Optimal Spinning Reserve Capacity in Power Market

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Abstract— In this paper, the spinning reserve (SR) capacity in a power system is considered to be flexible. The expected energy not served (EENS) is calculated by the equivalent energy approach. Based on the reliability evaluation of the generation system, a clearing model of the spinning reserve market is proposed to determine the optimal reserve capacity and simultaneously clear the spinning reserve market. The spinning reserve model for flexible spinning reserve is discussed on both uniform-price and pay-as-bid auction mechanisms. The results show that the flexible spinning reserve model is more beneficial than the fixed spinning reserve model and increases the social benefit of the system. For case studies reliability test system (RTS 96) is used in this paper

I. INTRODUCTION

Today in the competitive electrical market the consumer now requires more reliable supply of electricity. Thus the liberalization of the electricity supply market requires more services that are able to maintain the quality and the security of the supply of the electricity. The main purpose of these services is to maintain the quality level of the supply industry. To control the frequency of the system we require a certain amount of active power to be kept in reserve which can be used in re-establishment of the balance between the demand and the generation at all times. A general definition of reserve is given as the amount of generation capacity that can be used to produce active power over a given period of time. This generation capacity is not committed to produce energy for normal time periods.

In practical, there are different reserve services which respond to different types of events over different time periods. There are several approaches for the spinning reserves optimization. Anstine and Burke [1] were the first to consider the probabilistic nature of the outages in the calculation of the spinning reserve provision. They proposed a technique that takes into account the forced outage probabilities of the generating units. Gooi [2] are the first who considered how the spinning reserve could be optimized within the unit commitment problem. Their approach consists in post processing the unit commitment schedule to compute the level of risk in disconnection the load at each hour. Combining the reliability calculation with the unit commitment, Tseng et al. [3] produce a new model on optimal scheduling of the spinning reserve. The reserve benefit can be evaluated by reduction of Energy Expectation Not Served. Because the effect of unit forced -outage and maintenance is also considered. We can get system reliability indices such as Expected Energy Not Served. EENS is a very important and widely used reliability index in power system planning, which can be calculated by a reliability evaluation or probabilistic production simulation algorithm [4]. Wang et al. [5] say that the spinning reserve capacity should be optimized by cost-benefit analysis.

A stochastic method is used for the optimal operation of a power system with wind generators and SMES systems [6]. The suggestion that all reserve markets are cleared together is given in [7]. It says that the electric power industry all over the world is undertaking major regulatory and operational changes. The understanding of power supply as a public service is being replaced by the notion that competitive markets constitute a more appropriate framework to supply reliable and cheap electric energy to consumers. The pricing of the spinning reserve is based on the type of pricing method we are adopting. There are two pricing methods such as the pay as bid method and uniform pricing method and these are discussed in [8]. The differences in these two pricing methods are discussed in [9]-[12]. In this paper the spinning reserve capacity based on both the pricing methods is discussed in section IV and is shown in Fig.6.

II. OPTIMAL SPINNING RESERVE CAPACITY

A. Flexible Spinning Reserve

On the basis of the fixed reserve criteria, the operating cost can be minimized by dividing the requirement of spinning reserve among the various generating units to get the minimum operating cost. Here the operating cost is minimized, but the social benefit is not maximized. In the flexible spinning reserve model sum of the operating cost and cost of outages exhibits a minimum, and this will define the optimal amount of spinning reserve to be scheduled. In flexible reserve the main aim is to find out the optimal spinning reserve capacity that maximizes the social benefit(B) or minimizes the social cost(L) .Thus the whole problem can be expressed mathematically as the sum of operating cost and the expected cost of outages as given below [5].

\[
\text{Min } L = L_R(R) + C(R) \tag{1}
\]

Or

\[
\text{Max } B = B_R(R) - C(R) \tag{2}
\]

Here R is the spinning reserve capacity \( B_R(R) \) is the decrease of the interruption loss and \( L_R(R) \) is the interruption loss when the system spinning reserve capacity is R.

The interruption loss and the decrease in the interruption loss is given below as;

\[
L_R(R) = IEAR \times EENS(R) \tag{3}
\]

Or

\[
B_R(R) = IEAR \times \{EENS(0) - EENS(R)\} \tag{4}
\]

Here IEAR is the Interrupted Energy Assessment Rates. Where, EENS (0) is the Expected Energy Not Served before
purchasing any spinning reserve amount while EENS(R) is the Expected Energy Not Served after purchasing R amount of spinning reserve capacity. Interrupted Energy Assessment Rates can also be called as Value of Lost Load in different systems [13]. Interrupted Energy Assessment Rates is an approximate value as it is very difficult to evaluate. Here the function C(R) is the cost function which is based on different pricing methods.

B. Constraints
The constraints include that reserve capacity R of unit i must remain in minimum and maximum limits of reserve capacity of a unit i as shown below:

$$\text{Min}(R) \leq R_i \leq \text{Max}(R)$$  \hspace{1cm} (5)

And

$$R_i \leq T \text{ (required)} \times \text{Ramp rate of unit i}$$  \hspace{1cm} (6)

Where, max(R) is maximum reserve capacity and min(R) is minimum reserve capacity of unit i. T (required) in this paper is taken as ten minutes while ramp rates are given in [14].

C. Condition for optimal spinning reserve capacity
The optimal condition for spinning reserve capacity can be obtained by taking partial derivative of the objective function given by equation (1) or (2) [5]. Taking partial derivative of equation (1) and we will get the optimal condition.

$$\frac{\partial L}{\partial R} = \text{IEAR} \left( \frac{\partial \text{EENS}(R)}{\partial R} \right) + \frac{\partial C}{\partial R} = 0$$  \hspace{1cm} (7)

We can also write equation (7) as a difference equation and this can be written as

$$\text{IEAR} \times \Delta \text{EENS}(R) + \Delta C = 0$$  \hspace{1cm} (8)

Or

$$\text{IEAR} \times \Delta \text{EENS}(R) + \Delta C = 0$$  \hspace{1cm} (9)

Here $\Delta C$ is the change in cost for the change in the reserve capacity $\Delta R$. $\Delta \text{EENS}(R)$ is the change in Expected Energy Not Served. Now we will get the condition for optimal spinning reserve capacity when equation (9) is satisfied. If the given below inequality holds for the increasing reserve capacity $\Delta R$ then the purchasing of the reserve capacity is

$$\text{IEAR} \times \Delta \text{EENS}(R) + \Delta C < 0$$

Or

$$-\text{IEAR} \times \Delta \text{EENS}(R) > \Delta C$$  \hspace{1cm} (10)

Favorable otherwise the purchasing should be stopped at this condition.

Due to the increasing reserve capacity the change in Expected Energy Not Served is usually negative. Now according to the pay as bid the cost of the reserve is expressed as [5]

$$C_{\text{Pay as bid}} = \sum_{i=1}^{N} (P_{Ri} \times R_i)$$  \hspace{1cm} (11)

Where $P_{Ri}$ is the bid price for the unit i and N is the number of units that provides the reserve capacity.

From equation (11) we can write the change in reserve cost as

$$\Delta C_{Ri} = P_{Ri} \times R_i$$  \hspace{1cm} (12)

And can obtain the curve C(R) as shown in the Fig.1.

The another curve is interruption loss and can be obtained from the relation given below as;

$$\Delta L_{Ri} = \text{IEAR} \times \text{EENS}(t-1) - \text{EENS}(i)$$  \hspace{1cm} (13)

Or

$$\Delta L_{Ri} = \text{IEAR} \times \{\text{EENS}(0) - \text{EENS}(1)\}$$

Here the change in Expected Energy Not Served is difference between two consecutive values of Expected Energy Not Served. The reserve will be purchased step by step until the below relation is satisfied

$$\Delta L_{Ri} \leq \Delta C_{Ri}$$

And we get the optimal condition point O as shown in Fig.1 and $R_S$ becomes the optimal reserve capacity, where $R_S$ is the total reserve selected and is shown as;

$$R_s = R_1 + R_2 + \cdots + R_i \hspace{1cm} i = 1, 2, 3, \ldots, N$$

The cost of reserve according to uniform pricing method is as;

$$C_{\text{uniform}} = P_{\text{clear}} \sum_{i=1}^{N} R_i$$  \hspace{1cm} (14)

Here $P_{\text{clear}}$ is clearing price of the reserve market.
III. FLOWCHART

A merit-order based method is used here to get the optimal solution. The solution process of the pay as bid pricing method is shown in the Fig.3. Here the merit order is formed of the cost of the reserve capacity of N units as shown below

\[ P_{R1} < P_{R2} \ldots \ldots < P_{RN} \]

Thus replacing equation (16) with (17) in Fig.3, we will get flowchart for uniform pricing method.

\[ \text{IEAR} \times \left( \text{EENS}'(R) - \text{EENS}''(R) \right) - \sum_{i=1}^{i=R_i} P_{R_i} \times R_i = 0 \]  

(17)

Fig. 3: Flowchart of spinning reserve market

In the algorithm the reserve capacity is purchased one unit by one unit according to their price based merit order. EENS(R) and EENS''(R) are the Expected Energy Not Served of the system before and after purchasing the spinning reserve of unit i. Thus the decrease in Expected Energy Not Served due to increasing of reserve is

\[ \Delta \text{EENS}(R) = \text{EENS}''(R) - \text{EENS}'(R) \]  

(15)

And (9) for pay as bid pricing method can be written as

\[ \text{IEAR} \times \left( \text{EENS}'(R) - \text{EENS}''(R) \right) - P_{R_i} \times R_i = 0 \]  

(16)

And (9) for uniform pricing method can be written as Eq. 17

The main difference in pay as bid and uniform pricing method is the equations used for calculating social cost.
IV. CASE STUDY

The IEEE test system—RTS96—is employed to demonstrate the proposed spinning reserve model. The single line diagram of IEEE-RTS for one area system is shown in Fig.2. The one area system has six hydro units, twenty four thermal units, and two nuclear units. The total capacity of the system is 3405 megawatts (MW). The load curve for twenty four hour period is shown in Fig.4. The peak load is 2500 MW at 18:00 hour and base load is 1475 MW at 05:00 hour. In the paper the IEEE-RTS one area system has been taken and the unit information is given in reference [14]. Maximum data are taken from IEEE-Reliability Test System, and tabulated using EXCEL sheet. In the Fig.5 the spinning reserve capacity is shown for 24 hours. The spinning reserve capacity is taken in MW.

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![Spinning reserve for different value of IEAR](image1)

**Fig. 7: Spinning reserve for different the Interrupted Energy Assessment Rates**

![CPU processing time for different spinning reserve capacity](image2)

**Fig. 8: CPU processing time for different spinning reserve capacity**

The reserve market is cleared by cost benefit analysis in every period. In Fig.5 it indicates that the spinning reserve curve follows the same pattern as that of load curve. The peak values of spinning reserve correspond with the peak value of the load curve. Further the analysis is done for different conditions in the market. In Fig.6 the comparison between the reserve capacity under pay as bid method and the uniform pricing is shown and it indicates that pay as bid pricing method is better than the uniform method. The effect of the IEAR on the spinning reserve capacity is indicated in Fig.7. It shows that for higher value of IEAR the system has to buy more reserve capacity. So according to this more reserves required for less reliable system. In this paper simulation has been now carried out to obtain some more results like the CPU processing time, social benefit for different reserve capacities and behavior of spinning reserve capacity with different IEAR values for different values of spinning reserves. The CPU processing time for different reserve capacities is shown in Fig. 8. Here Fig.9 indicates that the social benefit for pay as bid pricing method is better than that of the uniform pricing method. The social benefit of all the reserve units is calculated in every loop of the algorithm and unit with higher social benefit is selected. In Fig.10 the graph is plotted between the spinning reserve capacity and the Interrupted Energy Assessment Rates. Fig.11 shows the comparison of reserve ratio for scheduled reserves and the flexible reserves. The traditional model has a smaller ratio at peak load and larger at base load, while the flexible reserve has just opposite of it, means higher at peak load and smaller at base load.

![Comparison of social benefit for reserve](image3)

**Fig. 9: Comparison of social benefit for reserve**

![Spinning reserve vs. Interrupted Energy Assessment Rates](image4)

**Fig. 10: Spinning reserve vs. Interrupted Energy Assessment Rates**
It also shows that the value of Interrupted Energy Assessment rates increases the requirement of spinning reserve capacity increases approximate linearly.

V. DISCUSSION

Due to assumption in taking constant incremental cost (actually they are nonlinear (quadratic) in nature), the cost curve become linear but even after that it is possible to show the performance of proposed spinning reserve model. The EENS calculation is very time consuming, it is almost taking 2 to 4 second for higher IEAR rate on Intel i3 processor, VAIO-window based PC (38 % CPU use for mat lab). Even after that the method is very fast from previous methods. In the flexible spinning reserve market then value of reserve capacity is not predetermined. Here the spinning reserve capacity is purchased according to the reliability of the system; if system is less reliable more reserve is required. So this paper suggests that the spinning reserve capacity should be purchased when the system is less reliable and the Interrupted Energy Assessment Rates are higher. To reduce the time of computation for spinning reserve capacity, further research can be done using the soft computing techniques.

REFERENCES


