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Contract coordination of the grid-connected microgrids considering power generation and market demand uncertainties[1]

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Abstract. The microgrid power producer considers generation uncertainty and chooses power generation based on the electricity purchase contract with a grid company. The grid company decides the price of the electricity purchased from microgrid power producer, as well as the electricity contracted price and electricity selling price of the microgrid when power generation and sale are both uncertain. On this basis, the paper comparatively analyzes the optimal behaviors of grid company and power producer in the decentralized and integrated decision-making. Studies have shown that "double marginal effect" exists inside the channel, and the significance of such effect is positively correlated with price elastic coefficient of microgrid generation. With the grid-connection contract and dominant role, grid company can obtain the majority of expected profits. The popular mechanism of "buying price floor protected, price fluctuation in line with market conditions" in practice cannot prevent the opportunism of grid company when the market quotation is not good. Therefore, the paper introduces a Nash negotiation based profit-sharing contract to coordinate such grid-connected microgrid channel. Numerical examples have verified that the implementation of contract coordination not only achieves perfect coordination of the cooperative system, but also Pareto improves both parties' expected profits.

Key words. Microgrid, grid-connection contract, uncertainties, profit-sharing contract, Nash negotiation model.

1. Introduction

Microgrid combines distributed power generation, load, power storage and control system, which compose a small power supply system with autonomous operation capability [1–2]. Independent microgrid is not connected to the external grid, so ensures the balance between power generation and power supply in the microgrid,

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and supplies power to the loads in the grid reliably. Independent microgrid is mainly used in remote areas [3]. Connected microgrid can either be connected to the grid, or be a pre-designed isolated island. It is essentially used to boost local economic profit and enhance local electricity supply level. It mainly improves the power supply reliability and electricity quality in grid-connected areas [4]. Connecting distributed power source to the power distribution network in the form of microgrid, had been widely accepted as an effective method of using distributed power sources [5–6].

Microgrid is a controllable and adjustable load. With microgrid, power dispatch no longer deals with individual distributed power source, but effectively controls and manages these distributed power sources through microgrid [7]. In addition, when distributed power sources are connected to the network, they may have certain impact on distribution network [8–9], the access of distributed power supplies to high reliability and high electricity quality power distribution network must be cautious. Several developed countries and regions have preliminarily established microgrid modeling and simulation analysis tool, completed microgrid control strategy, protection strategy and communication agreement, conducted verification through laboratory test and site demonstration, and found the solutions for fundamental theoretical problems in the operation, protection and economic aspects of microgrid [10–12]. Meanwhile, the development of microgrid in China is also in the experiment and demonstration stage. At present, although certain progress has been made in domestic studies [13–15], it is still in its beginning phase.

Related literature overview shows that researches on microgrid connected electricity generation mainly discuss microgrid connection control, microgrid protection and access standard, and how microgrid affects the reliability of distribution network [16]. Very few researches talk about the connected microgrid optimization, business, or coordination policy. How microgrid power producers take advantage of their strength and participate effectively in the market competition, as well as how grid companies achieve connected microgrid optimized configuration in addition to fully satisfying the electric power quality and supply safety requirements, call for deeper exploration of both parties from microgrid connection concepts and perspectives, to the design of policy orientation and economic management mechanism.

2. Basic model construction

2.1. Problem description

Before the trade day of studied microgrid begins, grid company will sign an electricity purchase contract by mutual consent with microgrid power producer to meet the expected electricity demands. This contract declares that once the power generation finishes, grid company will acquire all the generated electricity at a certain price from the power producer (assuming the price is under market protection scheme). In each session of the trade, power producers determine the power generation cost to invest according to the contract price and the expected market demand. On this basis, grid company acquires all the generated electricity from the producer in accordance with the provisions of the contract, then transmits, distributes and transforms the purchased electric power, and finally sells it to end users at a certain price in the power market. The details are shown in Fig. 1.

2.2. Assumptions and symbols

Only the microgrid connection contract coordination issues of One Period is considered here. The channel structure only contains one grid company and one power producer, and both are rational risk-neutral decision-making individuals.

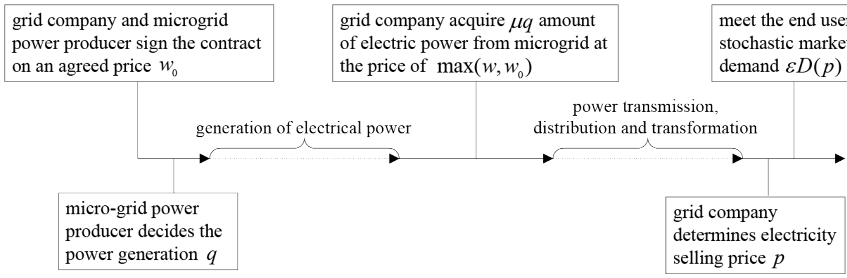

Fig. 1. Microgrid connection decision-making procedure

The electricity generation cost of the power producer is related to the quantity of electricity generations q. The relation is expressed by a cost function of microgrid power generation $C(q) = \alpha + \beta q + \gamma q^2$, where α is the fixed cost, βq is the material cost in power generation, γq^2 is the time and energy the power producer putting in power generation process.

The random factor $\mu \in [\mu_1, \mu_2]$ of the microgrid power generation is a non-negative continuous random variable, with the probability density function and cumulative distribution function written as $g(\cdot)$ and $G(\cdot)$ respectively.

The grid company involves in electricity buying and selling in the market. The buying price with the microgrid power producer $w \in [w_1, w_2]$ is a non-negative continuous random variable, with the probability density function and cumulative distribution function written as $r(\cdot)$ and $R(\cdot)$, respectively. The selling price for end users is p. Without loss of generality, it is assumed that $p > w$.

Referring to [17], the equivalent microgrid power demand can be expressed as $D(p) = y_0 p^{-\kappa_c}$, where $y_0 > 0$ is a constant, indicating the scale of market demand for microgrid power generation; $\kappa_c$is the price elasticity coefficient of market demand, assuming market demand is flexible, i.e. $\kappa_c > 1$. Market demand factor ε is a non-negative continuous random variable, with the probability density function and cumulative distribution function written as $f(\cdot)$ and $F(\cdot)$, respectively. And $F(\cdot)$ is a continuous, differentiable and monotonously increasing function. Without loss of generality, the mean value of ε is set to 1.

To protect the interests of power producer, grid company adopts the rule "buying price floor protected, price fluctuation in line with market conditions" in determination of contract price in acquisition of microgrid electricity from power producers. Specifically, If the electricity price at the time of contract performance w is lower than the contract price w_0, i.e. $w < w_0$, the grid company will still purchase the microgrid electricity at the contract price w_0; Otherwise, If the electricity price at the time of contract performance w is higher than the contract price w_0, the microgrid electricity will be purchased at the actual electricity price w.

3. Integrated decision-making model

3.1. Equilibrium selling price

Under the integrated decision-making mode, Grid Company and microgrid power producers find the optimal power supply and selling price, in order to maximize the overall expected profit. The expected profit of the channel is

$$\Pi_C(p,q) = pE\left[\min\left(\mu q, \varepsilon D(p)\right)\right] - C(q)\,. \tag{1}$$

Similar to [17], the power loss factor for microgrid electricity is $z = \dfrac{\mu q}{y_0} p^{\kappa_c}$. Thus, the selling price from the Grid Company can be written as $p = \left(\dfrac{y_0 z}{\mu q}\right)^{\kappa_c^{-1}}$. By substituting it into above equation, the decision variables (p,q) are now equivalent to (z,q). For an arbitrarily given random factor μ, the overall expected profit can be written as

$$\Pi_C(z,q) = (y_0 z)^{\kappa_c^{-1}} (\mu q)^{1-\kappa_c^{-1}} \left[1 - \int_0^z \left(1 - \frac{\varepsilon}{z}\right) f(\varepsilon)\mathrm{d}\varepsilon\right] - C(q)\,. \tag{2}$$

Theorem 1: For arbitrarily given microgrid power generation q and random factor μ, the optimal selling price can be determined by solving $p_C^{\times}(q) = \left(\dfrac{y_0 \bar{z}}{\mu q}\right)^{\kappa_c^{-1}}$, where $\bar{z}$ is the unique solution for $(\kappa_c - 1)\int_0^z \varepsilon f(\varepsilon)\mathrm{d}\varepsilon = z\left(1 - F(z)\right)$.

3.2. Optimal microgrid power generation

Substituting the optimal selling price $p_C^{\times}$ into Equation (2), following equation can be obtained

$$\Pi_C(q) = \frac{\kappa_c (y_0 \bar{z})^{\kappa_c^{-1}} \left(1 - F(\bar{z})\right) E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)}{k-1} q^{1-\kappa_c^{-1}} - C(q)\,. \tag{3}$$

Theorem 2: Under the integrated decision-making mode, exists a unique optimal power generation $q_C^{\times}$ which maximizes the sum of expected profit of both parties of the channel. The value of $q_C^{\times}$ satisfies the following equation

$$q_C^{\times}(\beta + 2\gamma q_C^{\times})^{\kappa_c^{-1}} = \left[(y_0 \bar{z})^{\kappa_c^{-1}} \left(1 - F(\bar{z})\right) E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)\right]^{\kappa_c^{-1}}\,. \tag{4}$$

Corollaries 1 and 2 can be derived from Theorems 1 and 2.

Corollary 1: The optimal power generation $q_C^{\times}$ for microgrid power producer and the optimal selling price $p_C^{\times}$ of the grid company have the following relations with the power generation cost coefficient of the power producer: $q_C^{\times}$ is not influenced by α but increases with decreasing β or γ; $p_C^{\times}$ is not influenced by α either, but increases with increasing β or γ.

Corollary 2: If the random market demand factor ε shows the nature of increasing generalized failure rate (IGFR), then: $q_C^{\times}$ increases with increasing k; $p_C^{\times}$ increases with decreasing k.

Furthermore, the highest expected profit can be calculated by substituting $q_C^{\times}$ into Equation (3), for best overall performance $\Pi_C^{\times} = \dfrac{q_C^{\times}\left(\alpha + (\kappa_c + 1)\gamma q_C^{\times}\right)}{\kappa_c - 1} - \alpha$.

4. Decentralized decision-making model

4.1. Optimal power generation of microgrid producers

At this point, the decision-making problem between the grid company and the microgrid producer has become a Stackelberg leader-follower game with the grid company as the leader and the microgrid producer as the follower. Backward induction method can be used to get the game's equilibrium. The decision-making problem faced by the power producer can be described as

$$\Pi_s(q) = E\left(\mu q \max(w, w_0)\right) - C(q)\,. \tag{5}$$

The expected profit of the power producer $\Pi_s(q)$ is proven to be a strictly concave function of microgrid power generation q. Thus, the optimal power generation can be obtained by the first-order condition of the function

$$q_s^* = \frac{\displaystyle\int_{\mu_1}^{\mu_2} \mu \mathrm{d}G(x)\left(\int_{w_1}^{w_2} w\mathrm{d}R(w) + \int_{w_1}^{w_0}(w_0 - w)\mathrm{d}R(w)\right) - \beta}{2\gamma}\,. \tag{6}$$

4.2. Grid company's equilibrium decision-making

Under decentralized decision-making mode, the grid company will decide the microgrid electricity selling price p and the contract price w_0 so as to maximize the expected profit of the grid company itself. Then the grid company's expected profit will be calculated from the following equation

$$\Pi_g(p, w_0) = pE\left[\min\left(\mu q, \varepsilon D(p)\right)\right] - \mu q E\left(\max(w, w_0)\right)\,. \tag{7}$$

Likewise, substituting $z = \dfrac{\mu q}{y_0} p^{\kappa_c}$ into Equation (7) and simplifying the equation we get

$$\begin{aligned}\Pi_g(z,w_0)=\left(\frac{y_0 z}{\mu q}\right)^{\kappa_c^{-1}} E_\varepsilon\left[\min\left(\mu q,\frac{\varepsilon\mu q}{z}\right)\right]-\\ \mu q\left(\int_{w_1}^{w_2} w\mathrm{d}R(w)+\int_{w_1}^{w_0}(w_0-w)\mathrm{d}R(w)\right).\end{aligned}\tag{8}$$

Theorem 3: For a given microgrid connection contract price w_0 and natural random factor μ, grid company's optimal electricity selling price of microgrid power generation is $p_g^\times(w_0)=\left(\frac{y_0\bar{z}}{\mu q}\right)^{\kappa_c^{-1}}$.

With complete information, the grid company can predict the optimal power generation decided by the microgrid producer, which shall meet Equation (6). And the relation between contract price w_0 and power generation q is a one-to-one mapping [18]. Substituting q_s^* and $p_g^\times$ into Equation (8) we have

$$\Pi_g(q_s^*)=\frac{\kappa_c(y_0\bar{z})^{\kappa_c^{-1}}\left(1-F(\bar{z})\right)E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)}{\kappa_c-1}q_s^{*1-\kappa_c^{-1}}-q_s^*(\beta+2\gamma q_s^*).\tag{9}$$

Theorem 4: Under decentralized decision-making mode, the grid company's optimal contract price w_0^* meets the following equation groups

$$\begin{cases}\displaystyle\int_{w_1}^{w_0^*}(w_0^*-w)\mathrm{d}R(w)=\frac{\beta+2\gamma q_s^*}{\displaystyle\int_{\mu_1}^{\mu_2}\mu\mathrm{d}G(x)}-\int_{w_1}^{w_2}w\mathrm{d}R(w),\\ q_s^*(\beta+4\gamma q_s^*)^{\kappa_c^{-1}}=\left[(y_0\bar{z})^{\kappa_c^{-1}}\left(1-F(\bar{z})\right)E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)\right]^{\kappa_c}.\end{cases}\tag{10}$$

From Theorem 4 the following corollaries can be obtained:

Corollary 3: If $q_s^*\le\frac{y_0\bar{z}}{\mu}w_0^{*-\kappa_c}$, then $p_g^\times\ge w_0^*$, and both of the two prices are equal only when $q_s^*=\frac{y_0\bar{z}}{\mu}w_0^{*-\kappa_c}$; Otherwise, if $q_s^*>\frac{y_0\bar{z}}{\mu}w_0^{*-\kappa_c}$, then $p_g^\times<w_0^*$.

Corollary 4: Under decentralized decision-making mode, microgrid power producer's optimal power generation will be less than the optimal power generation under integrated decision-making mode, i.e. $q_s^*<q_C^\times$. But the grid company's optimal electricity selling price under decentralized decision-making mode will be higher than the optimal selling price under integrated decision-making mode, i.e. $p_g^\times>p_C^\times$. These facts are called "double edge effect". As the price elastic coefficient of market demand increases, the "double edge effect" will becomes more obvious.

Substituting the optimal strategies of both parties under decentralized decision-making mode into their expected profit function, the expected profits of the grid company, the microgrid power producer and the channel will be

$$\begin{cases} \Pi_g^* = \dfrac{q_s^*\left(2(\kappa_c+1)\gamma q_s^* + \beta\right)}{\kappa_c - 1}, \quad \Pi_s^* = \gamma q_s^{*2} - \alpha\,, \\ \Pi_C^* = \dfrac{q_s^*\left((3\kappa_c+1)\gamma q_s^* + \beta\right)}{\kappa_c - 1} - \alpha\,. \end{cases} \tag{11}$$

5. Cooperative systematic decision-making under coordinated contract

To ensure stable microgrid electricity supply and improve grid-connected channel's performance, grid company adopts profit-sharing contracts to encourage power producers boosting power generation. In this case, the profit function of the grid company can be expressed as

$$\pi_g(p,q,\lambda) = (1-\lambda)p\min\left(\mu q, \varepsilon D(p)\right) - w_g\mu q\,, \tag{12}$$

where $\lambda \in [0,1]$ denotes the profit-sharing coefficient; w_g denotes the coordinated electricity buying price of the grid company. At this point, the microgrid producer's profit function can be expressed as follows

$$\pi_s(q,\lambda) = \lambda p\min\left(\mu q, \varepsilon D(p)\right) + w_g\mu q - C(q)\,. \tag{13}$$

Similar to decentralized decision-making without coordinated contracts, there is also a uniquely determined optimal selling price $\tilde{p}_g(\lambda) = \left(\dfrac{y_0\bar{z}}{\mu q}\right)^{\kappa_c^{-1}}$. Substituting $\tilde{p}_g$ into Equations (12) and (13) and simplifies them we have

$$\begin{cases} \Pi_g(\tilde{p}_g,q,\lambda) = \dfrac{\kappa_c(1-\lambda)(y_0\bar{z})^{\kappa_c^{-1}}\left(1-F(\bar{z})\right)E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)}{\kappa_c - 1} q^{1-\kappa_c^{-1}} - \\ \qquad w_g q\displaystyle\int_{\mu_1}^{\mu_2}\mu \mathrm{d}G(x)\,, \\ \Pi_s(q,\lambda) = \dfrac{\kappa_c\lambda(y_0\bar{z})^{\kappa_c^{-1}}\left(1-F(\bar{z})\right)E_\mu\left(\mu^{1-\kappa_c^{-1}}\right)}{\kappa_c - 1} q^{1-\kappa_c^{-1}} + \\ \qquad w_g q\displaystyle\int_{\mu_1}^{\mu_2}\mu \mathrm{d}G(x) - C(q)\,. \end{cases} \tag{14}$$

Microgrid connection Nash negotiation model in contract price form is constructed below

$$\begin{cases} \max\limits_{q,\lambda} \left(\Pi_g(\tilde{p}_g, q, \lambda) - \Pi_g^*\right)^{\xi} \left(\Pi_s(q, \lambda) - \Pi_s^*\right)^{1-\xi} , \\ \text{s.t.} \Pi_g(\tilde{p}_g, q, \lambda) \geq \Pi_g^*, \Pi_s(q, \lambda) \geq \Pi_s^* , \end{cases} \tag{15}$$

where $\xi \in (0, 1)$ denotes the grid company's bargaining power.

Theorem 5: When using profit-sharing contract in the coordination of microgrid connection channel, the optimal power generation strategy grid company and power producer mutually agree will be [19]

$$\tilde{q}_s(\beta + 2\gamma\tilde{q}_s)^{\kappa_c} = \left[(y_0\bar{z})^{\kappa_c^{-1}} (1 - F(\bar{z})) E_\mu \left(\mu^{1-\kappa_c^{-1}}\right)\right]^{\kappa_c} . \tag{16}$$

Accordingly, the optimal profit-sharing coefficient $\tilde{\lambda}$ of cooperative system satisfies the following equation

$$\tilde{\lambda} = \frac{\Pi_s^* - w_g\tilde{q}_s \int_{\mu_1}^{\mu_2} \mu \mathrm{d}G(x) + C(\tilde{q}_s) + (1 - \xi)(\Pi_C^{\times} - \Pi_g^* - \Pi_s^*)}{\Pi_C^{\times} + C(\tilde{q}_s)} . \tag{17}$$

Substituting Equation (17) into Equation (14), the expected profits of the grid company and of the power producer under optimal coordination will be

$$\begin{cases} \tilde{\Pi}_g = \xi(\Pi_C^{\times} - \Pi_s^*) + (1 - \xi)\Pi_g^* , \\ \tilde{\Pi}_s = (1 - \xi)(\Pi_C^{\times} - \Pi_g^*) + \xi\Pi_s^* . \end{cases} \tag{18}$$

6. Analysis of examples

The scale of the market demand for microgrid is set to be $y_0 = 100$, and price elastic coefficient κ_c falls in range $[3, 6]$. Grid company's selling random factor ε follows Normal distribution $N(1, \sigma^2)$, where $\sigma = 0.2$ or 0.4, and a greater value of σ implies the market demand to be more uncertain. The natural random factor μ in microgrid power generation follows Uniform distribution $U(1 - \delta, 1 + \delta)$, where $\delta = 0.6$ or 0.8. When calculating the grid company's optimal selling price, the mean value of μ is used, and δ reflects the uncertainty of power generation [20]. In addition, microgrid power generation cost coefficients are $\alpha = 2$, $\beta = 0.03$, and $\gamma = 0.005$. Grid company's electricity buying price is subject to Normal distribution $N(0.4, 0.1^2)$.

The table 1 shows that grid company's optimal power purchase contract price for microgrid electricity w_0^* and the power producer's equilibrium power generation q_s^* both increase with increasing price elastic coefficient, but grid company's optimal selling price p_g^* decreases with increasing price elastic coefficient. In addition, the grid company's optimal expected profit Π_g^* reduces with the increasing price elastic coefficient, but the microgrid power producer's equilibrium expected profit Π_s^* increases with the increasing price elastic coefficient. Furthermore, since the price elastic coefficient affects more of the grid company, the channel's overall expected profit $\Pi_g^* + \Pi_s^*$ under separated decision-making mode will reduces with the increasing price elastic coefficient.

When the uncertainty of microgrid power generation becomes significant, i.e. $\delta = 0.8$, grid company's optimal power purchase contract price becomes lower, correspondingly the power producer's equilibrium power generation would also decrease. When the uncertainty of electricity selling becomes significant, i.e. $\sigma = 0.4$, the grid company will lower its optimal power purchase contract price to regulate microgrid power generation of the power producer, as well as raise the selling price to end users to alleviate the impact of market demand uncertainty.

Table 1. Channel members' optimal strategy and equilibrium expected profit under decentralized decision-making mode

σ	κ_c	$\delta = 0.6$					$\delta = 0.8$				
		w_0^*	p_g^*	q_s^*	Π_g^*	Π_s^*	w_0^*	p_g^*	q_s^*	Π_g^*	Π_s^*
0.2	3.0	0.41	1.80	40.93	46.93	5.41	0.39	1.84	39.61	43.98	4.93
	3.5	0.45	1.58	43.63	41.24	6.45	0.430	1.60	42.25	38.71	5.92
	4.0	0.47	1.46	45.21	37.85	7.10	0.45	1.47	43.88	35.66	6.55
	4.5	0.48	1.39	46.35	35.72	7.57	0.47	1.40	45.08	33.78	7.04
	5.0	0.50	1.34	47.15	34.16	7.91	0.48	1.34	45.94	32.44	7.39
	5.5	0.51	1.30	47.74	32.98	8.16	0.50	1.31	46.61	31.43	7.67
	6.0	0.51	1.28	48.27	32.13	8.39	0.50	1.28	47.19	30.72	7.92
0.4	3.0	0.363	1.90	38.70	42.01	4.61	0.33	1.94	37.46	39.38	4.18
	3.5	0.407	1.62	40.99	36.45	5.43	0.39	1.64	39.70	34.22	4.96
	4.0	0.429	1.47	42.41	33.32	5.97	0.42	1.49	41.14	31.39	5.50
	4.5	0.451	1.39	43.42	31.37	6.37	0.43	1.40	42.22	29.67	5.90
	5.0	0.462	1.32	44.22	30.06	6.69	0.44	1.33	43.09	28.56	6.24
	5.5	0.473	1.84	44.86	29.13	6.94	0.45	1.29	43.78	27.75	6.51
	6.0	0.473	1.25	45.39	28.44	7.16	0.46	1.25	44.37	27.18	6.74

Using channel members' expected profit under separated decision-making mode as the benchmark, after coordination their respective performance level improvement will be $\Delta\varphi_i = \dfrac{\tilde{\Pi}_i - \Pi_i^*}{\Pi_i^*}$. In addition, both parties' expected profit after coordination also associate with their bargaining power, with $\xi = 0.7$.

It can be seen from Table 2 that after the implementation of profit-sharing contract coordination, the performance levels of the grid company and the microgrid power producer are both improved, i.e. $\Delta\varphi_g > 0$and $\Delta\varphi_s > 0$. Besides, channel members' performance level increment $\Delta\varphi_g$ and $\Delta\varphi_s$ increase with increasing price elastic coefficient. One thing to note is that the uncertainty of microgrid power generation and market demand exhibits opposite effect on the grid company and the power producer. In other words, as the uncertainty amplifies, the performance level improvement of the grid company after coordination $\Delta\varphi_g$ tends to be smaller, but the performance level improvement of microgrid power producer $\Delta\varphi_s$ tends to be bigger. In fact after the adoption of profit-sharing contract, the power producer shares not only the market profit of microgrid electricity with the grid company, but also the market uncertainty risks of the grid company. When the power producer bears more risks, it also obtain more selling profit, which is consistent with the "High risk, high profit" investment theory.

Table 2. Influence of power generation and market demand uncertainties and price elasticity on both parties' performance level

σ	κ_c	$\delta = 0.6$		$\delta = 0.8$	
		$\Delta\varphi_g$	$\Delta\varphi_s$	$\Delta\varphi_g$	$\Delta\varphi_s$
0.2	3.0	0.156	0.290	0.156	0.293
	3.5	0.162	0.302	0.161	0.306
	4.0	0.166	0.319	0.166	0.323
	4.5	0.170	0.343	0.169	0.348
	5.0	0.172	0.380	0.172	0.387
	5.5	0.175	0.444	0.174	0.452
	6.0	0.177	0.580	0.176	0.595
0.4	3.0	0.155	0.298	0.155	0.302
	3.5	0.161	0.312	0.160	0.316
	4.0	0.165	0.330	0.165	0.335
	4.5	0.168	0.356	0.168	0.362
	5.0	0.171	0.395	0.171	0.402
	5.5	0.173	0.463	0.173	0.474
	6.0	0.175	0.607	0.175	0.625

Above all, when grid company's bargaining power is greater than microgrid power producer's bargaining power, power producer's performance level is improved significantly after the contract coordination proposed in this paper. So the power producer will actively respond to the coordination contract implementation in the cooperation system, which can help the power producer achieve more reasonable expected profit. Therefore, the optimal decision-making behaviors of the cooperation system under this coordinated contract can achieve "risks shared, and interests shared". It not only reduces the pressure of the grid company to bear the market risk alone, but also helps prevent grid company's opportunistic behavior.

7. Conclusion

The paper focuses on a channel structure composed by a risk neutral grid company and microgrid power producer, based on the characteristics of grid-connected power generation and uncertainties of power generation and market demand, constructs the optimized decision-making model for the grid connection contract between the grid company and the power producer. In this model, the contract price form of "buying price floor protected, price fluctuation in line with market conditions" is considered so that microgrid power producer's expected profit is protected and its grid connection compliance rate is also raised. In addition, the paper investigates and compares the optimal behaviors and equilibrium profits of the grid company and the power producer under both decentralized and integrated cooperative and separated decision-making modes. On this basis, the paper further introduces the coordination which incorporates profit-sharing contract and Nash negotiation model and achieves perfect coordination of microgrid contract channel structure. Both members of the cooperation system receive Pareto improvement from their expected profit to their performance levels. The analytic relations among optimal profit-sharing coefficient, the buying price and the bargaining power of the grid company are deduced.

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