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Application of firefly algorithm for multi-stage transmission expansion planning with adequacy-security considerations in deregulated environments

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ABSTRACT

Electric energy is the most popular form of energy because it can be transported easily at high efficiency and reasonable cost. Nowadays the real-world electric power systems are large-scale and highly complex interconnected transmission systems. The transmission expansion planning (TEP) problem is a large-scale optimization, complicated and nonlinear problem that the number of candidate solutions increases exponentially with system size. Investment cost, reliability (both adequacy and security), and congestion cost are considered in this optimization. To overcome the difficulties in solving the non-convex and mixed integer nature of this optimization problem, this paper offers a firefly algorithm (FA) to solve this problem. In this paper it is shown that FA, like other heuristic optimization algorithms, can solve the problem in a better manner compare with other methods such genetic algorithm (GA), particle swarm optimization (PSO), Simulated Annealing (SA) and Differential Evolution (DE). To show the feasibility of proposed method, applied model has been considered in IEEE 24-Bus, IEEE 118-Bus and Iran 400-KV transmission grid case studies for TEP problem in both adequacy and security modes. The obtained results show the capability of the proposed method. A comprehensive analysis of the GA, PSO, SA and DE with proposed method is also presented.

1. Introduction

An electric power system can be subdivided into four major parts that are generation, transmission, distribution and load. The purpose of a transmission system is to transfer electric energy from generating units at various locations to the distribution systems that ultimately supply the load. Transmission lines that also interconnect neighboring utilities permit economic power dispatch across regions during normal conditions as well as the transfer of power between regions during emergency. Over the past few decades, the amount of electric power energy to be transferred from generation sites to major load areas has been growing dramatically. Due to increasing costs and the essential need for reliable electric power systems, suitable and optimal design methods for different sections of the power system are required. Transmission systems are a major part of any power system therefore they have to be accurately and efficiently planned. In this research, electric power transmission systems are studied with regard to optimizing the transmission expansion planning (TEP) problem. Electric power transmission lines are initially built to link remote generating power plants to load centers, thus allowing power plants to be located in regions that are more economical and environmentally suitable. As systems grew, meshed networks of transmission lines have emerged, providing alternative paths for power flows from generators to loads that enhance the reliability of continuous supply. In regions where generation resources or load patterns are imbalanced, transmission interconnection eases the requirement for additional generation. Additional transmission capability is justified whenever there is a need to connect cheaper generation to meet growing load demand or enhance system reliability or both. TEP has always been a rather complicated task especially for large-scale real-world transmission networks. First of all, electricity demand changes across both area and time. The change in demand is met by the appropriate dispatching of generation resources. As an electric power system must obey physical laws, the effect of any change in one part of network (e.g. changing the load at a node, raising the output of a generator, switching on/off a transmission line or a transformer) will spread instantaneously to other parts of the interconnected network, hence altering the loading conditions on all transmission lines. The ensuing

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Nomenclature

Constants

γ_{ij} suceptance of the circuits in right-of-way i–j
P_{D_i} active load in Bus i
$d_i^{(0)}$ initial active load in Bus i
$P_{G_i}^{\max(0)}$ initial maximum active power generation at Bus i
$P_{G_i}^{\min} = 0$; minimum active power generation at Bus i
a_i, b_i coefficient of bid function of Bus i
$\bar{f}_{ij}$ maximum capacity of branch $(i-j)$
D discount factor
$pf = 10,000$ a large penalty factor
s_{ij} node-branch incidence, if i connected to j then $s_{ij} = 1$ else $s_{ij} = 0$
$TPL = 10$; total planning horizon
C_{ij} investment cost to build a line in the right-of-way i–j ($/year)
L_F load factor
G_F generation factor

Variables

f_{ij} active power flow in the right-of-way i–j
f_{ij}^{mn} active power flow in the right-of-way i–j while a line in right-of-way m-n is out of service
P_{G_i} active power generation in Bus i
δ_i voltage angle at Bus i
δ_i^{mn} voltage angle at Bus i while a line in right-of-way m–n is out of service
r_k curtailed load at bus k in normal operation
r_k^{mn} curtailed load at bus k while a line in right-of-way m–n is out of service
n_{ij} number of new circuit added to the right-of-way i–j (integer variable)
$\lambda, \eta, \varphi, \sigma, \varsigma$ vector of Lagrange multipliers for inequality and equality constraint

Indexes and numbers

i, j and m, n Bus index
Γ set of load Buses
n_{ij}^0 number of available branches in corridor ℓ
$\bar{n}_{ij}$ maximum number of new added branches
n_g number of generators
Ω set of all new right-of-ways

consequences may be more marked on some transmission lines than others, depending on electrical characteristics of the lines and interconnection. The electric transmission expansion planning problem involves determining the least investment cost of the power system expansion and operation through the timely addition of electric transmission facilities in order to guarantee that the constraints of the transmission system are satisfied over the defined planning horizon. The transmission system planner is entrusted with ensuring the above-stated goals are best met whilst utilizing all the available resources. Therefore the purpose of transmission system planning is to determine the timing and type of new transmission facilities. The facilities are required in order to provide adequate transmission capacity to cope with future additional generation and power flow requirements. The transmission plans may require the introduction of higher voltage levels, the installation of new transmission elements and new substations. Transmission system planners tend to use many techniques to solve the transmission expansion planning problem. Planners utilize automatic expansion models to determine an optimum expansion system by minimizing the mathematical objective function subject to a number of constraints. The primary goal of TEP in power systems is to determine an optimal strategy to expand the existing transmission network to meet the demand of possible load growth and the proposed generators, while maintaining reliability and security performance of the power system [1]. Nowadays modern electric power systems consist of large-scale and highly complex interconnected transmission systems, thus TEP is now a significant power system optimization problem. The TEP problem is a large-scale, complex and nonlinear combinatorial problem of mixed integer nature where the number of candidate solutions to be evaluated increases exponentially with system size. The accurate solution of the TEP problem is essential in order to plan power systems in both an economic and efficient manner. Therefore, applied optimization methods should be sufficiently efficient when solving such problems. In recent years a number of computational techniques have been proposed to solve this efficiency issue. Such methods include algorithms inspired by observations of natural phenomena for solving complex combinatorial optimization problems. These algorithms have been successfully applied to a wide variety of electrical power system optimization problems like linear programming [1–3], dynamic programming [4], non-linear programming [5], benders decomposition [6] and mixed integer programming [7]. A review of various computational intelligence techniques for TEP has come in [8–10]. The heuristic methods are the current alternative of mathematical optimization models. The term "heuristic" is used to describe all those techniques that, instead of using a classical optimization approaches, go step-by-step generating, evaluating and selecting expansion options, with or without the user's help. However, they cannot guarantee to achieve global solution. The TEP has been solved using meta heuristic models, for example, harmony search algorithm (HSA) [11], simulated annealing [12,13], tabu search [14,15], genetic algorithm (GA) [16–22], particle swarm optimization (PSO) [23–26] and ant colony optimization (ACO) [27]. The TEP problem has been also solved using object-oriented models [28], game theory [29,30], expert systems [31–34], fuzzy set theory [35] and greedy randomized adaptive search procedure (GRASP) [36]. Based on the treatment of planning horizon, TEP can be traditionally classified into two categories, namely static (single-stage) and dynamic (multi-stage) planning. In static planning, only a single time period is considered as planning horizon. In contrast, dynamic planning considers the planning horizon by separating the period of study into multiple stages [10]. For static planning, the planner searches for an appropriate number of new circuits that should be added into each branch of the transmission system and in this case, the planner is not interested in scheduling when the new lines should be constructed and the total expansion investment is carried out at the beginning of the planning horizon [37]. Many research works regarding the static TEP are presented in [12,38–46] that are solved using a variety of the optimization techniques. In contrast various stages are considered in dynamic planning while an optimal expansion schedule or strategy is considered for the entire planning period. Thus, multi-stage TEP is a larger-scale and more complex problem as it deals with not only the optimal quantity, placement and type of transmission expansion investments but also the most appropriate times to carry out such investments. Therefore, the dynamic TEP unavoidably considers a great number of variables and constraints that consequently require huge computational effort to obtain an optimal solution, particularly for large-scale real-world transmission systems. Many research works regarding the dynamic TEP have been reported [3,5,13,37,46–50]. Restructuring in the power networks imports new objectives and requirements in TEP. Separation of generation and transmission sector causes an increase competition to TEP. In general the purpose of TEP is to provide a network development plan to meet economical power so that the plan maintain or improve the level