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A two stage model for rotor angle transient stability constrained optimal power flow

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ABSTRACT

Transient stability constrained optimal power flow (TSCOPF) is a nonlinear optimization problem with both algebraic and differential equations. This paper utilizes the Imperialist Competitive Algorithm (ICA) as an evolutionary optimization algorithm and Artificial Neural Network (ANN) to develop a robust and efficient two stages scheme to solve TSCOPF problem. In the first stage an Artificial Neural Network is constructed to predict the rotor-angle transient stability margin, and is then incorporated in the TSC-OPF as the transient stability estimator. To solve the proposed TSC-OPF problem the ICA is used as the optimizer. The performance of the proposed method is verified over the WSCC three-machine, nine-bus system under different loading conditions and fault scenarios.

Introduction

Nowadays modern power systems are operated close to their stability boundaries due to the rapid increase of electricity demand and competitive environment resulted by the power system restructuring. This issue increases the probability of instability phenomena such as rotor-angle transient instability. A severe disturbance or super-contingency can make severe oscillations in the rotor angles of synchronous generators. When a generator loses its synchronism, the out-of-step relays trip the related unstable generators and cascading events may be initiated. Therefore prediction of transient instability in a power system could be very helpful to avoid a widespread blackout. The initial loading of generators (i.e. before occurrence a severe contingency) affects the transient stability margin significantly. Active power outputs of generators are scheduled by economic dispatch study. Indeed the economic dispatch is modeled as on OPF problem with the aim of minimizing total production cost. The OPF formulation with considering transient stability constraint is named transient stability constrained OPF, TSC-OPF. TSC-OPF problem is a nonlinear programming problem with algebraic differential equations. To solve a TSC-OPF problem two main issues must be considered:

1. the procedure of modeling transient stability margin in OPF problem,
2. the optimization algorithm to solve TSC-OPF problem.

To determine the transient stability margin it is required to include swing equations of each generator inside the OPF formulation. Therefore in each iteration of TSC-OPF problem, in addition to steady state load flow equations, it is required to solve a non-linear second-order differential equation for each generator. In other word the solution of TSC-OPF problem as a set of differential–algebraic equations using available analytic optimization techniques is difficult and time consuming. A well-known approach for TSC-OPF problem is to convert the differential equations into their discredited algebraic forms [1–3]. Another proposed method is to convert the infinite-dimensional TSC-OPF problem to a solvable finite-dimensional programming problem, based on the functional transformation techniques [4]. In [5] authors have proposed a method to stabilize the contingencies by redispatching active power generations and then optimizing the other variables via a conventional OPF, using sensitivity analysis. Most of previously proposed methods have used the maximum rotor angle deviation as the Transient Stability Index (TSI) [1,4]. Others have developed transient energy functions which is determined by the kinetic and potential energy of a post-fault power system as a quantitative index of the transient stability margin [6,7]. Here the Critical Clearing Time (CCT) is used as the transient stability index. CCT is the largest possible time for which a power system

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could be remained in fault condition without losing stability. This index must be determined by considering all credible contingencies [1,2,6].

To overcome the disadvantages of analytic optimization techniques, modern heuristic optimization techniques such as evolutionary algorithms have been utilized to solve the TSC-OPF problem [8,9]. On-line stability assessment using time-domain simulation fails to give efficient on-time results. Therefore it is needed to develop alternative transient stability estimators. Transient stability assessment could be carried out using Artificial Neural Network [10]. In this paper, a Multi-Layer Perceptron is used to estimate the CCT of the power system. In other word instead of direct calculation of stability margin (e.g. by a transient stability simulator) a MLP estimator is constructed using a comprehensive list of operation and fault scenarios and is then inserted in OPF formulation as TSI estimator.

Due to differential equations the proposed TSC-OPF couldn't be solved using mathematical optimization techniques. Therefore an ICA technique is developed to solve the proposed ANN-based TSC-OPF problem. The rest of this paper is organized as follows. In next section, the formulation of conventional OPF will be described. The ICA optimization technique is presented in Sectio n "Imperialist Competitive Algorithm". The transient stability index and overall structure of the proposed model are discussed in Sections "Transient stability index" and "Overall structure of the proposed scheme". The details of utilized neural network are presented in Section "Artificial Neural Network". The simulation results are given in Section "Simulation results". Finally a conclusion is provided in Section "Conclusion".

Conventional OPF

The main purpose of an OPF problem is to determine the optimal economic and secure operating point of a power system and the corresponding settings of control variables. This issue is achieved by minimizing a pre-defined objective function (usually total production cost) subject to steady state physical and operational constraints. The conventional OPF problem is an optimization model with an objective function and a set of equality and inequality constraints. The formulation of a conventional OPF model could be expressed as follows:

$$Minimize\ F = \sum_{i=1}^{N_g}(a_i + b_i p_{gi} + c_i p_{gi}^2) \quad (1)$$

$$s.t.\ P_{gi} - P_{di} - V_i \sum_{j=1}^{N} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \quad (2)$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \quad (3)$$

$$P_{gi}^{\min} \leqslant P_{gi} \leqslant P_{gi}^{\max} \quad (4)$$

$$Q_{gi}^{\min} \leqslant Q_{gi} \leqslant Q_{gi}^{\max} \quad (5)$$

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \quad (6)$$

$$|S_{Li}| \leqslant S_{Li}^{\max} \quad (7)$$

where the aim of objective function Eq. (1) is to minimize the total production cost of thermal units. The equality constrains given by Eqs. (2) and (3) refer to the steady state load flow algebraic equations. The inequality constraints presented in Eqs. (4)–(7) express the limitations of active power generations, reactive power generations in all voltage controlled nodes, voltage magnitudes at load buses and power flow in all transmission lines, respectively.

Set of voltage controlled nodes and transmission lines are shown by N_g and N_l ,respectively. Variables P_{gi} and Q_{gi} are the active and reactive power generations of ith unit; a_i, b_i, c_i are the cost coefficients of ith generator. In this study the cost function of each generating units is formulated as a quadratic function of active power generations. Also P_{di} and Q_{di} are the active and reactive power loads of bus i, V_i is the voltage magnitude of bus i, θ_{ij} is the voltage angle difference between bus i and bus j, G_{ij} and B_{ij} are the transfer admittance between bus i and bus j, P_{gi}^{max} and P_{gi}^{min} are the upper and lower limits of active power output of the ith generator, Q_{gi}^{max} and Q_{gi}^{min} are the upper and lower limits of reactive power outputs of the ith generator, V_i^{max} and V_i^{min} are the upper and lower limits of voltage magnitudes at ith bus, S_{Li} is the line loading in MVA at ith line and S_{Li}^{max} is the maximum loading of line i.

Many mathematical programming and meta-heuristic techniques have been proposed to solve the OPF problem, such as genetic algorithm [11] and evolutionary programming [12]. In this article the imperialistic competitive algorithm is developed as the optimizer and the obtained results are then compared with one of the gradient based optimization technique (i.e. quadratic programming technique).

Imperialist Competitive Algorithm

Imperialist Competitive Algorithm is a new evolutionary algorithm to find the optimal solution of an optimization problem [13]. This method has many similarity to Genetic Algorithm. Extending the power and rule of a country beyond its own physical boundaries is called imperialism. The imperialist countries compete strongly for increasing the number of their colonies and expanding their empires all over the world. In ICA method the decision or control variables are defined as trial solution called *country*. The ICA algorithm starts with an initial population of countries [13].

Generating initial empires

In N-dimensional optimization problem, each country and its cost function, could be expressed as follows.

$$country = [P_1, P_2, P_3, \ldots, P_N] \quad (8)$$

$$cost = f(country) = f(P_1, P_2, P_3, \ldots, P_N) \quad (9)$$

First of all, $N_{country}$ countries are generated as initial population. N_{imp} countries with minimum objective functions are then considered as the initial imperialists and the remaining countries, i.e. N_{col}, are selected as the colonies. To create the initial empires, colonies are divided between the imperialists. Number of colonies of each imperialist depends on the imperialist's power. Therefore the normalized cost of an imperialist is calculated as follows [13]:

$$NC_n = C_n - \max\{C_i\} \quad (10)$$

where C_n is the cost of nth imperialist, NC_n is its normalized cost and C_i is the cost of ith imperialist. Normalized power of each imperialist is then calculated as follows.

$$P_n = \left| \frac{NCn}{\sum_{i=1}^{N_{imp}} NC_i} \right| \quad (11)$$

The normalized power of an imperialist depends on the number of its colonies. Therefore the number of initial colonies of nth imperialist will be equal to:

$$NCO_n = round\{P_n \cdot (N_{col})\} \quad (12)$$

where NCO_n is the number of initial colonies of nth imperialist and N_{col} is the total number of colonies. Also *round* is a function that gives the closest integer to a decimal number. With respect to