Capacity expansion model of wind power generation based on ELCC

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Abstract. Capacity expansion is an indispensable prerequisite for power system planning and construction. A reasonable, efficient and accurate capacity expansion model (CEM) is crucial to power system planning. In most current CEMs, the capacity of wind power generation is considered as boundary conditions instead of decision variables, which may lead to curtailment or over construction of flexible resource, especially at a high renewable energy penetration scenario. This paper proposed a wind power generation capacity value (CV) calculation method based on effective load-carrying capability, and a CEM that co-optimizes wind power generation and conventional power sources. Wind power generation is considered as decision variable in this model, and the model can accurately reflect the uncertainty nature of wind power.

1. Introduction

Capacity expansion model (CEM) is a crucial part of power system planning. It is widely used to find and evaluate the least-cost capacity expansion plan of electricity generators, transmission and energy storage under various economical, technological and social constraints to reliably serve the load demand of certain regions over the evolution of many years or decades.[1] Research on CEM has been carried out since 1960s in both China and abroad. Various models and tools have been developed to help decision makers to meet different need, such as ReEDS developed by National Renewable Energy Laboratory, OGP developed by General Electric Company, JASP developed by Xi’an Jiaotong University and GESP developed by State Grid Energy Research Institute.

In most of the existing CEMs, the decision variables are generally the capacity of predictable and controllable generating units, such as thermal, hydro, pumped storage and nuclear units. Intermittent and uncertain power source such as wind power generation is not considered or considered as ‘negative load’ to the system.[2-3] A most popular method to deal with wind power in many CEMs is to set its construction sequence and capacity according to government policy or national clean energy development goal before the optimization starts, then capacity of other power sources and transmissions are optimized to fit the development pattern of wind power.[4-5]

However, the rapid development of wind energy during recent years has brought more and more significant impact of on capacity expansion models. Existing grid integration analyses have shown that
the wind power generation will increase the demand of flexibility of the system to accommodate its variability and uncertainty. Moreover, as the penetration of wind power grows higher, its capacity value(CV), i.e. the contribution it can provide to maintain system reliability during peak load periods, declines rapidly.[6] These new features of wind power impose new requirements on CEMs.[7] Wind power should be considered as decision variables and its construction timing and capacity should be co-optimized with other conventional power sources, particularly at high VG penetrations when the sensitivity and magnitude of these impacts are amplified.[8-10]

This paper proposes a new method based on effective load carrying capability(ELCC) to evaluate the CV of wind power and it is applied to traditional CEM to establish a capacity expansion co-optimization model of wind power and conventional power sources.

2. Capacity value of wind power

2.1. Equivalent load-carrying capability
CV evaluates the contribution of wind power to system reliability and resource adequacy. Generally, it is defined as the rate of the capacity of conventional units that can be replaced to the capacity of wind power generation while maintaining the same reliability level in a certain area. There are several different methods to calculate CV, such as Equivalent firm capacity (EFC), Equivalent conventional generation capacity (ECGC), Guaranteed capacity (GC), and Equivalent load-carrying capability (ELCC). Those methods all define the CV of wind power from uncertainty perspective. ECGC and GC are very sensitive to the parameters of the virtual unit, therefore the calculation results are less comparable. EFC and ELCC are more frequently used for capacity expansion. ELCC decomposes the individual generator’s contribution to system reliability and is more effective and accurate to calculate the CV of wind power at high penetration level.

2.2. Calculation method of CV based on ELCC
ELCC is a measure of the additional load that the system can supply with the particular generator of interest. The calculation of CV based on ELCC can be defined as:

$$\sum_{t \in T} R_t \{P_{w,t} + \sum_{g \in G} C_g \cdot d_t\} = \sum_{t \in T} R_t \{\sum_{g \in G} C_g \cdot d_t - C_i\}$$

(1)

Where $R_t\{a,b\}$ represents the reliability of the system with unit capacity $a$ and load demand $b$ during time period $t$; $P_{w,t}$ is the output of wind power during time period $t$; $C_g$ is the capacity of conventional unit; $d_t$ is the load demand during time period $t$; $C_i$ is the credit capacity of wind power.

The method to calculate ELCC depends on hourly data of wind power output $P_{w,t}$ and corresponding load demand curve $d_t$. Suppose we have a one year hourly VG output curve and a load demand curve. Firstly, the load demand curve is sorted from highest to lowest to get a load duration curve (LDC) $d'_t$; secondly, we subtract wind power output from load demand curve to get a net load duration curve (NLDC) $d''_{net,t}$; then the peak load period (for instance, top 100 hours) of NLDC is subtracted from LDC, we can get the ELCC of wind power generation

$$d'_{w,t} = d'_t - d''_{net,t}, \quad t \in T'$$

(2)

Where $T'$ is the peak load period, $d'_{w,t}$ is the ELCC of wind power generation. The mean value of $d'_{w,t}$ divided by wind power generation capacity $C_W$ is the CV of wind power generation.

$$CV_W = \sum_{t \in T'}^{} d'_{w,t} / T'$$

(3)

2.3. Calculation method of marginal CV
In the previous section, the method to calculate CV of existing wind power generation is presented. For capacity expansion, the marginal-CV of newly-built wind power generation should also be
calculated. If we assume the incremental piece to be 100MW, then we add 100MW wind power generation capacity to the system, subtract the new wind power output curve from load demand curve and recalculate its CV, this CV is the marginal CV of the newly-built wind power, as Figure 1 shows.

![Figure 1. Calculation of CV and marginal-CV based on ELCC.](image)

Note that marginal CV decreases rapidly when wind power generation capacity increases, as Figure 2 shows. Therefore we need to calculate a series CV value corresponding to different newly installed wind power generation capacity and feed them into CEM model.

![Figure 2. Marginal-CV of wind power generation.](image)

3. CEM based on marginal-CV of wind power generation

3.1. Decision variables

Decision variables include capacity investment decision variables $M_{e,u}^y$, which are 0-1 variables that decide whether unit $u$ in area $e$ is put into construction at year $y$; and operational decision variables $U_{e,u}^{y,s,d}$ and $P_{e,u}^{y,s,d,t}$ that simulate the operation of the system, where $U_{e,u}^{y,s,d}$ is the operational capacity of unit $u$ in area $e$ at day $d$, season $s$ in year $y$; $P_{e,u}^{y,s,d,t}$ is the output of unit $u$ in area $e$ at time period $t$, day $d$, season $s$ in year $y$. 

3.2. Objective function
The objective of the generation expansion planning model proposed in this paper is to minimize system cost $Z$, which can be defined as follow,

$$
\min Z = I - S + F + V + W
$$

where $I$ is the capital cost during the planning period; $S$ is the residual value of newly increased fixed assets; $F$ is the fixed operational cost of the system; $V$ is the variable operational cost of the system; $W$ is the cost of expected energy not served (EENS). Note that all the above-mentioned costs are all converted to the present value at the beginning of the planning period. Detailed formula of the objective function is not discussed in this paper due to space limitation, and its calculation is similar to existing generation expansion planning models.

3.3. Constraints involving capacity investment
(1) Capacity investment constraint
A unit can only be put into construction in one year during the planning period, which can be described as

$$
\forall e, \forall u, \sum_{y=1}^{N} M_{e,u}^y = 1
$$

where $N$ is the planning year.

(2) Earliest construction constraint

$$
\forall e, \forall u, \forall y < y_0, M_{e,u}^y = 0
$$

Where $y_0$ is the earliest year that unit $y$ can be put into construction.

(3) Resource adequacy constraint
Wind power mainly impacts the resource adequacy of the system, therefore this is the most important constraint to evaluate wind power generation in the CEM.

$$
\forall e, \forall y, \sum_{u \in \Omega_0} M_{e,u}^y U_{e,u} + \sum_{u \in \Omega_{RE}} C_{e,u} U_{e,u} + \sum_{u \in \Omega_{W}} C_{\text{marginal},e,u} U_{e,u} \geq (1+R_{e}^{y})D_{e}^{y}
$$

where $\Omega_0$ is the set of conventional units; $\Omega_{RE}$ is the set of existing wind power generation units; $\Omega_{W}$ is the set of newly-constructed wind power generation units; $U_{e,u}$ is the capacity of unit $u$ in area $e$; $C_{e,u}$ is the CV of unit $u$ in area $e$; $C_{\text{marginal},e,u}$ is the marginal CV of unit $u$ in area $e$; $R_{e}^{y}$ is the reserve demand rate of area $e$ in year $y$; $D_{e}^{y}$ is the peak-load of area $e$ in year $y$.

3.4. Constraints involving production simulation
(1) Available unit capacity constraint

$$
\begin{cases}
U_{e,u}^{y,s,d} \geq 0, & U_{e,u}^{y,s,d} \geq 0 \\
U_{e,u}^{y,s,d} + U_{e,u}^{y,s,d} \leq U_{e,u}^{y,s,d}
\end{cases}
$$

where $U_{e,u}^{y,s,d}$ is the capacity of unit $u$ that carrying peak-load and can be turned on or off; $U_{e,u}^{y,s,d}$ is the capacity of unit $u$ that carrying peak-load; $U_{e,u}^{y,s,d}$ is the available capacity of unit $u$ in area $e$ at day $d$, season $s$ in year $y$, and is calculated by

$$
U_{e,u}^{y,s,d} = \sum_{u \in \Omega_{e}} K_{e,u} Z_{e,u} U_{e,u}^{y,s,d}
$$

where $K_{e,u}$ represents the type of unit $u$; $Z_{e,u}$ is the overhaul state of unit $u$; $U_{e,u}^{y,s,d}$ is the credit capacity of unit $u$ in area $e$ at day $d$, season $s$ in year $y$. 
It is obvious that for those units that always carry base-load, $U_{e,u^d}^{y,s,d}$ is zero; and for uncontrollable units such as wind power, we have

$$\forall e \in \Omega_y, U_{e,u^d}^{y,s,d} = C_{e,u^d}P_{e,u^d}$$

(10)

where $P_{e,u^d}$ is the forecasted wind power output curve.

(2) Spinning reserve constraint

$$\begin{align*}
\sum_{e \in \Omega_y} \left( \sum_{u \in \Omega_y} (U_{e,u^d}^{y,s,d} + U_{e,u}^{y,s,d}) \right) & \geq (1+R_y^y)D_{\text{MAX}}^{y,s,d} \\
\sum_{e \in \Omega_y} \left( \sum_{u \in \Omega_y} J_u U_{e,u}^{y,s,d} + \sum_{k \in \Omega_y} C_{e,k} U_{e,k}^{y,s,d} \right) & \leq (1- R_y^y)D_{\text{MIN}}^{y,s,d}
\end{align*}$$

(11)

where $\Omega_y$ is the set of areas; $J_u$ is the ratio of minimum output to maximum output of unit $u$; $R_y^y$ and $R_y^y$ are the up and down spinning reserve requirement of the system; $D_{\text{MAX}}^{y,s,d}$ and $D_{\text{MIN}}^{y,s,d}$ are the highest and lowest load demand.

(3) Maximum and minimum output constraint

$$\forall e, \forall u, P_{e,u}^{\text{min}} \leq P_{e,u}^{y,s,d,t} \leq P_{e,u}^{\text{max}}$$

(12)

where $P_{e,u}^{y,s,d,t}$ is the power output of unit $u$; $P_{e,u}^{\text{min}}$ and $P_{e,u}^{\text{max}}$ are the maximum and minimum output of unit $u$.

(4) Power balance constraint

$$\sum_{e \in \Omega_y} \sum_{u \in \Omega_y} P_{e,u}^{y,s,d,t} = D_{s}^{y,s,d,t}$$

(13)

where $D_{s}^{y,s,d,t}$ is the system load demand at time period $t$, day $d$, season $s$ in year $y$.

(5) Ramp rate constraint

$$\forall e, \forall u, -R_{e,u}^{y,s,d} \Delta T \leq P_{e,u}^{y,s,d,t} - P_{e,u}^{y,s,d,t-1} \leq R_{e,u}^{y,s,d} \Delta T$$

(14)

where $\Delta T$ is the time interval; $R_{e,u}$ is the ramp rate limit of unit $u$ in area $e$.

4. Conclusions

With the rapid development of wind power, it is more and more important that variable energy such as wind power generation to be more accurately modelled in CEM. CV is a key factor to reflect the uncertainty nature of wind power and its impact on system capacity expansion. In this paper, a method based on ELCC to calculate the CV and marginal CV of wind power is proposed. Then a capacity expansion co-optimization model of wind power and conventional power sources is presented, where CV and marginal CV are used to describe the system resource adequacy and forms relevant constraints in the proposed CEM. The capacity of wind power generation is considered as decision variable in this model, and the model could fully reflect the impacts of new energy development on the power system security, reliability and economic.
References

[1] J. Zhang 2009 Generation expansion planning with wind power plants [D] Shanghai Jiao Tong University, Shanghai, China

[2] I. G. Damousis, M. C. Alexiadis, J. B. Theochari 2004 A Fuzzy Model for Wind Speed Prediction and Power Generation in Wind Parks Using Spatial Correlation [J] IEEE Trans on Energy Conversion 19(2) 352-361

[3] M. Milligan, K. Porter 2008 Determining the capacity value of wind: an updated survey of methods and implementation [C] Wind Power 2008 352-361

[4] X. Wang 2013 The multi-objective model and algorithm of generation expansion planning including wind farms [D] Shanghai University, Shanghai

[5] B. Zhang 2011 Benefit assessment of wind farms and generation expansion planning model with wind farms [D] Huazhong University of Science & Technology, Wuhan

[6] N. Zhang, C. Kang, J. Xiao 2015 Review and prospect of wind power capacity credit"[J], Proceedings of the CSEE 35(2) 82-94

[7] M. Amelin 2009 Comparison of capacity credit calculation methods for conventional power plants and wind power IEEE Trans. on Power Systems 24(2) 685-691

[8] N. Zhang, C. Kang 2012 Wind power receiving end credible capacity and its impact factor evaluation" [J] Proceedings of the CSEE 32(10) 72-79

[9] S. Zhang, G. Li, M. Zhou 2010 Calculation of wind-farm capacity credit considering transmission line faults [J] Proceedings of the CSEE 30(16) 19-25

[10] N. Zhang, C. Kang, Q. Xia 2013 Rigorous model for evaluating wind power capacity credit” [J] IET Renewable Power Generation 7(5) 504-513