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Cost-based Risk Approach for Spinning Reserve Assessment in Bulk Power Systems

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P A P E R I N F O

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A B S T R A C T

Spinning reserve (SR) is one of the most prevalent methods for balancing grid uncertainties, such as generator faults, to maintain grid reliability. Literature review shows that several deterministic as well as probabilistic methos have been proposed for determining SR. It is always a challenge for a system operator to decide which approach better from security and reliability point of view. This is important because the allocated SR may provide in some cases a misleading sense of confidence with respect to safe, secure, reliable and economic operation of power systems. This paper presents a cost-based risk index approach for assessing the spinning reserve requirements in a power system. To that end, the performance of spinning reserve is classified in three types, namely, not-effective, partially-effective, and not-meeting-load. Then probability of each type and its consequences are subsequently computed and finally that the risk associated with any spinning reserve value is determined. It is shown that one might consider various spinning reserve values for an operating condition (randomly or using approaches proposed in literature), then calculate risks associated with each value, and finally use the calculated risk indices to determining the optimal level of spinning reserve. As an example, we have shown that in the studied network with 6600MW load, maintaining 240MW SR will increase cost of 1MW hour energy by $0.154 while the optimal value of 200MW SR will increase cost of 1MWhour energy by just $0.126. This paper initially focuses on providing a measure of the quality of an ex-ante specified spinning reserve, latter on the flowchart of using the proposed approach for determining optimal level of spinning reserve is presented. The proposed risk index can also be used for comparing different deterministic as well as probabilistic approaches presented in literature for spinning reserve requirements.

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1. INTRODUCTION

For frequency stabilization, meeting varying load demand, and backing up in case of any unexpected loss of generation as well as solar power variation, power systems are operated with significant SR. Although there is no widely used agreement on the amount of active power which should be kept as SR, traditionally, SR requirement has been based on deterministic criteria such as loss of the largest online generator or a given percentage of the load [1-3]. Deterministic criteria normally provide suboptimal SR because they consider only basic factors including unit size, unit availability and etc., without taking in to account the stochastic nature of power system components such as probability of generation and transmission outage, uncertainties in load forecast, variation of solar power especially in cloudy sky days, and security criteria [4-5].

Asgari et al. [5] reported that the network constraints in the SR interval were neglected because transmission lines are generally allowed to be overloaded and operated at emergency capacity for a short time. Anstine et al. [6] were the first who proposed the consideration of probabilistic nature of load forecast in SR determination. Thereafter, various researches focused on determining SR using probabilistic methods considering a tradeoff between system reliability and economy. In literature, one or joint combination of loss of load probability (LOLP), expected energy not supplied (EENS) and unit commitment were used as probabilistic reliability indices for reserve assessment [7]. Ansari and Malekshah [8] have used the combination of LOLP and EENS for reserve allocation. Amirahmadi and Akbari Foroud [9] have used hybrid probabilistic and deterministic based approaches for security assessments and optimal spinning reserve allocation. Although in hybrid

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approaches reliability indices are directly included in the model, due to the heavy computation and complexity of these indices, it is difficult to obtain the optimal solution [10-11].

Zhang et al. [12] presented a linearized technique for determining a risk based index for dynamic security assessment. The risk based static security indices were also presented by Emarati et al. [13], Datta and Vittal [14]. Wang et al. [15] presented a method suitable to examine impacts of a high penetration of renewable energy on the total transfer capability considering uncertainties associated with the renewable energy. Jabari et al. [16] have proposed a probabilistic security evaluation algorithm for bulk power system based on analytical approach to consider the single or double failure of line or transformer as well as the multiple failures caused by protection relays. De Caro [17] presented an approach to evaluate the composite system indices under a security constrained framework. Wang [18] has investigated the impact of transmission system failures on spinning reserve allocation and he has proposed a technique to determine the locations of spinning reserve based on the minimum unit commitment risk. A probabilistic based approach was proposed by Rajabdorri et al. [19] to calculate the appropriate reserve margin value based on loss of load expectation index. Bento and Ramos [20] suggested a model for estimating spinning reserves in power systems containtnig renewable-energy sources. Rather than quantifying spinning reserve conditions, the model focuses on factors of stability. The proposed approach's numerical efficiency is accomplished by the use of the cross entropy (CE) concept.

Bento [21] has provided a cost-benefit analysis-based approach for calculating the reserves needs of integrated grid networks. To minimize the total number of buses in the power grid, the suggested model employs the radial-equivalent-independent approach. The optimization of reserve requirements is performed using either security constrained unit commitment (SCUC) or security constrained economic dispatch.

The stochastic nature of load demand, generation and transmission outages along with other uncertainties have made the effectiveness of SR an uncertain parameter such that its effectiveness is very dependent on operating condition, probability of contingencies and randomness of other parameters. In other words, it is always a challenge to decide which approach or what SR value, works best for a power system from economic as well as security and reliability point of view.

Literature review showed that several deterministic as well as probabilistic methods have been proposed for determining SR. However, as emerging technology and business mechanisms arise, this paper proposes a cost-based risk evaluation framework which can be used to determine the optimal level of SR requirement. To that end, the performance of SR is classified in to three possible types, namely, not-effective, partially-effective, and not-meeting-load. The probability of occurrence of each performance type is subsequently computed and associated risk is determined. Thereafter, the flowchart and procedure of using the proposed index for determining the optimal level of SR to economically respond to generation outages, error in load forecasts, and other uncertainties related to renewable resource generation is presented.

2. COST-BASED RISK INDEX FOR SR ASSESSMENT

Performance of SR can be classified in three possible types, namely, not-effective, partially-effective, and not-meeting-load demand.

In a system operating with a predefined level of SR, under some conditions (conditions like over forecasting of system load, no generation failure, etc.) the allocated SR will not be utilized to supply the load demand, and system continues to serve the load without utilizing any part of allocated SR. This condition is named as not necessary or not effective (NEFF) SR. On the other hand, there will be conditions that only a portion of allocated SR (from zero plus to 100 percent of the allocated SR) is needed and will be used to serve the load demand. This condition is termed as partially- effective (PEFF) SR. The third scenario is conditions in which allocated SR is not sufficient to supply the load demand. This is termed as not sufficient or notmeeting (NMEET) SR. Therefore, the general expression for a comprehensive risk index shall include all type of SR as below:

$$\begin{aligned} R(X_0) &= p(NEFF \mid X_0) \times Expected\ [Impact(NEFF)] + p(PEFF \mid X_0) \times \\ & Expected\ [Impact(PEFF)] + p(NMEET \mid X_0) \times Expected\ [Impact(NMEET)] \end{aligned} \quad (1)$$

where, $R(X_0)$ is the risk associated with operating condition X_0. Moreover, $p(NEFF \mid X_0)$ is probability that SR being not-effective $p(PEFF \mid X_0)$ is probability that SR being partially-effective, probability of SR and $p(NMEET|X_0)$ is probability that SR is not sufficient to meet demand $Expected\ [Impact(NEFF)]$ is the expected consequence when SR is not-effective, . $Expected\ [Impact(PEFF)]$ is the expected consequence when SR is partially-effective, and $Expected\ [Impact(NMEET)]$ is the expected consequence when SR is not sufficient to meet demand.

3. BENEFIT, IMPACT AND PROBABILITY OF SR PERFORMANCE

As stated before, Regardless of the method used for determining the level of SR requirement, performance of

SR is a random and uncertain parameter which is affected by several factors such as stochastic nature of power systems, accuracy of load forecast, generation failure, variability of renewable resources, transmission contingencies, etc. Randomness of SR may let us classify its performance in three possible types named as not-effective, partially-effective, and not-meeting-load.

3. 1. Probability, Benefit and Impact of Not Effective SR If allocated SR is not used for supplying the load demand, the allocated SR is not-effective (NEFF). This condition may happen in case of over forecasting of load demand, under-forecasting of renewable resource generations, load tripping, etc. for example, if actual load demand is lower than forecasted load demand, the SR will not be utilized for supplying load demand and will not be effective. Accordingly, probability of SR being not-effective if contingency $Event_i$ happens can be calculated using Equation (2):

$$p(NEFF|Event_i) = \begin{cases} p(\Delta L_i < 0|E_i) & if\ Event_i = E_i \\ p(\Delta L_i < -Capacity(G_i)|G_i) & if\ Event_i = G_i \end{cases} \quad (2)$$

where, E_i is equipment failure (except generation tripping), G_i is generation tripping contingency and ΔL_i is load variation. From Equation (2) it is observed that if equipment failure E_i causes load reduction, the SR will not be utilized and will be not-effective. The same is applicable if capacity of generation tripping is lower than load reduction, for example, if load reduces by 200MW when only 100MW generation trips. Considering all events, total probability of not-effective SR is as below [20]:

$$p(NEFF|Event_i) = \sum_{E_i} p(\Delta L_i < 0|E_i) \times p(E_i) + \sum_{G_i} p(\Delta L_i < -Capacity(G_i)|G_i) \times p(G_i) \quad (3)$$

No benefit is derived from a not effective SR, however, cost of its provision can be considered as negative impact of not-effective SR.

3. 1. Probability, Benefit and Impact of Partially Effective SR If only limited portion of allocated SR is used for supplying the load demand, the allocated SR is partially-effective (PEFF). This condition may happen if actual load exceeds the forecasted load by less than load margin, or actual output of renewable resource generations is less than the forecasted ones, or capacity of generation tripping is less than load variation, etc. Accordingly, probability of SR being partially-effective if contingency $Event_i$ happens can be calculated using Equation (4):

$$p(PEFF|Event_i) = \begin{cases} p(0 < \Delta L_i < \Delta M_i|E_i) & if\ Event_i = E_i \\ p\left(\begin{matrix} -Capacity(G_i) < \Delta L_i \\ < M_i - Capacity(G_i) \end{matrix}\middle| G_i\right) & if\ Event_i = G_i \end{cases} \quad (4)$$

where, E_i is equipment contingency (except for generation tripping), G_i is generation tripping contingency, ΔL_i is load variation and M_i is load margin (load margin is the amount of additional load which can be supplied without any security and reliability criteria violation such as voltage violation, equipment overloading, etc.). From equation (4) it is observed that if equipment failure E_i causes load to increase and amount of this increase is lower than the SR, only small part of SR will be utilized to supply the load and remaining portion of SR will not be utilized. The same is applicable if capacity of generation tripping is higher than load increase, for example, if load increases by 200MW when 300MW generation trips but load margin is 250MW. Considering all events, total probability of partially-effective SR is as follows [13]:

$$p(PEFF|Event_i) = \sum_{E_i} p(0 < \Delta L_i < M_i|E_i) \times p(E_i) + \sum_{G_i} p\left(\begin{matrix} -capacity(G_i) < \Delta L_i \\ < M_i - capacity(G_i) \end{matrix}\middle| G_i\right) \times p(G_i) \quad (5)$$

Negative impact of partially-effective SR is cost of provision for not utilized portion of SR. The benefit derived from partially-effective SR is additional energy served through partially-effective SR.

3. 2. Probability, Benefit and Impact of Not Meeting SR If allocated SR is not sufficient to supply the load demand, it is called not-meeting (NMEET) SR. This condition may happen if actual load significantly exceeds the forecasted load, or actual output of renewable resource generations is significantly lower than the forecasted ones, or capacity of generation tripping is more than load variation, etc. Accordingly, probability of not-meeting SR if contingency $Event_i$ happens can be calculated using the following equation [21]:

$$pp(NMEET|Event_i) = \begin{cases} p(\Delta L_i > M_i|E_i) & if\ Event_i = E_i \\ p\left(\begin{matrix} \Delta L_i > \\ M_i - Capacity(G_i) \end{matrix}\middle| G_i\right) & if\ Event_i = G_i \end{cases} \quad (6)$$

where, E_i is equipment contingency (except for generation tripping), G_i is generation tripping contingency, ΔL_i is load variation and M_i is load margin. Considering all events, total probability of not meeting SR is as below [21]:

$$p(NMEET|Event_i) = \sum_{E_i} p(\Delta L_i > M_i|E_i) \times p(E_i) + \sum_{G_i} p(\Delta L_i > M_i - capacity(G_i)|G_i) \times p(G_i) \quad (7)$$

when SR is not sufficient to supply the load demand, load curtailment will be necessary. Therefore, negative impact of not meeting SR is cost of non-served energy and the benefit derived from not meeting SR is the additional energy served through allocated SR.

4. CASE STUDY

As an illustration, the proposed cost- based risk approach for spinning reserve assessment is applied to a power system with 6600MW system load and 235MW as the largest capacity of online units. Assume that SR under current operating condition is 240MW (one might consider that 240MW SR has been derived based on either of deterministic or probabilistic methods proposed literature methods. However, this value is only a figure for us here to explain the proposed approach). The power system under study includes 45 online generators and consists of, in addition to the generator buses, 400kV (10 buses), 230kV (5 buses), 132kV (101 buses), 63kV (68 buses) and 20kV (149 buses) voltage level. Number of 400kV, 230kV, 132kV and 63kV circuits is 29, 9, 160 and 87 circuits, respectively. The quality of the allocated 240MW SR using the proposed cost-based risk evaluation approach is measured. The time frame is considered to be one hour and during this one hour, it is assumed that the forecasted expectation of system is the same as the current operating condition. Standard deviation for system load is assumed to be 2%. Therefore, expected system load is 6600MW and its standard deviation is 132MW. Figure 1 shows probability density function (PDF) for the system load and Table 1 summarizes list of online generation units along with their capacity and output.

There are several uncertainties associated with SR such as transmission and generation outages, forecasted load, forecasted wind power in wind power generation, forecasted solar power of photovoltaic generation and other parametric deviations, e.g. failure of a generation unit to synchronize, etc.

However, for the simplicity, we consider only 5 different contingencies in the next one hour as shown in Table 2 (the occurrence probability is just for illustrative purpose).

Further simulations using power flow and contingency analysis showed that load margin (i.e. additional load which can be supplied without any security and reliability criteria violation such as voltage violation, equipment overloading, etc.) for contingency 1, 4 and 5 is 240MW and for contingency 2 and 3 is only

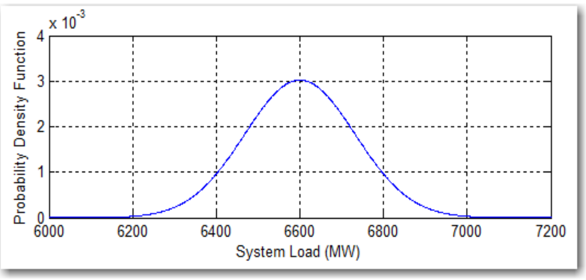

Figure 1. PDF of system load

TABLE 1. List of online generation units and their respective capacity and MW outputs

Station	Units and Capacities (MW)	Units and Outputs (MW)	SR (MW)
APOW	$420 = 3 \times 140$	408=3×136	12
BPOW	$3 \times 216 + 2 \times 135$	3×210+2×131	26
CPOW	3×135	3×131	12
DPOW	7×68	420=7×60	56
EPOW	5×91+1×105	5×85+1×100	35
FPOW	4×135+1×70	4×130+1×65	25
GPOW	3×216+2×155+ 2×235+2×226	3×214+2×150+ 2×230+2×220	38
HPOW	4×235+1×221	4×230+1×215	26
IPOW	2×205	400=2×200	10

TABLE 2. Probability of contingencies

Contingency Number	Contingency	Occurrence Probability	Load margin (MW)
1	No Outage	0.999	240
2	Outage of L1321-1322 circuit	2.5×10^{-4}	93
3	Outage of L1321-1323 circuit	2.5×10^{-4}	96
4	Tripping of FPOW-5 generator with 70MW capacity	2.5×10^{-4}	240
5	Tripping of HPOW-5 generator with 221MW capacity	2.5×10^{-4}	240

93MW and 96MW respectively. In other words, when system load is more than 6693MW and contingency 2 occurs, cascaded circuit overloading will take place which can result in brownout or entire system black out. The same was observed in contingency 3 for load greater than 6696MW. Therefore, in case of requirement, only 93MW of allocated 240MW SR for contingency 2 and 96MW for contingency 3 can be utilized for supplying the load demand.

4. 1. Probability and Impact When SR does not Meet Load Variation

We would like to calculate the probability and associated impacts when SR is not sufficient to supply the load demand and therefore, it does not meet load variation during the one-hour study horizon. As stated before and depicted in Figure 1, the system load has normal distribution with 6600MW expected value and 132MW standard deviation. Randomness of the system load and uncertainties in contingencies will lead to randomness and uncertainties of SR. For contingency 1 to 5, the probability that SR does not meet load variation is as below:

$$p(NMEET|E_1) = p(Load > 6840|E_1) = 0.0345 \quad (8)$$

$$p(NMEET|E_2) = p(Load > 6693|E_2) = 0.2405 \quad (9)$$

$$p(NMEET|E_3) = p(Load > 6696|E_3) = 0.2335 \quad (10)$$

$$p(NMEET|G_4) = p(Load > 6770|G_4) = 0.0989 \quad (11)$$

$$p(NMEET|G_5) = p(Load > 6619|G_5) = 0.4428 \quad (12)$$

Therefore, the probability that SR is not sufficient to supply load demand over the next hour is as below:

$$p(NMEET|Load = 6600MW) = 0.999 \times 0.0345 + 2.5 \times 10^{-4} \times 0.2405 + 2.5 \times 10^{-4} \times 0.2335 + 2.5 \times 10^{-4} \times 0.0989 + 2.5 \times 10^{-4} \times 0.4428 = 0.0347 \quad (13)$$

The associated impact when SR is not sufficient to supply load variation is load interruption which can be interpreted in two different ways. The first option is to assume that if the system load is greater than generation capacity, the outcome is the entire system blackout, i.e. there is no manual or automatic load shedding protection to prevent system against frequency instability. The second option which may be more realistic is assuming that manual or automatic load shedding will be activated to reestablish the balance between load and generation. Here the second option was considered in which, if for example in contingency 1, the system load becomes 6900MW, only 6840MW of the load demand will be supplied and the remaining 60MW load will be shed manually or automatically to reestablish generation and load balance. Figures 2 to 6 show the amount of load which will be shed when SR does not meet load demand in contingency 1 to 5, respectively.

Considering 4 hours load interruption with expected cost of $20 per MW hour, the expected load interruption when SR is not sufficient to meet load variation is:

$$Expected\big(Impact(NMEET|Load = 6600MW)\big) = 4 \times 20 \times (0.999 \times 0.0345 \times 50.97 + 2.5 \times 10^{-4} \times 0.2405 \times 77.18 + 2.5 \times 10^{-4} \times 0.2335 \times 76.45 + 2.5 \times 10^{-4} \times 0.0989 \times 61.91 + 2.5 \times 10^{-4} \times 0.4428 \times 98.23) = \$142.27 \quad (14)$$

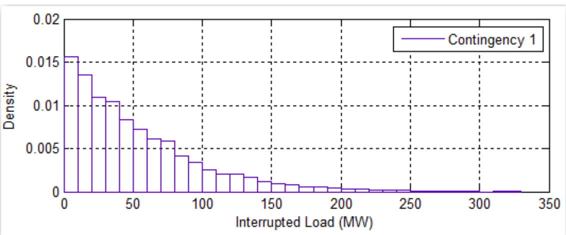

Figure 2. Load interruption in contingency 1

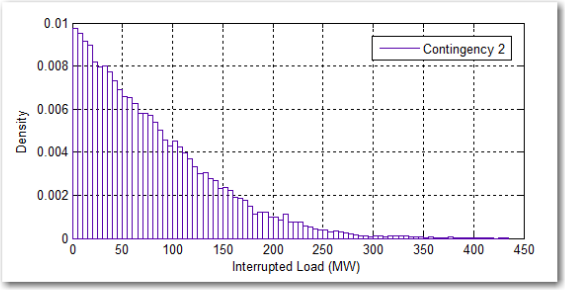

Figure 3. Load interruption in contingency 2

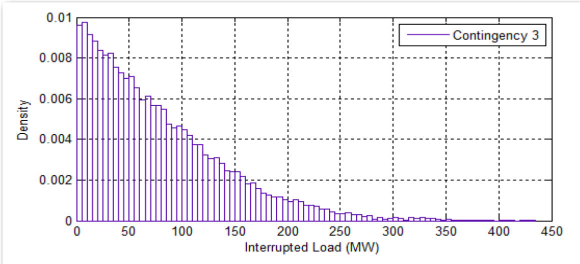

Figure 4. Load interruption in contingency 3

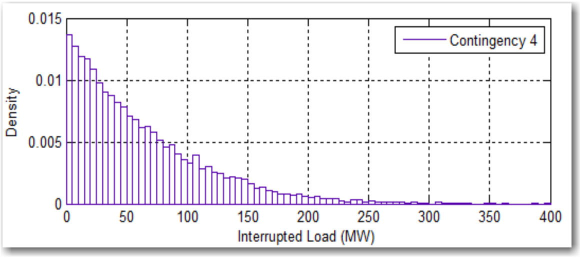

Figure 5. Load interruption in contingency 4

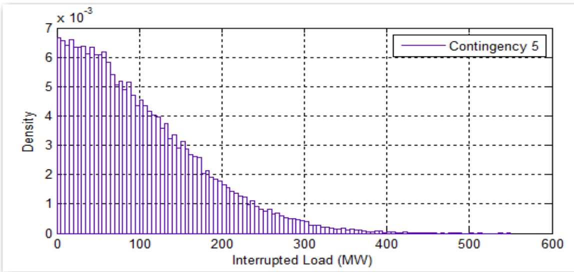

Figure 6. Load interruption in contingency 5

The expected benefit from SR when SR is not sufficient to meet load variation is as below:

$$Expected\big(Benefit(NMEET|Load = 6600MW)\big) = 1 \times 20 \times (0.999 \times 0.0345 \times 240 + 2.5 \times 10^{-4} \times 0.2405 \times 93 + 2.5 \times 10^{-4} \times 0.2335 \times 96 + 2.5 \times 10^{-4} \times 0.0989 \times 240 + 2.5 \times 10^{-4} \times 0.4428 \times 240) = \$166.31 \quad (15)$$

Table 3 summarizes probability of not-effective SR and its associated impact and benefit for each contingency.

4. 2. Probability and Impact When SR is Not Effective For contingency 1 to 5 the probability that SR is not necessary to meet load demand is as below:

$$p(NEFF|E_1) = p(Load < 6600|E_1) = 0.5 \quad (16)$$

$$p(NEFF|E_2) = p(Load < 6600|E_2) = 0.5 \quad (17)$$

$$p(NEFF|E_3) = p(Load < 6600|E_3) = 0.5 \quad (18)$$

$$p(NEFF|G_4) = p(Load < (6600 - 70)|G_4) = 0.298 \quad (19)$$

$$p(NEFF|G_5) = p(Load < (6600 - 221)|G_5) = 0.047 \quad (20)$$

Therefore, the probability that SR is not required to supply load demand over the next hour is as below:

$$p(NEFF|Load = 6600MW) = 0.999 \times 0.5 + 2.5 \times 10^{-4} \times 0.5 + 2.5 \times 10^{-4} \times 0.5 + 2.5 \times 10^{-4} \times 0.298 + 2.5 \times 10^{-4} \times 0.047 = 0.4998 \quad (21)$$

Considering \$10 per MW hour as expected cost of maintaining SR, the expected impact of not effective SR is as below:

$$Expected\big(Impact(NEFF|Load = 6600MW)\big) = 1 \times 10 \times (0.999 \times 0.5 \times 240 + 2.5 \times 10^{-4} \times 0.5 \times 240 + 2.5 \times 10^{-4} \times 0.5 \times 240 + 2.5 \times 10^{-4} \times 0.298 \times 240 + 2.5 \times 10^{-4} \times 0.047 \times 240) = \$1199.6 \quad (22)$$

The expected benefit which is derived from SR when SR is not necessary to meet load variation is as below:

$$Expected\big(Benefit(NEFF|Load = 6600MW)\big) = \$0.0 \quad (23)$$

Table 4 summarizes probability of not effective SR and its associated impact and benefit for each contingency.

4. 3. Probability and Impact When SR is Partially-Effective For contingency 1 to 5 the probability that SR is partially effective is as below:

$$p(PEFF|E_1) = p(6600 < Load < 6840|E_1) = 0.4655 \quad (24)$$

$$p(PEFF|E_2) = p(6600 < Load < 6693|E_2) = 0.2595 \quad (25)$$

$$p(PEFF|E_3) = p(6600 < Load < 6696|E_3) = 0.2665 \quad (26)$$

$$p(PEFF|G_4) = p(6530 < Load < 6770|G_4) = 0.6032 \quad (27)$$

$$p(PEFF|G_5) = p(6379 < Load < 6619|G_5) = 0.5102 \quad (28)$$

Therefore, the probability that SR is partially effective (i.e. only limited portion of allocated SR will be utilized to supply the load demand) over the next hour is as below:

TABLE 3. Probability and impact when SR does not meet load variation

Contingency#	Contingency	Occurrence Probability	Probability of not meeting load	Impact: Load interruption (MW)	Benefit: Load supplied through SR (MW)
1	No Outage	0.999	0.0345	51.0	240
2	Outage of L1321-1322 circuit	2.5×10^{-4}	0.2405	77.2	93
3	Outage of L1321-1323 circuit	2.5×10^{-4}	0.2335	76.5	96
4	Tripping of FPOW-5 generator with 70MW capacity	2.5×10^{-4}	0.0989	61.9	240
5	Tripping of HPOW-5 generator with 221MW capacity	2.5×10^{-4}	0.4428	98.2	240

TABLE 4. Probability and impact when SR is not effective

Contingency#	Contingency	Occurrence Probability of Contingency	Probability of NEFF SR	Impact: Not utilized SR (MW)	Benefit: Load supplied through SR (MW)
1	No Outage	0.999	0.5	240	0.0
2	Outage of L1321-1322 circuit	2.5×10^{-4}	0.5	240	0.0
3	Outage of L1321-1323 circuit	2.5×10^{-4}	0.5	240	0.0
4	Tripping of FPOW-5 generator with 70MW capacity	2.5×10^{-4}	0.298	240	0.0
5	Tripping of HPOW-5 generator with 221MW capacity	2.5×10^{-4}	0.047	240	0.0

TABLE 5. Probability and impact when SR is partially effective

Contingency#	Contingency	Occurrence Probability of Contingency	Probability of PEFF SR	Impact: Not-utilized SR (MW)	Benefit: Load supplied through SR (MW)
1	No Outage	0.999	0.4655	149.8	91.2
2	Outage of L1321-1322 circuit	2.5×10^{-4}	0.2595	195.5	44.5
3	Outage of L1321-1323 circuit	2.5×10^{-4}	0.2665	194.1	45.9
4	Tripping of FPOW-5 generator with 70MW capacity	2.5×10^{-4}	0.6032	132.5	107.5
5	Tripping of HPOW-5 generator with 221MW capacity	2.5×10^{-4}	0.5102	95.5	144.5

$$p(PEFF|Load = 6600MW) = 0.999 \times 0.4652 + 2.5 \times 10^{-4} \times 0.2595 + 2.5 \times 10^{-4} \times 0.2665 + 2.5 \times 10^{-4} \times 0.6032 + 2.5 \times 10^{-4} \times 0.5102 = 0.4651 \quad (29)$$

Figures 7 to 11 shows the amount of SR which is not utilized in contingency 1 to 5, respectively. Considering \$10 per MW hour as expected cost of maintaining SR, the expected impact of partially effective SR is as below:

$$Expected\big(Impact(PEFF|Load = 6600MW)\big) = 1 \times 10 \times (0.999 \times 0.4652 \times 148.8 + 2.5 \times 10^{-4} \times 0.2595 \times 195.5 + 2.5 \times 10^{-4} \times 0.2665 \times 194.1 + 2.5 \times 10^{-4} \times 0.6032 \times 132.5 + 2.5 \times 10^{-4} \times 0.5102 \times 95.5) = \$692.1 \quad (30)$$

The expected benefit which is derived from SR when SR is partially effective is as below:

$$Expected\big(Benefit(NEFF|Load = 6600MW)\big) = 1 \times 20 \times (0.999 \times 0.4652 \times 91.2 + 2.5 \times 10^{-4} \times 0.2595 \times 44.5 + 2.5 \times 10^{-4} \times 0.2665 \times 45.9 + 2.5 \times 10^{-4} \times 0.6032 \times 107.5 + 2.5 \times 10^{-4} \times 0.5102 \times 144.5) = \$848.49 \quad (31)$$

Table 5 summarizes probability of partially effective SR and its associated impact and benefit for each contingency.

4. 4. Total Risk

Quality of SR can be assessed using a cost-based risk index. Considering three possible types of SR performance (i.e. not-effective, partially-effective, and not-meeting load), expected impact of maintaining 240MW SR under current operating

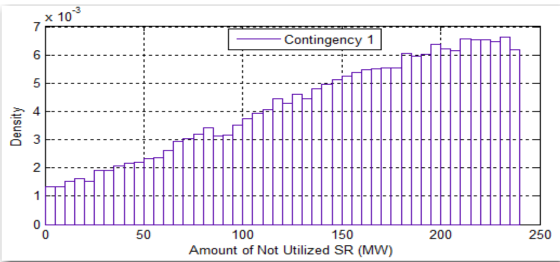

Figure 7. Amount of non-effective SR in contingency 1

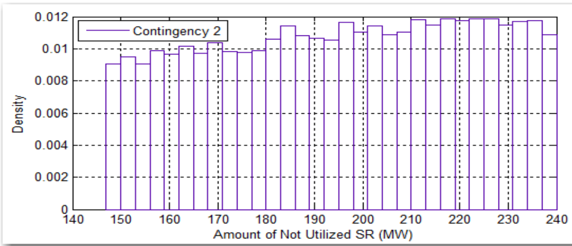

Figure 8. Amount of non-effective SR in contingency 2

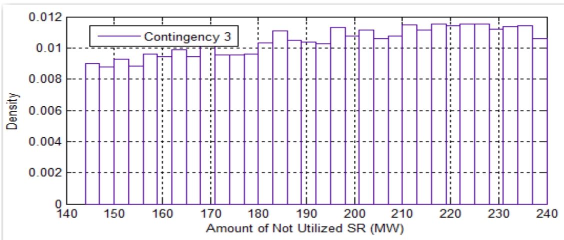

Figure 9. Amount of non-effective SR in contingency 3

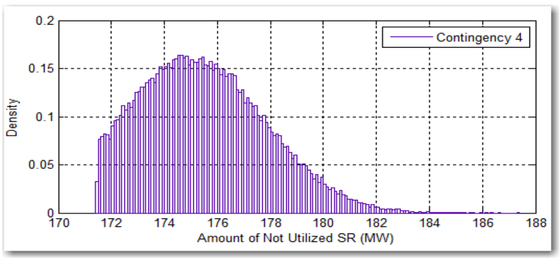

Figure 10. Amount of non-effective SR in contingency 4

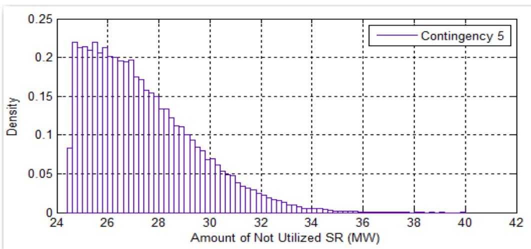

Figure 11. Amount of non-effective SR in contingency 5

condition is $2034 over the next hour which is sum of three parts; i.e. impact of not-effective, impact of partially-effective and impact of not-meeting-load. The expected benefit derived from maintaining 240MW SR is $1016 over the next hour which is sum of three parts, i.e., benefit derived from not-effective, benefit derived from partially-effective and benefit derived from not-meeting-load.

This implies that total risk associated with maintaining 240MW SR under current operating condition is $1018 (=$2034-$1016). Therefore, maintaining 240MW SR imposes additional cost of $1018 to the system, hence, $0.154 additional implicit cost will be added to the cost of 1MW hour of delivered energy. As it is shown in next section, using the proposed procedure, one might consider various level of SR for an operating condition, calculate risks associated with each level of the considered SR, and finally use the calculated risks as indicators for determining the optimal level of SR.

5. OPTIMAL LEVEL OF SR

In previous sections it was shown that performance of SR can be calculated through a cost-based risk index. Using this index, the optimal level of SR can be determined such that the calculated risk is either minimum or less than a chosen risk level. Figure 12 shows the flowchart of determining the amount of required SR according to a given desired level of risk. Using this flowchart, a plot of risk associated with different level of SR for the studied system with 6600MW has been depicted in Figure 13.

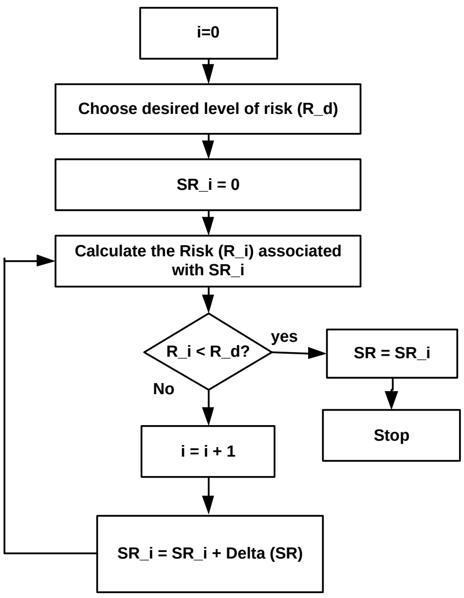

Figure 12. Determining the optimal level of SR according to a desired level of risk

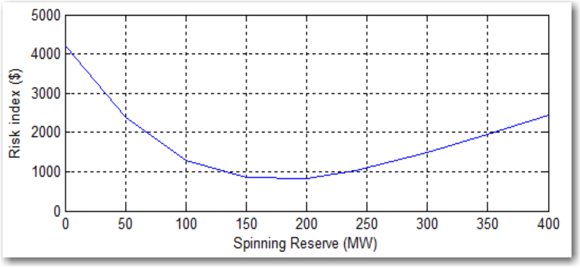

Figure 13. Calculated Risk associated with different level of SR

This figure provides a quantitative measurement of efficacy of different level of SR for current operating condition which can be used as a decision-making tool in determining the optimal level of SR. For example, it suggests optimal value of 200MW spinning reserve for the system with an expected total risk of $831 which adds $0.126 as additional implicit cost to the cost of 1MW hour of delivered energy. It is worth mentioning that the proposed risk index provides an expectation of future cost associated with the allocated SR; however, it does not guarantee that the future cost of allocating SR is exactly the same as this expectation (one might consider the variance of calculated risk also to make better operational decision about the optimal level of SR requirement).

6. CONCLUSION

A cost-based risk index approach for assessing the spinning reserve requirement in a power system is presented in this paper. In order to evaluate the efficacy of the allocated SR for a power system, the performance of SR was classified in three possible types, namely, not-effective, partially-effective, and not-meeting-load. The probability of occurrence of each performance type and its consequences were subsequently computed so that the associated risk could be determined. The flowchart of using the proposed cost-based risk approach for determining the optimal level of spinning reserve was presented. It is shown that the proposed index can be used as an indicator for determining the optimal level of SR in a power system.

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Persian Abstract

چکیده

یکی از مرسوم ترین روشها برای ایجاد تعادل بین تولید و مصرف به هنگام عدم قطعیت در شبکه استفاده از رزرو چرخان است. روشهای قطعی و احتمالی مختلفی برای تعیین مقدار رزرو چرخان در مقالات مختلف ارایه شده است. انتخاب روش مناسب از بین روشهای موجود برای تعیین مقدار رزرو چرخان همواره یک چالش برای اپراتور شبکه است چرا که ممکن است رزرو چرخان انتخاب شده باعث اطمینان کاذب برای اپراتور شبکه از نقطه نظر عملکرد پایدار و مطمین شبکه گردد. در این مقاله یک روش مبتنی بر ریسک–هزینه برای ارزیابی رزرو چرخان ارایه شده است. برای این کار کارایی رزرو چرخان به سه دسته غیر موثر، نسبتا موثر و ناکافی تقسیم شده است. سپس احتمال و پیامد هر کدام از این سه دسته محاسبه شده و در نهایت ریسک مرتبط با رزرو چرخان های مختلف مشخص شده است. همچنین نشان داده شده است که با استفاده از روش ارایه شده در این مقاله می‌توان مقادیر مختلفی رزرو چرخان در نظر گرفته و ریسک مرتبط با هر رزرو را محاسبه کرده و از آن برای تعییت مقدار بهینه رزرو چرخان استفاده کرد. بعنوان مثال برای شبکه مورد مطالعه با ٦٦٠٠ مگاوات بار نشان داده شده است که ٢٤٠ مگاوات رزرو چرخان باعث افزایش قیمت انرژی به اندازه MWh/$ ٠.١٥٤ خواهد شد در حالیکه مقدار بهینه ٢٠٠ مگاوات رزرو چرخان تنها MWh/$ ٠.١٢٦ قیمت انرژی را افزایش می‌دهد. روش ارایه شده در این مقاله را می‌توان برای مقایسه روشهای مختلف تعیین رزرو چرخان نیز استفاده کرد.