

Robust energy storage allocation for transmission grid integrated by multiple wind farms

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Abstract. Since optimal planning for energy storage sizing and locating is critical to meet the requirement of total wind power absorption, a robust optimization theory based energy storage allocation model for transmission grid with multiple wind farms integrated is proposed in this paper. The model fully considers the transmission capacity limitation, and uses linear decision rule to optimize the allocation of the reserve capacity of the adjustable units and energy storage devices to cope with the fluctuation of wind power, which makes full use of the regulation capacity in the system. Some statistical information of wind power, such as expectation and interval, is used to describe the uncertainty of wind power. The uncertainty model is transformed into a deterministic model by using the duality optimization theory, which provides convenience for engineering application. The Garver's 6-bus transmission system model is used for example analysis, which shows that the proposed method can effectively solve the energy storage planning problem for uncertain wind power integrated power systems.

1 Introduction

Due to the depletion of fossil energy and the aggravation of environmental pollution, new energy power generation has attracted worldwide attention. Among them, the installed capacity of wind power is rising continuously, and the power system with highly penetrated wind power has been formed in some areas with abundant wind resources, which makes the uncertainty of wind power have a serious impact on the system operation. Energy storage devices have the ability of bidirectional power regulation. Energy conversion is considered to be one of the important means to solve the caused by the uncertainty of wind generation[1].

However, the research on improving the wind power absorption capacity of power system by energy storage configuration mainly focuses on balancing the active power of power system by smoothing the output of wind farms by using energy storage. In building optimization models, two-stage stochastic optimization[2], chance-constrained optimization[3] and multi-scenario optimization[4] are all used to study the optimal allocation of energy storage. The above stochastic optimization methods depend on the probability distribution of wind power. Therefore, how to accurately describe the probability distribution of wind power in these methods becomes a key factor affecting the results. However, it is difficult to accurately calculate the probability distribution of wind power in engineering application due to insufficient statistical data in planning stage.

Based on robust optimization theory, a robust energy storage allocation model for transmission network with multi-wind farms is proposed to cope with the uncertainty of wind power, and to find a storage allocation scheme that meets the requirement of total wind power absorption. The model fully considers the transmission capacity limitation of the transmission grid, and uses linear decision rule to optimize the allocation of the reserve capacity of adjustable units and energy storage devices in the system to cope with the fluctuation of wind power. Some statistical information of wind power, such as expectation and interval, is used to describe the uncertainty of wind power. Dual optimization theory is used to transform the uncertainty model into a deterministic model. The results show that the robust allocation model proposed in this paper is effective and feasible, and the obtained results have practical application value for location and capacity determination of energy storage in transmission network with multiple wind farms.

2 Energy storage allocation model for transmission grid integrated by multiple wind farms

Taking the power system with multi-wind farms as the research object, under the condition that the structure and capacity of transmission lines are determined, the power output range of existing adjustable units is fully utilized to cope with the fluctuation of wind power. When the system regulation capacity is limited, the allocation of a

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certain capacity of energy storage devices at appropriate nodes provides additional wind power fluctuation regulation capacity to ensure the safe and economic operation of power systems with large-scale wind power.

The objective function of energy storage capacity allocation model based on DC power flow equation is to minimize the sum of energy storage capacity of configurable nodes. The following linear objective function is adopted in this paper.

$$\min \sum_{k=1}^n e_k^{\max} \quad (1)$$

where e_k^{\max} is the maximum capacity of energy storage located at the k -th node, n denotes the total number of nodes in the power systems.

Constraints are as follows.

1) Nodal power balance:

$$-\mathbf{B}\boldsymbol{\theta} + \mathbf{g}_s + (\mathbf{g}_r + \Delta\mathbf{g}_r) + \boldsymbol{\omega} + \mathbf{e} = \mathbf{d} \quad (2)$$

where \mathbf{B} is the nodal admittance matrix of transmission network, $\boldsymbol{\theta}$ represents the phase angle vector, \mathbf{g}_s and \mathbf{g}_r correspond to the scheduled output vectors of output-fixed units and spinning reserve units, respectively, $\Delta\mathbf{g}_r$ represents the power compensation for the real-time mismatch, $\boldsymbol{\omega}$, \mathbf{e} and \mathbf{d} denote the wind power vector, energy storage power vector and the load vector, respectively.

2) Generation and energy storage limits:

$$\begin{aligned} \mathbf{g}_r^{\min} &\leq \mathbf{g}_r \leq \mathbf{g}_r^{\max} \\ -\mathbf{e}^{\max} &\leq \mathbf{e} \leq \mathbf{e}^{\max} \end{aligned} \quad (3)$$

where superscript min denotes the lower bounds, while the superscript max denotes the upper bounds. In addition, e_k^{\max} is the k -th element of \mathbf{e}^{\max} .

3) Transmission capability constraints:

$$\begin{aligned} \mathbf{F} &= \mathbf{T}\boldsymbol{\theta} \\ -\mathbf{f}_{\max} &\leq \mathbf{F} \leq \mathbf{f}_{\max} \end{aligned} \quad (4)$$

where \mathbf{T} denotes the admittance matrix of network branches, \mathbf{f}_{\max} denotes the deterministic limits of transmission capacity \mathbf{F} .

4) Wind power uncertainty:

$$\begin{aligned} \boldsymbol{\omega}_{\min} &\leq \boldsymbol{\omega} \leq \boldsymbol{\omega}_{\max} \\ E(\boldsymbol{\omega}) &= \boldsymbol{\mu}_w \end{aligned} \quad (5)$$

where $E()$ denotes calculation of the mean value and $\boldsymbol{\mu}_w$ is the mean value of the wind power vector $\boldsymbol{\omega}$, whose lower bound is $\boldsymbol{\omega}_{\min}$ and upper bound is $\boldsymbol{\omega}_{\max}$.

Responding to the time scale and practical demand in engineering, the random variable $\boldsymbol{\omega}$ can be divided into two parts: the forecasted mean value and the uncertain deviation:

$$\boldsymbol{\omega} = \boldsymbol{\mu}_w + \square\boldsymbol{\omega} \quad (6)$$

where $\square\boldsymbol{\omega}$ denotes the uncertain deviation between the real-time output and the mean value. Moreover,

$$\boldsymbol{\omega}^F \leq \square\boldsymbol{\omega} \leq \boldsymbol{\omega}^B, \boldsymbol{\omega}^F = \boldsymbol{\omega}_{\min} - \boldsymbol{\mu}_w, \boldsymbol{\omega}^B = \boldsymbol{\omega}_{\max} - \boldsymbol{\mu}_w.$$

5) Linear decision rule between the uncertain deviation and power compensation:

$$\begin{aligned} \Delta\mathbf{g}_r &= -\mathbf{G}\Delta\boldsymbol{\omega} \\ \mathbf{e} &= -\mathbf{E}\Delta\boldsymbol{\omega} \end{aligned} \quad (7)$$

where \mathbf{G} and \mathbf{E} are sensitivity coefficient matrixes, which denote the linear relationship between the uncertain deviation and the power compensation of spinning reserve units or energy storage. The element g_{ij} of \mathbf{G} denotes the ability of spinning reserve unit at node i for wind farm at node j . Similarly, the element e_{ij} of \mathbf{E} denotes the ability of energy storage at node i for wind farm at node j . In addition, for the wind farm at node j , the uncertain deviation should be equal to the sum of the power compensation of spinning reserve units and energy storage, it yields to the following equation.

$$\sum_{i=1}^n g_{ij} + \sum_{k=1}^n e_{kj} = 1 \quad (8)$$

3 Tractable reformulation

3.1 Robust optimization theory

The model proposed in the previous sections can be formulated as a nominal linear optimization model considering uncertain data5:

$$\begin{cases} \min & \mathbf{c}\mathbf{x} \\ \text{s.t.} & \mathbf{A}\mathbf{x} \leq \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{cases} \quad (9)$$

where $\mathbf{x} \in R^n$ is the decision variable; $\mathbf{u}, \mathbf{l} \in R^n$ denote the upper and lower bounds of \mathbf{x} ; $\mathbf{c} \in R^n$ is the coefficient vector; $\mathbf{b} \in R^m$ is a deterministic vector. And we assume that uncertain data only affects the elements in matrix $\mathbf{A} \in R^{m \times n}$.

Robust optimization theory6 is proposed to find a solution of (9) immune to the uncertain data. Robust optimization methods are based on the following notation. The element of \mathbf{A} is denoted by $a_{ij} \in [a_{ij}^L, a_{ij}^U]$, $i = 1, \dots, m$, $j = 1, \dots, n$; the mean value of a_{ij} is \bar{a}_{ij} ; moreover, the uncertain data in different inequality constraints are assumed to be independent of each other. Let $t_{ij}^B = \bar{a}_{ij} - a_{ij}^L$, $t_{ij}^F = a_{ij}^U - \bar{a}_{ij}$; J_i represents the set of uncertain data in row i of matrix \mathbf{A} , and $|J_i|$ represents the number of elements in set J_i .

To handle the asymmetrical uncertainty where $t_{ij}^B \neq t_{ij}^F$, we introduce the uncertainty set with a robustness budget Γ_i ($\Gamma_i \leq |J_i|$), which can be defined as:

$$\mathfrak{R}_i(\Gamma_i) = \left\{ \mathbf{a}_i \left| \begin{aligned} &a_{ik} \in [\bar{a}_{ik} - \beta_{ik} t_{ik}^B, \bar{a}_{ik} + \beta_{ik} t_{ik}^F], \\ &0 \leq \beta_{ik} \leq 1, \sum_{k \in J_i} \beta_k \leq \Gamma_i, \forall k \in J_i \end{aligned} \right. \right\} \quad (10)$$

where \mathbf{a}_i denotes the uncertain data vector in row i of matrix \mathbf{A} , $i = 1, \dots, m$; β_{ik} depends on the robustness budget Γ_i , which serves to adjust the conservative level of $\mathfrak{R}_i(\Gamma_i)$, i.e., larger the value of Γ_i is, more robust will $\mathfrak{R}_i(\Gamma_i)$ be. With the dual theory, the robust counterpart of (9) and (10) can be given in (11):

$$\begin{cases} \min \quad \mathbf{c}\mathbf{x} \\ \text{s.t.} \quad \sum_{j=1}^n \bar{a}_{ij}x_j + \Gamma_i z_i + \sum_{k \in J_i} p_{ik} \leq b_i, i=1, \dots, m \\ z_i + p_{ik} \geq \max(t_{ik}^F x_k, -t_{ik}^B x_k), i=1, \dots, m, \forall k \in J_i \\ z_i \geq 0, p_{ik} \geq 0, i=1, \dots, m, \forall k \in J_i \\ \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{cases} \quad (11)$$

where z_i and p_{ik} ($i=1, \dots, m, \forall k \in J_i$) are auxiliary variables with no actual physical meaning. The robust counterpart (11) is a determined linear programming. By increasing Γ_i from Γ_{i1} to Γ_{i2} ($\Gamma_{i1} \leq \Gamma_{i2}$), the conservative level of the solution with Γ_{i1} will be lower than that with Γ_{i2} .

By introducing the robust counterpart, the nominal linear programming is converted into a deterministic formulation.

3.2 Robust energy storage allocation model

Nodal phase angle vector θ serves as a redundant variable and can be eliminated only by substituting the constraints (4) to the power balance constraint(2). We use the linear sensitivity matrix \mathbf{S} between branch power flow and nodal injection power in further detail to take the place of $-\mathbf{B}\mathbf{T}^{-1}$. Then, the equality of nodal injection power and branch power flow is obtained:

$$\mathbf{S}\mathbf{F} + \mathbf{g}_s + (\mathbf{g}_r + \Delta\mathbf{g}_r) + \omega + \mathbf{e} = \mathbf{d} \quad (12)$$

where \mathbf{S} denotes the linear sensitivity matrix.

The power balance constraint covered in equality (12) can be formulated as:

$$\mathbf{1}^T (\mathbf{g}_s + \mathbf{g}_r + \mu_w - \mathbf{d}) = 0 \quad (13)$$

where $\mathbf{1}$ denotes a vector whose elements are all 1.

Further, by substituting equality constraints (12) to the transmission limit constraints(4), inequality constraints with uncertain wind power are obtained:

$$-\mathbf{f}_{\max} \leq \mathbf{S}^{-1}[\mathbf{d} - \mathbf{g}_s - (\mathbf{g}_r + \Delta\mathbf{g}_r) - \omega - \mathbf{e}] \leq \mathbf{f}_{\max} \quad (14)$$

So far, the equality constraint with uncertain variables (2) is converted into the constraints (13) and (14) without nodal phase angle vector θ .

4 Case study

In this section, a simulation analysis will be conducted with uncertain wind power.

The revised Garver's 6-bus system⁷ is used to verify the effectiveness of the introduced approach. As shown in Fig. 1, four wind farms are connected to the power grid from different buses. Parameters of the load (L1-L5), generators, wind farms, branches, and the cost coefficients are shown in Table 1-2, respectively. All of the thermal generators are engaged in the spin reserve allocation; d denotes the load; g^{\min} and g^{\max} denote the lower and upper limits of units; n_{ij} denotes the number of transmission lines between node i and j ; x_{ij} denotes the imaginary part of admittance of each branch; f_{ij} corresponds to the active power limit of one line between node i and j .

The optimization is solved by the solver CPLEX in the interface YALMIP of MATLAB8.

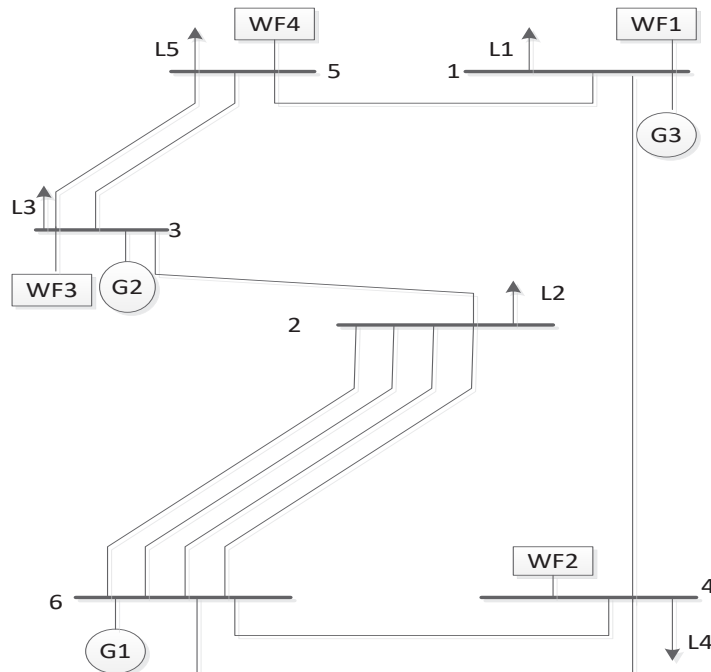


Fig. 1. Configuration of modified Garver's network.

Table 1. System bus data (MW⁻¹).

Bus	<i>d</i>	<i>g</i> ^{min}	<i>g</i> ^{max}	<i>u</i> _w	<i>w</i> ^B	<i>w</i> ^F
1	100	90	150	20	49.5	0
2	300	-	-	-	-	-
3	50	180	360	35	99	0
4	200	-	-	20	49.5	0
5	300	-	-	30	49.5	0
6	-	300	600	-	-	-

Table 2. System branch data.

Node	<i>n</i> _{ij}	<i>x</i> _{ij}	<i>f</i> _{ij} /MW	Node	<i>n</i> _{ij}	<i>x</i> _{ij}	<i>f</i> _{ij} /MW
1-2	1	0.4	100	2-4	1	0.4	100
1-4	1	0.6	80	2-6	4	0.3	400
1-5	1	0.2	100	3-5	2	0.2	200
2-3	1	0.2	100	4-6	2	0.3	200

Without losing generality, it is assumed that the energy storage configuration nodes are not limited, which means that all nodes in the system can configure energy storage devices. In the calculation process, the robustness index Γ_i is equal to the number of wind farms integrated. The minimum storage capacity and location for improving the capacity of wind power admission are given, as shown in table 3.

Table 3. Optimal allocation of energy storage.

Node	1	2	3	4	5	6
Energy storage (MW)	0	0	5.9	0	42.	0
			6		49	

Table 4. Range of branch power flow (MW).

branch	Minimum power flow	Maximum power flow
1-2	89.4	90.7
1-4	71.6	71.7
1-5	84.9	98.4
2-3	89.2	90.3
2-4	89.5	90.6
2-6	297.4	390.9
3-5	159.6	200
4-6	166.5	197.9

The range of absolute value of branch power flow are shown in table 4. It is noted that the power flow of line 3-5 is near to the upper limit, which is the critical line that determined the energy storage allocation. The above result can illustrate the effectiveness of the proposed method.

5 Conclusion

Based on linear decision rule and robust optimization method, an energy storage allocation method is proposed to solve the optimal allocation of energy storage devices in power systems with multiple wind farms. By using this method, the minimum capacity of energy storage, as well as the location and sizing to improve the wind power admissibility are given. In addition, the branch power flow under the worst case is analysed with or without energy storage, whose results verify that the power systems with multiple wind farms will address the uncertain wind power by install the energy storage.

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