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Probabilistic transmission expansion planning to maximize the integration of wind power

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A B S T R A C T

In many electricity markets, wind power producers are paid by the Locational Marginal Price (LMP) of the bus where they are located. Therefore, transmission network and its future expansion plans can play a determinative role in revenue and profitability of a wind power project. This paper aims to exploit this potential of the transmission expansion planning (TEP) studies which can lead to private investment absorption for development of the wind power. To this end, a framework for transmission and wind power expansion planning is developed and modeled as a stochastic bi-level optimization problem. The upper-level problem represents wind power and transmission investment decisions. The lower-level comprises two optimization problems based on the optimal power flow including market clearing and reliability assessment of the bulk system. An approach based on the multi-objective shuffled frog leaping algorithm is proposed to cope with the multi-objective, bi-level, and non-linear nature of the model. The feasibility and effectiveness of the proposed methodology is demonstrated in the IEEE-RTS test system. The obtained results show that adoption a proper strategy for TEP can lead to more private investment absorption in wind power without a significant additional, even with a lower, transmission investment cost.

1. Introduction

1.1. Motivation, objectives, and approach

Nowadays, sustainable development issues are considerably noticed for energy policy-making. In electric industry, major portion of the transition to a sustainable energy system is relying on wind power [1,2]. However, due to some characteristics of wind power plants such as intermittency, high capital investment, and financial risk, they may not be an attractive investment option for independent investors. Nevertheless, the public demand and the environmental concerns have persuaded energy policy-makers to support the integration of wind energy into the power system using different support policies such as feed-in tariff, tax credits, investment subsidies, and certificate systems [3,4]. Although the pursuit of these policies lead to development of renewable energy, but they impose a considerable economic aspect on governments [5].

On the other side, investment in wind power projects (WPPs) is tightly conditioned by transmission network expansion [6,7]. Inadequate transmission capacities can reduce the absorption of the wind power capacity. Moreover, wind producers generally offer power at zero price and are paid by the Locational Marginal Price (LMP) of the bus where they are located [6]. Therefore, the transmission network and its future expansion plans can play a determinative role in revenue and profitability of a WPP. In an electricity market, transmission system operator (TSO) is responsible for efficient expansion of transmission network. Hence, TSO can consider the investors' concerns in its expansion strategies and provide economic motivation to stimulate more private investment in WPPs. In this paper, we exploit this potential of the transmission expansion planning (TEP) studies which can lead to private investment absorption for development of the wind power. For this purpose, a new framework is presented for transmission and wind power expansion planning which is formulated as a bi-level optimization model. Fig. 1 illustrates the structure of the proposed model. In the upper-level (UL) problem, TSO decides on the number and routes of the new transmission lines. The siting and sizing of the economically attractive WPPs are also determined in the UL. The objective functions of the UL optimization problem are TSO objectives in its expansion planning strategy which include:

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Nomenclature

Indices and sets

Ψ^K	Set of corridors
Ψ^D	Set of demand blocks
Ψ_{sd}	Set of scenarios in demand block d
Ψ_n	Set of network buses
Ψ^C	Set of contingencies
Ψ^G	Set of generators
Ψ^m	Set of blocks of the mth generator
Ψ_n^G	Set of generators at bus n
Ψ_n^L	Set of loads at bus n
Ψ_n^W	Set of wind power generation buses

Parameters and constants

C_k^{line}	Investment cost of a new line in corridor k
Nh_d	Number of hours in demand block d
β_{sd}	Weight of the scenario s in demand block d
C_n^{wind}	Wind power investment cost at bus n
d	Discount rate
L_n	Economic life of the wind power plant at bus n
$Risk^L$	Desirable risk level for wind power investment
P_c	Probability of the cth contingency
c_{mb}	Offer price for the bth block of the generator m
$Pd_{nl,sd}^{rated}$	Load demand l at bus n in scenario s and demand block d
$Pd_{nl,sd}^{\min}$	Lower limit of load l at bus n in scenario s and demand block d
$\alpha_{n,sd}$	Capacity factor of the nth wind power plant in scenario s and demand block d
B_k	Lines susceptance in corridor k
G_k	Lines conductance in corridor k
n_k^{exist}	Number of existing lines in corridor k
$f_k^{\max}$	Maximum capacity of a line in corridor k
$Pg_{mb}^{\max}$	Power generated by the bth block of generator m
$X_n^{\max}$	Maximum capacity of wind power plant at bus n
$o(k)$	Sending-end bus of corridor k
$r(k)$	Receiving-end bus of corridor k
$n_k^{\max}$	Maximum number of new lines in corridor k

Variables

TC^{line}	Total transmission lines investment cost
LC^{net}	Total cost of the network losses
n_k^{new}	Number of added lines in corridor k
Rev_n^{wind}	Expected revenue of the nth wind power plant
$Profit_n^{wind}$	Profit of the nth wind power plant
X_n^{wind}	Capacity of the nth wind power plant
$Risk_n^{wind}$	Investment risk of the nth wind power plant
IC^{wind}	Total installed wind power capacity
ENS_{HLII}	Energy not served of the composite power system
$\lambda_{n,sd}$	Locational marginal price (LMP) at bus n in scenario s and demand block d
$Pw_{n,sd}$	Wind power produced at bus n in scenario s and demand block d
$Rev_{n,sd}^{wind}$	Revenue of the nth wind power plant in scenario s and demand block d
$IL_{c,sd}^T$	Total interrupted load due to contingency c in scenario s and demand block d
$Cgen_{sd}^T$	Total generation cost in scenario s and demand block d
$Pg_{mb,sd}$	Power produced by the bth block of the generator m in scenario s and demand block d
$f_{k,sd}$	Power flow of the kth corridor in scenario s and demand block d
$Pw_{n,sd}$	Power produced by the nth wind power plant in scenario s and demand block d
$\theta_{n,sd}$	Voltage angle of the nth bus in scenario s and demand block d
$IL_{nl,c,sd}$	Interrupted load of the lth load demand at bus n due to contingency c in scenario s and demand block d
$Pd_{nl,c,sd}$	Supplied load of the lth load demand at bus n for contingency c in scenario s and demand block d

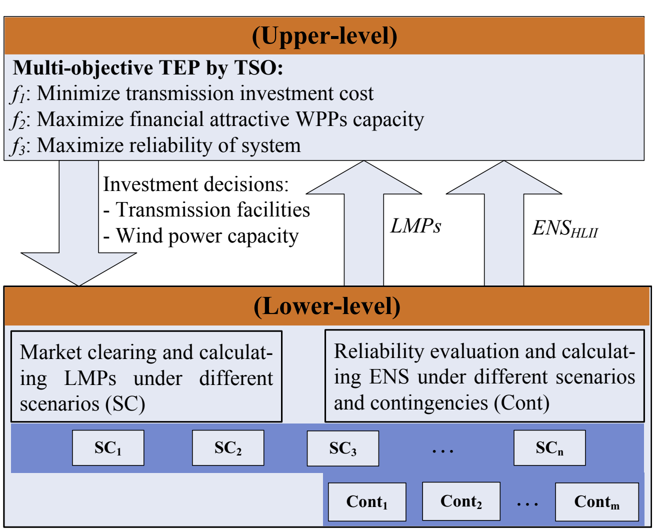

Fig. 1. Structure of the proposed model.

minimization of new transmission line costs, maximization of the financial attractive WPPs capacity, and maximization of power system reliability. The mean-variance (MV) theory is used to analyze the attractiveness of WPPs. In the MV theory, the profit and financial risk are simultaneously taken into account. In the lower-level (LL) there is two sets of optimization problems. The first one represents the market clearing which calculates the LMPs of network buses for each load and wind scenario (SC) and the second one represents composite power system reliability evaluation which calculates expected energy not served at hierarchical level II (ENS_{HLII}). Here, the uncertain parameters are load and wind power generation. To represent these uncertainties, a new hybrid method is proposed that uses the features of both K-means clustering technique and the load- and wind-duration curves method. An approach based on the multi-objective shuffled frog leaping algorithm (MOSFLA) is proposed to solve the model. In order to compare the obtained results, we also used the well-known non-dominated sorting genetic algorithm II (NSGA II), which is the most commonly used method by several other authors who tackled the TEP problem in a multi-objective framework.

1.2. Literature review and contributions

There are many studies which investigate the expansion planning for transmission and wind power generation. These literature can be classified by their problem formulation structures. Some studies only investigate transmission expansion or wind power investment, while other researches consider both transmission and