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A Coordinative Method for Interruptible Loads Management in an Electricity Market

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Abstract: There are two compensation methods for interruptible loads (ILs), namely low price compensation before supply unavailability and high price compensation after supply unavailability. Low price compensation is independent of power supply unavailability, while the high compensation is performed only after actual power supply unavailability. However, the IL with low price (ILL) and the IL with high price compensation (ILH) have only been studied separately till now. Based on risk management, this paper analyzes the different economic properties of the two compensation methods and concludes that their coordination is beneficial to restrain market power and reduce the cost of reserve capacity. The authors propose the coordination models and optimization algorithms by taking the sum of the deterministic reduction of revenue resulting from ILL and the risk of compensating ILH as the objective function. Simulation results are presented to validate the effectiveness of the proposed method.

Key words: interruptible load with low price (ILL); interruptible load with high compensation (ILH); risk management; coordinative optimization; electricity market

I. INTRODUCTION

It has been identified that system capacity fault has high level of uncertainty and serious impact on the electricity market [1-2], and therefore appropriate system reserve capacity is very important and extensive research has been carried out in this area. The authors of [3] show that reserve capacity of the supply side and interruptible load (IL) capacity of the demand side can be purchased in order to improve the overall generation capacity adequacy. IL can be employed as emergency reserve capacity resource, especially for dealing with capacity fault with low probability and high risks. Introduction IL into the reserve capacity market is therefore of great importance [4].

So far, IL services have attracted significant attention from both academia and industry. The existing research broadly falls into two main categories. A major research problem of IL services is to design appropriate incentive rate structures for customers to participant voluntarily in to the IL programs. IL services are equivalent to forward contracts bundled with a call option, [5]. A comprehensive analysis of such contracts is presented in [5] as well. A double call option is introduced in [6] to account for the effect of early notification of curtailment. In [7] and [8], optimal incentive-rate structures are designed for IL contracts using mechanism-design theory.

Another category of IL research focuses on evaluating the influences of IL services on the whole market. In [9], a technique is proposed to evaluate how IL services can improve the operating benefits of a composite generation and transmission system. Sequential Monte Carlo (SMC) simulation is employed in [10] to analyze the effects of IL services. In [11], a method is proposed to optimize the generation and demand-reduction scheduling in an electricity market considering ILs.

IL contracts have been widely practiced in many countries through their reserve markets. According to North America Electricity Reliability Council (NERC) Operating Policy − 10, interruptible load management (ILM) is recognized as one of the contingency reserve services, [12]. New York ISO (NYISO) has an interruptible load scheme to encourage its customers to reduce their demand during peak hours [13]. In Albert Power Pool of Canada, customers can offer IL services as an additional operation reserve to the pool [14]. PJM market also provides a load reduction program by which customers may be compensated for voluntarily load reduction during emergency situations [15]. In the UK electricity market, IL service providers are encouraged to compete with generators in the provision of all types of reserve services [16]. In the Australian National Electricity Market (NEM), scheduled load (interruptible load) is recognized both as a frequency control ancillary service and a network loading control ancillary service [17]. IL option has been offered to contestable consumers in the National Electricity Market of Singapore from 1 January 2003 [18]. Similarly, Taipower employs a program for load shedding and relevant compensation when tripping a large unit during peak [19].

In order to encourage IL to participate in system reserve, discount price for interruptible loads before capacity fault during emergency [20-22] and high compensation after capacity fault approaches [21-23] are widely used. Low price interruptible load (ILL) is compensated by price discount before the fault in order to get interruptible option of load. High compensation interruptible load (ILH) is compensated after faults and interruption actions. However, to the best of the authors knowledge, no research has been conducted to integrate ILL and ILH methods till now.

Because ILH incurs no fees when there are no faults and interruption actions, it is more economical to deal with the

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capacity faults with small probability and high risk. However, the compensation risk of ILH is relatively high for capacity faults with higher probability. The economical property of ILL is on the contrary compared with that of ILH. Obviously, to cope with all kinds of possible capacity faults, both methods are important because they are mutually complementary to each other. Very similar to the case of preventive control and emergency control for power system stability in [24], the ILL method of low electricity fee losses before capacity fault and the ILH method of high compensation risk after capacity fault can be coordinated by risk management methods. Thus the economical effectiveness of coordination of the two methods is much better than using of ILL or ILH alone

This paper unifies security and economy of a power system by formulating an optimization problem. The objective function of this problem includes proper pricing of system security. Coordination model of demand side reserve service market is established and solved as well. The coordination between IL reserve service market and supply-side reserve capacity market has been developed by the authors in [25].

II. ECONOMIC AND MUTUALLY COMPLEMENTARY PROPERTY OF THE TWO METHODS

ILL method obtains the interruptible option of IL by electricity price discount at the commencement of trading .The electricity tariff lost due to discount can be attributed to regular certain cost because this cost is independent of the occurrence of capacity faults. The amount of discount is correlated with the reliability specified in power supply contracts. ILL method does not compensate customer for the capacity faults when the contracts are effective. However, no matter whether the capacity faults occur or not, the losses caused by discount is fixed.

When ILH method is employed, the electricity is traded in normal price. ILH is compensated after implement of interruption action according to contracts. This kind of compensation can be attributed to risk costs which are relevant to the probability of faults.

ILL and ILH can respectively bid into the reserve service market according to market rules. The trading objective of ILL and ILH markets is interruptible option of IL. Both ILL and ILH are interrupted after capacity faults, from the aspect of their physical properties they should be categorized as emergency or corrective control. Table 1 compares these two market inducement methods both economically and physically.

Demand-side reserve service market consists of a reserve management centre and customers. Reserve management centre is responsible for enabling trading in IL market. Customers participate in IL marketing bidding according to equally incremental interruptible cost criteria. By employing IL market, the market power of supply-side market can be greatly restrained, and the total cost of purchasing reserve capacity is lower. Moreover, the risk of the serious capacity faults with small probability can be greatly reduced as well.

TABLE 1 COMPARISON OF TWO IL COMPENSATION METHODS

Compensation methods	Economic layer					Physical Layer	
	Trading object	Trading period	Trading Methods	Economic property	Unit cost	Control Action	Control property
ILL	Interruptible option of real time load	Shorter	Price discount before blackout	Certain	Lower	After blackout	Emergency or corrective control
ILH		Longer	Compensation after blackout	risk	Higher		

III. ECONOMIC LOSSES OF TRANSMISSION COMPANY IN THE ILL MARKET

In this section, let p_0 be the normal price of electricity. Q_i is the interruptible capacity of customer i traded in the transaction. Q_l is the interruptible capacity that a company needs to purchase. $d_i(Q_i)$ is average reducing rate of electricity price of customer i in the ILL market. $d_i(Q_i)$ is the incremental function of Q_i ($Q_i^{\min} \le Q_i \le Q_i^{\max}$), such as $u_i + v_i Q_i$ with positive intercept u_i and slope v_i, as shown in Fig.1. u_i and v_i are bidding strategies of customer i in the ILL market and can be constant in extreme cases. The loss of electricity fee of the grid company for customer i is $C_i(Q_i) = p_0 d_i(Q_i) Q_i$ which is the incremental function of Q_i. When d_i is constant, $C_i(Q_i)$ is a half radial with slope $p_0 d_i$.

When a company purchases Q_l from the ILL market, the objective is to obtain the minimum loss of electricity fee occurred in trading with all ILL customers. This cost minimization problem can be formulated as

$$\min \sum_i p_0 d_i(Q_i) \times Q_i \tag{1}$$

$$s.t. \quad \sum_i Q_i = Q_l \tag{2}$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \qquad \forall i \tag{3}$$

Eqs. (1) and (2) can be solved regardless of (3) by the Lagrange multiplier method, as follows,

$$\lambda = \frac{Q_l + \sum_i \frac{u_i}{2v_i}}{\sum_i \frac{1}{2p_0 v_i}}, \tag{4}$$

$$Q_i = \frac{\lambda - p_0 u_i}{2p_0 v_i}, \qquad \forall i, \tag{5}$$

where λ is the Lagrange multiplier. Taking the non-equality constraint (3) into account, if $Q_i \le Q_i^{\min}$, set $Q_i = Q_i^{\min}$; if $Q_i \ge Q_i^{\max}$, set $Q_i = Q_i^{\max}$. λ and interruptible capacity of other ILL can be recalculated using (4) and (5) till (3) is satisfied. During t_z period, the loss of electricity fee of a company for purchasing interruptible option of Q_l is defined as the cost of ILL reserve service, which can be formulated as follows,

$$C_l(Q_l) = \sum_i p_0 d_i(Q_i) Q_i t_z \tag{6}$$

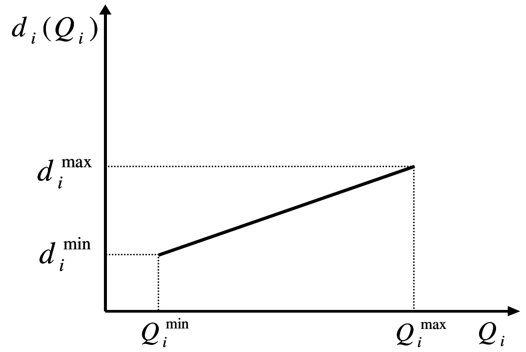


Fig.1 Bidding curve for price discount rate of ILL customer *i*

IV. Compensation Risk in the ILH Market

A. Interruption Cost of ILH

In this section, we let Q_j be the interruptible capacity of customer j traded in an ILH market transaction. $Q_{h,m}$ is the interruptible capacity that a company needs to purchase. $h_j(Q_j)$ is a high compensation multiple of customer j in the ILH market. Its is the ratio of unit interruption cost to p_0. $h_j(Q_j)$ is the incremental function of Q_j ($Q_j^{\min} \le Q_j \le Q_j^{\max}$), such as $\alpha_j + \beta_j Q_j$ with positive intercept α_j and slope β_j, as shown in Fig.2. α_j and β_j are bidding strategies of customer j in the ILL market and can be constants in extreme cases. The Compensation expense of company to customer j is $C_j(Q_j) = p_0 h_j(Q_j) Q_j$, which is incremental function of Q_j .When h_j is constant, $C_j(Q_j)$ is a half radial with slope $p_0 h_j$.

In the ILL market, when a company purchases $Q_{h,m}$ for the individual fault m, the objective is to obtain the minimum compensation expenses occurred in trading with all ILH customers. This cost minimization problem can be formulated as,

$$\min \sum_j p_0 h_j(Q_j) \times Q_j, \tag{7}$$

$$s.t. \quad \sum_j Q_j = Q_{h,m}, \tag{8}$$

$$Q_j^{\min} \le Q_j \le Q_j^{\max}, \qquad \forall j, \tag{9}$$

The solution procedure to find the interruptible capacity of each ILH from (7) and (8) is similar to that of (4) and (5). If the capacity $Q_{h,m}$ is interrupted, its compensation cost can be calculated as,

$$L_{d,m} = \sum_j p_0 h_j(Q_j) Q_j. \tag{10}$$

B. Interruption Compensation Risk

Interruption compensation risk is defined as the cost of ILH reserve service. For a fault set M, compensation risk can be formulated as

$$C_h = \sum_{m \in M} q_m L_{d,m} t_m, \tag{11}$$

where q_m is the occurrence probability of fault m. t_m is the duration of fault m.

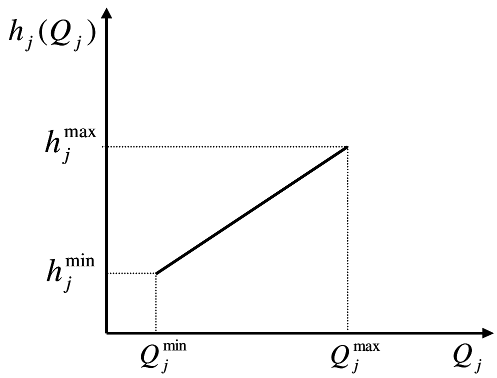


Fig.2 Bidding curve for high compensation multiple of ILH customer *j*

V. The Proposed ILL-ILH Coordination Model

A. Model Formulation

In an IL market, the optimal trading quantities ($Q_l, Q_{h,m}$) in ILL and ILH markets, can be achieved by using mutually complementary property of ILL and ILH economic compensation methods and their supply curves. Objective function of the proposed coordination model is the minimum of total compensation cost C, which is the sum of the loss of electricity fee $C_l(Q_l)$ and the compensation risks C_h caused by all interruption faults. IL capacity equation condition and available capacity of IL market inequality condition are included in the constraints. The over all ILL-ILH coordination model can be expressed as follows,

$$\begin{cases} \min C = C_l(Q_l) + C_h(Q_{h,1}, \cdots Q_{h,m} \cdots, Q_{h,M}) \\ s.t. \quad \begin{cases} Q_{h,m} = Q_m - Q_l \\ Q_l^{\min} \le Q_l \le Q_l^{\max} \\ Q_h^{\min} \le Q_{h,m} \le Q_h^{\max} \end{cases} \end{cases} . \tag{12}$$

B. Model Characteristics

According to different trading methods, this coordination model considers the loss of electricity fee of ILL capacity as certain cost, and the compensation risk is taken as risk cost. By introducing risk management and coordinative optimization, the objective function of the proposed model is to minimize the sum of the loss of electricity tariff and compensation risks wholistically.

C. Solution to the Coordination Problem

The solution to the coordination problem in this model is illustrated in Fig. 3. When Q_l goes up, C_l monotonically increases. With the increment of Q_l, $Q_{h,m}$ decreases and consequently C_h drops monotonically. Total cost curve C has a positive second-order derivative with respect to Q_l. Therefore, the minimum of C, $C_{\min}$, is achieved at $Q_{l.o}$, which is the optimal trading capacity of ILL. In Fig. 3, point *B* corresponds to the cost of purchasing IL completely from ILH market, while point *C* corresponds to that of the ILL market.

To solve this problem, the first step is to obtain C_l and C_h curves in the ILL and ILH markets respectively. Secondly, $C_{\min}$, $C_{l.o}$ and $C_{h.o}$ will be calculated. Finally, $Q_{l.o}$ and $Q_{h,m}$ can be achieved in ILL and ILH market.

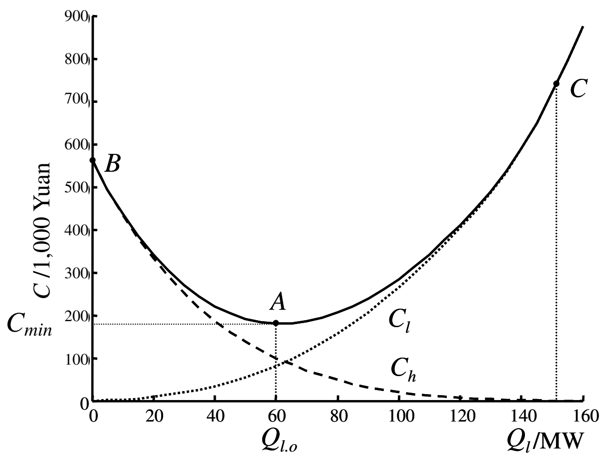


Fig.3 Coordinative optimization between ILL and ILH

For computation simplicity, the complete curves of C_l and C_h are not calculated here. Instead, numerical sensitivity analysis is employed here to search the point of ${dC(Q_l)}/{dQ_l} = 0$, which corresponds to $(Q_{l.o}, C_{\min})$. During the iteration, the initial value of Q_l can be set as a certain percent of the maximum of all $Q_{h,m}$ in the fault set. The step length and convergence threshold can be selected according to precision requirement.

VI. CASE STUDIES

A. Simulation Setting

In the case studies, p_0 is 400 RMB¥/MWh and t_z is set to be 24 hours. Parameters of ILL and ILH market are shown in Tables 2 and 3. Table 4 contains information of the fault set.

TABLE 2 PARAMETERS OF THE ILL MARKET

Consumer i	1	2	3	4
Minimum of interruptible capacity (MW)	0	0	0	0
Maximum of interruptible capacity(MW)	20	40	40	60
Bidding strategy v_i	0.005	0.01	0.012	0.015

TABLE 3 PARAMETERS OF THE ILH MARKET

Consumer *j*	5	6	7	8
Minimum of interruptible capacity(MW)	0	0	0	0
Maximum of interruptible capacity(MW)	15	40	45	60
Bidding strategy β_j	1	2	3	4

TABLE 4 FAULT SCENARIOS

Fault *m*	probability	Total interruptible capacity/MW	Persistence time/h
1	0.050	50	3
2	0.015	100	5
3	0.005	150	7

B. Economic Comparison of Different Schemes

There are three schemes for purchasing of IL capacity.

Scheme 1: only purchase ILL capacity;

Scheme 2: only purchase ILH capacity;

Scheme 3: optimized purchasing of ILL and ILH capacities.

The costs of each scheme at each given individual fault are shown in Table 5. From Table 5, we can see that for fault 1 with high probability, it is more economical to purchase ILL than to purchase ILH. However, for the fault 3 with small probability, purchasing ILH is more economical than purchasing ILL. It can also be clearly seen that the coordination method is much more economical for all faults.

TABLE 5 COST OF THREE SCHEMES FOR EACH INDIVIDUAL FAULT

Fault *m*	Scheme 1 (ILL) Cost (1,000 RMB)	Scheme 2 (ILH) Cost (1,000RMB)	Scheme 3 (coordination) Cost (1,000RMB)
1	53.7	81.3	30.6
2	264.9	206.8	93.9
3	717.1	273.0	150.2

C. Key Factors Which may Affect the Outcome of the Coordination Model

1) INFLUENCE OF BIDDING STRATEGY

The relationship between the bidding strategies of consumers and the trading quantity in the ILH market is demonstrated in Fig.4. With the increase of v_i (or β_j), the equally incremental ratio of the loss of electricity fee in the ILL market (or compensation risk in the ILH market) will increase. According to equally incremental cost criteria, the trading quantity of ILH market will increase (or decrease). The relationship between the bidding strategy of each consumer and distribution of trading quantity in ILL market can also be analyzed by this method.

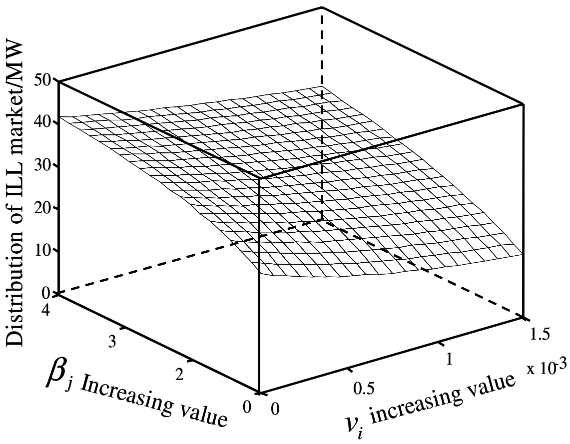
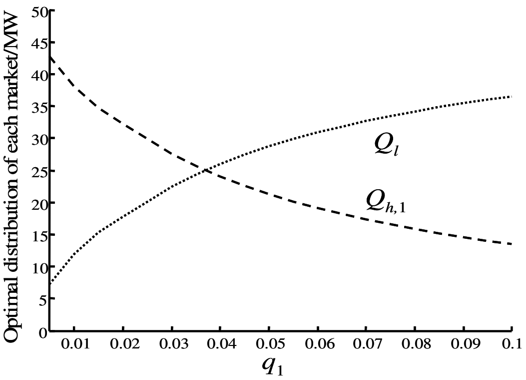


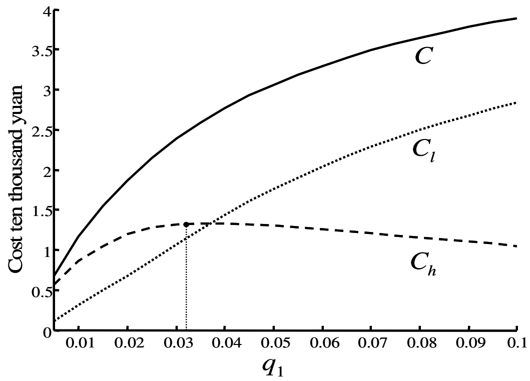
Fig.4 Variation curve of trading quantity with different bidding strategies in the ILH market

2) INFLUENCE OF FAULT PROBABILITY

The relationship between the probability of fault 1, which is q_1, and optimal trading quantity is shown in Fig.5 (a) and the relationship between q_1 and the total cost, C, is shown in Fig.5 (b). When q_1 increases, the optimal ILL capacity Q_l also increases. The economy of ILH compensation method will decrease accordingly. It can also be seen that the compensation risk is relevant to both compensation probability and compensation intensity (or ILH capacity). This combined influence makes $C_h(q_1)$ first increase and then decrease with the increment of q_1.



(a) Influence on the optimal trading quantity



(b) Influence on the total cost

Fig.5 Influence of the fault probability

D. Optimal Decision on ILL Capacity

The relationship between the total compensation cost and ILL capacity for each individual fault is illustrated in Fig. 6. The optimal configuration for the three faults is {28.72，47.23，48.96} MW and the corresponding total cost is {3.06，93.9，150.2} (× RMB¥1,000). Obviously, the higher the compensation risk is, the greater the optimal ILL capacity will be.

All faults must be considered when designing ILL capacity schemes. The outcome of the above case is shown in Fig.6. Optimal ILL capacity is 60 MW and total compensation cost is 180.5 (¥1,000RMB). Accordingly, the losses of electricity fee and compensation risks are 80.6 and 99.9 (¥1,000RMB) respectively.

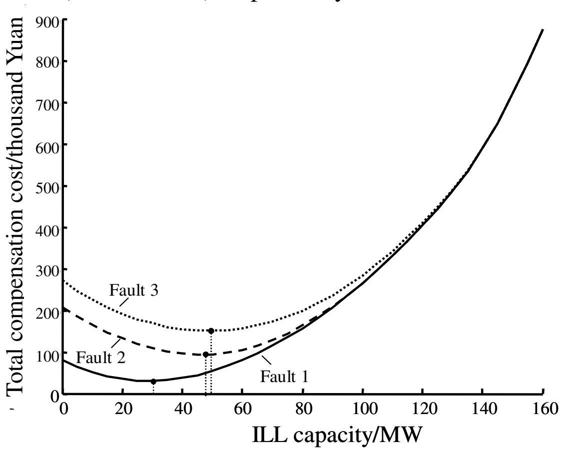


Fig.6 Optimal ILL capacity for individual fault

VII. CONCLUSION

This paper proposes a coordinative method for interruptible load trading in an electricity to enhance system reliability. By introducing risk management and coordination optimization, An efficient method has been developed by using IL effectively in an electricity market. The proposed method can greatly enhance the economic benefit of the demand-side reserve market. A theoretical foundation is established for coordinating the demand-side and the supply-side reserve markets using the different economic property of ILL and ILH. The optimization problem is formulated by minimizing the sum of the losses resulted from ILL and compensation risks of ILH. Preliminary analysis has shown that the method can improve the market efficiency of demand-side reserve market. It can also provide market signals serving as incentives to potential market participants for better system reliability and security. The proposed method is tested with case studies based on a particular electricity market.

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