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Composite System Well-Being Analysis Using Sequential Monte Carlo Simulation and Fuzzy Algorithm

Bahman Alinejad
b alinezhad@gmail com

Mahmud Fotuhi-Firouzabad
fotuhi@sharif.edu

Masood Parvania
parvania@ee sharif edu

Center of Excellence in Power System Management and Control
Department of electrical Engineering
Sharif University of Technology

Abstract—**Health, Margin and Risk states which are known as Well-Being indices provide a comprehensive adequacy assessment of bulk power system reliability studies. Conventional reliability information about power system operation only considered health and risk states which were not often adequate criteria both in system planning and utilization. It seems margin state as the intermediate condition between health and risk must be considered. Well-Being method which is a approach to power system generation adequacy evaluation incorporates deterministic criteria in a probabilistic framework and provides system operating information in addition to risk assessment and can be evaluated using analytical techniques. The most important part of this approach is the algorithm for calculating the probability of each state. Besides, all system components, their behavior and their operational conditions should be considered in the calculations. In this context, this paper proposes a method to calculate more precise well-being indices using Monte Carlo simulation and Fuzzy algorithm while AC load flow is utilized for contingency analysis. The proposed method is then demonstrated on the RBTS.**

Index Terms—**Monte-Carlo simulation, Fuzzy Algorithm, AC Load Flow, Well-being Analysis.**

I. INTRODUCTION

The methods utilized by utilities for generation capacity adequacy assessment and reliability evaluations have been changed from pure deterministic to probabilistic approaches over the last years. Power system operators and system planners, however, still are reluctant to implement probabilistic indices due to concerns relating to the ability to interpret a single numerical risk or health index such as loss of load expectation (LOLE) and the lack of system operating information in a single risk index [1]. Therefore, deterministic approaches are, routinely applied even though they do not recognize the actual system risk and failure [2].

Well-Being analysis is a technique which provides a balanced connection between the deterministic and the conventional probabilistic methods [3], [4]. The well-being indices can be easily evaluated using a contingency enumeration approach in the case of a small system with a constant load [4]. This method, however, can be a time consuming and boring algorithm when applied to a system with many generating units and time-varying loads. In this case, an analytical method which uses the capacity outage probability table of the power system generating system and the conditional probabilities of the largest units being available at different times can be used to evaluate the basic well-being indices of larger systems [1]. These techniques should also consider a large number of system elements and their variables which, in addition, become very complex in the evaluation process of a large power system. Reliable and complete results, especially in determining the margin probability, must consider all constrains and operational conditions of generating units, transmission lines and loads.

Power system reliability calculations using analytical techniques suffer from some difficulties. Theoretically, it is possible to include system effects which may not be possible without excessive approximation in a direct analytical approach and can generate a wide range of indices within a single study. Another concern of conventional analytical techniques is that they cannot provide the probability distribution functions associated with the various reliability indices. Thus, in this paper, the Monte Carlo simulation (MCS) method is used to estimate the indices by simulating the actual process and random behavior of the power system elements [5]. Unlike the analytical approaches, the MCS method can easily generate distribution probability functions of reliability indices, without making undue approximations. However, the large amount of required computation time was a major difficulty with MCS in the past. Nowadays, with modern and fast computers, this is no longer a problem for a wide range of studies.

In well-being analysis procedure, one should find if the power system is in health, margin or risk condition. The most and prevalent criterion is checking if one or more power system loads are disconnected from the supply [1]. Some algorithms as one discussed in [1], suggests that any load interruption in N-1 criterion must be considered as margin state regardless to the amount and the priority of this interruption. This is a deterministic criterion which cannot tend to real answers. Because this method isn’t able to consider the amount of curtailed load, while in many situation the load curtailment is very low and it is unreasonable to consider the whole of this state as margin. To achieve more exact results, the algorithm must discriminate between power system loads, and in any load interruption both health and margin indices must be updated according to the amount and the priority of this interruption. This can be easily done by means of fuzzy algorithm. The aim of this paper is to calculate the Well-Being indices by combining the MCS method and fuzzy algorithm to achieve more precise results.

The MATLAB software has been used for mathematical calculation and the Power Station/ETAP software was implemented for load flow and contingency analysis.

The rest of the paper is organized as follows. Section II presents the basic concepts of power system well-being analysis. The procedure of the sequential MCS method is presented in Section III. The proposed method for calculating well-being indices using fuzzy algorithm is presented in Section IV. The proposed method is then implemented on the RBTS in Section V. Finally, conclusions are presented in Section VI.

II. POWER SYSTEM WELL-BEING ANALYSIS

The operation of a power system can be divided into different operating states in terms of the degree to which the adequacy and security constraints are satisfied. Reliability constraints refer to the generation and transmission lines capacity, power system load demand and bus voltage range and generation units MVAR limits. Based on these constraints, the well-being analysis divides the operating states to health, margin and risk states. To include the concept of well-being analysis in the form of health, margin and risk states in the composite power system planning context [4], the framework was slightly modified, as shown in Fig. 1. The power system can transfer directly from one state to another as shown in figure.

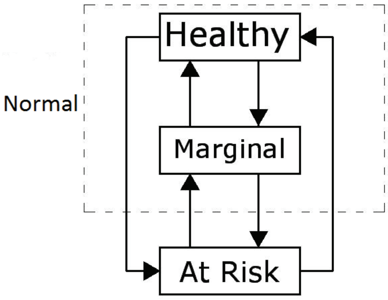

Fig. 1. System well-being model

In the healthy state, the system has enough capacity of generation and transmission to satisfy a deterministic criterion contingency, such as the loss of the largest generating unit while all the equipment and the operating constraints are within the admissible limits. The system operates in the marginal state when it has no difficulty but does not have sufficient adequacy to meet the specified deterministic contingency criterion, that is, withstand the loss of any single generating unit or transmission line. If the individual load is either equal to or greater than the available capacity of total generating units, the system will enter the risk state. The probability of risk, also known as the loss of load probability, is the probability to find the system in the risk state. The system reliability is the sum of health and margin probabilities.

A bulk power system can directly enter the risk state or margin state from the healthy state due to the loss of certain operating capacity or due to a sizable increase in the system load without sufficient increment in generation capacity. In the well-being analysis, the system performance is evaluated using deterministic considerations and quantified by probabilistic indices which gives more flexibility to system operators in selecting a meaningful reliability index for unit commitment and other useful evaluation.

Therefore, reliability indices calculated with the inclusion of appropriate deterministic criteria, provide power system planners, designers, engineers, and operators with additional and more applicable system information. The degree of system well-being can be quantified in terms of the probabilities and frequencies of the healthy and marginal states in addition to the conventional pure risk indices. This paper is focused on system well-being analysis using sequential Monte-Carlo simulation and Fuzzy algorithm. The advantage of using sequential simulation is the ability to create probability distribution for power system elements which leads to more accurate and acceptable results. It is important to value the inherent variability in the reliability indices and the possibility of specific values being exceeded. This knowledge can be estimated from the probability distributions associated with the expected values. At the present time, sequential simulation is the only applicable option available to investigate the distributional aspects associated with system index mean values [5].

III. SEQUENTIAL MONTE CARLO SIMULATION PROCEDURE

The Monte Carlo simulation procedure for calculating the system well-being states (heath, margin and risk) is presented in this section. More detail description of the technique can be found in references [6], [7], and [8]. The procedure is as follows:

1. Specify the initial state of each component (all generating units and all transmission lines). Normally, it is assumed that all components are in the UP (healthy) state initially.
2. Estimate the state (up, down) of each element. In this stage a random number (v) is generated:
   If v > element FOR, then the element is assumed to be in up state,
   If v < element FOR, then the element is assumed to be in down state.
3. Repeat step 2 for all generating units and transmission lines in the system. Note that for each element, generation of the random numbers should be performed individually.
4. Calculate total available system generation capacity:
   $G_{total} = \sum_{i=1}^{n} G_i$ where G is single generation capacity.
5. The load profile of the system is divided into a number of up and down steps to produce the multi step model shown in Fig. 2 which is an example for a 24 hours period.

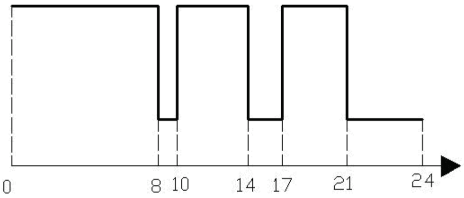

Fig. 2. Load model in a 24 hours period

The accuracy of the MCS method can be improved by increasing the number of time steps. The total time period d_i, for which a particular load level $_i$ can exist in the period of interest T determines the likelihood (or probability) of $_i$ and an estimate for this probability is given by $d_i / T (= {}_i)$. The cumulative probabilities are easier to use than the individual ones. These cumulative probabilities can be calculated as follows:

$$P_1 = p_1$$

$$P_2 = p_1 + p_2$$

$$P_i = \sum_{j=1}^{i} p_j$$

$$P_n = 1$$

The simulation process is as follows:

If the generated random number (v), located between P_{i1} *and* P_i (P_{i1} < v < P_i), then load level $_i$ is probable to occur. Thus, a good algorithm for load level simulation is obtained:

6. If $G_{total} < L$, then some load must be interrupted and risk index is updated, otherwise, health or margin indices are updated. The method for calculating well-being indices is presented in section IV-B.
7. Steps 2- to 6- are repeated sequentially until the coefficient of variation is less than the specified tolerance error.

The fast decoupled ac power flow technique [9] and linear programming methods [10], [11] are implemented in this paper for contingency analysis. Corrective actions such as generation rescheduling, line overload alleviation, operating constraint corrections and load curtailment are considered. Approximate techniques are applied when split network and system ill-conditioning problems occur.

IV. SIMULATION PROCEDURE FOR WELL-BEING ANALYSIS BY MEANS OF FUZZY ALGORITHM

The method for calculating well-being indices using fuzzy logic is presented in this section. First, a brief review of the fuzzy logic is presented and then the well-being indices calculation procedure is fully discussed.

A) Brief Summary of Fuzzy Logic [12]

In fuzzy logic, the truth of any statement becomes a matter of degree. The tool that fuzzy reasoning gives, is the ability to reply to a yes-no question with a not-quite-yes-or-no answer. This is the kind of thing that human do all the time but it is a benefit trick for computers, too. Fuzzy logic is just a matter of generalizing the familiar yes-no (Boolean) logic. If we give 'true' the numerical value of 1 and 'false' the numerical value of 0, fuzzy logic also permits in between values like 0.2 and 0.7453.

What define the relation between inputs and outputs in fuzzy, are membership functions. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The only condition a membership function must really satisfy is that, it must vary between 0 and 1. The function itself can be arbitrary curves whose shape can be defined as a function that suits us from the point of view of simplicity, convenience, speed and efficiency.

In this paper, the fuzzy logic is used to determine the percentage of any well-being indices in each Monte Carlo simulation by monitoring the condition of the power system loads.

B) System Well-Being Indices Calculations

The procedure described in the previous section is generally the overall procedure for bulk power system reliability evaluation using sequential MCS. The well-being analysis can be implemented and extended as a sub procedure in step 6. The following procedures are the extension of step 6 to include system well-being indices.

6a. In each simulation, the results can be classified into the following three categories:

Category one: There is no system contingency; go to step 6b.

Category two: There exists one or more system contingency, but load curtailment has not occurred; go to step 6c.

Category three: There exists system contingency(s) and load curtailment has occurred. If the system is in this category, it implies that the system is in the risk state. The amount of the load that is curtailed should be transferred to fuzzy algorithm and the percentage of health and risk indices are determined and updated, and then directly proceed to the next simulated section. For example, suppose the amount of curtailed load is *A* MW and the total load at that bus is *B* MW, then A/B transfer to fuzzy algorithm and a number between (0~1) becomes available from the output of fuzzy, i.e., *C*. Therefore this number added to risk index and 1-*C* is added to health index.

6b. If there is no system contingency, the critical generating unit, such as the largest unit, is assumed to be out of service. The system is then assessed and a load flow is performed to find out that whether there is any load curtailment or not. If load curtailment has occurred, corrective actions should be performed to recover the interrupted loads. If these rearrangements can successfully remove the load curtailment, health indices are updated. However, if corrective actions can not completely remove the curtailed loads, the remained load curtailment is calculated and the heath and margin indices are updated using the fuzzy algorithm shown in Fig. 3. In this paper a linear membership function is adopted for the probability calculation of health and margin states in the fuzzy algorithm.

6c. If there is a system contingency(s) but no load curtailment, contingency selection is investigated and a contingency list is built (contingency selection methods are fully discussed in [1]). Components in the contingency list are tested one at the time. If outage of a selected component lead to system violations, corrective actions are required to alleviate the condition, and load is curtailed if necessary. If load is curtailed, update the margin and health indices using the described fuzzy algorithm, and then skip the rest of components in the contingency list and proceed to the next simulation hour. If the entire component in the contingency list do not cause any load curtailment, update the healthy state and proceed to the next simulation hour.

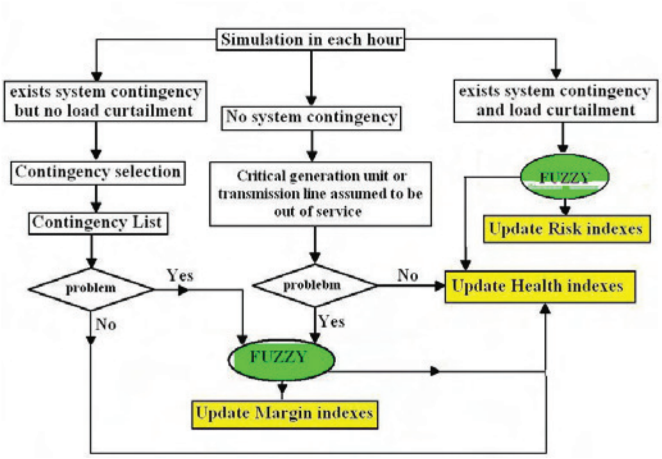

Fig. 3. Well-Being indices calculation by means of Fuzzy algorithm

V. SIMULATION RESULTS

The proposed method for power system well-being analysis using MCS and fuzzy algorithm is implemented on the Roy Billinton Test System (RBTS) [13]. The single line diagram of the RBTS is shown in Fig. 4. The RBTS is an educational test system was developed by the Power System Research Group at the University of Saskatchewan. The RBTS is a six-bus system composed of two generation buses, five load buses (delivery points), nine transmission lines and eleven generating units. The system non-simultaneous peak load is 185 MW, and the total generation is 240 MW. The peak demand occurring at each individual delivery point may not be coincident when using chronological load models. The system peak demand therefore, is lower than that of load model in which all the delivery points reach their peak load at the same time. In this case, the system peak is 179 MW rather than 185 MW. The complete information about RBTS, such as generating units' data, load factor, transmission lines and other specifications has been given in [13]. The up section of the RBTS, including busses 1 and 2, has been named the "Generation Center" and the bottom section is called "Load Center".

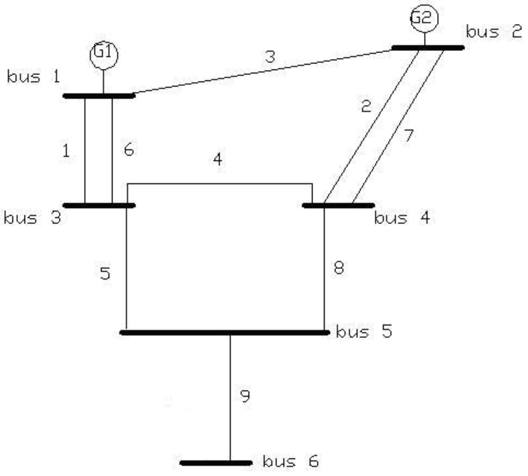

Fig. 4. Single line diagram of the RBTS

The proposed model was coded in MATLAB environment and the Power Station/ETAP software was implemented for load flow and power system analysis. The RBTS Well-Being indices are calculated using the developed MATLAB software. Table 1 presents the calculated Well-Being indices for the delivery points and for the whole RBTS. It has to be noted that the delivery point indices are directly affected by load curtailment philosophy utilized in the analysis. However, this effect is effectively minor for the whole system indices. The contingency selection process also directly affects the delivery point well-being indices. The main focus in system well-being analysis is on the security of the system as a whole rather than on individual delivery points as violations of a delivery point are considered to be a system security operation problem. The delivery point well-being indices, however, provide supplementary information to the overall system well-being indices.

The indices obtained using combining fuzzy algorithm with MCS, however, are different to some extent from those obtained in [1]. The margin index in this study has been larger because of the consideration of the overloads and voltage drops in the simulation. As mentioned in section IV, selecting various membership functions and considering different power system and load constrains and specification in the algorithm will result another health and margin indices.

TABLE I
DELIVERY POINT AND WHOLE SYSTEM WELL-BEING INDICES

Index	Delivery Point					Whole System
	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	
Prob(H)	0.989815	0.901112	0.899396	0.900025	0.899353	0.904568
Prob(M)	0.010178	0.098773	0.100515	0.099953	0.100545	0.094547
Prob(R)	0.000007	0.000115	0.000089	0.000022	0.000102	0.000885

VI. CONCLUSION

The system well-being concept provides a probabilistic framework that incorporates a practical simplification of the traditional operating states associated with the well-known deterministic N-1 security criterion. Well-Being analysis, therefore, provides a combined framework that incorporates both deterministic and probabilistic perspectives. Power system well-being analysis using the sequential MCS technique and fuzzy algorithm is presented in this paper. One advantage when utilizing the proposed fuzzy algorithm is that the operator can incorporate the main factors which is more important for suppliers by means of membership functions in fuzzy. However, in order to have better and more accurate results it is necessary to consider all power system constraints such as transmission lines temperature, protection system sensitivity, load dependency to frequency and voltage, 1-phase auto reclose, under frequency relays and any other important element which could be affect the results in the load flow calculations.

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BIOGRAPHIES

Bahman Alinejad Received the BSc. degree in electrical engineering (Transmission and Distribution Systems) from Power and Water University of Technology (PWUT), Tehran, Iran, in 2005. MSc degree in department of Electrical Engineering from Sharif University of Technology, Tehran, Iran, in 2007. He is a technical Engineer in Parsian HV Substation Development Company for two years. His areas of interests include wind generation, power system protection, power system dynamic and simulation.

Mahmud Fotuhi-Firuzabad (SM' 99) received B.Sc. and M.Sc. degrees in Electrical Engineering from Sharif University of Technology and Tehran University in 1986 and 1989 respectively and M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan, Canada, in 1993 and 1997 respectively. Presently he is a professor and Head of the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. Dr. Fotuhi-Firuzabad is a member of center of excellence in power system control and management. He serves as the Editor of the IEEE TRANSACTIONS ON SMART GRID.

Masood Parvania (S' 09) received the B.S. degree in Electrical Engineering from Iran University of Science and Technology (IUST) in 2007, and M.S. degree in Electrical Engineering from Sharif University of Technology in 2009, where he is currently pursuing his Ph.D. degree. His research interests include power system reliability and security assessment, as well as operation and optimization of smart electricity grids.