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Decentralized stochastic optimization based planning of integrated transmission and distribution networks with distributed generation penetration

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HIGHLIGHTS

- A coordinated design model for transmission and distribution networks is proposed.
- SOCP relaxation and SDP relaxation are deployed to transform the original problems.
- The exactness of the SOCP or SDP relaxation for the planning problem is discussed.
- The non-linear model of transformer is linearized in the planning model.
- Cases T24D9 and T118D3 are designed to verify the effectiveness of the approach.

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ABSTRACT

In a current power system, numbers of distribution networks are physically connected to a transmission network at different boundary buses. As the planning solution of one network significantly influences the decisions made by planners of other networks, the transmission and distribution networks should coordinate and cooperate with each other to design the entire power system in a secure and economic manner. Inspired by decentralized and hierarchical optimization theories, this paper proposes a coordinated decision-making framework to determine the planning scheme and scenario based generation schedule for integrated transmission and distribution networks (ITDNs) with the penetration of distributed generations (DGs). A stochastic bi-level hierarchy is presented to decompose the centralized optimal planning of ITDNs. The obtained subproblems for independent transmission and distribution networks are formulated and relaxed to convex models. An improved iterative solution procedure is developed by exploiting the cascaded structure of the problems. Theoretical analysis and numerical results demonstrate the convergence properties of the decentralized optimization algorithm. The proposed coordinated planning framework outperforms conventional independent methods by decreasing expansion investment and improving DG accommodation.

1. Introduction

The modern transmission and distribution networks are physically connected at substation buses. According to the conventional power flow direction, transmission networks are normally upper levels while distribution networks are usually lower levels. Thus, the transmission network can be regarded as a pseudo generation to the distribution network, and the distribution network can be simplified as a load injection to the transmission network, as shown in Fig. 1. However, as transmission and distribution networks are separately designed by independent system planners and distribution companies to protect privacy of data, there is the lack of coordination and cooperation between transmission and distribution network planning. The transmission system operator (TSO) separately operates the transmission network without information (e.g., power flow variation and potential control) from the distribution network. Similarly, the distribution system operator (DSO) operates the distribution network without any information from the transmission network. As a result, very limited interaction (e.g., voltage magnitudes and angles) can be shared at the boundary bus, currently.

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Nomenclature

Sets

Ω_0	set of existing lines
Ω_C	set of new lines
Ω_D	set of distribution networks
Ω_{DG}	set of DG installation buses
Ω_G	set of generation installation buses
Ω_L	set of all lines ($\Omega_L = \Omega_0 \cup \Omega_C$)
Ω_s	set of existing substations

Parameters

C_{ij}^{ref}	reformation cost of line ij per unit length ($/km)
C_{ij}^{new}	construction cost of line ij per unit length ($/km)
C_{ss}	expansion cost of substation ss ($)
$C_{DG,i}(\bullet)$	DG cost function at bus i
$C_{G,i}(\bullet)$	generation cost function at bus i
D_s	number of hours in scenario s (h)
l_{ij}	length of line ij (km)
m	number of scenarios
N_+	number of new load buses
$P_{L,i,s}$, $Q_{L,i,s}$	active (MW) and reactive (MVar) power demand of loads at bus i in scenario s
r_{ij}, x_{ij}, y_{ij}	resistance (Ω), reactance (Ω) and admittance (Ω^{-1}) of line ij
k_0^{trans}	initial turn ratio of each transformer
Y^{max}, $Y^{\min}$	upper and lower limits of variable Y
y_{i0}	admittance-to-ground at bus i (Ω^{-1})
$\rho_{X,q}$	price of energy exchanged between transmission network and distribution network q from the X's perspective ($/MWh)
σ	turn ratio increment per step of each transformer

Variables

$a_{ij,1,d,s}$, $a_{ij,2,d,s}$	continuous variables to express $U_{j,s}$ in the dth equation
$FP_{ij,s}$	fictitious active power flow of line ij in scenario s (MW)
$I_{ij,s}$	current magnitude from buses i to j in scenario s (kA)
n^{ref}	number of reformed lines
n_{ij}^{new}	number of new lines for line ij
$P_{DG,i,s}$, $Q_{DG,i,s}$	active (MW) and reactive (MVar) powers generated by DGs at bus i in scenario s
$P_{G,i,s}$, $Q_{G,i,s}$	active (MW) and reactive (MVar) powers generated by generations at bus i in scenario s
$P_{ij,s}$, $Q_{ij,s}$, $S_{ij,s}$	active (MW), reactive (MVar) and apparent (MVA) power flows of line ij in scenario s
$P_{X,q,s}$, $Q_{X,q,s}$	active (MW) and reactive (MVar) power exchange between transmission network and distribution net work q in scenario s from the X's perspective
$K_{ij,s}^{trans}$	number of steps of the transformer in line ij in scenario s
$k_{ij,s}^{trans}$	turn ratio of the transformer in line ij in scenario s
$U_{i,s}$	square of voltage magnitude of bus i in scenario s (p.u.^{2})
u_{ij}^{ref}	binary variable for the reformation of line ij
u_{ij}^{new}	binary variable for the construction of line ij
u_{ij}^{sta}	binary variable for the status of line ij
u_{ss}	binary variable for the expansion of substation ss
$V_{i,s}$	voltage magnitude of bus i in scenario s (p.u.)
$V_{X,q,s}$	voltage magnitude of the bus connected to distribution

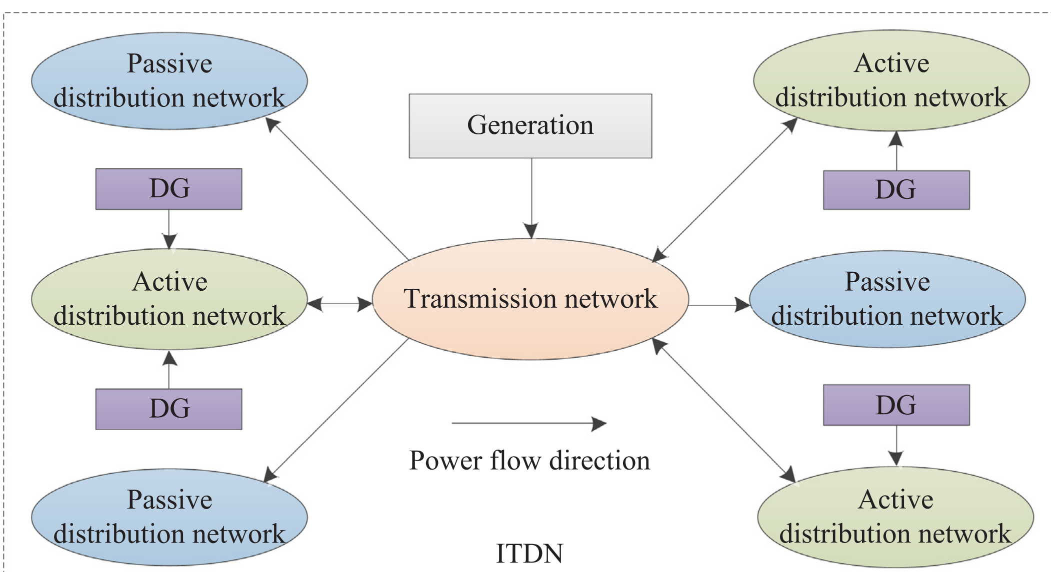

Fig. 1. Illustration of the operational structure of ITDN.

The penetration of distributed generations (DGs) at different power and voltage levels has greatly changed the passive characteristics of conventional distribution networks and consequently introduces active distribution networks in the current power systems [1–3], as shown in Fig. 1. Numbers of problems, such as voltage violation, DG accommodation, line congestion and boundary power mismatch, associated with integrating DGs are difficult to solve using the current separate planning manner. The conventional equivalent models for loads and DGs in distribution networks may not be valid for future grids [4]. In fact, those forthcoming problems have arisen recently. For example, researchers have noted that a high penetration of DGs in California [5] will pose significant difficulties for both traditional separated planning and operation problems [6]. A comprehensive survey from 9 countries, including Austria, Belgium, Canada, China, France, the United States, etc., has reported that some critical operational issues, such as transmission-distribution interface congestion, transmission line congestion and balancing challenges, should be considered in the future integrated planning approach [7]. Moreover, the power system planning should