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Transmission Expansion Planning in the presence of wind farms with a mixed AC and DC power flow model using an Imperialist Competitive Algorithm

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ABSTRACT

Renewable generation and distributed resources are becoming increasingly relevant due to their various advantages and intense regulatory support. Therefore, there is a need to consider the effects of these new sources in the transmission network. In addition, the accurate assessment of losses is necessary in order to evaluate the impact of distributed generation. In this paper, we present a single-objective optimization method that is applied to different case studies that include an AC and a DC power flow in order to consider losses accurate and efficiently. The proposed algorithm considers uncertainty in wind generation and demand, as well as the costs for investment, repair, maintenance, and losses. This problem is solved using an Imperialist Competitive Algorithm (ICA), a meta-heuristic method that has been proposed recently and has shown promising results compared to the other well-established evolutionary methods such as Genetic Algorithm (GA). The proposed method is investigated on the IEEE 24-bus and IEEE 118-bus test systems. The results are compared to the results reported in the literature. Our results confirm that an accurate evaluation of losses using an ACPF does modify the optimal plan and hence it is important to include an ACPF when performing Transmission Expansion Planning (TEP). In addition, the implemented ICA displays a more efficient performance than a plan GA in the same case study.

1. Introduction

It has long been discussed that the increase in distributed generation (DG) can alleviate some of the problems of the traditional electric energy generation such as electrical losses, voltage drops, high generation costs or environmental effects, as well as the high dependence on a few power plants. In general, DG resources refer to small-scale electric power generators (typically 1 kW–50 MW) that are placed next to customers and are usually connected to the electrical distribution system. These resources have a lower rated power than traditional plants, but also are placed closer to demand and therefore lead to lower losses and present interesting properties with respect to the reliability of the system [1,2]. One of the renewable energy resources which have attracted more attention is wind energy, given the level of development of current technology and the ubiquitous of the resource [3]. Since wind is variable and uncontrollable, it is necessary to consider its effects in the power system [3,4].

TEP and Distribution Expansion Planning (DEP), that is, the expansion of both the transmission and the distribution networks, should reflect the recent changes in the power system. These problems deal with determining the time, location and type of the required facilities in the network for a specific time horizon, subject to supplying demand reliably with minimum costs [2,5–7]. The effect of wind farms and other non-controllable generation, as well as uncertainty in general, should be taken into account in TEP as reflected in a vast array of research works [7–9]. There are two fundamental types of uncertainty that are presented in the problem. Long-term planning uncertainties include factors such as annual demand growth, changes in the investment or operation costs or the installation of new generation. Short-term uncertainties are mainly related to the operation of the system and comprise the availability of renewable generation or fluctuations in demand. Given their importance, they have been included in the

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Nomenclature

Indices

i, j	Nodes in the network
t	Turbines
$ij \in \Omega$	Lines between two nodes i and j in the network
k	Monte Carlo simulation index

Parameters

S	Line-node incidence transposed matrix of the power system
f	Vector of real power through lines
g	Vector of real power production
d	Load-demand vector prediction
θ	Phase-angle of each bus
γ_{ij}	Total susceptance of circuits in the line between nodes i and j
L_{ij}	Length of a new line between nodes i and j line i-j
R_{ij}	Resistance of line between two nodes i and j.
$\overline{f_{ij}}$	Maximum of transmissible active power through a candidate line between two nodes i and j, which will have two different rates according to the voltage level of candidate line
N_{ij}^{0}	Number of initial circuits in the line between nodes i and j
$\overline{N_{ij}}$	Maximum number of candidate circuits in line between nodes i and j
$\bar{g}$	Generation capacity at a generator buses
VAR_k	Power flow result considering the conditions in the kth replication

Variables

P_t	Real-power output of wind turbine
P_r	Rated power of wind turbine
V_r	Rated speed of wind turbine
V_{ci}	Cut-in speed of wind turbine
V_{co}	Cut-out speed of wind turbine
$C_{inv_{ij}}$	Capital cost of constructing the line between nodes i and j
$C_{op_{ij}}$	The cost of maintenance and construction of the line between nodes i and j.
Cl_{ij}	Construction cost of each candidate line between nodes i and j (it is different for 230 and 400 KV lines)
I_{ij}	Flow of line between nodes i and j
C_{loss}	Annual losses cost of network
$loss$	Total losses of network
C_{MWh}	Power incremental cost ($/MWh)
k_{loss}	Loss coefficient
N_{ij}	New lines added between nodes i and j
f_{ij}	Power flow between nodes i and j

TEP developments in the literature. The effects of wind farm and photovoltaic power plant technology' is considered in references [4,10,11]. The dependency between wind power production and wind speed is particularly important [2,12]. Uncertain demand is considered widely, for instance in references [13–15]. Modelling these uncertainties in the power system planning leads to more robust expansion plans that can adapt to different conditions [1,3].

In general, TEP is an optimization problem that decides the relevant expansion decisions modelling system operation by either using a transportation model for the power flow, a DC model, an AC model, or a hybrid of these three models [3]. The AC model is the most accurate approach, but requires complicated calculations, while the DC approximation model is a simple and fast model. Each model has some advantages and drawbacks. The AC model considering all the active and reactive parts of the power network as real world power system conditions has as its main disadvantage the need of non-linear programming and therefore effective and fast problem-solving techniques. On the other hand, the DC model is simple and fast. However, it cannot calculate losses accurately. This has led to improved versions of the DC model [2], which can also be very useful in a planning context.

Losses are an important driver for network expansion. It should be noted their value in the next few years and in different parts of power system can be deeply affected by investment inflation and annual load growth rates, which are fundamental assumptions when solving the TEP problem [16]. Hence, there is a need for accurate loss assessment. In addition, DG can have a crucial impact on losses, so using an ACPF is especially interesting in the presence of DG. As explained above, the AC model is nonlinear, which can lead to unmanageably complex problems in real-sized systems, especially when applying classical optimization techniques. This has motivated most authors to use a linearized DCPF models. Some of them develop approximations for the value of losses [17–21]. However, the number of works that have considered an ACPF for TEP is still very limited [22–25].

Given the importance of the problem, a wide array of techniques has been applied to TEP. These techniques can be generally classified into three main categories: classical, heuristic, and meta-heuristic optimization techniques. Classical optimization methods search for an optimal expansion plan. Some of the most important methods in this type are Linear Programming (LP) [26–28], Mixed Integer Programming (MIP) [29,30], Mixed Integer Quadratic Programming (MIQP) [31,32] and Dynamic Programming (DP) [33].

There have been interesting partitioning techniques applied to MIP such as Benders' decomposition, which has been used to solve the TEP problem in the literature [34–36]. In general, partitioning techniques can be applied to problems that are linear with a few integer variables (not too many, as the time savings start disappearing otherwise). This method has also been applied to nonlinear problems that were however convex [37]. This separation between linear and binary variables is relatively easy to undertake in TEP, as discrete investment decisions are taken, but the operation of the system is usually modeled using linear variables only (except if relatively sophisticated variables such as transformer tap positions are considered [38]). However, the operation problem when considering an ACPF is nonlinear and also non-convex. This means that TEP can be solved using Benders decomposition (or any other related technique) only if a linear DCPF is used.

On the other hand, there have been some remarkable advances in partitioning techniques applied to nonlinear problems [39]. This means that, even though in most cases there are no optimality guarantees, now it is possible to solve nonlinear problems that were once unmanageable in acceptable times. This has been applied to TEP problems in a couple of references in the literature [25,40]. However, there are not so many references that use NLP because there are some limitations [38], mostly related to size. It should be noted that the above references deal with relatively small case studies. That is, given the number of variables (discrete and continuous) and the non-convexity of the ACPF, NLP is still far from being the solution method of choice.

This means that methods that are based on meta-heuristics can perform better than classical ones in this problem [41]. This has led to a literature that is currently exploring the possibilities of very diverse meta-heuristics applied to this problem, which is complex and also practically relevant for the power systems community (so that having good solutions in affordable computation times is valuable).Heuristic methods are usually experience-based techniques that speed up the process of finding a better solution where an

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