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Transmission expansion planning based on Locational Marginal Prices and ellipsoidal approximation of uncertainties

Aleksa B. Babić [a], Andrija T. Sarić [b,c,*], Aleksandar Ranković [b]

[a] South California Edison, CA, USA
[b] Faculty of Technical Sciences, University of Kragujevac, Čačak, Serbia
[c] Faculty of Technical Sciences, University of Novi Sad, Čačak, Serbia

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ABSTRACT

This paper proposes an algorithm for transmission expansion planning (TEP) which minimizes the congestion surplus calculated from optimized nonlinear (AC) Optimal Power Flow (OPF) and Locational Marginal Prices (LMPs). Uncorrelated and correlated uncertainties related to operating conditions of the future transmission network and expected costs of the submitted energy bids to the energy market are constrained by bounding hyper-ellipsoid around base case AC OPF solution, with assumption of additive uncertainties. Perturbed uncertain points inside a hyper-ellipsoid are selected by proposed quasi-random sampling algorithm. For these points, the linearized OPF around base case AC OPF solution is proposed. The Genetic Algorithm (GA) does selection of lines and years for transmission expansion, where the increments of the fitness function are calculated by proposed linearized AC OPF model. The results and practical aspects of the proposed methodology are illustrated on 12- and 118-bus test power system examples.

1. Introduction

Optimum electric power system expansion planning is multi-layered and multi-staged process in both regulated and deregulated environments. The main goal is to select the optimum configuration between possible variants through planning horizon on the basis year-by-year or two-years-by-two-years time interval until reaching the planning horizon year. Selected expanded configuration should satisfy planning criterion economically, reliably and environmentally. Possible right of way selection is very important fact faced with variety of land ownership and environmental problems. The problem of existing rights of way expansion is barely less difficult.

In general, required inputs for optimization problem are:

- Nodal active/reactive power injections on hourly, daily, weekly, monthly or annual basis.
- Network topology for the beginning year and all possible analyzed expansion variants, including the requested time for constructing the new elements (lines or transformers).
- Existing and new generating units with time schedule [which is planned usually in separate process from transmission expansion planning (TEP)].

In the deregulated environment, the solution of transmission expansion problem should provide nondiscriminatory access to all producers/consumers and plays in this way vital role. As in regulated (vertically organized), so in deregulated power system it is hard to prove that a new expansion transmission capacity could be added on the basis improving power system economic efficiency to get from improved operation for reimbursement of capital spending and system operation and maintenance spending costs.

There is long history of methods, models and algorithms applied to the TEP. Usually all methods are linear or nonlinear (AC) power flow oriented. With both of those models variety of mathematical techniques and models are applied:

- *Classical optimization techniques*: (non-)linear programming [1,2], mixed integer linear programming [3], Benders decomposition [4,5] and multi stage optimization [6].
- *Advanced optimization techniques*: particle swarm optimization method [7], improved Pareto multi-objective evolutionary algorithm [8], meta-heuristic based optimization methods [9,10] and different artificial intelligence based techniques [11,12].

Defining the objective function for all above mentioned approaches, equality and inequality constraints characterizing the assumed condition of the power system are initial steps for the optimal TEP problem. Later, for specified optimization problem

* Corresponding author at: Faculty of Technical Sciences, University of Kragujevac, Čačak, Serbia. Tel.: +381 32302748.
E-mail address: andrija.saric@ftn.kg.ac.rs (A.T. Sarić).

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Nomenclature

Indices

b	branch (lower index)
G, L	generator and load, respectively (lower indices)
g	annual value (upper index)
I	investment cost (lower index)
i, j	load and generator buses, respectively (lower indices)
(k)	contingency condition, where $k = K$ is maximum number of analyzed contingencies, while $k = 0$ denotes base case condition (upper index)
n	current year (lower index)
m, M	minimum and maximum values, respectively (lower index)
r	reference (slack) bus (lower index)
$*$	optimal base case (non-perturbed) solution (upper index)

Variables

arpb, ***ARPB***	active and reactive power balance equations at the reference (slack) bus and at all other buses, respectively
f	objective function
g/***h***	set of equality/inequality constraints
Lines	set of added lines in the planning period
LVC	set of voltage magnitude inequality constraints
P, Q	active and reactive powers, respectively
PQx	set of inequality constraints for amount of active/reactive power produced and active power consumed, as well as lower/upper bounds for state variables
TLC	set of transmission line active power flow inequality constraints
Years	set of years for adding new lines
W	welfare objective function
$\boldsymbol{x}$	vector of state variables [composed from bus voltage magnitudes (V) and angles (θ)]
λ, μ, π	dual variables

Parameters

a, b, c	cost coefficients
C	investment cost for a new line
c	specific investment cost per unity line length
i	annual interest rate
L	total line length
N	total number of load (N_L) and/or generator (N_G) system buses ($N = N_L + N_G$)
N^g	total number of years in the planning period
$p(k)$	probability of kth normal/contingency condition, where $\Sigma p(k) = 1$
T^g	= 8760 h number of hours in the year
σ	variance

Abbreviations

(AC) OPF	(nonlinear) Optimal Power Flow
CP, *GP*	consumer and generator payments, respectively
GA	Genetic Algorithm
LMP	Locational Marginal Price
PDF	Probability Density Function
CS	congestion surplus

and for all time snapshots of power system (all years in the planning horizon) trying to find optimum solution.

Analysis of an impact of different types of uncertainties to the optimal TEP is an aspect of the problem that is researched in particular. Basic problems besides methods and model differences are data uncertainty related to: (1) load/generation forecast, (2) selection of the parameter for newly added lines/transformers [13,14], (3) generator availability, (4) closing of old transmission facilities, (5) transmission expansion cost, (6) expected unserved energy and (7) investment risk assessment. In deregulated environment there are other sources of uncertainty, such as: (8) submitted to the energy market load and generation bids [15,16], (9) confidentiality of generation expansion plans, (10) long range market participants behavior, (11) change of the energy market rules and (12) change of the government policies.

TEP in deregulated environment is much complicated (compared with regulated environment) and decision making process is more complex due the following reasons [15–18]:

- Problem of the optimal TEP is multi-stage, where in main stage (“Master problem”) is the investment subproblem, while minimization of the operation costs (or maximization of the social welfare) is second-stage subproblem (“Slave problem”), where these two stages are mutually coupled.
- Strong coupling of the expansion and operation subproblems leads to certain problems in defining input data (blocks of electric power demand offers) in solving the electric market optimization problem for several years ahead. In vertically integrated type of energy market it is possible to solve this kind of problem to the certain extent, since all of these decisions are brought or verified centrally. However, in deregulated energy markets it is very hard in practice to predict behavior of the energy market participants in long time horizons based planning periods. In that way, modeling and behavior of all market participants become the essential question for quality of power system design and development planning.
- Problem of input uncertainties becomes significantly more expressed, such that the additional risk investment and the management analysis are necessary. The risk investment is usually expressed as actualization rate variable (dependent upon level of acceptable risk). Due to these uncertainties and risks in accomplishing planning results, the time planning horizons are often shortened to twenty (or less) years time span, aimed towards shorter time for return of the capital investment.
- On the offer side for purchase of electric energy, the time discretization is used to determine the short-term load level variation, which must be accepted in the model. This of course has an impact on the demand elasticity level. Bordering case is completely inelastic load model (based only on the load forecast with corresponding uncertainties).

For transmission companies to have competitive access to the electric market, the main objective is maximizing the profit, which can be obtained by difference what consumers pay and generators collect. This is a so-called “congestion surplus” (CS). This difference should cover all expenses and invested capital at applied rate of return.

In this paper is proposed a new optimization criterion for TEP in the deregulated power systems based on the total CS and congestion components (as their dominant parts), which are calculated from Locational Marginal Prices (LMPs) on the optimized energy market. For the sake to cope uncertainty of input data (operating condition and expected costs of the submitted energy bids), the ellipsoid-based variable domain generated by quasi-random