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Revised well-being analysis applied to reserve adequacy studies in vertically integrated power utilities

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Summary
Implanting deterministic considerations into probabilistic complex system reliability analysis for arriving at insightful indices has paved the way for the emergence of well-being analysis. The application of well-being analysis to power systems is an important step to support the decision making processes at different stages from expansion to operation. It allows a better insight into the comprehensive status of the power system states, and effective system reinforcement measures can be taken up accordingly. However, there is always the danger of extensive optimistic appraisals or indulgent pessimistic appraisals, resulting in insufficient contingency measures or unwarranted redundancy in the consequent implications. Due care must be exercised while taking on heuristic measures, if any, in arriving at the benchmark power system reliability indices. A glaring drawback in the conventional well-being analysis was recently identified in the literature and some modifications were suggested, where smaller load variations were found to yield drastically altered well-being indices, especially so when the size of the largest generating unit was relatively larger than other units of the system. This paper compares the conventional well-being analysis based generation reserve allocation with the revised well-being analysis, putting forward some improvisations that can be utilized for a well balanced power system appraisal.

Key words: *Generation systems, power system reliability, reserve assessment, well-being analysis.*

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1. INTRODUCTION

Probabilistic reliability assessment (PRA) is widely used to capture the prevailing effects of uncertainties in the operation of power systems. Quantification of the impact of randomness in equipment outages and load growth/fall on the ability of power systems to deliver commensurate electric power in response to load requirements without violating the operational constraints is invariably achieved by PRA. While deterministic attempts at quantifying the system reliability do not recognize the varied likelihoods of occurrence of events, probabilistic methods do take these weighted measures into account. Several indices can be evolved to measure the adequacy of power systems to quantify the successful performance of the system, and the adequacy enforcement in a practical power system can be realized through some pre-fixed criteria based on acceptable values of these reliability indices [1].

The probabilistic indices obtained through traditional power system reliability evaluation approaches mostly result in comprehensive – interpretation related difficulties by some system designers and planners [3,5,6,7,10,11].

Deterministic approaches, in isolation, cannot be truly representative of the existing risk as they do not consider the inherent nature of randomness that prevails in the factors that actually affect reliability. An emerging concept – well-being analysis (WBA), which implants deterministic considerations into the adoption of variants of probabilistic indices, has been the focus of attention in the recent years [2-21].

Different frameworks can be conceived depending upon whether the extensions of contingency enumeration or Monte Carlo simulation (MCS) are used [20]. Though the usage of Monte Carlo simulation is widespread in evaluating the reliability indices of generation systems [13], its deployment for bulk power system well-being analysis is a recent development [20]. Using MCS, not only the probability, but also the frequency and duration associated with the well-being indices could be obtained.

The application of well-being analysis at the various hierarchical levels (HLI, HLII and HLIII) of power system studies yields results that bring about value addition to the whole aspect of power system reliability evaluation [5,8,9,12,14,18,19]. Further, in the wake of deregulation which throws a gamut of structural changes into consideration, existing reliability techniques do not suffice. Well-Being analysis assumes prominence and can prove to be invaluable in dealing with the numerous challenges that restructuring offers.

2. GENERAL PROCEDURE OF WELL-BEING ANALYSIS FOR HLI

The distinctive feature of the well-being framework is the division of the operating states of a power system in accordance with a set of mutually exclusive, exhaustive operating states designated as healthy, marginal, and at-risk (or failure). The events leading to each operating state are identified and the probabilities associated with these operating states evaluated, resulting in the well-being indices.

The requisite definitions which make it possible to typecast the various ways in which the state space of a generating system can evolve are to be found in [4]. Unlike the conventional reliability studies, where the focus is on the finality of system binary states (i.e. healthy and non-healthy/at-risk), well-being analysis permits a further dissection of the healthy states so as to identify those states which are potentially located at the precipice of risk.

In the healthy state, in addition to the existence of generation-load balance, there must be enough reserve margin to withstand the loss of any further units as dictated by the laid-down deterministic criteria. In the marginal state, though the load equilibrium is maintained, there isn't enough generation reserve to cope with the failure of additional units over and above the existing state space. There is loss of load in the risk state due to insufficient generation to meet the load demand. The definitions for the various well-being states of composite system vary, depending upon the role of corrective actions that could be employed to restore security constrained adequacy and can be found in [4,7,14,15,17].

3. APPLICATION OF WELL-BEING ANALYSIS TO RESERVE ASSESSMENT

Instead of adopting a pure deterministic criterion that relates the reserve margin to the size of the largest unit or to some pre-fixed percentage of the peak load, or a probabilistic criterion as in the PJM method [22] which holds the reserve at or above the threshold levels w.r.t a certain 'acceptable' unit commitment risk, well-being analysis provides the flexibility of incorporating deterministic considerations into the intended probabilistic analysis, offering a more intuitively interpretable way and wider alternatives to distribute the reserve stipulations. Some of the application details could be found in [12,14,18,19].

4. REVISED WELL-BEING ANALYSIS

There is always the danger of extensive optimistic appraisals or indulgent pessimistic appraisals, resulting in insufficient contingency measures or unwarranted redundancy in the consequent implications. Due care must be exercised while taking on heuristic measures, if any, in arriving at the benchmark indices.

A glaring drawback in the conventional well-being analysis was recently identified in [21], where smaller load variations were found to yield drastically altered well-being indices, especially so when the size of the largest generating unit was relatively larger than other units of the system. Modification factors were introduced to revise the way healthy and marginal state probabilities are now calculated depending on the amount of actual reserve associated with a particular contingency irrespective of whether or not the remaining reserve is in accordance with the stipulated deterministic criteria. Building on the conception elaborated in [21], this paper compares the conventional well-being analysis based generation reserve allocation with the revised well-being analysis, duly putting forward some improvisations that can be utilized for a well balanced appraisal.

5. ILLUSTRATIVE CASE STUDIES

Roy Billinton Test System (RBTS) is a six bus test system with two generator buses and four load buses. The system peak load is 185 MW and total installed generating capacity is 240 MW, comprising 110 MW at bus 1 (4 units) and 130 MW at bus 2 (7 units). There are nine transmission lines connecting the six buses and five bulk load points. A single line diagram of this benchmark test system is shown in Figure 1, on which illustrative studies are carried out to demonstrate the intended goal of this paper. Table 1 shows the generating unit data of RBTS, which also details the priority loading order to be followed while performing unit commitment.

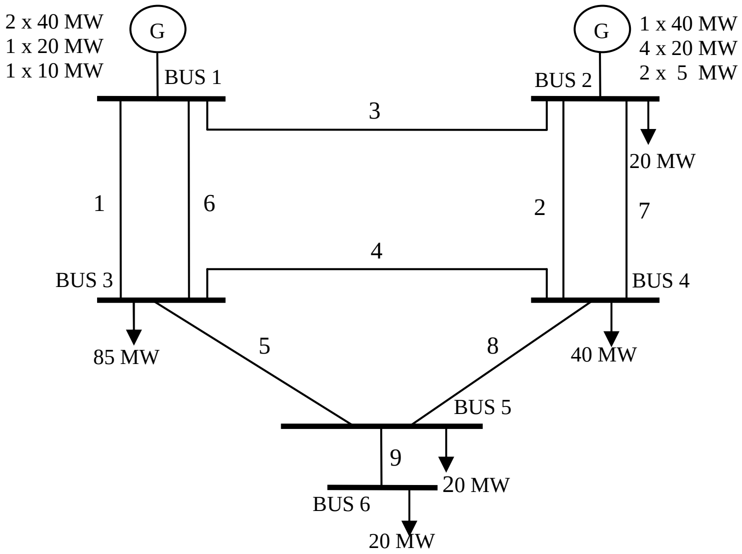

Figure 1. Single line diagram of RBTS

Table 1. Generating unit data of RBTS

Priority Loading Order	Unit Size (MW)	Failure Rate (failure per year)	Repair Time (h)	Bus No.
1	40	3	60	2
2–3	20	2.4	55	2
4–5	40	6	45	1
6	20	5	45	1
7	10	4	45	1
8–9	20	2.4	55	2
10–11	5	2	45	2

5.1 Calculations for Conventional Well-being Analysis

In order to provide a broader window of selection criteria, multiple risk unit commitment [9, 14] is made use of. The standard procedure of reserve allocation could be summarized as follows [18, 19]: Desired values of healthy state and risk state well-being indices are fixed in advance. Generating units are then committed based on the priority order until the load demand is met. Generating unit analytical contingency simulations are then performed for the associated state space sets. A suitable deterministic criterion is employed to obtain the probabilities of healthy, marginal and at-risk states. These values are compared against the initial desired values according to the multiple risk unit commitment criteria. Until the calculated well-being indices are lesser than the desired thresholds, generating units are added one at a time in sequence. Required reserve is the difference in the combined capacity of committed units and the load demand.

Consider the illustrative sample case when load level is 111 MW (60% of the peak load) in the RBTS. Let multiple risk unit commitment criteria be adopted, where the system is required to satisfy an acceptable healthy state probability of 0.9 in addition to satisfying a specified risk state probability of 0.01. The deterministic criterion in this case is assumed to be the loss of a single generating unit. Depending upon the operating philosophy of a utility, this criterion may vary. Generating units are taken from Table 1 until the total committed capacity is exactly equal to or greater than 111 MW, i.e. four units. The total number of contingencies is 16 when four units are committed. The system has 9 MW spinning reserve and the outage of any single unit will result in load curtailment and hence, no contingency belongs to the healthy state.

Table 2. Contingency analysis of generation units of RBTS

S. No.	Units on Outage	Capacity Available (MW)	Reserve (C.A – Load) (MW)	State
1	-	160	49	H
2	1	120	9	M
3	2	140	29	M
4	3	120	29	M
5	4	120	9	M
6	5	120	9	M
7	1-2	100	-11	R
8	1-3	100	-11	R
9	1-4	80	-31	R
10	1-5	80	-31	R
11	2-3	120	9	R
12	2-4	100	-11	R
13	2-5	100	-11	R
14	3-4	100	-11	R
15	3-5	100	-11	R
16	4-5	80	-31	R
17	1-2-3	60	-31	R
18	1-2-4	60	-51	R
19	1-2-5	60	-51	R
20	2-3-4	80	-31	R
21	2-3-5	80	-31	R
22	2-4-5	60	-51	R
23	3-4-1	60	-51	R
24	3-4-5	60	-51	R
25	3-5-1	60	-51	R
26	4-5-1	40	-71	R
27	1-2-3-4	40	-71	R
28	1-2-3-5	40	-71	R
29	2-3-4-5	40	-71	R
30	1-2-4-5	20	-91	R
31	1-3-4-5	20	-91	R
32	1-2-3-4-5	0	-111	R

The base case of all 4 units being up belongs to the marginal state because even though the load demand is supplied, no single unit outage can be tolerated. All the other contingencies belong to the risk state. The calculated risk state probability is less than 0.01 and no more units are required to be committed. However, in order to satisfy a healthy state probability of 0.9, a fifth unit is committed to the system to provide more spinning reserve. With five committed units, the total number of contingencies is 32 from which the first one (all committed units in service) belongs to the healthy state, 6 belong to the marginal state and 25 belong to the risk state, according to the definitions of well-being states.

Sample calculations are as follows: Unit 1 has a failure rate of 3f/yr, which when converted into failures/hour is 3/8760 = 0.000342465. Lead time is 4 hours. Hence, the value of Outage Replacement Rate (ORR) = 4* 0.000342465 = 0.001369863. Therefore, availability of the unit is (1 - 0.001369863) = 0.998630137. These values for the remaining units, calculated likewise, are: Units 2 and 3: A = 0.998904109; $\bar{A}$ = 0.00109589; Units 4 and 5: A = 0.997260724; $\bar{A}$ = 0.002739726. With this input, the capacity outage probability table is next constructed. The cumulative probability corresponding to the existing capacity of 140 MW is the probability of risk state, also known as loss of load probability (LOLP). This probability can also be obtained from the generating unit contingency enumeration table by adding up all the probabilities that pertain to the judged risk states.

Since all the units do not have identical capacities and failure rates, Unit Addition Algorithm [22] is made use of to obtain the capacity outage probability table. Contingency analysis yields 2^5 states as shown in Table 2. Only state 1 belongs to the healthy state, since the load demand is satisfied and even a loss of any one of the units will not lead to load curtailment. Though states 2, 3, 4, 5 and 6 meet the load demand, any single element failure in the respective states will lead to load curtailment. Probability of occurrence of state 1 (healthy state) is the product of availabilities of the five units, which is 0.9909901. The risk state probability is obtained from the capacity outage probability table as 0.0000292. Hence, the marginal state probability is (1 - 0.9909901 - 0.0000292) = 0.0089807 (since the probabilities of healthy, marginal and risky states combined together should be 1).

5.2 Revised Well-Being Analysis and Improvisations

Two modification factors have been introduced in [21] to address the limitation of severe change in the value of healthy state probability even when load variations are merely in the incremental range. This is especially true when capacity of the largest unit (CLU) is relatively larger than other units of the system. The first modification factor takes into account the number of additional single unit outages in each contingency where there is no load curtailment. The second factor shows how predominant the effect of loss of the largest unit in the associated contingency is. Here, the sample case when load level is 111 MW (60% of the peak load) in the RBTS is again chosen to illustrate the steps involved in this modified procedure of computing well-being indices for reserve allotment. Five generating units are committed based on the priority loading order given in Table 1.

Consider the sample state when unit 2 is subjected to analytical contingency simulation. Out of the 5 committed units, loss of unit 2 leaves the available capacity (AC) in the system at 140 MW. Number of in-service units (ISU) = 4; Number of out-of-service units (OSU) = 1. Arrange the units of this state space into two sets: safe set (SS) and unsafe set (US). The first set is such that the constituent elements are those units in service whose further removal one at a time would not lead to load curtailment. The second set is such that the constituent elements are those units in service whose further removal one at a time would lead to load curtailment. Here, SS=1 (unit 3); US=3 (units 1, 4 and 5).

The modification factors (MFs) as defined in [21] are as follows:

$$MF_1 = \frac{\text{No. of elements in SS}}{\text{No. of ISU in the State Space}}$$

$$= \frac{1}{4}, \tag{1}$$

$$MF_2 = 1 - \frac{[\text{Load} - (\text{AC} - \text{CLU})]}{\text{CLU}} \tag{2}$$

$$= 1 - \frac{[111 - (140 - 40)]}{40} = 0.725,$$

Assuming a binary state model of representation for each generating unit, the well-being indices, viz., probability of healthy state (P(H)), probability of marginal state (P(M)) and probability of at-risk state (P(R)) can now be calculated based on the formulae given below:

$$P(H) = \sum_{j=1}^{2^n} P(C_j) * MF_1 * MF_2, \tag{3}$$

$$P(R) = \sum_{j=1}^{2^n} [P(C_j) \mid MF_1 = 0, MF_2 = 0], \tag{4}$$

$$P(M) = 1 - P(H) - P(R), \tag{5}$$

$$P(C_j) = \prod_{i=1}^{ISU_j} (1 - ORR_i) \prod_{k=1}^{OSU_j} (ORR_k), \tag{6}$$

where ORR = (λT); T is the lead time of the generating unit, and λ is its failure rate.

However, the heuristic approach involved in arriving at a formula for the modification factors can be further refined by assimilating deterministic criteria that is more realistic. Taking cue from the standard deterministic reserve criterion employed prior to the emergence of probabilistic techniques, it is proposed that in addition to the availability of the largest unit being the pre-fixed deterministic criterion for the well-being analysis, there also be a provision for taking into account the extent of remaining capacity in light of a given contingency with respect to a pre-fixed percentage of peak load chosen as reserve. It is suggested that the numerator in the fractional expression of Equation (2) be multiplied by an enhancement factor α, whose value is dependent upon how relatively significant the numerator is to the pre-set percentage of peak load as deterministic reserve on the system:

$$MF_2 = 1 - \frac{\alpha[\text{Load} - (\text{AC} - \text{CLU})]}{\text{CLU}}. \tag{7}$$

From Table 2, states 2, 3, 4, 5 and 6 are known to be residing in the marginal states. Of these, each of the states 3 and 4 have non-zero modification factors with MF_1 = 0.25 and MF_2 = 0.725. The contribution of state 3 to healthy state probability can be found from the term associated with this state in Equation (3), which is 0.000197. Similar is the contribution of state 4 to healthy state probability. In the conventional studies, these contributions have been slighted, where the involved straight forward assumptions are responsible for extreme change in the magnitude of health probability for small load variations when a wide variety of generation network and load configurations are encountered, some times even resulting in zero healthy state probability for certain base cases as well.

In effect, the over all healthy state probability has gone up as a result of toning down the pessimistic appraisal through the incorporation of heuristic modification factors. The net healthy state probability is 0.991384; marginal state probability is 0.008586; and the risk state probability remains the same as before. If 10% of the peak load on the system (18.5 MW) is set as the additional deterministic criterion that also needs to be satisfied in the event of a contingency, states 3 and 4 which meet this deterministic reserve criterion must be suitably 'rewarded' in their relative contributions to the healthy state probability. The value of enhancement factor cannot exceed a threshold which will render the fractional expression in Equation (7) as unity. It should always be lesser than 1 whenever the additional deterministic reserve criterion is successfully met. However, it will act as a penalty whenever this supplementary constraint is not satisfied. With an α reward value of 0.567 (15.67% of peak load reserve is available), MF_2 = 0.844, boosting the healthy state probability from the earlier value to 0.991448.

Though the reserve requirements are the same for conventional studies and revised studies of well-being analysis for the sample case of 60% peak load as described above (5 units should be committed to satisfy the multiple risk criteria. Reserve = (committed units – load served) = 160 – 111 = 49 MW), there is marked difference in the reserve allotment when the espousal of revised well-being analysis changes the zero health probability base cases to non-zero health probability cases.

Table 3 summarizes the comparative well-being indices for the sample case of 60% peak load on RBTS. Though the improvements in the numerical values are seen as being merely incremental, the difference would be marked in the case of a practical power system.

Table 3. Comparison of Well-being indices for various methods

Type of Well-being Analysis	P(H)	P(M)	P(R)
Conventional Well-being Analysis	0.9909901	0.0089807	0.0000292
Well-being Analysis with Modification factors	0.9913840	0.0085860	0.0000292
Well-being Analysis with improvised Modification factors	0.991448	0.0085228	0.0000292

6. CONCLUSIONS

Revised well-being analysis re-distributes a segment of the marginal state probability to the healthy state probability by toning down the vigorous approach adopted for pessimistic appraisals using suitable heuristic modification factors. In order to account for the incorporation of additional supplemental deterministic criteria, the concept of enhancement factors has been introduced in this paper. The reserve requirements for a centralized power utility can be allotted realistically by implanting deterministic criteria into the probabilistic reliability framework through the adoption of revised well-being analysis and the improvisations that are made in the underlying heuristic approximations. This proposal is potentially seen as having a marked impact on the various applications of well-being analysis, significantly extending even to the restructured scenario.

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