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Economic Evaluation for Systems with High Penetration of Wind Power Based on Price Sensitivity Analysis

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Abstract: This paper propose a method for pricing energy and reserve in the system with storage to balance its high penetration of wind power. A two-stage network-constrained schedule model based on stochastic programming co-optimizes energy and reserves is provided by generating units and storage in the system. Constraints include DC Kirchhoff laws throughout the network for all possible wind production scenarios. The values of generating units and storage for reserve and energy, as well as wind energy, to system operation, are derived from the optimality conditions in terms of locational marginal prices. The proposed pricing scheme provides proper signals of the system cost of energy and reserve provision as well as utilization. It also recognizes the contribution of storage systems to accommodate uncertainties induced by stochastic renewable energy for systems.

Key words: storage systems; Karush-Kuhn-Tucker (KKT) conditions; marginal pricing theory; stochastic programming; wind energy

0 Introduction

Concerns of global warming and energy crisis are aggressively prompting governments throughout the world to upgrade their power systems. A concept of smart grid is widely discussed[1], which promises a reliable, secure, economic, efficient, environmentally friendly and safe energy infrastructure. And it is believed that the storage system is one of the key technologies in a smart grid construction[2].

The importance of storage system has been well identified in the power system. The introduction of storage systems will change the operating paradigm of modern electric power systems. Currently, electric power systems are operating with the philosophy called load tracking, i.e., the highly predictable demand is met with highly controllable generation[3]. As a result, the generation and demands should be balanced instantaneously. Due to the essential uncertainty and variability of renewable energy sources[4], the traditional load tracking operating philosophy is challenged under the new energy paradigm. Power systems have to involve more flexible resources to achieve balance. Storage systems are one of the key technologies to mitigate new challenges of power system operation.

Physically, storage systems benefit power systems in many aspects, especially for systems with high penetration renewable energy integration[5]. Over the past decades, pumped hydro storage facilities dominated the large-scale storage landscape. Due to its efficiency and responsibility, the pumped hydro is usually employed to implement load shift. Nowadays, storage technologies, such as battery chemistries, high-speed mechanical flywheels, compressed air energy storage and electric vehicles, provide new dimension of system operation[6]. The benefits of storage systems include following aspects: (1) mitigating uncertainty and variability associated with renewable energy, primarily wind and solar power; (2) smoothing fluctuation of demand to achieve a more economic and reliable operation[7]; (3) mitigating congestion of transmission systems by shifting peak load; (4) providing blackstart resources to crank non-blackstart units or pickup critical loads during system restoration after a complete or partial outage; (5) contributing energy to damp oscillation of frequency and phase angles[8].

Even with well-identified benefits of storage, the quantification of the value of a storage system remains to be discussed[9]. A comprehensive pricing scheme includes not only the operating cost, but also the contributions to the system. A sound pricing scheme prompts the utilization of storages, which is critical for a new energy paradigm. However, few comprehensive storage pricing methodologies

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have been established. Contributions for system operation and the storage system cost are separately studied at present. The idea of nodal price provides a systematic method to price different kinds of services, such as energy reserve for power systems. Based on the concept of locational marginal price (LMP), all of costs and system constraints are integrated into a general framework[10-11].

The idea of LMP is adopted to price the storage system in this paper. A continuous and convex model is established associated with constraints of transmission systems, generating units and storage systems. A scenario-based approach is employed to consider renewable energy output. By deriving Karush-Kuhn-Tucker (KKT) conditions, the price of the storage system is obtained from Lagrange multipliers of all balance equations in both normal and emergency states.

1 Schedule Energy and Reserve Under Uncertainty

LMP is a pricing tool of the electricity production in the systems around the world. The methodology of LMP is to mathematically deduct the value of a particular energy or reserve service to the system operation in terms of total system cost or social welfare[9]. In this paper, the theory of LMP is introduced to quantify the values of storage, wind power, energy, and reserve thermal units in a system.

The dispatch model considering wind uncertainty is based on a two-stage stochastic programming model: (1) at the scheduling stage, the system operator schedules the energy and reserve capacity in the generation side, as well as the scheduled output/absorb energy of storage units; (2) at the second stage, which is related to the actual operation of the system, the uncertainties resulted from wind fluctuation are modeled by the scenarios with probabilities. The deviations in the actual operation are balanced by the up- and down-regulation services provided by both generating and storage units.

The objective function is to minimize the expected cost from generation side C by

$$C=\sum_{n}\Bigg(C_{Gn}(P_{Gn}^{0})+C_{\mathrm{R},Gn}^{\mathrm{U}}R_{Gn}^{\mathrm{U}}+C_{\mathrm{R},Gn}^{\mathrm{D}}R_{Gn}^{\mathrm{D}}+\sum_{k}\pi_{k}C_{Gn}(r_{Gn}^{\mathrm{U},k}-r_{Gn}^{\mathrm{D},k})\Bigg) \tag{1}$$

where n is the index of system buses; k the index of wind power scenarios; $C_{Gn}(\cdot)$ the production cost function of the unit at bus n; P_{Gn}^{0} the production scheduled for the unit at bus n, limited to $P_{Gn}^{\min}$ and $P_{Gn}^{\max}$; $C_{\mathrm{R},Gn}^{\mathrm{U}}$ and $C_{\mathrm{R},Gn}^{\mathrm{D}}$ the costs of the unit at bus n to provide up- and down-reserve powers, respectively; R_{Gn}^{U} and R_{Gn}^{D} the up- and down-reserve capacity scheduled for the unit at bus n, limited to R_{Gn}^{Umax} and R_{Gn}^{Dmax}, respectively; $r_{Gn}^{\mathrm{U},k}$ and $r_{Gn}^{\mathrm{D},k}$ the up- and down-reserve regulation provided by the unit at bus n in scenario k, respectively; and π_k is the probability of wind power scenario k.

In Eq. (1), the first term is the energy production cost; the second and third terms are the costs of units to provide up- and down-reserve; the last term is the expected cost of up-/down-reserve regulation realized by units during each scenario of the actual system operation. For simplicity, we assume a single generator, storage and a single bus located at each bus of the system.

The objective function is subject to the following constraints, with corresponding Lagrange multiplier defined.

1) Constraints of power balance equations pertaining to the scheduling stage and the actual system operation:

$$P_{Gn}^{0}+P_{Sn}^{0}-L_{n}+P_{Wn}^{0}=\sum_{r\in\Theta_{n}}B_{nr}(\theta_{n}-\theta_{r}):\lambda_{n}^{0},\ \forall n \tag{2}$$

$$P_{Gn}^{0}+P_{Sn}^{0}+r_{Gn}^{\mathrm{U},k}-r_{Gn}^{\mathrm{D},k}+r_{sn}^{\mathrm{U},k}-r_{sn}^{\mathrm{D},k}-L_{n}+P_{Wn}^{k}=\sum_{r\in\Theta_{n}}B_{nr}(\theta_{nk}-\theta_{rk}):\lambda_{n}^{k},\ \forall n,\ \forall k \tag{3}$$

where Θ_n is the set of buses directly connected to bus n; P_{sn}^{0} the production scheduled for the storage at bus n; L_n the load at bus n; P_{Wn}^{0} the wind power forecasted at bus n; B_{nr} the susceptance of the line (n,r); θ_n and θ_r the voltage angles at bus n and r at scheduling stage, respectively; $r_{sn}^{\mathrm{U},k}$ and $r_{sn}^{\mathrm{D},k}$ the up- and down-reserve regulation provided by the storage at bus n in scenario k, respectively; P_{Wn}^{k} the wind power realized at bus n in scenario k; θ_{nk} and θ_{rk} the voltage angles at bus n and r in scenario k; and λ_n^0 and λ_n^k are the Lagrangian multipliers of corresponding constraints.

Equations (2) and (3) are the power balances for the scheduling stage and the actual operation of the system. DC load flow is considered.

2) Transmission capacity constraints:

$$-K_{nr}^{0}\leqslant B_{nr}(\theta_{n}-\theta_{r})\leqslant K_{nr}^{0}:v_{nr}^{\min,0},v_{nr}^{\max,0},\ \forall(n,r) \tag{4}$$

$$-K_{nr}^{k}\leqslant B_{nr}(\theta_{nk}-\theta_{rk})\leqslant K_{nr}^{k}:v_{nr}^{\min,k},v_{nr}^{\max,k},\ \forall k,\ \forall(n,r) \tag{5}$$

where K_{nr}^{0} is the scheduled capacity of line (n,r); K_{nr}^{k} the capacity of line (n,r) in scenario k; and $v_{nr}^{\min,0}$, $v_{nr}^{\max,0}$, $v_{nr}^{\min,k}$, $v_{nr}^{\max,k}$ are Lagrangian multipliers of corresponding constraints.

Network constraints are considered in both scheduling stage and actual operation of the system.

3) Constraints related to generating units:

$$r_{Gn}^{\mathrm{U},k}\leqslant R_{Gn}^{\mathrm{U}}:\beta_{Gn}^{\mathrm{Umin},k},\beta_{Gn}^{\mathrm{Umax},k},\ \forall n,\ \forall k \tag{6}$$

$$r_{Gn}^{\mathrm{D},k}\leqslant R_{Gn}^{\mathrm{D}}:\beta_{Gn}^{\mathrm{Dmin},k},\beta_{Gn}^{\mathrm{Dmax},k},\ \forall n,\ \forall k \tag{7}$$

$$P_{Gn}^{\min}\leqslant P_{Gn}^{0}-r_{Gn}^{\mathrm{D},k}:\rho_{Gn}^{\min,k},\ \forall n,\ \forall k \tag{8}$$

$$P_{Gn}^{0}+r_{Gn}^{\mathrm{U},k}\leqslant P_{Gn}^{\max}:\rho_{Gn}^{\max,k},\ \forall n,\ \forall k \tag{9}$$

$$P_{Gn}^{\min}\leqslant P_{Gn}^{0}\leqslant P_{Gn}^{\max}:\rho_{Gn}^{\min,0},\rho_{Gn}^{\max,0},\ \forall n \tag{10}$$

$$R_{Gn}^{\mathrm{U}}\leqslant R_{Gn}^{\mathrm{Umax}}:\delta_{Gn}^{\mathrm{Umax}},\ \forall n \tag{11}$$

$$R_{Gn}^{\mathrm{D}}\leqslant R_{Gn}^{\mathrm{Dmax}}:\delta_{Gn}^{\mathrm{Dmax}},\ \forall n \tag{12}$$

where $\beta_{Gn}^{\mathrm{Umin},k}$, $\beta_{Gn}^{\mathrm{Umax},k}$, $\beta_{Gn}^{\mathrm{Dmin},k}$, $\beta_{Gn}^{\mathrm{Dmax},k}$, $\rho_{Gn}^{\min,k}$, $\rho_{Gn}^{\max,k}$, $\rho_{Gn}^{\min,0}$, $\rho_{Gn}^{\max,0}$, $\delta_{Gn}^{\mathrm{Umax}}$, $\delta_{Gn}^{\mathrm{Dmax}}$ are Lagrangian multipliers of corresponding constraints.

Equations (6)-(12) are variable bounds and technical constraints for generating units, which also link variables in actual operation of the system to those at the scheduling stage. For instance, reserve regulations are bounded by scheduled reserve capacities and generation technical limits, and scheduled reserve capacity is limited by the ramping rate of the unit.

4)Constraints related to storage:

$$0 \leqslant S_{sn} - P_{sn}^{0} \leqslant S_{n}^{\max} : \sigma_{sn}^{\min,0}, \sigma_{sn}^{\max,0}, \ \forall n \tag{13}$$

$$S_{n}^{\min} \leqslant S_{sn} - P_{sn}^{0} - r_{sn}^{\mathrm{U},k} : \sigma_{sn}^{\min,k}, \ \forall n, \ \forall k \tag{14}$$

$$S_{sn} - P_{sn}^{0} + r_{sn}^{\mathrm{D},k} \leqslant S_{n}^{\max} : \sigma_{sn}^{\max,k}, \ \forall n, \ \forall k \tag{15}$$

where S_{sn} is the initial energy in storage unit at bus n; $S_{n}^{\min}$ and $S_{n}^{\max}$ the lower and upper limits of storage unit at bus n, respectively; and $\sigma_{sn}^{\min,0}$, $\sigma_{sn}^{\max,0}$, $\sigma_{sn}^{\min,k}$, $\sigma_{sn}^{\max,k}$ are Lagrangian multipliers of corresponding constraints.

Equations (13)-(15) are variable bounds and technical constraints for storage units in both scheduling stage and actual operation of the system. The technical constraints for storage can either be the storage capacity or the rated power.

2 Price Derivation

2.1 KKT Conditions

The pricing scheme of each service provided in the system are deducted from the KKT conditions associated with Eqs.(1)-(15). Some of these conditions, which are particularly useful for establishing the price derivation, are stated below. Note that L is the Lagrangian function of Eqs.(1)-(15) as

$$\frac{\partial L}{\partial P_{Gn}^{0}} = \frac{\partial C_{Gn}}{\partial P_{Gn}^{0}} - \lambda_{n}^{0} - \sum_{k} (\lambda_{n}^{k} - \rho_{Gn}^{\max,k} + \rho_{Gn}^{\min,k}) = 0, \forall n \tag{16}$$

$$\frac{\partial L}{\partial r_{Gn}^{\mathrm{U},k}} = \pi_{k} \frac{\partial C_{Gn}}{\partial r_{Gn}^{\mathrm{U},k}} - \lambda_{n}^{k} + \beta_{Gn}^{\mathrm{Umax},k} + \rho_{Gn}^{\max,k} = 0, \forall n, \ \forall k \tag{17}$$

$$\frac{\partial L}{\partial r_{Gn}^{\mathrm{D},k}} = -\pi_{k} \frac{\partial C_{Gn}}{\partial r_{Gn}^{\mathrm{D},k}} + \lambda_{n}^{k} + \beta_{Gn}^{\mathrm{Dmax},k} + \rho_{Gn}^{\min,k} = 0, \forall n, \ \forall k \tag{18}$$

$$\frac{\partial L}{\partial P_{sn}^{0}} = \lambda_{n}^{0} - \sum_{k} (\lambda_{n}^{k} - \sigma_{sn}^{\min,k} + \sigma_{sn}^{\max,k}) = 0, \forall n \tag{19}$$

$$\frac{\partial L}{\partial r_{sn}^{\mathrm{U},k}} = -\lambda_{n}^{k} + \sigma_{sn}^{\min,k} = 0, \forall n, \ \forall k \tag{20}$$

$$\frac{\partial L}{\partial r_{sn}^{\mathrm{D},k}} = \lambda_{n}^{k} + \sigma_{sn}^{\max,k} = 0, \forall n, \ \forall k \tag{21}$$

$$\frac{\partial L}{\partial R_{Gn}^{\mathrm{U}}} = C_{\mathrm{R},Gn}^{\mathrm{U}} - \sum_{k} \beta_{Gn}^{\mathrm{Umax},k} + \delta_{Gn}^{\mathrm{Umax}} = 0, \forall n \tag{22}$$

$$\frac{\partial L}{\partial R_{Gn}^{\mathrm{D}}} = C_{\mathrm{R},Gn}^{\mathrm{D}} - \sum_{k} \beta_{Gn}^{\mathrm{Dmax},k} + \delta_{Gn}^{\mathrm{Dmax}} = 0, \forall n \tag{23}$$

2.2 Pricing Scheme for Generating Units

1)Energy price:

$$\frac{\partial C}{\partial L_{n}} : \mu_{n}^{\mathrm{E}} = \lambda_{n}^{0} + \sum_{k} \lambda_{n}^{k}, \ \forall n \tag{24}$$

where μ_{n}^{E} is the energy price at bus n.

The energy price indicated above is consistent with that proposed in Ref. [11]. We refer the reader to the appendix of Ref. [11] for its derivation.

2)Reserve capacity price:

$$\frac{\partial C}{\partial R_{Gn}^{\mathrm{U}}} : \mu_{Gn}^{\mathrm{U}} = \sum_{k} \beta_{Gn}^{\mathrm{Umax},k}, \ \forall n \tag{25}$$

$$\frac{\partial C}{\partial R_{Gn}^{\mathrm{D}}} : \mu_{Gn}^{\mathrm{D}} = \sum_{k} \beta_{Gn}^{\mathrm{Dmax},k}, \ \forall n \tag{26}$$

where μ_{Gn}^{U} and μ_{Gn}^{D} are the prices of up- and down-reserve power provided by the unit.

Note that the reserve prices proposed in this paper differ with the security price defined in Ref. [11]. Prices in Eq. (25) and Eq. (26) are derived in Appendix B.

3)Reserve regulation prices:

$$\frac{\partial C}{\partial r_{Gn}^{\mathrm{U},k}} : \mu_{Gnk}^{\mathrm{EU}} = \pi_{k} \frac{\partial C_{Gn}}{\partial r_{Gn}^{\mathrm{U},k}} + \rho_{Gn}^{\max,k} = \lambda_{n}^{k} - \beta_{Gn}^{\mathrm{Umax},k}, \ \forall n, \ \forall k \tag{27}$$

$$\frac{\partial C}{\partial r_{Gn}^{\mathrm{D},k}} : \mu_{Gnk}^{\mathrm{ED}} = \pi_{k} \frac{\partial C_{Gn}}{\partial r_{Gn}^{\mathrm{D},k}} - \rho_{Gn}^{\min,k} = \lambda_{n}^{k} + \beta_{Gn}^{\mathrm{Dmax},k}, \ \forall n, \ \forall k \tag{28}$$

where μ_{Gnk}^{EU} and μ_{Gnk}^{ED} are the prices of up- and down-reserve regulation provided by unit at bus n in scenario k, respectively.

From the classical theory of electricity price, the reserve regulation price contains fuel cost with the probability as well as the Lagrange multiplier of capacity constraints of generating unit in such scenario. Note that the equality in Eq. (27) comes from Eq. (17).

4)Energy price:

$$\frac{\partial C}{\partial P_{sn}^{0}} : \mu_{n}^{\mathrm{E}} = \lambda_{n}^{0} + \sum_{k} \lambda_{n}^{k}, \ \forall n \tag{29}$$

From the view of power balance, the energy supplied by generators and storages has no differences. Thus, energy prices for both generation and storage are the same, as shown in Eq. (27).

5)Prices of regulations provided by storages:

$$\frac{\partial C}{\partial r_{sn}^{\mathrm{U},k}} : \mu_{snk}^{\mathrm{EU}} = \lambda_{n}^{k}, \ \forall n, \ \forall k \tag{30}$$

$$\frac{\partial C}{\partial r_{sn}^{\mathrm{D},k}} : \mu_{snk}^{\mathrm{ED}} = \lambda_{n}^{k}, \ \forall n, \ \forall k \tag{31}$$

where μ_{snk}^{EU} and μ_{snk}^{ED} are the prices of up- and down-reserve regulation provided by storage at bus n in scenario k.

The prices of regulations provided by storage are shown in Eq. (29). Note that the regulation prices of storage are higher than that of generating units with the value of $\beta_{Gn}^{\mathrm{Umax},k}$.

2.3 Pricing Wind Power

The prices of the wind power are:

$$\frac{\partial C}{\partial P_{Wn}^{0}} : \mu_{n}^{\mathrm{E}} = \lambda_{n}^{0} + \sum_{k} \lambda_{n}^{k}, \ \forall n \tag{32}$$

$$\frac{\partial C}{\partial P_{Wn}^{k}} : \mu_{Wn}^{k} = \lambda_{n}^{k}, \ \forall n, \ \forall k \tag{33}$$

where μ_{Wn}^{k} is the price of wind deviation at bus n in scenario k.

The price of wind production in Eq. (32) is derived directly from the Lagrange multipliers of Eq. (3) of the bus, in which the wind production is located. Note that the wind price represents its value to system operation (power balance), even though its operating cost is trivial and similar to hydro-power units.

The price of wind production at the scheduling stage is the energy price. The price for wind deviation ($P_{Wn}^{k} - P_{Wn}^{0}$) in each scenario is μ_{Wn}^{k}. Note that mathematically the price of wind deviation equals the price of regulation provided by storage. The relations between the wind deviation price and the reserve regulation price are given in the following section. The total payment to wind production C_W includes two parts:

$$C_W = \sum_n \left[\left(\lambda_n^0 + \sum_k \lambda_n^k\right) P_{Wn}^0 + \sum_k \lambda_n^k (P_{Wn}^k - P_{Wn}^0)\right] = \sum_n \left(\lambda_n^0 P_{Wn}^0 + \sum_k \lambda_n^k P_{Wn}^k\right) \tag{34}$$

The payment to wind producer according to the prices above is equal to that for the scheduled wind production P_{Wn}^0 at the energy price μ_n^E minus all the payments for reserve capacity, reserve regulation provided by the generator and storage, as well as the congestion fee resulting from accommodating wind realization in actual operation of the system. The derivation is given in Appendix A.

3 Price Property

The proposed method is important to evaluate the economic value of each service provided for the system, especially the value of reserve service provided by both generating units and storage to absorb the uncertainty induced by wind power. Some important properties of the proposed pricing scheme are described.

3.1 Link Between Storage Regulation Price and Generation Regulation Price

Considering that Eq. (3) for a specific scenario k is reduced by 1 MW·h of storage regulation or wind power. To balance the additional reduction of storage regulation or wind power, two kinds of services of generating units may be required: the scheduling of 1 MW of reserve capacity and its subsequent deployment in the form of 1 MW·h of regulation energy during the operation of actual system. Thus, the marginal cost of balancing such 1 MW·h reduction of storage regulation or wind power in scenario k, which is storage regulation and wind deviation price in Eqs. (30) and (33), is equal to the marginal cost of additional 1 MW of the reserve capacity in $\beta_{Gn}^{\mathrm{Umax},k}$ plus the marginal cost of additional 1 MW·h of reserve regulation by the generation, which is reserve regulation price given by Eq. (27). As shown in Eq. (35), the relationship is also consistent with the equation of KKT condition in Eq. (16).

$$\mu_{Gnk}^{\mathrm{EU}} + \beta_{Gn}^{\mathrm{Umax},k} = \mu_{snk}^{\mathrm{EU}} = \mu_{Wn}^{k},\ \forall n \tag{35}$$

As a result, the regulation by storage and up-wind deviation is more valuable than that by generating units in specific scenario. Thus, it not only supply energy, but also help to lower the minimum requirement of total reserve capacity in the system.

3.2 Wind Payment

If wind producers provide part of the energy supply, they should receive a positive payment for their contribution to the social welfare. This property directly stems from the previous one, considering that the generation cost of the wind farm is virtually zero. According to Eq. (A6) in the Appendix A, the payment to wind producers results from the price of the energy minus the costs of the scheduled reserve capacity by generators, the reserve regulation (to absorb wind fluctuations) by both generator and storage, as well as the fee associated with network congestion events.

3.3 Full Cost Recovery

From the view of social welfare, every producer that is committed in the system to provide a given service, either energy or reserve, has the guarantee of recovering the costs derived from its provision and utilization, unless such a commitment is imposed by technical reasons, such as the unit must run constraints. The proof of the property can be found in Appendix C.

3.4 Revenue Reconciliation

The proposed pricing mechanism guarantees that the collection of payments from loads equals total payments to all services in the system. By applying Eqs. (2), (A2) and (A6), the revenue reconciliation is presented as:

$$\sum_n \mu_n^E L_n = C_W + C_{\mathrm{Gen}} + C_{\mathrm{storage}} + C_{\mathrm{congest}} \tag{36}$$

$$C_{\mathrm{Gen}} = \sum_n \left[\mu_n^E P_{Gn}^0 + \mu_{Gn}^U R_{Gn}^U + \mu_{Gn}^D R_{Gn}^D + \sum_k (\mu_{Gnk}^{\mathrm{EU}} r_{Gn}^{\mathrm{U},k} - \mu_{Gnk}^{\mathrm{ED}} r_{Gn}^{\mathrm{D},k})\right]$$

$$C_{\mathrm{storage}} = \sum_n \left[\mu_n^E P_{sn}^0 + \sum_k (\mu_{snk}^{\mathrm{EU}} r_{sn}^{\mathrm{U},k} - \mu_{snk}^{\mathrm{ED}} r_{sn}^{\mathrm{D},k})\right]$$

$$C_{\mathrm{congest}} = \sum_{(n,r)} \left\{ (\mu_r^E - \mu_n^E) B_{nr} (\theta_n - \theta_r) + \sum_k (\lambda_r^k - \lambda_n^k) B_{nr} [\theta_{nk} - \theta_{rk} - (\theta_n - \theta_r)] \right\}$$

where C_{Gen}, C_{storage} and C_{congest} are total payments for units, storage and congestion, respectively.

By applying Eq. (34), it yields the revenue reconciliation: the collection of payment from load for their energy consumption equals the payment to generation for energy supply and reserve back-up, storage for the energy supply and regulation services, wind producer for the production, congestion fees and other services to absorb wind fluctuations.

4 Case Study

The proposed pricing schemes and their properties are illustrated by a 3-bus system shown in Fig. 1. Line reactances are all 0.13 (per-unit value) on the base of 41 MW and 120 kV. The dispatch model including Eqs. (1)-(13) is solved by CPLEX solver on the platform of GAMS[12].

Table 1 lists the data of generators and storage. The minimum output limits of generators are zero. An inelastic load of 285 MW is located at bus 3. A storage unit is installed at bus 1. A wind plant (WP) is placed at bus 2 with a power production characterized by a base case and four scenarios given in Table 2.

Table 3 shows the reserve and energy dispatches of generators and storage. Only generating unit 2 is scheduled to provide the reserve. The storage is scheduled to supply 23 MW·h at the scheduling stage, reserving 2 MW space to provide 2 MW of regulation in the scenario of wind power shortage.

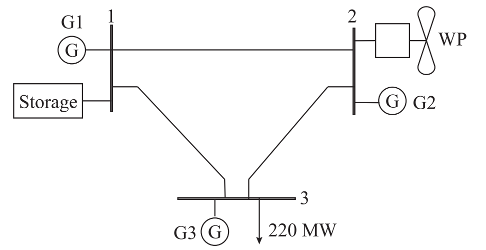

Fig.1　3-bus example system

Table 1　Data of generators and storage

Units	$P_{Gn}^{\max}$/MW	C_{Gn}/(\$·(MW·h)$^{-1}$)	$C_{R,Gn}^{U}$/(\$·MW^{-1})	$C_{R,Gn}^{D}$/(\$·MW^{-1})	R_{Gn}^{Umax}/MW	R_{Gn}^{Dmax}/MW
G1	100	20	15	5.5	5	5
G2	50	30	14	4.3	15	15
G3	100	25	19	4.5	10	20
Storage	Initial energy	5 MW·h	Upper bound	30 MW·h	Lower bound	0

Table 2　Data of wind power scenarios

Scenarios	P_{Wn}^{k}/(MW·h)	π_k
Base case	42	0.6
k=1	50	0.1
k=2	45	0.1
k=3	25	0.2

Table 3　Dispatch results of base case without congestion

Units	Scheduling			P_{Wn}^{k}/(MW·h)		
	P_{Gn}^{0}/(MW·h)	R_{Gn}^{U}/MW	R_{Gn}^{D}/MW	k=1	k=2	k=3
G1	100	0	0	0	0	0
G2	20	15	5	−5	−5	15
G3	100	0	0	0	0	0
Storage	23	—	—	−3	2	2

Table 4 lists the prices for generating units, storage and wind production. The energy price is \$30/(MW·h), the same as the marginal cost of most expensive unit G2. The prices of up- and down-reserve capacity provided by G2 are \$22.2/MW and \$4.2/MW, and the prices of its regulations in each scenario are \$3/(MW·h), \$1.2/(MW·h) and \$6/(MW·h), respectively.

The price of wind production at scheduling stage is the energy price. The prices for wind deviations in each scenario are 0, \$1.8/(MW·h), and \$22.2/(MW·h), respectively, which are equal to the prices of regulation provided by storage.

Note that the wind price in scenario 3 is relatively high. Because the additional wind power in scenarios with low wind is more valuable, it not only contributes to the energy supply, but also indicates a reduction of wind volatility. In addition, the price of wind deviation and regulation provided by storage in scenario 1 is 0. Physically, in scenario 1 with a high wind production, a disturbance of load or wind production can be balanced by storage, and does not affect the objective function.

Table 4　Energy reserve ve prices and regulation price for base case

Units	μ_n^{E}/(\$·(MW·h)$^{-1}$)	μ_{Gn}^{U}/(\$·MW^{-1})	μ_{Gn}^{D}/(\$·MW^{-1})	μ_{Gnk}^{EU}(or μ_{snk}^{EU})/(\$·(MW·h)$^{-1}$)			μ_{Gnk}^{ED}(or μ_{snk}^{ED})/(\$·(MW·h)$^{-1}$)		
				k=1	k=2	k=3	k=1	k=2	k=3
G2	30	22.2	4.2	—	—	6	3	1.2	
Storage	30	—	—	0	1.8	28.2	0	—	—
Wind	30	—	—	0	1.8	28.2	—	—	—

Note: $\mu_1^{E}=\mu_3^{E}=$ \$30/(MW·h) for G1 and G3.

5　Conclusions

This paper provides a marginal pricing scheme adapted to systems that include a large amount of stochastic energy sources. The price of storage system is derived. It accounts for both the costs derived from the energy dispatch and the costs related to the scheduling and allocation of reserves (provision and deployment). The conclusions are as follows.

1) The pricing scheme reported in this paper is specially suited to power systems with high penetration of wind powers. Even for a system without mature power market, the proposed method can provide an approach to assess values of a storage system.

2) Due to the characteristics of the renewable energy, the scenario based method is employed in this paper. The method can be extended to meet the requirements of renewable generation analysis in realistic systems.

Further research is needed to extend the scheme proposed to price storage system considering their contributions to the dynamic performances of the system.

Appendices in this paper are available on line at website of Automation of Electric Power Systems(http://aeps.sgepri.sgcc.com.cn/aeps/ch/index.aspx).

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基于价格灵敏度分析的风储系统经济性评估

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摘要： 提出一种针对含大规模风电的电力系统储能和备用的灵敏度定价方法。结合随机场景分析技术，建立考虑直流潮流约束的调度优化模型，可涵盖所有可能的风电出力场景。基于所提模型，采用边际定价方法，通过最优性条件和拉格朗日乘子，推导了传统发电机、风电和储能系统的能量价格及备用服务价格因子。该定价方法可量化电网中各种机组和储能装置对于系统运行的经济价值，为调度运行和规划提供了参考和依据。

关键词： 储能；Karush-Kuhn-Tucker (KKT)条件；边际定价理论；随机规划；风电

附录 A　Equivalence of Wind Payment

Considering (6), the total payment for wind power is

$$C_W = \sum_n \left(\lambda_n^0 P_{Wn}^0 + \sum_k \lambda_n^k P_{Wn}^k \right) \tag{A1}$$

Total payment to scheduled wind power at energy prices is

$$C_W^S = \sum_n \mu_n^E P_{Wn}^0 = \sum_n \left(\lambda_n^0 + \sum_k \lambda_n^k \right) P_{Wn}^0 \tag{A2}$$

The difference of these two payments is

$$C_W^S - C_W = \sum_n \sum_k \lambda_n^k \left(P_{Wn}^0 - P_{Wn}^k \right) \tag{A3}$$

From the difference of (1.2) and (1.3) for each ,

$$C_W^S - C_W = \sum_n \sum_k \lambda_n^k [r_{Gn}^{U,k} - r_{Gn}^{D,k} + r_{sn}^{U,k} - r_{sn}^{D,k} - B_{nr}\left(\theta_{nk} - \theta_{rk}\right) + B_{nr}\left(\theta_n - \theta_r\right)] \tag{A4}$$

Applying Eqs. (14)-(19) to replace λ_n^k ,

$$\begin{aligned} C_W^S - C_W &= \sum_n \sum_k \lambda_n^k \left(P_{Wn}^0 - P_{Wn}^k \right) = \sum_n \sum_k \left(\pi_k \frac{\partial C_{Gn}}{\partial r_{Gn}^{U,k}} + \beta_{Gn}^{U\max,k} + \rho_{Gn}^{\max,k} \right) r_{Gn}^{U,k} + \\ &\sum_n \sum_k \left(\pi_k \frac{\partial C_{Gn}}{\partial r_{Gn}^{D,k}} - \beta_{Gn}^{D\max,k} - \rho_{Gn}^{\min,k} \right) \left(-r_{Gn}^{D,k} \right) + \sum_n \sum_k \sigma_{sn}^{\min,k} r_{sn}^{U,k} + \\ &\sum_n \sum_k (-\sigma_{sn}^{\max,k})(-r_{sn}^{D,k}) + \sum_n \sum_k \sum_{r \in \Theta_n} -\lambda_n^k [B_{nr}\left(\theta_{nk} - \theta_{rk}\right) - B_{nr}\left(\theta_n - \theta_r\right)] \end{aligned} \tag{A5}$$

Considering (A4) and (A5),

$$\begin{aligned} C_W^S - C_W &= \sum_n \left(\mu_{Gn}^U R_{Gn}^U + \mu_{Gn}^D R_{Gn}^D \right) + \sum_n \sum_k \left(\mu_{Gnk}^{EU} r_{Gn}^{U,k} - \mu_{Gnk}^{ED} r_{Gn}^{D,k} + \mu_{snk}^{EU} r_{sn}^{U,k} - \mu_{snk}^{ED} r_{sn}^{D,k} \right) \\ &+ \sum_k \sum_{(n,r)} \left(\lambda_{rk} - \lambda_{nk} \right) [B_{nr}\left(\theta_{nk} - \theta_{rk}\right) - B_{nr}\left(\theta_n - \theta_r\right)] \end{aligned} \tag{A6}$$

The first term of Eq.(A6) is the payment for reserve capacity. The second term the payment for regulations. The third term the payment for the congestion fee due to wind power realization.

Appendix　B　Derivation of Reserve Price

Since reserve capacity variables do not appear in the balance equation Eqs. (2) and (3), the reserve price is derived by perturbation analysis.

Let the optimal reserve be R^*. The stochastic dispatch model in Eqs. (1)-(13)can be written as

$$\min C(\mathbf{x}, R^*) \tag{B1}$$

$$\text{s.t.} \quad \mathbf{f}(\mathbf{x}) = \mathbf{0} : \boldsymbol{\lambda} \tag{B2}$$

$$R^* - \mathbf{g}(x) \geq \mathbf{0} : \boldsymbol{\beta} \tag{B3}$$

$$\mathbf{h}(\mathbf{x}) \geq \mathbf{0} : \boldsymbol{\sigma} \tag{B4}$$

where **C** is the objective function, vector **x** all variables other than R, **f** the balance equations (B2) and (B3), constraints (B2) the linking of R to **x**, **h** other inequality constraints in the problem, and $\boldsymbol{\lambda}, \boldsymbol{\beta}, \boldsymbol{\sigma}$ are the Lagrange multipliers of the corresponding constraints. Bold symbols represent vectors.

The optimal solution must satisfy the KKT optimality condition, i.e.

$$\begin{cases}\frac{\partial \mathbf{L}}{\partial \mathbf{x}} = \frac{\partial C}{\partial \mathbf{x}} - \boldsymbol{\lambda}^T \frac{\partial \mathbf{f}}{\partial \mathbf{x}} - \boldsymbol{\beta}^T \frac{\partial \mathbf{g}}{\partial \mathbf{x}} - \boldsymbol{\sigma}^T \frac{\partial \mathbf{h}}{\partial \mathbf{x}} = \mathbf{0} \\ \mathbf{f}(\mathbf{x}) = 0, R^* - \mathbf{g}(\mathbf{x}) \geq \mathbf{0}, \mathbf{h}(\mathbf{x}) \geq \mathbf{0} \\ \boldsymbol{\beta}^T [R^* - \mathbf{g}(\mathbf{x})] = \mathbf{0}, \boldsymbol{\sigma}^T \mathbf{h}(\mathbf{x}) = \mathbf{0} \\ \boldsymbol{\lambda}, \boldsymbol{\beta}, \boldsymbol{\sigma} \geq \mathbf{0} \end{cases} \tag{B5}$$

Assuming that with a differential perturbation dR over R^*, Eq.(B3) is still satisfied as

$$R^* - \mathbf{g}(\mathbf{x}) \geq \mathbf{0} \rightarrow R^* - dR - \mathbf{g}(\mathbf{x}') \geq 0 \tag{B6}$$

where **x'** is the new optimal solution after the perturbation.

Constraints (B3) can be equalities or inequalities at the optimum. Firstly, considering that constraints are satisfied as equalities:

$$\beta_i > 0, R^* - g_i(x) = 0 \tag{B7}$$

With a negative differential perturbation dR, constraints Eqs(B7) can be still assumed as equalities.

$$R^* - dR - g(x') = 0 \tag{B8}$$

Considering (B7) and (B8)

$$dg_i = \frac{\partial g_i}{\partial \mathbf{x}} d\mathbf{x} = g_i(\mathbf{x}') - g_i(\mathbf{x}) = dR \tag{B9}$$

$$\beta_i dg_i = \beta_i dR \tag{B10}$$

Secondly, considering the inequality case, i.e.,

$$\beta_i = 0, R^* - g_i(\mathbf{x}) \geq 0 \tag{B11}$$

If β_i is equal to 0, it is noted that (B10) is finally satisfied for inequality constraints.

Supposing that the optimal value of the objective function is changed by the perturbation dR as

$$dC = \frac{\partial C}{\partial \mathbf{x}} d\mathbf{x} \tag{B12}$$

Considering the first equation in (B5)

$$dC = \boldsymbol{\lambda}^T \frac{\partial \mathbf{f}}{\partial \mathbf{x}} d\mathbf{x} + \boldsymbol{\beta}^T \frac{\partial \mathbf{g}}{\partial \mathbf{x}} d\mathbf{x} + \boldsymbol{\sigma}^T \frac{\partial \mathbf{h}}{\partial \mathbf{x}} d\mathbf{x} = \boldsymbol{\lambda}^{\mathrm{T}} \mathbf{df} + \boldsymbol{\beta}^{\mathrm{T}} \mathbf{df} + \boldsymbol{\sigma}^{\mathrm{T}} \mathbf{df} \tag{B13}$$

Considering Eq.(B2) and the third equation in Eq.(B5)

$$\boldsymbol{\lambda}^{\mathrm{T}} \mathbf{df} = \boldsymbol{\lambda}^{\mathrm{T}} (\mathbf{f} + \mathbf{df}) = \mathbf{0} \tag{B14}$$

Likewise ,if Eq.(B4) is satisfied as inequality

$$\boldsymbol{\sigma} = \mathbf{0}, \mathbf{h} \geq \mathbf{0} \rightarrow \boldsymbol{\sigma}^T \mathbf{dh} = \mathbf{0} \tag{B15}$$

Else ,if Eq.(B4) is satisfied as equality

$$\boldsymbol{\sigma} > \mathbf{0}, \mathbf{h} = \mathbf{0}, \boldsymbol{\sigma}^T \mathbf{h} = \mathbf{0} \tag{B16}$$

Constraints (B4) after the perturbation also satisfy the KKT optimality condition as

$$(\boldsymbol{\sigma} + \mathbf{d}\boldsymbol{\sigma})^T (\mathbf{h} + \mathbf{dh}) = \mathbf{0} \tag{B17}$$

where $\boldsymbol{\sigma} + \mathbf{d}\boldsymbol{\sigma}$ is the Lagrange multipliers after perturbation. Then it follows that

$$\boldsymbol{\sigma}^{\mathrm{T}} \mathbf{dh} = \boldsymbol{\sigma}^{\mathrm{T}} \mathbf{dh} + \boldsymbol{\sigma}^{\mathrm{T}} \mathbf{h} - (\boldsymbol{\sigma} + \mathbf{d}\boldsymbol{\sigma})^{\mathrm{T}} (\mathbf{h} + \mathbf{dh}) = \mathbf{-d}\boldsymbol{\sigma}^{\mathrm{T}} (\mathbf{h} + \mathbf{dh}) = \mathbf{-d}\boldsymbol{\sigma}^{\mathrm{T}} \mathbf{dh} = \mathbf{o}(\boldsymbol{\Delta}) \approx \mathbf{0} \tag{B18}$$

Then (B12) becomes

$$dC = \boldsymbol{\beta}^{\mathrm{T}} \mathbf{dg} = \sum_i \beta_i dR \tag{B19}$$

Consequently, the price of R^* is

$$\mu_R = \frac{dC}{dR^*} = \sum_i \beta_i \tag{B20}$$

Applying Eq.(B20) to the up- and down-reserve powers provided by generations and storage yields Eq.(23).

Appendix C Proof of Cost Recovery of Energy and Reserve

The cost recovery of energy, reserve capacity and regulation are proved below, under the assumption that minimum power output constraints of units are not binding.

1) *Cost recovery of energy*

From Eqs.(14) and (22), the energy price must satisfy

$$\mu_n^E = \frac{\partial C_{Gn}}{\partial P_{Gn}^0} + \sum_k \rho_{Gn}^{\max,k} \geq \frac{\partial C_{Gn}}{\partial P_{Gn}^0}, \forall n \tag{C1}$$

Thus the payment guarantees full recovery of the cost.

2) *Cost recovery of reserve*

For up-reserve power provided by units, from Eq.(15), the reserve capacity price in Eq.(23) must satisfy

$$\mu_{Gn}^U = \sum_k \beta_{Gn}^{\max,k} = CR_{Gn}^U + \delta_{Gn}^{U\max} \geq CR_{Gn}^U, \forall n \tag{C2}$$

Hence Eq. (C2) guarantees that the cost for providing up-reserve is fully recovered by the payment. The cost recovery of down-reserve power can be proved in a similar fashion.

3) *Cost recovery of reserve regulation*

From Eq. (25), the prices of the up-reserve regulation by units must satisfy

$$\mu_{Gnk}^{EU} = \pi_k \frac{\partial C_{Gn}}{\partial r_{Gn}^{U,k}} + \rho_{Gn}^{\max,k} \geq \pi_k \frac{\partial C_{Gn}}{\partial r_{Gn}^{U,k}}, \forall n \tag{C3}$$

thus, the cost of such regulation is fully recovered by the payment. Also the cost recovery of down-reserve regulation can be proved similarly.