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Hybrid Optimization of System Adequacy Management in an Electricity Market

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Abstract: **System adequacy has been recognized as one of the essential properties of a power market; however, there is no research work to date specifically on integrating demand-side management, demand-side reserve market and supply-side reserve market. To ensure system adequacy and improve the performance of reserve control, the time-of-use (TOU) power price can be employed as a preventive control. Dispatching the supply-side reserve, shedding interruptible loads with low and high price compensation in the demand-side reserve market are considered as emergency or corrective controls after a system event. Based on the different technical and economic properties of the emergency and preventive controls, this paper proposes to quantitatively analyze the performance of different control schemes using an integrated system model, An optimization algorithm is applied to individual emergency controls, preventive controls and the combination of these two controls. Simulation results are presented to validate the effectiveness of the proposed method.**

Key words: **system adequacy, reserve capacity of generation side (RCGS); interruptible load (IL); time of use (TOU), multi-market coordination optimization**

I. INTRODUCTION

IN a deregulated electricity market, the Independent System Operator (ISO) has the overall responsibility for proving and procuring various services that are essential for the maintenance of system adequacy and security, which are the two aspects of power system reliability. In order to fulfill the basic objective of a power market, both aspects should be maintained carefully. In this paper, both adequacy and security are holistically handled in an optimal way based on a new approach to handle generation reserve capacity, time of use (TOU) power pricing, and interruptible loads.

Generation reserve capacity and can be measured through several parameters including time scale (real-time, daily or long-term), responding speed (spinning reserve and non-spinning reserve such as ready reserve, and cold start reserve), locations, physical property (active or reactive), etc [1]. A too low reserve capacity may not be able to satisfy the system reliability requirement, never the less, a too high reserve capacity may decrease the economy of the market. TOU power pricing is an effective load management scheme for curtailing the system peak load during times of resource shortage [2]. IL can be employed as emergency reserve capacity resource, especially for dealing with capacity fault with small probability and high risk. Introducing IL into the reserve capacity market is therefore of great importance [3].

The existing research of IL 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 IL programs. It is discussed in [4] that, IL services are equivalent to forward contracts bundled with a call option. A comprehensive analysis of this kind of contracts is presented. A double call option is introduced in [5] to account for the effect of early notification of curtailment. In [6,7], 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 [8], a technique is proposed to evaluate how IL services can improve the operating benefits of a composite generation and transmission system. Sequential Monte Carlo simulation is employed in [9] to analyze the effects of IL services. In [10], a method is proposed to optimize the generation and demand-reduction scheduling.

In practice, IL contracts have been widely used in the reserve markets in a number of countries throughout the world. As per North America Electricity Reliability Council (NERC) Operating Policy-10 [11], interruptible load management (ILM) is recognized as one of the contingency reserve services. New York ISO (NYISO), has an interruptible load scheme to induce customers to reduce their demand during peak [12].In Albert Power Pool in Canada, customers can offer IL services to provide for additional operation reserve [13]. PJM market also provides a load reduction program by which customers may be compensated for voluntarily load reduction during emergencies [14]. In the electricity market of UK, ILs are actively encouraged to compete with generators in the provision of all types of reserve services [15]. In Australian National Electricity Market, scheduled load, which is similar with interruptible load (IL) is recognized both as a frequency control ancillary service and a network loading control ancillary service [16]. Similarly, Taipower, the power utility in Taiwan, employs a program for load shedding and relevant compensation when tripping a large unit during peak [17].

The coordination between purchasing reserve capacity of generation side (RCGS) and interruptible load (IL) capacity according to different time of reserve payments is studied in [18]. In [19], the authors propose a coordination model for low price interruptible load (ILL) and high compensation

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interruptible load (ILH). The objective of the coordination model is to minimize the total compensation cost C, which is the sum of the loss of the electricity tariff C_l in the ILL market and the compensation risks C_h in the ILH market.

In this paper, the control of system adequacy is studied from the technical aspect. The implementation of time-of-use power price (TOU) belongs to the category of preventive controls. Dispatching RCGS and interrupting IL belong to the category of emergency or corrective controls after faults. The direct influence of TOU on normal load supply is small, because it requires the consumer to change their routine timetable but can be significant if automated load control is implemented in domestic premises. The TOU and other methods can be mutually complementary because some of the technical property of other emergency or corrective controls may have different features to the one of TOU.

Furthermore, the optimization of system adequacy management is investigated from the economic aspect. It is demonstrated that the mutually complementary property between the long-term preventive payment with low cost, including the cost of TOU, the capacity cost of RCGS, and the loss of electricity tariff of ILL, and post-payment with high cost, including the energy cost of RCGS and the interruption compensation of ILH, makes it possible and necessary to coordinate them [20].

Based on the research of [19], this paper extends the coordination scope to TOU and RCGS. The objective of hybrid optimization model of system adequacy management is to minimize the sum of risk cost and regular cost of control schemes. The optimal peak demand capacity can be obtained by minimizing the objective function.

II. THE DEFINITION OF SYSTEM ADEQUACY CONTROL

A. Preventive Controls

Preventive control is implemented before the occurrence of system adequacy faults. Since TOU is implemented before the fault, it is a preventive control. In this method, the load of peak-period is decreased by demand-side economic incentives, and therefore the value of system adequacy is increased. The peak demand capacity is considered as the measure of the level of preventive control.

B. Emergency or Corrective Controls

Emergency or corrective controls are implemented after the occurrence of capacity faults or a system adequacy event. From the technical aspect, RCGS, ILL and ILH can be executed either according to a feedforward rule (emergency control) or a feedback rule (corrective control). No matter which rule is employed; they are all implemented after faults. From the economic point of view, the dispatching right of RCGS and the interruption right of IL capacity must be purchased in advance to ensure enough control capacity after faults [8-9].

C. Comparison of System Adequacy Control Methods

The different control methods of system adequacy management are compared from economic and physical aspects and the results are shown in Table 1. In this comparison, TOU is assumed as a form of RCGS consisting of instantaneous and delayed reserve. Both TOU and RCGS are initiative reserve. ILL and ILH are assumed as instantaneous reserve, and are designated as passive reserve.

The cost of TOU and ILL are certain, while the cost of ILH is uncertain. As for RCGS, the capacity cost is certain but the energy cost is uncertain.

TABLE 1 CONTROL MEASURES FOR SYSTEM ADEQUACY

system adequacy control means		TOU	RCGS	ILL	ILH
Physical aspect	Control property	Preventive control	Emergency/corrective control		
	Control time	Before faults	After faults		
	Influence to system adequacy	Improvement			
	Influence on generation	reduce peak demand	No direct influence		
	Influence to load	Changing time of use of power	No interruptions or a short-time interruption	Long time interruption	
Economic aspect	Traded item	Peak capacity lowering	Reserve generation capacity and energy	Interruption option of real-time load	
	Relevant market	Demand side	Supply side	Demand side	
	Settlement time	sign	Capacity: sign Energy: after interruption	sign	After interruption
	Cost property	certain	Capacity: certain Energy: risk	certain	risk

D. The Mutual Influence between the Preventive Controls and the Emergency or Corrective Controls

Though TOU has no direct influence on the degree of severity and probability of capacity faults, it increases real available generation capacity by correcting the load demand curve. This reduces market power of RCGS and helps coordination of RCGS, ILL and ILH.

III. THE COST OF SYSTEM ADEQUACY CONTROL

A. The Cost of Preventive Control

For a transmission company, the cost of applying TOU consists of the investment in the system and relevant devices, management expense and the loss of electricity fee. During t_z period (period of investigation), the regular cost of this preventive control can be formulated as,

$$C_p(Q_t) = \boldsymbol{P}_T^T \boldsymbol{Q}_T t_z , \tag{1}$$

$$\boldsymbol{P}_T = [p_{t,1}, \cdots, p_{t,l}, \cdots p_{t,L}]^T , \tag{2}$$

$$\boldsymbol{Q}_T = [Q_{t,1}, \cdots, Q_{t,l}, \cdots Q_{t,L}]^T , \tag{3}$$

$$Q_{t,l}^{\min} \le Q_{t,l} \le Q_{t,l}^{\max} , \tag{4}$$

$$Q_t = \sum_l Q_{t,l} , \tag{5}$$

where $\mathbf{P}_T$ is the price vector of purchasing peak capacity lowering, which consists of L elements corresponding to L consumers respectively. $\mathbf{Q}_T$ is the vector of peak demand capacity. $Q_{t,l}$ is the peak demand capacity of consumer l. $p_{t,l}$ is denoted as the cost of system adequacy control, which is an incremental function of $Q_{t,l}$ and can be constant in extreme cases. Q_T is the total peak capacity lowering traded in the transaction in a TOU market. The peak capacity lowering of consumer l may be influenced by the rules of the power price, the responsivness model of customer, l including bidding strategies, and total peak demand capacity.

B. The Cost of Emergency or Corrective Controls

1) PURCHASING GENERATION RESERVE CAPACITY AND ENERGY

The cost of purchasing reserve generation capacity and energy can be formulated as

$$C_1 = \mathbf{P}_C^T \mathbf{Q} t_z + \sum_{m\in M} q_m \mathbf{P}_E^T \mathbf{A} \mathbf{T}_{E,m} + \sum_{m\in M} q_m \sum_{x=k,r,c} (C_l(Q_{x,l}) + L_d(Q_{x,h}) t_x) \tag{6}$$

$$\mathbf{P}_C = [p_{cs}, p_{ck}, p_{cr}, p_{cc}]^T, \tag{7}$$

$$\boldsymbol{Q} = [Q_s, Q_k, Q_r, Q_c]^T, \tag{8}$$

$$\mathbf{P}_E = [p_{es}, p_{ek}, p_{er}, p_{ec}]^T, \tag{9}$$

$$\boldsymbol{A} = diag[Q_{s,m}, Q_{k,m}, Q_{r,m}, Q_{c,m}], \tag{10}$$

$$\boldsymbol{T}_{E,m} = [t_m, t_m - t_k, t_m - t_r, t_m - t_c]^T \tag{11}$$

$$Q_{s,m} \le Q_s, \tag{12}$$

$$Q_{k,m} \le Q_k, \tag{13}$$

$$Q_{r,m} \le Q_r, \tag{14}$$

$$Q_{c,m} \le Q_c, \tag{15}$$

$$Q_{x,l} + Q_{x,h} = Q_x, \tag{16}$$

where $\mathbf{P}_C$ is the vector of capacity price. The subscripts of these vectors, including *s, k, r, c,* denote instantaneous reserve, quick reserve, slow reserve, and cold-start reserve respectively. Q is the vector of capacity traded in the transaction. $\mathbf{P}_E$ is the vector of electricity prices. '*A*' is the vector of actual cold-start reserve capacity for each individual fault m. q_m is the occurrence probability of fault m in fault set M. t_m is duration of fault m. t_x denotes the delay time of the non- instantaneous reserves. C_l and L_d are the loss of electricity tariff of ILL and compensation cost of ILH respectively. $Q_{x,l}$ and $Q_{x,h}$ are interruption capacities during the delay time of ILL and ILH.

The first item in (6) is the cost of purchasing RCGS. The second item is the energy cost. The third item is the interrupted load during the delay time of the non-instantaneous reserves.

Based on the research in [10], ILL methods are proposed as shown in (6). The capacity cost in RCGS is not related to the specific occurrence of faults, so it is a fixed cost. The energy cost is an uncertain cost since it depends on the uncertain faults. The ILL method employs power price discount, which is certain compensation before fault; however, the customer will not be compensated for the interruption when the contracts are implemented. In the ILH method, the customer is compensated after interruption, and usually the compensation cost exceeds the consumer's real interruption cost.

2) PURCHASING ILL AND ILH

The cost of purchasing interruptible capacity of ILL and interruptible energy of ILH can be calculated by, [11],

$$\begin{aligned} C_2 &= C_l + C_h \\ &= \sum_i p_0 d_i(Q_i) Q_i t_z + \sum_{m\in M} q_m \sum_j p_0 h_j(Q_j) Q_j t_m \end{aligned} \tag{17}$$

where certain cost C_l is the loss of electricity tariff, which is unrelated to faults. p_0 is the normal price of electricity. $d_i(Q_i)$ is the average reducing rate of electricity price of customer i in 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 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 $p_0 d_i$.

The compensation cost C_h is uncertain, which depends on faults. $h_j(Q_j)$ is a high compensation multiple of customer j in ILH market, which 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 ILL market and can be constant 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 $p_0 h_j$.

3) THE COST OF EMERGENCY OR CORRECTIVE CONTROLS

The total cost of emergency or corrective controls C_e is related to the fault set. C_e reflects the risk level of system adequacy in this operating state. It can be expressed as

$$C_e = C_1 + C_2 \tag{18}$$

This total cost (18) will be used as the objective function for the proposed hybrid system adequacy optimization.

IV. THE HYBRID OPTIMISATION MODEL

A. Model Formulation

TOU method can induce the operating state to a target point with high system adequacy by decreasing the peak-valley margin of power demand. When the adequacy of power system is destroyed by fault m, the emergency or corrective controls will be implemented to avoid big blackout. Increasing the system adequacy of target point can decrease the pressure of emergency or corrective controls. Thus preventive controls and emergency or corrective controls can be coordinated.

The objective of coordination model is to minimize the coordinative control cost C, which is the sum of the regular cost C_p of preventive controls and the uncertain cost C_e of emergency or corrective controls. The coordination model can be expressed as

$$\begin{cases} \min C(Q_t) = C_p(Q_t) + C_e(Q_t, Q_1, \cdots, Q_m, \cdots, Q_M) \\ s.t.\ \ g(Q_t) = 0 \\ \quad\ \ h(Q_t, \mathbf{Q}, Q_l, Q_h) \geq 0 \end{cases}, \quad (19)$$

where $g(Q_t) = 0$ is the equality constraint of power flow. $h \geq 0$ is the inequality constraint of control capacity and the requirement of adequacy. Q_l (or Q_h) is traded capacity in the transaction in ILL market (or ILH market).

B. The Sub-problem of Emergency or Corrective Controls

In this section, Q_m is power inadequacy caused by fault m. The optimization of emergency or corrective controls can be expressed as

$$\min C_{e,m}(Q_t, Q_m) \quad (20)$$

$$s.t.\ \ f(\mathbf{Q}, Q_l, Q_h) \geq 0, \quad (21)$$

$$(Q_{s,m} + Q_{k,m} + Q_{r,m} + Q_{c,m}) + Q_{l,m} + Q_{h,m} \geq Q_m \quad ,(22)$$

$$Q_{l,m} \leq Q_l, \quad (23)$$

$$Q_{h,m} \leq Q_h, \quad (24)$$

where $Q_{l,m}$ and $Q_{h,m}$ are interruptible capacity of ILL and ILH. The constraints of capacity of all kinds of control methods are included in (21). Equation (22) is the system adequacy constraint.

C. Solution to the Hybrid Optimisation Problem

The solution to the optimal problem in this model is illustrated in Fig. 1. When Q_t goes up, C_p monotonically increases. With the increase of Q_t, the available capacity of RCGS in the market is increased and the interruptible capacities of ILL and ILH, which have high cost, decrease and consequently, C_e drops monotonically. Total cost curve C has a positive second-order derivative with respect to Q_t. Therefore, the minimum of C, $C_{\min}$, is achieved at $Q_{t.o}$, which is the optimal peak demand capacity. Numerical sensitivity analysis is employed here to search the point where $\frac{dC(Q_t)}{dQ_t} = 0$, which corresponds to $(Q_{t.o}, C_{\min})$. The step length and convergence threshold can be selected according to precision requirement.

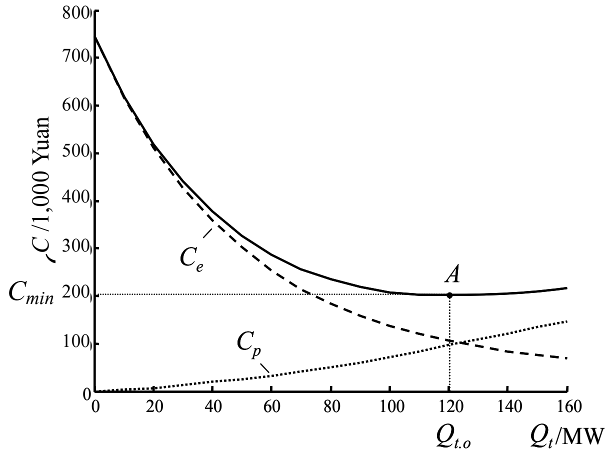


Fig.1 Coordinative optimization of preventive and emergency/corrective controls

If the actual available capacity of RCGS and ILL has are certain and adequate, the capacity cost will be certain. The optimal control scheme under a given fault will only be influenced by its energy cost. Therefore, the optimal problem can be solved by three steps. The first step is to calculate the capacity cost without considering capacity cost of RCGS and ILL. By using the demand and supply matching curve of ILL market and ILL interruption capacity, $Q_{t.o}$, $C_{\min}$, optimal RCGS, $Q_{l,m}$, and $Q_{h,m}$ can be obtained for a given fault m. The second step is to calculate the maximum of RCGS, $Q_{l,m}$, and $Q_{h,m}$ for all faults in the fault set. These maxima will be used as configuration capacity for the fault set. The last step is to calculate the capacity costs of RCGS and ILL, which is the cost of purchasing the capacity before faults. These costs will be allocated to relevant costs and total cost.

V. CASE STUDIES

A. Simulation Setting

Part of the Chinese state grid system is taken for case studies. In these case studies, p_0 is ¥400RMB/MWh and t_z is 8h. The total static available generation capacity of the studied system is 650 MW. Before implementing TOU, the maximal load is 640MW. Each generator submits bids according to the linear functional relationship between the energy and reserve market. Each customer also submits bids according to linear functional relationship between the ILL and ILH market as well. Parameters of the customers in TOU market are shown in Table 2. Parameters of energy market and RCGS market are shown in Table 3 and Table 4 respectively. Parameters of ILL market and ILH market are shown in Table 5 and Table 6. Table 7 is information of the fault set.

TABLE 2 CONSUMER PARAMETERS IN TOU MARKET

Customer l	1	2	3	4
Minimal interruptible capacity(MW)	0	0	0	0
Maximal interruptible capacity(MW)	20	40	40	60
Price $p_{t,l}$ (RMB/MWh)	40	80	120	160

TABLE 3 PARAMETERS OF ENERGY MARKET

Generator g	1	2	3	4
Maximal active output(MW)	90	160	160	240
Minimal active output(MW)	10	20	20	30
Bidding strategy a_g	0.4	0.3	0.2	0.1
Bidding strategy b_g	150	160	170	180

TABLE 4 RESPONDING TIME AND BIDDING STRATEGY OF RCGS

RCGS type	s	k	r	c
Response time(min)	0	10	30	120
Bidding strategy c_g	0.4	0.3	0.2	0.1

TABLE 5 PARAMETERS OF ILL MARKET

Customer i	5	6	7	8
Minimal interruptible capacity(MW)	0	0	0	0
Maximal interruptible capacity(MW)	10	20	20	30
Bidding strategy v_i	0.005	0.01	0.012	0.015

TABLE 6 PARAMETERS OF ILH MARKET

Customer j	9	10	11	12
Minimal interruptible capacity(MW)	0	0	0	0
Maximal interruptible capacity(MW)	20	40	40	60
Bidding strategy β_j	1	2	3	4

TABLE 7 FAULT SCENARIOS

Fault m	Probability	Total interruptible capacity(MW)	Persistence time (h)
1	0.050	120	3
2	0.025	180	5
3	0.005	240	7

B. Peak Capacity Lowering Impact on the Trading in Energy Market and Available Generation Capacity

The influence of peak shedding capacity on the available generation capacity and market clearing price is shown in Figure 2. It can be seen from Fig. 2 that with the increase of peak demand capacity, the available generation capacity will increase, while the energy market clearing price will decrease.

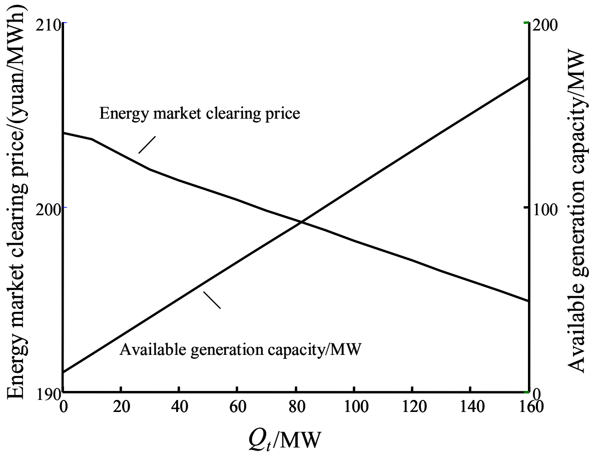


Fig.2 The influence of peak shedding capacity on the available generation capacity and market clearing price

C. The Influence of Peak Capacity Lowering on Optimal Configuration of Emergency or Corrective Controls

Fig. 3 shows that the increase of peak capacity lowering will increase the dispatching capacity of RCGS and decrease the interruption quantity of IL capacity. The total uncertain cost of emergency or corrective controls will decrease consequently.

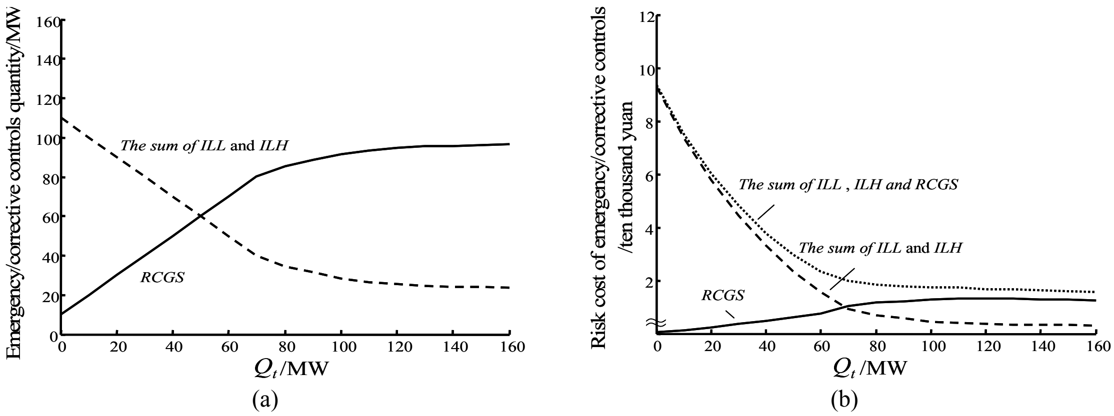


Fig.3 The influence of peak shedding capacity on optimal reserve capacity

D. Risk-Based Coordinative Control and Optimisation Decision

The influence of peak demand capacity on the cost of coordinative control is shown in Fig. 4. The lowest point of this curve corresponds to the optimal peak capacity lowering and its cost. Fig.1 demonstrates the results when considering all faults in the fault set. The optimal peak capacity lowering is 120 MW and total cost of coordinative control is ¥283.9 × 1,000RMB. The simulation results of the optimal coordinative control are given in Table 8.

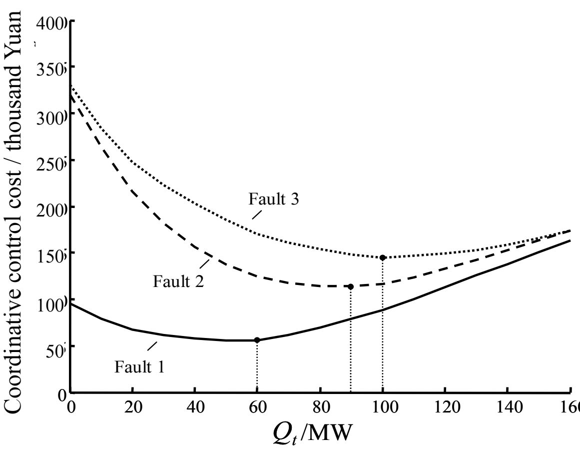


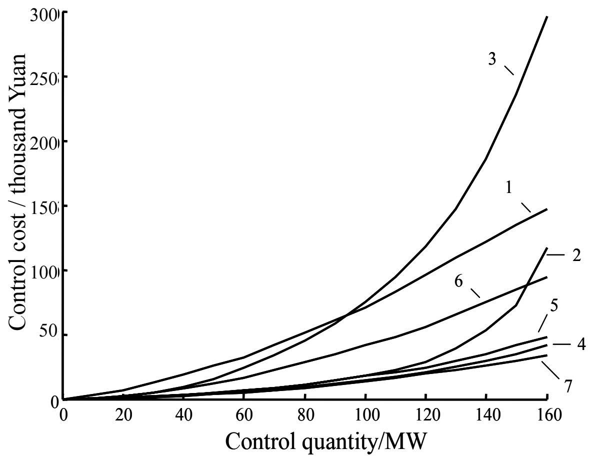
Fig.4 Optimal peak shedding capacity configuration for each individual fault

TABLE 8
RESULTS OF COORDINATIVE OPTIMIZATION

Fault *m*	RCGS		ILL capacity		ILH capacity		Peak capacity lowering (MW)	Coordi-native Control cost (1,000RMB)
	Configuration capacity before fault (MW)	Real dispatching capacity (MW)	Configuration capacity before fault(MW)	Real interrupting capacity (MW)	Configuration capacity before fault (MW)	Real interrupting capacity (MW)		
1		70		37.85		12.15	60	87.0
2	110	100	60.71	55.95	69.29	24.05	90	128.7
3		110		60.71		69.29	100	154.1
All faults	110	uncertain	60.71	uncertain	69.29	uncertain	120	283.9

VI. COMPARING THE EFFECTIVENESS OF THE PREVENTIVE, EMERGENCY OR CORRECTIVE AND COORDINATION CONTROLS

The Effectiveness of different control schemes are compared with the same model, parameters and fault scenarios. Table 9 shows the control schemes, including implementing TOU individually that corresponds to curve 1 in Fig. 5, dispatching RCGS individually that corresponds to curve 2 in Fig. 5, interrupting IL individually that corresponds to curve 3 in Fig. 5, and all possible combination. In Fig.5, we can see that the more of the coordinative control methods are employed, the greater the economic benefit that will be achieved. Curve 7 in Fig.5 shows the optimal case by employing all control methods.



1~7：Index number of the control scheme

Fig.5 Costs of various control schemes for system adequacy

TABLE 9
VARIOUS TYPES OF CONTROL SCHEMES FOR SYSTEM ADEQUACY

Control scheme	Preventive control	Emergency/corrective controls	
	Implementing TOU	Dispatching RCGS	Interrupting ILL and ILH capacity
Scheme 1	√		
Scheme 2		√	
Scheme 3			√
Scheme 4		√	√
Scheme 5	√	√	
Scheme 6	√		√
Scheme 7	√	√	√

VII. CONCLUSION

In this paper, an optimal preventive and emergency control method of load management is proposed.. TOU is employed as preventive control. Dispatching of RCGA, interrupting demand-side capacity (ILL/ILH) are applied as emergency or corrective controls after faults. The uncertain cost of emergency or corrective controls can reflect the risk level of system adequacy. The economic benefit can be greatly enhanced by fully utilizing mutually complementary properties in technical and economic aspects between preventive controls and emergency or corrective controls, and applying risk management and coordinative optimization. The proposed method has some limitations to be applied in a mature electricity market, because TOU is usually exercised by retail companies, rather than ISO, in this kind of markets. The retailer can incorporate transmission requirements in the consumer contract for a suitable price. The proposed method, however, can be very effective in the electricity market of China, given its special characteristics.

The problem of hybrid optimization of system adequacy is an optimal coordinative control problem. The objective function of the proposed model is the sum of the costs of preventive controls and emergency or corrective controls with the constraint of system adequacy requirement. The proposed method can not only well coordinate ILL, ILH and RCGS markets, but also can guarantee the system adequacy and economic benefit. Simulation results are presented to validate the proposed method.

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