Determination of Interruptible Load as an Ancillary Service in a Coordinated Multi-Commodity Market

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Abstract - This paper studies the problem of the reliability-constrained generation and ancillary service dispatch including interruptible load in a spot market. An OPF-based technique for simultaneous scheduling of generation and ancillary services (AS) is proposed. Instead of using the deterministic system reserve criterion, a probabilistic reserve criterion based on the required reliability index is introduced and derived as reserve constraint. The reliability test system RBTS is used to illustrate the technique.

Keywords: Reliability, interruptible load, operating reserve, ancillary services, generation scheduling

I Introduction

As a result of power system restructuring, the distinct functions of power generation, transmission and distribution are managed by different companies. In this new environment, system reliability has been gaining increasing amount of attention due to the reduction of system operational margin with increasing market competition. Nowadays, all market participants want to minimize their costs or maximize their profits in generation and ancillary service trading. This requires the improved techniques for optimizing energy and ancillary service dispatch.

Different techniques for energy and AS dispatch such as the Merit-Order-Based Dispatch, Sequential Dispatch and Joint Dispatch (JD) were discussed in [1]. The Linear-programming-based JD approach is presented [1] for solving the multi-product (i.e. energy and AS products) market dispatch problem. A hybrid approach which combines the sequential and JD method was proposed [2] to solve the energy and AS dispatch problem in New England ISO. A coordinated real-time optimal dispatch method for unbundled electricity market was proposed and a modified P-Q decoupled OPF was used in this technique [3]. The sequential quadratic programming (SQP) method is adopted [4] to implement optimal allocation of primary reserve service in energy market. The deterministic system reserve criteria as reliability constraint has been adopted and interruptible load has not been considered in these techniques.

Interruptible load (IL), as one of contingency reserve sources, not only can reduce the operating reserve provided by different Gencos, which may sometime be expensive, but also provides an alternative mechanism to incorporate the demand-side participation into reserve market. A security-constrained bid-clearing system for the New Zealand Wholesale Electricity Market was presented using advanced Linear-programming solution method [5]. In this market, interruptible load bidding is introduced. However, the impact of interruptible load on the clearing prices of energy and other AS has not been investigated.

The pre-determined system reserve requirement can not represent the effect of generator reliability performance on system reserve margin. For example, when the committed generators are very reliable, it is not necessary to impose a large system reserve requirement. A probabilistic spinning reserve (SR) criterion was introduced in [6]. The problem of reliability-constrained market-clearing in pool-based electricity markets with unit commitment was addressed in this paper. The hybrid operational reliability criteria defined in the paper includes some desirable probabilistic properties of the loss of the load and expected load not supplied (ELNS).

This paper proposes an AC OPF-based simultaneous auction design for energy and ancillary services including interruptible load. The formulation of the problem is presented in Section II. A probabilistic reserve criterion based on pre-required reliability index have been derived in section III and used as the reserve constraint in optimization problem. Sequential quadratic programming is employed to solve the nonlinear constrained optimization problem. The RBTS [7] is used to demonstrate the effectiveness of proposed approach and the market settlement results and nodal prices are analyzed in Section IV. Conclusion is given in section V.

II Problem Formulation

The basic problem is to simultaneously dispatch generation and ancillary services in a day-ahead spot market. The objective is to minimize total system cost which includes energy cost C_g^E, SR cost C_g^{SR}, and IL cost C_d^{IL} considering network security and reliability constraints. The objective function is:

$$Min\left(C_{sys} = \sum_{g=1}^{NG}\left(C_g^E + C_g^{SR}\right) + \sum_{d=1}^{ND} C_d^{IL}\right) \qquad (1)$$

where NG is the number of generators and ND is number of interruptible loads.

Subject to the following constraints:

Power flow balance constraint:

$$\sum_{g=1}^{NG} P_g - PD_{sys} = P_{loss}^{sys} \qquad (2)$$

where P_g is the active power output of generator g, PD_{sys} is system active power load, P_{loss}^{sys} is system active power loss.

Transmission line capacity limits:

$$|P_{ij}| \le P_{ij}^{max} \qquad (3)$$

where $|P_{ij}|$ and P_{ij}^{max} are actual active power flow and active power flow limit for the transmission line between bus i and j.

Bus voltage constraints:

$$|V_i|^{min} \le |V_i| \le |V_i|^{max} \qquad (4)$$

where $|V_i|^{min}$ $|V_i|^{max}$ are lower and upper limits of voltage magnitude $|V_i|$ at bus i.

Generator capacity constraints:

$$P_g^{min} \le P_g^E + P_g^{SR} \le P_g^{max} \qquad (5)$$

where P_g^{min} and P_g^{max} are the minimum and maximum outputs of the active power for unit g, P_g^E is the active power output and P_g^{SR} is spinning reserve.

Interruptible load constraints:

$$P_d^{low} \le P_d^{IL} \le P_d^{up} \qquad (6)$$

where P_d^{IL} is interruptible load for load d, P_d^{low} and P_d^{up} are down and upper limits of P_d^{IL} respectively.

System reserve constraint:

$$\sum_{g=1}^{NG} P_g^{SR} + \sum_{d=1}^{ND} P_d^{IL} \ge R_{req}^{sys} \qquad (7)$$

where R_{req}^{sys} is the required system reserve.

For the reliable operation of a power system, a sufficient system reserve is required. The deterministic reserve criteria such as the percentage of system load or the capacity of largest online generator are usually used in most power markets to dispatch the generation and AS. However, the deterministic reserve criteria can not represent the effect of generating unit reliability performance on reserve margin. A reliability-constrained reserve criterion is introduced and derived in the following section to incorporate this effect.

III Reliability-constrained reserve criterion

Energy and AS dispatch in an hourly market is an operation problem. The outage replacement rate (ORR) of a generating unit is used to determine system reliability in the market clearing process to replace the forced outage rate (FOR) used in long term system planning. The ORR of a generating unit is defined [8] as the probability that a generating unit fails and cannot be replaced by other units during the market settlement interval (T), which is usually less than an hour. The ORR of a generating unit with the failure rate of $\lambda(f/hr)$ can be calculated using the following equation:

$$ORR = 1 - e^{-\lambda \cdot T} \qquad (8)$$

Because $\lambda \cdot T << 1$ for one hour interval,

$$ORR \approx \lambda \cdot T = \lambda \qquad (9)$$

For a NG-unit-system, the probability of M components being out of service can be calculated using the following equation:

$$p_i = \prod_{j=1}^{M} \lambda_j \cdot \prod_{j=M+1}^{NG} (1 - \lambda_j) \qquad (10)$$

where j is generating unit index.

A reliability index-Expected Load Not Supplied (ELNS) caused by generator failures [8] is used to determine the required system reserve. The ELNS can be calculated using the following equation:

$$ELNS = \sum_{i=1}^{K} p_i \cdot \left(PD_{sys} + P_{loss}^{sys} - \sum_{j=M+1}^{NG} \left(P_j^E + P_j^{SR}\right) - \sum_{d=1}^{ND} P_d^{IL} \right) \qquad (11)$$

where K is the total number of system contingency states considered.

In order to relate the reliability index to the reserve requirement, the ELNS is modified as the follows:

$$\begin{aligned} ELNS &= \sum_{i=1}^{K} p_i \cdot \left(PD_{sys} + P_{loss}^{sys} - \sum_{j=M+1}^{NG} \left(P_j^E + P_j^{SR}\right) - \sum_{d=1}^{ND} P_d^{IL} \right) \\ &= \sum_{i=1}^{K} p_i \cdot \left\{ PD_{sys} + P_{loss}^{sys} - \sum_{j=M+1}^{NG} \left(P_j^E + P_j^{SR}\right) - \sum_{d=1}^{ND} P_d^{IL} + \sum_{j=1}^{M} \left(P_j^E + P_j^{SR}\right) - \sum_{j=1}^{M} \left(P_j^E + P_j^{SR}\right) \right\} \\ &= \sum_{i=1}^{K} p_i \cdot \left(PD_{sys} + P_{loss}^{sys} - \sum_{j=1}^{NG} \left(P_j^E + P_j^{SR}\right) - \sum_{d=1}^{ND} P_d^{IL} + \sum_{j=1}^{M} \left(P_j^E + P_j^{SR}\right) \right) \end{aligned}$$

Because $\sum_{j=1}^{NG} P_j^E = PD_{sys} + P_{loss}^{sys}$,

$$\begin{aligned} ELNS &= \sum_{i=1}^{K} p_i \cdot \left(- \sum_{j=1}^{NG} P_j^{SR} - \sum_{d=1}^{ND} P_d^{IL} + \sum_{j=1}^{M} \left(P_j^E + P_j^{SR}\right) \right) \\ &\le \sum_{i=1}^{K} p_i \cdot \left(- \sum_{j=1}^{NG} P_j^{SR} - \sum_{d=1}^{ND} P_d^{IL} + \sum_{j=1}^{M} P_j^{CAP} \right) \end{aligned}$$

$$= \sum_{i=1}^{K} p_i \cdot \sum_{j=1}^{M} P_j^{CAP} - \sum_{i=1}^{K} p_i \cdot \left(\sum_{j=1}^{NG} P_j^{SR} + \sum_{d=1}^{ND} P_d^{IL} \right) \quad (12)$$

where P_j^{CAP} is the installed capacity of generator.

Let

$$\sum_{i=1}^{K} p_i \cdot \sum_{j=1}^{M} P_j^{CAP} - \sum_{i=1}^{K} p_i \cdot \left(\sum_{j=1}^{NG} P_j^{SR} + \sum_{d=1}^{ND} P_d^{IL} \right) \leq ELNS^{req} \;,$$

then

$$\sum_{j=1}^{NG} P_j^{SR} + \sum_{d=1}^{ND} P_d^{IL} \geq \frac{\sum_{i=1}^{K} p_i \cdot \sum_{j=1}^{M} P_j^{CAP} - ENLS^{req}}{\sum_{i=1}^{K} p_i} \quad (13)$$

Comparing equation (7) with (13), the reliability constrained reserve requirement is:

$$R_{req}^{sys} = \frac{\sum_{i=1}^{K} p_i \cdot \sum_{j=1}^{M} P_j^{CAP} - ENLS^{req}}{\sum_{i=1}^{K} p_i} \quad (14)$$

With different reliability performance, the unavailability of generators may be different. Using the reliability-related system reserve index, the reliability performance of generators can be reflected in market dispatch. When committed generators are very reliable, the lower reserve margin is required. Otherwise the higher reserve margin is needed.

IV Case studies

A computer program has been developed using the proposed technique. The RBTS [7] is modified to illustrate the proposed technique. The single line diagram of RBTS is shown in figure 1. The generators connected to bus 1 and bus 2 are represented by Genco 1 and Genco 2, respectively. 20 percent of the load at each bus is used as interruptible load. Total system load is 185 MW. The generator failures up to the second order are considered in the reliability calculation. The required ELNS is assumed to be $ELNS^{req} = 0.2MW$. All the cost functions such as the energy, SR and IL are assumed to be quadratic equations. The coefficients of these equations are shown in Table 1. A, B and C in the table are coefficients of quadratic term, linear term and constant term of a quadratic equation, respectively.

Case 1: The deterministic system reserve constraint is used in this case. The reserve margin is set as 25 percent of total system load. The spinning reserve is the only ancillary service commodity. The system loss is 4.62 MW. The market settlement results are listed in Table 2. The energy price ($/MWh) at each bus and the SR prices for each Genco are shown in Table 3.

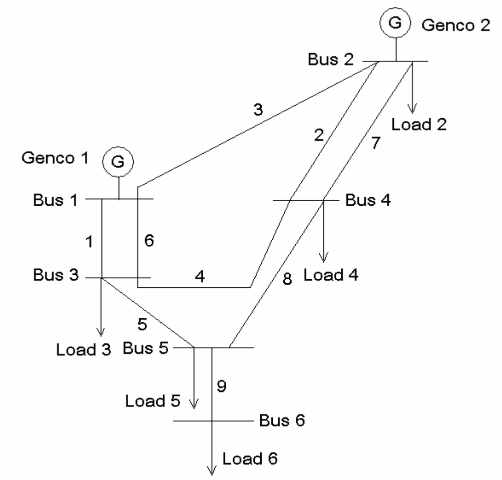

Figure 1: Single line diagram of RBTS

Cost functions	A	B	C
C_{Genco1}^{E}	0.02	12.45	10
C_{Genco2}^{E}	0.0175	10.75	10
C_{Genco1}^{SR}	0.002	1.245	1
C_{Genco2}^{SR}	0.00175	1.075	1
C_{d2}^{IL}	0.00255	1.46	5.0
C_{d3}^{IL}	0.00155	1.0	0.5
C_{d4}^{IL}	0.00195	1.2	4.0
C_{d5}^{IL}	0.00254	1.46	5.0
C_{d6}^{IL}	0.00254	1.46	5.0

Table 1: Coefficients of Bidding Functions

Generation (MW)		SR(MW)	
Genco1	Genco2	Genco1	Genco2
76.42	113.2	29.46	16.79

Table 2: Market Settlement Results (Case 1)

Bus	Energy($/MWh)
1	15.505
2	14.712
3	16.015
4	15.994
5	16.141
6	16.285
Genco	SR(($/MWh)
1	1.36
2	1.13

Table 3: Energy and SR Prices (Case 1)

Case 2: The deterministic system reserve constraint is the same as that used in case 1. Both the SR and IL are selected as ancillary service commodities. The system loss is 4.66 MW. The market settlement results are listed in Table 4. The nodal energy price, SR and IL prices are shown in table 5. The nodal energy prices for case1 and case 2 are shown in figure 2 for the comparison.

Generation (MW)		SR(MW)		IL(MW)	
Genco1	Genco2	Genco1	Genco2	IL3	IL4
75.35	114.31	5.56	15.69	17	8

Table 4: Market Settlement Results (Case 2)

Bus	Energy($/MWh)	IL($/MWh)
1	15.464	NA
2	14.751	1.46
3	15.968	1.05
4	15.945	1.23
5	16.093	1.46
6	16.237	1.46
Genco	SR(($/MWh)	
1	1.27	
2	1.13	

Table 5: Energy, SR and IL Prices (Case 2)

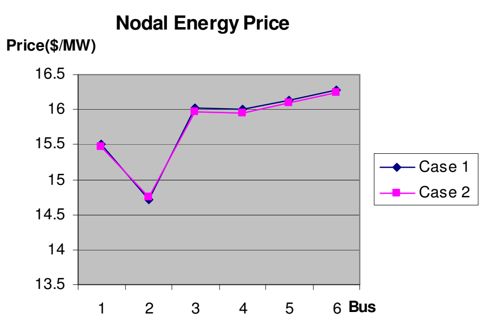

Figure 2: Nodal Energy Prices for Cases 1 and 2

It can be seen from the results that the nodal energy prices (except at bus 2) and SR price at bus 1 are reduced after considering ILs. The market is re-dispatched. The output of Genco1 is reduced by 1MW and the output of Genco 2 increases 1MW. The energy price at bus 2 increases slightly. Although the SR price of Genco 2 is even cheaper than the price of IL at bus 2, it cannot provide all the reserve due to its capacity limit. Because the SR bidding price of Genco1 is the most expensive among the reserve market participants, the reserve provided by Genco1 decreases dramatically with the IL bidding.

Case 3: In this case, the reliability-constrained system reserve requirement is used. Both SR and IL are used as AS commodities. The reliability data [7] are used to determine the reserve constraint. $ELNS^{req} = 0.2MW$. The system loss is 4.72 MW. The market settlement results are listed in table 6. The nodal energy prices, SR and IL prices are shown in table 7.

Generation (MW)		IL(MW)
Genco1	Genco2	IL3
73.75	115.97	11.65

Table 6: Market Settlement Results (case 3)

Bus	Energy($/MWh)	IL($/MWh)
1	15.400	NA
2	14.809	1.46
3	15.898	1.04
4	15.872	1.20
5	16.021	1.46
6	16.164	1.46
Genco	SR($/MWh)	
1	1.24	
2	1.07	

Table 7: Energy, SR and IL Prices (Case 3)

It can be seen from table 6 that no SR is required due to the cheep IL.

Case 4: In this case, the failure rates of all generators are doubled from their values in [7]. $ELNS^{req} = 0.2MW$. The reliability-constrained system reserve requirement is determined. Both the SR and IL are AS commodities. The market settlement results are listed in table 8. The system loss is 4.63 MW. The nodal energy price ($/MW), SR and IL prices are shown in table 9.

Generation (MW)		SR(MW)		IL(MW)	
Genco1	Genco2	Genco1	Genco2	IL3	IL4
76.21	113.42	24.82	16.58	17	8

Table 8: Market Settlement Results for Case 4

Bus	Energy($/MWh)	IL($/MWh)
1	15.498	NA
2	14.720	1.46
3	16.006	1.05
4	15.985	1.23
5	16.132	1.46
6	16.276	1.46
Genco	SR($/MWh)	
1	1.34	
2	1.13	

Table 9: Energy, SR and IL Prices for Case 4

The nodal energy prices of cases 3 and 4 are shown in figure 3.

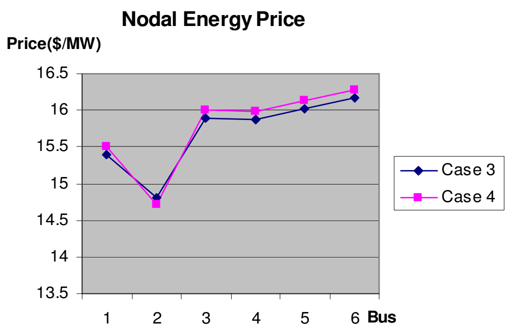

Figure 3: Nodal Energy Price for Cases 3 and 4

Compared with those obtained in case 3, both SR and IL are required for the specified *ELNS*. The nodal energy prices (except at bus 2), SR and IL prices increase due less reliable generators. The slight decrease of the energy price at bus 2 is due the redistribution between energy and reserve.

The numerical results show that the reliability-related reserve index can reflect the impact of generators reliability performance on system reserve requirement. With different value of $ELNS^{req}$ and different reliability data of generators, the different system reserve is required. Therefore, reliable generators require small system operational margin, while less reliable generators require more system reserve for power system reliable operation.

V Conclusions

This paper proposes an AC OPF-based simultaneous auction design for energy and ancillary services. The interruptible load as an ancillary service has been considered in the market trading. Numerical results demonstrate that the nodal energy price and spinning reserve price are reduced with including IL bidding in market trading. Instead of using the deterministic system reserve criterion, reliability-constrained reserve requirement is introduced and determined using reliability evaluation technique. The results also show that the reliability performance of generators has large impact on system reserve requirement.

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