Optimization Model of Purchasing Interruptible Load for Network Congestion Constrained Dispatch during the Peak Load Periods

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Abstract: Interruptible load management (ILM) is one of the demand response incentives. It's good to the reliability of the power system. During the peak time of the power system, there are always network congestion constraints. In this paper, based on the active power dispatch an optimal IL purchasing model including hybrid generation, network and demand side constraints is presented. This model not only puts emphasis on the network congestion capacity constraint but considering the influence of pre-informed time and the interruption duration period and the geographical position on network loss. The Binary version of the Particle Swarm Optimization (BPSO) method is used to solve this model. And the simulation result shows that the model is fit for using IL in peak load congestion constrained dispatch in developing power market.

Keyword: power market; interruptible load (IL); congestion constrained dispatch; peak load; spinning reserve; network loss

1. Introduction

With the development of power market, demand response(DR) has received much more recognition. As one of the important DR incentives, interruptible load(IL) can take fully use of the power usage elasticity of the customer, relieve the tensity of the power system in peak load period. It can also decrease the supply side power market price and improve the power system economy and safety in [1-4]. During the reform of the power market, in some countries and states the IL method was introduced into the market in[1,6,7].

IL is a kind of short term DR incentive method, and in the very short time interval of the peak load periods it is a kind of available demand side resource(DSR). In [8] a kind of providing reserve model utilizing IL in secondary reserve ancillary market is proposed, and the solving result of IL-OPF model shows that IL can help ISO keeping the adequacy of system operating reserve in the peak load period. In [9] an incentive compatible mechanism design theory is proposed in using IL to resolve congestion caused by voltage beyond limitation. In this theory the maximum expect profit can be achieved when the customer report the real loss of load cost, thus the customer is encouraged to report the real cost to take part in the congestion management. In [10, 11] effectiveness of IL in the transmission congestion management is proved, but only single period is considered. In [12] the multi-periods application is studied, and the intelligent algorithm is used. However, in the references above the IL is simply regarded as a load, the traditional load shedding method is used, the characteristics of IL is not considered, the activity of the customer is not excited.

In this paper on the basis of the developing power market's real operating condition including the IL characteristics in system operation, the implement of IL in developing power market is studied, and an IL dispatch model considering network congestion constrained in peak load periods is proposed. In this model the object function is minimization of total charge introduced by load interruption and generation re-regulation in peak load period. The constraints include the network congestion capacity, the ramp rates of the generation units in the pre-informing time and the interruption duration, the influence of ILs' location on the network loss are also considered. The BPSO method is used to solve this model. The result of IEEE30 case showed that the model in this paper is applicable to network congestion constrained dispatch utilizing IL dispatch during the peak load period.

2. Mode of IL implementation in peak load period

There are always system generation capacity scarcities during peak load periods and the spinning reserve capacities are also inadequacy. At the premise that the ancillary market is not open, the peak load period dispatch combined with special reserve resource as IL can relieve

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short term system installation scarcity and increase operating reserve to improve system reliability.

In theory, the capacity of IL can be used as equivalent generation units' capacity. However, as the customers' production characteristics are different the real optimal dispatch cannot take the customer interruption capacity as units' capacity. The differences are showed in three aspects: ①In the condition that the compensation function of load interruption capacity is a set of disperse points or a level line parallel to load axis. ②Once the interruption capacity is set; the interruption capacity is fixed during the interruption periods. ③The pre-inform time not only influence the customer's compensation charge but also relate to the accurate load interruption time, then what time level optimal dispatch the IL can attend is decided. In this paper according to different pre-inform time the IL customers are classified into two types: one is day-ahead IL customer the pre-inform time of which is more than one day, and the interruption duration is longer, for about 4 or 8 hours; the other is peak load periods dispatch IL customer, the pre-inform time of which is shorter and the interruption duration is short. To be convenient for the following discussion, it is supposed that the interruption duration of this kind of IL customer is 1 or 2 hours.

In the developing power market, to encourage the customer to take part in IL program, the grid company should pay interrupted capacity fee to the customer. When the purchased interruption capacity is fixed, the IL costs and the compensations of the customers' loss of load are compared, and then the profit maximization is the IL capacity purchasing standard. The interruption compensation charge should be paid only after the IL is dispatched. The grid company decides which time level dispatch the IL customer should attend. Normally the peak load duration is about 4 to 5 hours, the pre-dispatching time interval is 30 minutes. In this paper, the hour level IL customer is the researching object. In the developing power market, considering the characteristic of peak load dispatching the IL implement process is as following:

①Based on the peak load forecast, without considering ramp rates of units' and spinning reserve, the initial peak load dispatch project is formed.

②Based on the peak load forecast, the capacity scarcity of peak load period should be calculated considering units' ramp rates constraints, spinning reserve of each period and nodal load reserve requirement.

③If there is no capacity scarcity, and then on the basis of ①, the ramp rates constraints and reserve requirements are considered to execute peak load period dispatch. Or else, ④should be executed.

④Based on load forecast, combing with active power dispatch model, the purchasing project of IL contract is optimized, and the load curve is revised. The final peak load period dispatch is formed.

The initial peak load dispatch project is formed as following:

$$\min \quad W_{\text{loss}} = \sum_{t=1}^{T_p} P_{\text{loss}}(t)\Delta t \tag{1}$$

$$\text{s.t} \quad \sum_{i=1}^{N_g} P_g(i,t) = P_d(t) + P_{\text{loss}}(t) \quad , \quad t=1\sim T_p \tag{2}$$

$$P_{g\min}(i) \le P(i,t) \le P_{g\max}(i) \ , \quad i=1\sim N_g \tag{3}$$

$$-P_{f\min}(l) \le P_f(l,t) \le P_{f\max}(l) \ , \quad l=1\sim L \tag{4}$$

Where $P_g(i,t)$ is the ith generator's active power at the tth period; N_g and T_p are the sum of generators in the power system and sum of periods during peak load periods; $P_d(t)$ and $P_{\text{loss}}(t)$ are the sum of the loads and network loss at the tth period; $P_f(l,t)$ is the active power in the lth transmission line at the tth period, and L is the sum of the system branches; $P_{f\max}(l)$ is the maximum active power flow permission in the lth transmission line.

In this model the units' ramp rates constraints are not considered, and the result of formed dispatch is an initial project. If the spinning reserve and units' ramp rates are considered, thus the peak load dispatch model in ③ is formed.

3 Optimal IL purchasing model for power company

3.1 Power System Scarcity Capacity in Peak Load Period

In the developing power market, the ancillary market is not mature or not built. The information is unknown or cannot reflect the real power cost, so the IL contract cannot be operated based on price. The interruption condition needs to be on the basis of reliability. The IL implement based on system reliability index has two conditions: one is that system load is beyond some threshold, and the other is that the IL should be interrupted when the spinning reserve is below the set level. The latter condition not only considers the system reliability but also conform to the traditional dispatch regulation, therefore it is more reasonable. In this paper the latter condition is taken as the interruption condition to decide the system capacity scarcity level.

(1)Capacity scarcity introduced by units' response capability inadequacy

First considering the units' ramp rates limitation, the system capacity scarcity $P_{s1}(t)$ caused by units' ramp rates constraints is expressed by the following:

$$P_{s1}(t) = P_d(t) - P_{d0} + R_d(t) - R_{d0} - P_R(t) \tag{5}$$

Where $P_d(t)$ and P_{d0} are the system load at the tth period and the initial period. $R_d(t)$ and R_{d0} are the system reserve capacity at the tth period and the initial period respectively; $P_R(t)$ is the sum of the units' response capabilities from the initial period to the tth period, that is:

$$P_R(t)=\sum_{j=1}^{N}P_R(i,t) \tag{6}$$

Where $P_R(i,t)$ is the ith unit's response capability from the initial period to the tth period. It fulfils the following relationship:

$$P_R(i,t)=\min\{P_g^{\max}(i)-P_{g0}(i),\Delta t\cdot r_u(i)\} \tag{7}$$

Where $P_g^{\max}(i)$ is the maximum active power of the ith unit; $P_{g0}(i)$ is the output active power of the ith unit at the initial period; Δt is time interval between two periods; $r_u(i)$ is ramp rate of the ith unit.

3.2. Optimal Model of IL

The optimization of IL should not only fulfill the capacity scarcity, but also take part in congestion regulation with output of units and eliminate $P_{s2}(t)$.

$$\min J=C_{loss}+C_{IL} \tag{12}$$

The object function of the optimal model is as following:

$$\min J=C_{loss}+C_{IL} \tag{12}$$

Where

$$C_{loss}=\sum_{t=1}^{T_p}\sum_{l=1}^{L}\rho_e(t)\cdot r(l)\cdot[P_f(l,t)]^2 \tag{13}$$

$$C_{IL}=\sum_{t=1}^{T_p}\sum_{j=1}^{M}S(j,t)P_{IL}(j,t)\rho_{IL}(j)\Delta t \tag{14}$$

The object function means during the peak load period T_p the minimization of IL charge and the charge introduced by units' re-regulation. C_{loss} is the system network loss cost; $r(l)$ is the resistance of the lth transmission line; C_{IL} is the charges paid by grid companies to the IL customers. Where $S(j,t)$ is the jth interruption contracts(The sum of the contracts are M) at the tth period, $S(j,t)=1$ means the interruption is executed, $S(j,t)=0$ means no interruption is execution at this period; $P_{IL}(j,t)$ is capacity of the jth interruption contract at the tth period; $\rho_{IL}(j)$ is the compensation price of the jth IL; $\rho_e(t)$ is the price of the tth peak load period.

The IL constraints need to be fulfilled as follows:

$$\sum_{j=1}^{M}S(j,t)P_{IL}(j,t)\geq P_{s1}(t) \tag{15}$$

$$S(j,t+m)=1,\quad \text{If}\quad S(j,t-1)=0\wedge S(j,t)=1 \quad (m=1\sim n_d(j)-1) \tag{16}$$

$$\sum_{t=1}^{T_p}S(j,t)\leq n_s(j) \tag{17}$$

Where $n_d(j)$ is the interruption duration of the jth IL; $n_s(j)$ is the jth IL contracts' total interruption periods during the time interval studied.

Here the capacity scarcity need to be fulfilled by IL, and the characteristics of IL are all considered: (15) means the total interrupted load should be over or equal to system capacity scarcity; (16) means IL's interruption duration period constraints;(17) means the total interruption periods should be less than the total interruption time during time interval studied.

The power flow constraints should be fulfilled as follows:

$$\boldsymbol{A}_g\cdot\boldsymbol{P}_g^{'}(t)+\boldsymbol{A}_{IL}\cdot\mathrm{diag}[S(j,t)]\cdot\boldsymbol{P}_{IL}-\boldsymbol{A}_f\cdot\boldsymbol{P}_f(t)=\boldsymbol{P}_d(t) \tag{18}$$

$$\boldsymbol{A}_c\cdot\boldsymbol{X}\cdot\boldsymbol{P}_f(t)=\boldsymbol{0} \tag{19}$$

$$\boldsymbol{A}_r\cdot\boldsymbol{P}_r(t)-\boldsymbol{A}_f\cdot\Delta\boldsymbol{P}_f(t)=\boldsymbol{R}_d(t) \tag{20}$$

$$\boldsymbol{A}_c\cdot\boldsymbol{X}\cdot\Delta\boldsymbol{P}_f(t)=\boldsymbol{0} \tag{21}$$

Where $\boldsymbol{P}_d(t)$ is active load vector of all nodes at tth period; $\boldsymbol{R}_d(t)$ is active load reserve requirement vector of all nodes at tth period; $\boldsymbol{A}_g$ is the incident matrix between nodes and generators; $\boldsymbol{P}_g^{'}(t)$ is each nodal unit's output active power vector after re-regulation; $\boldsymbol{A}_{IL}$ is the incident matrix between nodes and IL customers; $\mathrm{diag}[S(j,t)]$ is a M ranks diagonal matrix the diagonal factor of which is $S(j,t)$; $\boldsymbol{P}_{IL}$ is the IL customers' interrupted load vector; $\boldsymbol{A}_f$ is the incident matrix between nodes and branches; $\boldsymbol{P}_f(t)$ is the active power flow vector in transmission lines at tth period; $\boldsymbol{A}_c$ is the incident matrix between network independent close loop and branches; $\boldsymbol{X}$ is the diagonal matrix formed by all the transmission lines in system; $\boldsymbol{P}_r(t)$ is the spinning reserve vector supplied by nodal units at the tth period; $\Delta\boldsymbol{P}_f(t)$ is the active power flow reserve vector of correponding transmission lines at tth period.

The maximum and minimum units' outputs constraints as follows:

$$P_g^{'}(i,t)+P_r(i,t)\leq P_g^{\max}(i) \tag{22}$$

$$P_g^{'}(i,t)\geq P_g^{\min}(i) \tag{23}$$

Where $P_r(i,t)$ is the ith unit's active power at the tth period.

The response rates constraints of units' active reserve is as following:

$$P_r(i,t)\leq r_u(i)\Delta t \tag{24}$$

The power flow in transmission lines constraints is as following:

$$-P_{f\max}(l)\leq P_f(l,t)+\Delta P_f(l,t)\leq P_{f\max}(l) \tag{25}$$

Where $\Delta P_f(l,t)$ is the active power reserve in the lth transmission line at the tth period, and $l=1\sim L$。

The units' ramp rates constraints:

$$-\Delta t\cdot r_u(i)\leq P_g^{'}(i,t+1)-P_g^{'}(i,t)\leq\Delta t\cdot r_u(i) \tag{26}$$

The up ramp rate and down ramp rate of the ith unit are supposed to be the same, represented by $r_u(i)$.

3.3 Solving Method of the Optimal Model

The model above includes integer variants and periods coupling constraints, so it is a multi-constraints hybrid integer programming problem. In this paper an

BPSO(Binary version of the Particle Swarm Optimization) combined with inner-point algorithm is used to solve this problem.

This optimal problem is divided into two sub-optimization problems as continuity variants problem and integer variants problem: the units' outputs optimization under the condition of selected IL customer is inner level optimization; and the IL customer interruption decision is the outer level optimization. The two-level optimization is solved by iteration and alternation. The integer variants $S(j,t)$ is used to coding, the particle in BPSO is the state of the jth IL customer at the tth period(interrupted or not). The BPSO is advanced based on the characteristics of the model: ①The production strategy of the new particles must be based on the characteristics of IL customers, that is the constraints in model (15)~(17);②By the queuing method in[5] For the maximum capacity scarcity period, the interruption prices are sorted from minimum to maximum, and the particles' positions are initially determined.

The solving process of this model is as following:

1) Input the IL customers' information and the generation units' technical parameters, the quantity of the particle swarm and the iteration numbers are defined.

2) Decide the initial position of particles by queuing method. And check by 1) to assure the initial positions of particles in feasible scope.

3) Produce new particles by iteration formula, and check by 1)

4) When all the particles are produced, the inner point method is used to solve continuity variants optimization problem, and then the adaptive value function is calculated, at the same time the individual and whole optimal value is preserved.

5) If the maximum iteration number is reached, the whole optimal value is the final optimization result. Or else turn to 3).

4 Case study

For an IEEE30 case, the initial generation active power, the transmission network parameter, the transmission capacity limitation and the initial load per-unit value are from[13], and some of them are regulated: the base value of the active power is 100MW, all the units' ramp rates are half of the primary, and the up limitations of the 2nd to the 6th units are doubled. The load of each period increases some percent than former period; the reserve requirement is 10% of the whole load. Eight periods are simulated, and the unit of each period is half an hour. To show the influence of network congestion constraint there are only constraints in branch 10-21 and 10-22, the limitation of which is 32MW.

The load increasing rate of each period, reserve percentage of the load and system capacity scarcity $P_{s1}(t)$ are in Table 1. The IL customers, position, interruption compensation charge and interruption duration time are in Table 2. For the load and reserve requirement in the 21st node there is capacity scarcity $P_{s2}(21,5)$=2.56MW at the 5th period.

Table1 Load, reserve and system capacity scarcity

period	Load Increasing Percentage	Reserve Percentage	$P_{s1}(t)$/MW
1	30%	7%	0
2	30%	7%	11.5
3	12%	10%	12.9
4	12%	10%	8
5	12%	10%	11.9
6	8%	10%	9
7	8%	10%	0
8	8%	10%	0

Table2 Customer interruptible load data

Customer （node）	Interruption Duration Time/h	Interruption Capacity/MW	Interruption Price/(yuan/MWh)
1(2)	2	3.8	660
2(5)	2	2.5	420
3(7)	4	4.2	435
4(8)	2	2.1	470
5(12)	2	1.9	590
6(2)	4	4.8	440
7(18)	2	0.8	1000
8(19)	2	5.6	330
9(21)	2	3.2	540
10(30)	2	3.1	538

The prices of peak load periods are supposed to be equal, $\rho_e(t)$=300yuan/MWh. The optimal dispatch project including IL customers is received by the method in this paper. The units' output active powers are listed in Table 3. the interrupted customers and corresponding interruption time, interruption compensation charge and the increased network loss fee are listed in Table 4.

Table3 Active Power of Generation Unit in Each Period

period\ node	1	2	5	8	11	13
1	100.01	35.07	108.05	48.03	56.29	21.23
2	100.03	35.79	130.08	72.07	89.99	40.93
3	100.09	35.99	127.93	86.16	90.11	48.36
4	100.01	35.16	139.97	87.68	90.21	48.79
5	100.06	36.26	127.96	93.79	93.03	55.68
6	100.03	37.19	139.95	97.72	93.79	61.10
7	100.08	46.31	139.79	102.20	93.44	73.64
8	100.05	55.40	139.94	102.80	93.92	80.01

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Table4 Optimal customer IL dispatch result

customer	Interruption compensation charge/yuan	Interruption period
2	2100	4~5
3	7308	3~6
4	1974	5~6
6	8448	2~5
8	3696	2~3
9	3456	5~6

The influence of IL on network loss is considered in the model of this paper. From Table1 and Table4, the customers take part in system dispatch as IL, the capacity scarcity which includes capacity scarcity introduced by inadequacy of units' response capability and capacity scarcity introduced by network congestion constraint in peak load period is decreased. Comparing the dispatch result in Table2 with the result in Table4, there is network congestion constraint, the 9^{th} customer is interrupted to discriminate the capacity scarcity caused by congestion constraint although the compensation price of the 10^{th} customer is less than the 9^{th} customer's, and the interruption capacities $P_{s1}(t)$ are all satisfied.

5 Conclusion

IL is an efficient method to attract customer to attend system operation, and it can also relieve the reserve inadequacy introduced by consumption increasing. In this paper integrated with in characteristics of peak load periods in developing power market the congestion constraint optimization model considering IL is built. In this model not only the influence of IL characteristics on IL purchasing charge is considered, but the influence of IL on congestion capacity in lines. And not only the inadequacy but the capacity scarcity in transmission network are solved. The efficiency of system is improved by this method. The IEEE30 case shows that when the IL customers attend the peak load period dispatch the strain condition of the transmission lines is relieved and the economy of the system operation is improved.

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