Reserve Management in Restructured Power System Considering Loads Reliability

Saeed Zolfaghari, Mohammad H. Hashemi, and Azam Zolfaghari

Abstract— Determining the spinning reserve capacity is amongst the most important tasks of system operator to insure safe and reliable operation of power system. So far, various methods are proposed to determine reserve capacity which are based on deterministic or probabilistic criteria. Due to considering the stochastic nature of system events, probabilistic approaches are more preferable in comparison to deterministic approaches. In practice, the value of interrupted loads is not the same for all consumers and some of them like industrial ones have higher value of lost load (VOLL). Thus, consumers with higher values of lost load are willing to pay more in order to gain higher reliability levels than consumers with less VOLL. In other words, they are more concerned with their individual load point reliability. In this paper a new method is presented to optimally determine the system spinning reserve requirement in a competitive simultaneous energy and reserve market render based on cost-benefit analysis and stochastic programming technique is proposed considering different values of lost load at each bus. Including units and lines outages and their corresponding likelihoods in the objective function, regard for loading rate of the generators constraints and transmission flow constraints are the advantages of the proposed method. Simulations performed on the 14-bus IEEE test system demonstrate effectiveness of the presented approach.

Index Terms— Spinning reserve (SR); Simultaneous market clearing; Reliability preference; Value of lost load (VOLL); Cost-benefit analysis; Stochastic programming.

I. INTRODUCTION

Observing the security and reliability of the system is amongst the most important tasks of a power system operator. Unexpected increase of load and sudden outages of generators or transmission lines are possible events which put the security of the power system at risk. Therefore, to insure safe and reliable operation of the power system, it is essential to consider some amount of generation capacity as reserve [1]. In fact, inequality between power generation and consumption caused by failure of power system components is compensated considering adequate amount of operating reserve. Operation reserve includes spinning reserve and non-spinning reserve. Spinning reserve is considered as the difference between the capacity of active generation system and the total amount of load and losses

which is able to rapidly, considering the ramp rates of generators, respond to load variation in case of failure incident.

The standard method to determine the operating reserve requirement of a system is use of deterministic criteria which considers the amount of required reserve as a certain percentage of load peak (in Spain) or equal to the capacity of largest operating generation unit (in Toronto). Also these criteria are easy to implement, they do not represent the stochastic nature of failure in power systems. To fill this gap, stochastic approaches are used in order to determine the reserve requirement of power system. Stochastic approaches estimate the amount of required reserve more realistically by combining different uncertainties in the power system such as availability of generation units and transmission system along with response rate of generators. However, lack of enough statistical data and load curves and huge amount of computations make statistical approaches more difficult to perform.

Different approaches are presented in the literature to calculate the required reserved using probabilistic criteria. The first probabilistic approach to determine capacity of reserve was PJM method which was proposed in 1963 [2]. In PJM method, forced outage rate (FOR) of generation unit is considered in determination of reserve capacity requirement. In [3]-[6] loss of load probability (LOLP) index or unit commitment risk is used. In [7] expected energy not supplied (EENS) is used instead of LOLP. Ref [8] has made use of both LOLP and EENS indices to allocate the reserve capacity and has used genetic algorithm in order to solve the optimization problem. Mixture of both deterministic and probabilistic approaches is used in [9]-[12] to provide more effective indices. In these approaches unit commitment (UC) programming is reprocessed to calculate the consumers' interruption risk level. If the calculated risk level is not acceptable, then capacity of spinning reserve is readjusted and UC is repeated until acceptable risk level is achieved.

Reference [13] introduces a UC model with security constraints which emphasizes on the simultaneous clearing of energy and ancillary services markets. In the mentioned paper, Benders decomposition method is used to decouple security-constrained unit commitment (SCUC) problem into main UC problem and sub-problem. Also, in order to solve UC problem more easy Lagrangian relaxation is used. Other methods based on reliability probabilistic indices consider the social costs of power outage as additional terms in the objective function UC problem [14],[15]. In [16] optimal reserve capacity is determined using benefit-cost analysis. Benefit of reserve allocation is estimated in terms of

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S. Zolfaghari is with the Electrical Engineering Department, Shahid Beheshti University, Tehran, Iran (e-mail: saeidzanjan@gmail.com).

M. H. Hashemi is with the Electrical Engineering Department, Islamic Azad University, Science and Research Branch, Tehran (Zanjan). (e-mail: m.hashemi.ir@ieee.org).

A. Zolfaghari is with the Electrical Engineering Department, University of Zanjan, Iran (e-mail: zolfaghari.azam87@gmail.com)

decrease in amount of EENS. On the other hand, reserve cost is the price that must be paid by the consumer to provide spinning reserve which is considered to be pay-as-bid in the mentioned study. So, reserve allocation is continued until its benefit is larger than its cost. Optimization of required reserve is done in such way that minimizes the total cost of operation and expected outage cost. Also the value of lost load is not the same for all the consumers; these methods consider a single value for VOLL.

Literature review shows that consumer's decision on their desired level of reliability is not considered clearly in programming of reserve capacity allocation. In this paper, consumers declare their desired level of reliability to ISO in terms of VOLL. ISO clears the simultaneous energy and reserve market for the next hour using benefit-cost analysis and stochastic programming method.

II. PROPOSED METHOD TO OPTIMALLY DETERMINE SPINNING RESERVE

In this paper an hour-ahead electricity pool market has been considered in which energy and spinning reserve markets are cleared simultaneously. In this market, consumers announce their desired reliability level to ISO in terms of VOLL. The optimal spinning reserve is determined by equilibrium between expected benefit due to decrease in load shedding because of spinning reserve and the total cost of it (benefit-cost analysis) using stochastic programming. Thus, the objective function which should be minimized in a market for the next hour is as follows:

$$\text{Min}_{P,R} \left\{ \sum_{i=1}^{N_g} [C_i \times P_i + q_i \times R_i] + \sum_{s=0}^{N_s} \rho_s \sum_{j=1}^{N_d} \text{VOLL}_j \times UP_j^s \right\} \quad (1)$$

Where: i indicates the unit index (the total number of units is N_g), j indicates the load index (the total number of loads is N_d), s indicates the scenario index (the total number of scenarios is N_s), ρ_s indicates the probability of scenario s , C_i indicates the bid of unit i to produce energy of P in (MW), q_i indicates the bid of unit i^{th} to provide spinning reserve of R in (MW), VOLL stands for value of lost load, UP_j^s indicates the unsupplied power at bus i in scenario s .

In the above objective function, the first term is related to operation cost and the second corresponds to the expected interruption cost. Solving the objective function of Equation (1) is a two-stage stochastic programming problem in which decision variables P and R , are chosen in the first stage while decision variable UP is determined in the second stage after the scenarios realization.

Because the interruption cost exists in the objective function and due to dependency of UP to P and R and scenarios realization, in order to make the solution faster, the problem is decoupled to a two-stage problem, a main problem (the first term) and a sub-problem (the second term). Fig.1 depicts a general view of the proposed algorithm. At the beginning, the main problem is solved using initialized reserve requirement and pre-contingency constraints to obtain preliminary generation capacity and

spinning reserve capacity. These values are sent to sub-problem as inputs. In the sub-problem a DC load flow problem is solved considering different scenarios and post-contingency constraints. By solving the sub-problem ISO will be capable of determination of expected interruption cost. This procedure is repeated until convergence is achieved and optimal cost is reached.

Fig. 1. Objective function optimization flowchart

III. MAIN PROBLEM

The main problem is formulated as follows:

$$\text{Min} \left\{ \sum_{i=1}^{N_g} [C_i \times P_i + q_i \times R_i] \right\} \quad (2)$$

In which the following constraints must be observed in order to insure the safe operation of power system:

$$\sum_{i=1}^{N_g} P_i = \sum_{j=1}^{N_d} P_{dj} \quad (3)$$

$$P_i + R_i \leq P_{i_max} \quad (4)$$

$$P_{i_min} \leq P_i \quad (5)$$

$$\sum_{i=1}^{N_g} R_i \geq SRR \quad (6)$$

$$B\theta = P_i - P_d \quad (7)$$

$$P_i = P_{mn} = \frac{\theta_m - \theta_n}{X_{mn}} \quad (8)$$

$$P_{l_min} \leq P_l \leq P_{l_max} \quad (9)$$

The first constraint represents the generation-consumption balance and the other three constraints correspond the DC load flow problem.

IV. SUB-PROBLEM

As it is mentioned before, the sub-problem is a DC load flow problem which is solved considering the post-contingency constraints. Solving the sub-problem ISO will be able to determine the forced outage of generating units and transmission lines, unsupplied loads and consequently expected cost of interruptions for each scenario considering the unit commitment and spinning reserve scheduled in the main problem. The sub-problem is formulated as follows:

$$\text{Min} \left\{ \sum_{s=0}^{N_s} \rho_s \sum_{j=1}^{N_d} \text{VOLL}_j \times \text{UP}_j^s \right\} \quad (10)$$

Individual outage of generation units and transmission lines are the considered scenarios in the sub-problem. The probability of each scenario is obtained using FOR indices of the system components as follows:

$$\rho_s = \prod_{c=1}^{n_t} \text{FOR}_c \times \prod_{c=1}^{n_t - n_s} (1 - \text{FOR}_c) \quad (11)$$

Where n_t is the total number of system components and n_s is the number of components that experienced forced outage in scenario s . The probability corresponding to normal operation of the system (i.e. no contingency) is calculated using the following equation:

$$\rho_0 = 1 - \sum_{s=1}^{N_s} \rho_s \quad (12)$$

To calculate the unsupplied load, scheduled generation capacity of each unit and also spinning reserve allocation of units which are obtained from the main problem are necessary. It is assumed that the reserve capacity of each unit acts as a separate synchronized unit besides it.

In other words, reserve capacity of a unit is modeled as a generation unit besides it which provides power of $0 < R < R^{\max}$. Note that $R^{\max}$ is obtained from solution of the main problem. Fig. 2 illustrates the model of spinning reserve providing units in connection to the grid.

Fig 2. Model of spinning reserve providing units in connection to the grid

DC load flow formulation is used to estimate the amount of energy not supplied. Each load is modeled as an imaginary unit with maximum capacity equal to the power of the load and bid price of the corresponding declared VOLL. So, there are three types of generators in the formulation of DC load flow problem, including imaginary

generators, energy providing generators and spinning reserve providing generators.

Constraints corresponding to the sub-problem are given as follows:

$$\sum_{i=1}^{N_g} P_i + \sum_{j=1}^{N_d} \text{UP}_j^s = \sum_{j=1}^{N_d} P_{dj} \quad (13)$$

$$\text{UP}_{j_min}^s \leq \text{UP}_j^s \leq \text{UP}_{j_max}^s \quad (14)$$

$$B^s \theta^s = P_i - P_d + \text{UP}_j^s \quad (15)$$

$$P_l = P_{mn} = \frac{\theta_m - \theta_n}{X_{mn}} \quad (16)$$

$$P_{l_min}^s \leq P_l^s \leq P_{l_max}^s \quad (17)$$

V. CASE STUDY

The proposed approach to determine the capacity of spinning reserve is evaluated on the IEEE 14-bus test system. Fig. 3 illustrates one-line diagram of this test system.

IEEE 14-bus test system includes 5 generators, 11 buses with energy consumption and 20 transmission lines. Data corresponding to the generators and the loads of this system are given in Table 1 and Table 2. In this paper, bids of generators for spinning reserve are considered to be 30% of their bids for energy.

Fig 3. Single-line diagram of IEEE 14-bus test system

TABLE I: DATA OF IEEE 14-BUS TEST SYSTEM

RAMP_UP (MW)	OFFER_R (\$/MWh)	OFFER_E (\$/MWh)	$P_g^{\max}$ (MW)	$P_g^{\min}$ (MW)	BUS	UNIT
35	3	10	120	0	1	1
40	3	10	150	0	2	2
30	6	20	100	0	3	3
30	4/5	15	100	0	6	4
25	13/5	45	50	0	8	5

TABLE II: LOAD DATA OF IEEE 14-BUS TEST SYSTEM

VOLL (\$/MWh)	$\text{UP}_{\max}$ (MW)	$\text{UP}_{\min}$ (MW)	P_{Load} (MW)	BUS
-	-	-	0	1
600	38	0	38	2

700	90	0	90	3
400	51	0	51	4
400	30	0	30	5
600	16	0	16	6
-	-	-	0	7
-	-	-	0	8
800	32	0	32	9
400	12	0	12	10
400	8	0	8	11
400	20	0	20	12
500	16	0	16	13
400	16	0	16	14

$UP_{\min}$ and $UP_{\max}$ in tables I and II denotes the minimum and maximum possible load shedding. In this study four of the generators and transmission lines are considered to be 0.01, the total amount of load is 329 MW, transmission lines have the normal capacity of 50 MW and are to be overloaded up to 20% in case of contingency.

VI. SIMULATIONS AND RESULTS

Contingencies considered in this study include the individual outage of generators and transmission lines. For the studied system simultaneous energy and spinning reserve market is cleared using the proposed method and the optimal spinning reserve is driven. As Fig. 4 illustrates, for the investigated case study, the objective function is minimized at spinning reserve equal to 807 MW. Fig. 5 shows the generators scheduled energy generation and spinning reserve allocation. As Fig. 2 depicts, due to the higher energy cost of unit 5, this unit is less participated in energy and reserve providing. The whole capacity of unit 4 is utilized because it is close to the loads at buses 6,10,11,12 and 13.

To investigate the effects of considering reliability terms in the objective function three different scenarios are studied. The first scenario is the basic scenario in which the optimal spinning reserve requirement is calculated. In the second scenario it is assumed that there is no spinning reserve provided in the system. In the third scenario a deterministic amount of spinning reserve equal to 120 MW is assumed.

EENS index related to load j is obtained as:

$$EENS_j = \sum_{s \in S} \rho_s \times UP_j^s \quad (18)$$

The EENS of the whole system is the summation over $EENS_j$ for all the loads. Cost of load j interruption is calculated as:

$$EENSC_j = EENS_j \times VOLL_j \quad (19)$$

EENS index and interruption cost corresponding to each load is reported in Table III and Table IV for each case. As was expected, by increasing the spinning reserve allocation cost of EENS decreases while operation cost become higher. Also, the optimal case has the minimum total cost among scenarios, even though it does not have the minimum operation cost or EENS cost.

Looking at Table IV it is obvious that as the amount of

allocated spinning reserve increases, EENS indices of loads decrease. However, decrease of EENS in loads 2, 3 and 4 is not significant. Interruption of load 2 in different scenarios is due to outage of unit G2. Due to congestion in Line 1-2 power delivered from unit G1 to load 2 is limited. So, in case of unit G2 outage some amount of load 2 is shed. Similarly, interruption in load 3 is due to outage of G3 and congestion in Line 2-3. Even in the third scenario in which unit G5 provides more energy, congestion in lines 3-4 and 4-7 causes some amount of load 3 to be shed. In the same way, congestion in lines 2-4 and 4-5 is the main cause of load 4 interruption. For loads 10 and 14 in the third scenario due to more participation of G5 no shedding occurs. However, in scenario 1 and 2 these loads experience interruption, while load 9 which has higher VOLL is not interrupted.

Fig. 4. Total cost as a function of spinning reserve capacity

Fig. 5. Optimal energy generation and spinning reserve scheduling

TABLE III: COMPARISON OF INVESTIGATED SCENARIOS

	Scenario II	Scenario I	Scenario III
Spinning reserve (MW)	0	80/7	120
Cost of EENS (\$)	1130/95	326/874	94/86
Operation cost (\$)	4430/67	4871	5305/4
Total cost (\$)	5561/62	5197/874	5400/26

TABLE IV: EENS INDICES AND INTERRUPTION COSTS FOR THE INVESTIGATED SCENARIOS

Load	Scenario II		Scenario I		Scenario III	
	EENS (MWh)	EENSC (\$)	EENS (MWh)	EENSC (\$)	EENS (MWh)	EENSC (\$)
2	0/2232	133/94	0/20064	120/384	0/03618	21/71
3	0/0718	50/29	0/0551	38/57	0/02167	15/17
4	0/6652	266/1	0/3071	122/84	0/145	57/98
5	0/936	374/4	—	—	—	—
10	0/2368	94/74	0/0604	24/16	—	—
11	0/142	56/8	—	—	—	—
12	0/2447	97/88	—	—	—	—
14	0/142	56/8	0/0523	20/92	—	—

Total	2/6617	1130/95	0/67554	326/874	0/20285	94/86
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VII. EFFECT OF VOLL ON SPINNING RESERVE ALLOCATION

To illustrate the effect of VOLL on amount of spinning reserve requirement and EENS, simulations are performed considering 3 different values for VOLL at buses 9 through 14. Corresponding VOLL are reported in Table 5 and simulation results are provided in Fig. 6 which illustrates the distribution of allocated spinning reserve for each generator. In the third case, because higher VOLL is chosen, G5 is scheduled to provide more energy and no interruption in loads 10 and 14 takes place. Fig. 7 shows the total reserve allocated and also EENS for each scenario. Results indicate that higher VOLL leads to more spinning reserve allocation and less EENS.

TABLE V: VOLL FOR THE INVESTIGATED SCENARIOS

Scenario 3	Scenario 2	Scenario 1	
%15	Basic Case	15%	VOLL
Increase		Decrease	Buses 9-14

Fig. 6. Allocated spinning reserve of each unit for the investigated scenarios

Fig 7. Total amount of reserve and EENS for the three investigated scenarios

VIII. CONCLUSION

In this paper an hour-ahead electricity pool market has been considered in which energy and spinning reserve markets are cleared simultaneously. In this market consumers declare their desirable reliability level to ISO in terms of VOLL. The optimal amount of spinning reserve is obtained by equilibrium between expected benefit of the reserve allocation due to decrease in interruption cost and the total cost of spinning reserve allocation (benefit-cost analysis) using stochastic programming.

In the proposed objective function operation cost, load interruption cost at each bus and also probability of first order contingencies are considered. Observing the rate constraints of generation units and transmission constraints in the proposed objective function the system operation security is assured as well.

The proposed approach has been evaluated on IEEE 14-bus test system and the obtained results have been discussed. Results suggest that variation in the consumers' desired VOLL besides variation in total allocated spinning reserve and EENS of system causes different distribution of spinning reserve among generators.

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