified power flow controller

The UPFC structure shown in Fig. 1 basically shares the same dc-link to operate the two switching converters supplied by a common energy stored dc capacitor. The shunt and series transformers are used to couple the switching converter 1 and switching converter 2 to the power system network respectively. The converter 1 is connected in shunt to bus *i* while the converter 2 is connected in series between bus *i* and bus *j*. The series converter injects the necessary control voltage with the desired magnitude and phase angle through the coupling transformer to control the flow of required active and reactive power in the transmission line. The basic function of shunt converter is to interchange the real power with the power system network to maintain the energy stored at the common dc-link