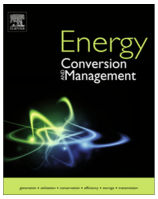
Energy Conversion and Management 123 (2016) 84–94

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



A bi-level integrated generation-transmission planning model incorporating the impacts of demand response by operation simulation

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ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 26 May 2016
Accepted 7 June 2016
Available online 17 June 2016

Keywords:
Unit commitment
Generation-transmission expansion planning
Bi-level planning model
Demand response
Peak load reduction

ABSTRACT

If all the resources in power supply side, transmission part, and power demand side are considered together, the optimal expansion scheme from the perspective of the whole system can be achieved. In this paper, generation expansion planning and transmission expansion planning are combined into one model. Moreover, the effects of demand response in reducing peak load are taken into account in the planning model, which can cut back the generation expansion capacity and transmission expansion capacity. Existing approaches to considering demand response for planning tend to overestimate the impacts of demand response on peak load reduction. These approaches usually focus on power reduction at the moment of peak load without considering the situations in which load demand at another moment may unexpectedly become the new peak load due to demand response. These situations are analyzed in this paper. Accordingly, a novel approach to incorporating demand response in a planning model is proposed. A modified unit commitment model with demand response is utilized. The planning model is thereby a bi-level model with interactions between generation-transmission expansion planning and operation simulation to reflect the actual effects of demand response and find the reasonably optimal planning result.

1. Introduction

Power system planning conventionally consists of generation expansion planning (GEP) and transmission expansion planning (TEP) [1]. GEP deals with the expansion of generation resources to serve growing electric power demand, while TEP concerns the expansion of the grid network to meet the requirements of power transmission [2–4]. These two planning issues tend to be executed separately, since they have not only different decision variables, objective and constraints but also different stakeholders. However, as the problem of renewable (wind and solar, etc.) generation curtailment becomes increasingly serious, it is currently believed that GEP and TEP should be conducted together to optimize energy utilization and improve investment efficiency, even though some power systems have been deregulated [5,6]. Some scholars have made contributions to this field in recent years. Seddighi and Ahmadi-Javid [1] present a multistage programming model to balance sustainable power generation expansion planning and transmission expansion planning. Aghaei et al. [7] introduce a probabilistic model for generation and transmission expansion planning considering reliability criteria. Moghaddam et al. [8] put forward a coordinated planning model based on interactive and iterative processes between GEP and TEP. Pozo et al. [9] describe a three-level equilibrium model for the expansion of generation and transmission. Rouhani et al. [10] propose a composite generation and transmission expansion model in which the objectives and constraints of GEP and TEP are integrated.

In addition to generation and transmission, load demand is another important part of power systems. Traditionally, the demand side is not considered in planning issues, because the supply-demand balance in power systems is achieved by adjusting supply to meet demand. However, with the development of smart grid, units in the supply side as well as resources in the demand side can be scheduled by the system operator [11]. The concept of Demand Response (DR) appears as “changes in electric usage by end-use customers from their normal consumption patterns

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http://dx.doi.org/10.1016/j.enconman.2016.06.020
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Nomenclature

Indices

i	candidate generator
j	candidate transmission line
k	demand response source
l	existing generator
n	node
t	year
u	unit
v	hour

Sets

Ω_d	set of demand response sources
Ω_{dlc}	set of demand response sources (load curtailment type)
Ω_g	set of candidate generation units
Ω_G	set of existing generation units
Ω_l	set of candidate transmission lines
Ω_T	set of planning years
Ω_{vg}	set of candidate variable energy generation units
Ω_{vG}	set of existing variable energy generation units

Parameters

C_i/C_l	capacity of the *i*th candidate generator/*l*th existing generator (MW)
$Cd_{k,\max}$	potential capacity the *k*th demand response source (MW)
Clc	cost of load curtailment (yuan)
Cls	cost of load shifting (yuan)
$Ed_{\max}$	upper limit on the amount of electricity output by demand response (MW h)
e_i/e_l	carbon dioxide emission factor of the *i*th candidate generator/*l*th existing generator (kg/MW h)
Ef_t	electricity demand forecast in the *t*th year (MW h)
FC_u	fuel cost of the *u*th generation unit (yuan)
G_i	construction cost per unit of capacity of the *i*th candidate generator (yuan/MW)
H_{it}/H_{lt}	utilization hour of the *i*th candidate generator/*l*th existing generator in the *t*th year (h)
H_{kt}	utilization hour of the *k*th demand response source in the *t*th year (h)
L_v	load demand in the *v*th hour (MW)
$L_v{}^0$	original load demand in the *v*th hour (MW)
$Lc_{n,\max}$	upper limit on daily load curtailment at the *n*th node (MW)
$Lc_{n,v,\max}$	upper limit on load curtailment at the *n*th node in the *v*th hour (MW)
$Ls_{n,\max}$	upper limit on daily load shifting at the *n*th node (MW)
$Ls_{n,v,\max}$	upper limit on load shifting at the *n*th node in the *v*th hour (MW)
MU_u/MD_u	minimum continuous on/off time of the *u*th generation unit
N	total number of nodes in the system
$Nl_{j,\max}$	maximum number of circuits in the *j*th candidate line
O_i/O_l	operating cost (including fuel cost) per unit of electricity generation of the *i*th candidate generator/*l*th existing generator (yuan/MW h)
Od_k	response cost of the *k*th demand response source (yuan/MW h)
$P_{G\max}$	maximum output of the generator (MW)
$P_{G\min}$	minimum output of the generator (MW)
P_v	price of electric power in the *v*th hour (yuan)
$P_v{}^0$	original price of electric power in the *v*th hour (yuan)
Pr_C	carbon emissions trading price (yuan/kg)
Pf_t	peak load forecast in the *t*th year (MW)
R_i/R_l	peak load regulation capacity ratio of the *i*th candidate generator/the *l*th existing generator (%)
Rur_u/Rdr_u	ramp-up/ramp-down rate bound of the *u*th unit (MW/h)
SUC_u/SDC_u	start-up/shut-down cost of the *u*th unit (yuan)
T_j	construction cost of the *j*th candidate transmission line (yuan)
U	number of generation units
Uce	upper limit of carbon emissions of the power system (kg)
$Upmax_u/Upmin_u$	maximum and minimum power generation bounds of the *u*th unit (MW)
$X_{\max}$	maximum number of new generation units in the expansion scheme
$Y_{\max}$	maximum number of new transmission lines in the expansion scheme
β	peak-valley difference rate of the load demand in the system
η	reserve factor
$\theta_{n,\max}/\theta_{n,\min}$	upper and lower limit on the phase angle of the *n*th node

Variables

Cd_k	capacity of the *k*th demand response source (MW)
$Lc_{n,v}$	load curtailment at the *n*th node in the *v*th hour (MW)
$Ls_{n,v}$	load shifting at the *n*th node in the *v*th hour (MW)
$I_{u,v}$	operation status of the *u*th unit in the *v*th hour {1, on; 0, off}
Pd_n	power demand of the *n*th node (MW)
Pg_i	output of the *i*th generator (MW)
Pg_n	power injection of the *n*th node (MW)
$Pmax_{n'n}$	upper limit on power flow transmission in the branch between the *n*'th node and the *n*th node (MW)
$Up_{u,v}$	power output of the *u*th unit in the *v*th hour (MW)
$X_{n'n}$	reactance of the branch between the *n*'th node and the *n*th node (p.u.)
x_i	construction decision of the *i*th candidate generator {1, to be constructed; 0, otherwise}
y_j	number of circuits planned to be constructed for the *j*th candidate transmission line
θ_n	phase angle of the *n*th node

in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [12]. Based on this definition, DR can be divided into Price Based Demand Response (PBDR) and Incentive Based Demand Response (IBDR) [13]. Refs. [14,15] carry out theoretical research on DR and conduct case study of PBDR and IBDR. Ref. [16] shows several typical implementations of DR programs in practice. Now that DR is playing an increasingly important role in power systems, its impacts on power system planning cannot be neglected. The reduction of peak load in the target year through DR is able to decrease the capacity of generation expansion and transmission expansion [17,18]. Against this background, some scholars have executed researches on planning issues incorporating DR. Yuan et al. [17] introduce a resource planning model considering IBDR, in which load curtailment is regarded as an option for replacing generation expansion to meet peak load demand. Li et al. [18] propose a TEP model with IBDR in order to find the optimal trade-off between transmission investment and load curtailment expenses. Choi and Thomas [19] put forward a GEP model incorporating PBDR, in which the electricity demand projection is revised according to the simulated electricity price. Koltsaklis