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COMPOSITE SYSTEM WELL-BEING ANALYSIS USING SEQUENTIAL MONTE CARLO SIMULATION AND FUZZY ALGORITHM

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Abstract: *Well-Being reliability indices (Health, Margin and Risk), provide a comprehensive measure to assess the adequacy of composite power systems. Conventional reliability information about power system operation only considered health and risk states, which were not often adequate criteria in both power system planning and operation. Well-being approach for 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 the states. Besides, all the power system components, their behavior and their operational conditions such as transmission lines overloads and voltage drops 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 procedure and Fuzzy Logic algorithm while AC load flow is utilized for contingency analysis. The proposed method is examined on the RBTS and the results are presented.*

Keywords: Well-Being Analysis, Monte Carlo Simulation, Fuzzy Algorithm**.**

1. Introduction

The methods utilized by power utility companies 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 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, normally applied to probabilistic criterion even though they do not recognize the real condition of the system risk and failure [2].

Well-being analysis is a technique which provides more balanced connections between the deterministic (N-1 criteria) and the conventional probabilistic methods that could be calculated by means of some pre-definite term of reliability indices [3], [4]. The well-being indices could be easily calculated by using contingency enumeration methods when the system is small and there is a little variation in power system loads [4]. This method, however, can be a time consuming when applied to a system with many generating units and time-varying loads. Actually, these algorithms could not be applied to a bulk electric system. In this case, another analytical method that uses the contingency table of the power system elements, e.g. important transmission lines and generation units, should be utilized. These techniques should also consider a large number of system elements and their constraints, which, in addition, become very complex in the evaluation process in a power system with enormous elements. Reliable and complete results, especially in determining the margin state probability, should consider all constraints and operational conditions of generating units, transmission lines and loads and any other special elements that can be vital to power system operation. However, calculating the reliability of power system using conventional analytical techniques also suffer from some difficulties. Theoretically, it is possible to include system effects in the calculations, but for preventing from excessive calculations, some approximation is inevitable. Additionally, the analytical techniques cannot provide the probability distribution functions associated with the various reliability indices. In this regard, this paper uses Monte Carlo simulation (MCS) method to estimate the indices by simulating the actual states and random behavior of the power system elements (generators and transmission in this case) [5]. Unlike the analytical approaches, the MCS method can easily generate distribution probability functions of reliability indices, without approximations. It can be time consuming but, in a

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large system, the MCS is one of the practical solutions to calculate the system reliability indices. In addition, nowadays, with implementation of modern and fast computer systems, this is no longer a concern 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-2 criterion must be considered as margin state regardless to the amount and the priority of this interruption. This is similar to a deterministic criterion which appears cannot tend to meaningful states probabilities. The reason for this is that this method is not able to consider the amount of curtailed load, while in many situation the amount of load curtailment is such low that it is unreasonable to consider the whole of this state as margin state. Another parameter that should be considered is the priority of loads, which is related to economic attributes. To achieve more exact and real results, the algorithm must discriminate different loads, and in any load interruption in N-2 criteria, both health and margin indices must be updated according to the amount and the priority of this interruption. This can be easily done by using the fuzzy logic algorithm. The aim of this paper is to calculate the Well-being indices by combining the MCS method and fuzzy algorithm to achieve the state probabilities that are more meaningful. The MATLAB software is used for mathematical calculation and the Power Station/ETAP software is utilized for AC load flow and contingency analysis.

The rest of the paper is organized as follows. Section 2 presents the basic concepts of power system well-being analysis. The procedure of the sequential MCS method is presented in Section 3. The proposed method for calculating well-being indices using fuzzy algorithm is presented in Section 4. The proposed method is implemented on the RBTS in Section 5. Finally, conclusions are drawn in Section 6.

2. Power System Well-Being Analysis

Power system operational conditions can be separated in terms of the degree to which the adequacy and security constraints of components and loads are satisfied. Generation capacity (both in active and reactive power), transmission lines overloads, voltage stability, power system load demand and bus voltage deviations are some main criterion of these constraints which power system planners and operators are always concerned about them. Based on these constraints, the well-being analysis divides the system operating states into Health, Margin and Risk [4].

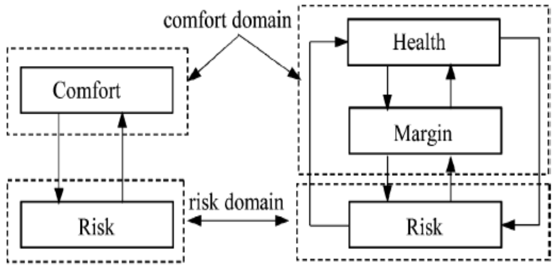

Figure 1. System well-being model

In the Health state, the system has enough capacity of generation and transmission to satisfy a deterministic contingency criterion, 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 Margin 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. The system resides in a comfort zone when it is in both the Health and Margin states. 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. Additionally, it is possible in risk state that some equipment or system constraints are violated and some load is curtailed [1]. 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, therefore, can be calculated by summing the health and margin state probabilities. The degree of system well-being can be quantified in terms of the probabilities and frequencies of the health and margin states in addition to the conventional pure risk indices [1], [5].

3. Monte Carlo Simulation for Power System Reliability Analysis

In MCS method, the model is run many times with random sampling of uncertain variables and events. The basic procedure for calculating the system risk index using the MCS method is presented in the following. References [6], [7], and [8] describe more details about the MCS method.

Step 1: In the MCS method, the states of components are modeled by binary values. The healthy (up) state of a component is denoted by 1 and the faulty (down) state is denoted by 0. At the beginning, one should specify the initial state of each component (for all elements under consideration such as transformers, transmission lines and generators). Normally, it is assumed that, initially, all components are in the healthy state.

Step 2: Estimate the next state (up, down) of each component. In this step, a random number v is generated, where v could have a uniform or Gaussian distribution. In this study a uniform distribution which generates random numbers in the range of (0,1) is used. Accordingly, the state of the components can be determined by check following conditions:

a- If (v < component Availability), then the element is assumed to be in up state,

b- If (v > component Unavailability), then the element is assumed to be in down state.

Step 3: Repeat step 2 until all generation units and transmission lines in the system are considered. Note that for each element and in any step, generation of the random numbers v is performed individually. After this step, we have a string of up and down state for each component.

Step 4: Calculate the total available system generation capacity as: $G_{total} = \sum_{i=1}^{n} G_i$ where G_i is single generation capacity.

Step 5: The load profile of the system is divided into a number of up and down steps to produce the multi step model. The accuracy of the MCs method can be improved by increasing the number of time steps for each load. The total time period d_i for which a particular load level L_i can exist in the period of interest T (24 hours in this example) determines the likelihood (or the probability) of load L_i and an estimate for this probability is given by $d_i / T=P_i$. In other words, P_i is the probability of occurrence of the load level L_i in the period of T. The cumulative probabilities are easier way to use than the individual ones. These cumulative probabilities can be calculated by (1):

$$\begin{aligned} P_1 &= p_1 \\ P_2 &= p_1 + p_2 \\ Pi &= \sum_{j=1}^{i} p_j \\ Pn &= 1 \end{aligned} \tag{1}$$

The simulation process for including the load profile in the simulation can be demonstrated as follows:

If the generated random number v, located between p_{i-1} and p_i ($p_{i-1}<v<p_i$), then load level L_i is probable to occur. Thus, a good algorithm for load level estimation is obtained.

Step 6: If, $G_{total}<L$, then some load should be curtailed and risk index is updated; otherwise, health or margin indices are updated. The method for calculating well-being indices is presented in the next section (4.2). The AC power flow technique is used in step 6 when Health, Margin and Risk indices should be calculated. In this paper, the AC load flow is implemented by means of ETAP/PowerStation software while implementing full Newton-Raphson algorithm [10], [11].

Step 7: Steps 2- to 6- are repeated sequentially, until the consecutive error is less than the specified tolerance.

4. Monte Carlo Simulation for Well-Being Analysis using Fuzzy Algorithm

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

4.1. Fuzzy Logic

In fuzzy logic, the truth of any statement becomes a matter of degree [12]. 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 like 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. A classical set might be expressed as:

$$B = \{x \mid x > 6\} \tag{2}$$

A fuzzy set is an extension of a classical set. If X is the universe of discourse and its elements are denoted by x, then a fuzzy set B in X is defined as a set of ordered pairs.

$$B = \{x, \mu B(x) \mid x \in X\} \tag{3}$$

$\mu B(x)$ is called the membership function (or MF) of x in B. The membership function maps each element of X to a membership value between 0 and 1.

There are many membership functions and it is possible to combine fuzzy logic with another intelligent algorithm (such as neural network) to obtain the dynamic membership functions in complicated case. The simplest membership functions are formed using straight lines. Of these, the simplest is the triangular membership function. This function is nothing more than a collection of three points forming a triangle. Figure 2 shows an example of linear membership function which any input less than 3 and greater than 8, maps to a zero value in the output [12].

In many cases, it is possible that more than one constraint should be considered. For example, consider we have two MF for X in above example as $\mu_1 B(x)$ and $\mu_2 B(x)$ as:

$$B = \{x, \mu_1 B(x) \text{ and } \mu_2 B(x) \mid x \in X\} \tag{4}$$

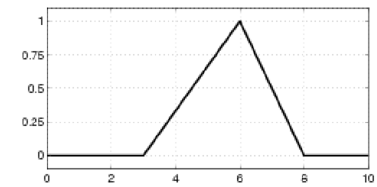

Figure 2. A typical linear MF

The output of each MF is a fuzzy set itself. The net output is combination of these sets, i.e., the output fuzzy sets for each rule are then aggregated into a single output fuzzy set. Finally, the resulting set is defuzzified, or resolved to a single number. The aggregation method is differing for various cases. One of the useful procedures is implementing weighting coefficients. Consider x_1 and x_2 are the fuzzy output of $\mu_1 B(x)$ and $\mu_2 B(x)$ respectively. x (the fuzzy output) can be calculated as (5):

$$x = min(w_1 * x_1, w_2 * x_2) \quad (5)$$

where w_1 and w_2 are weighting coefficients. The appropriate comparison functions according to the logic that incorporates to MF in MALAB software are as follows:

And (fuzzy intersection or conjunction) ≡ Min
OR (fuzzy union or disjunction) ≡ Max
Not (fuzzy complement) ≡ 1-B

In this paper, the fuzzy logic is used to determine the percentage of well-being indices in each sample of MSC by monitoring the condition of the power system loads and constraints. The procedure of using fuzzy algorithm and its technical specifications are explained in detail in the following.

4.2. Calculation of System Well-Being Indices

In Section 3, the MCS method for power system reliability analysis is described and divided into seven steps. It this section, step 6 of the described MCS procedure is revised as follows to calculate the system well-being indices using the proposed fuzzy algorithm. The procedure is outlined in Figure 3.

Step 6: In each MCS sample, the system may be exposed to three operating conditions as depicted in Figure 3.

Condition one: In this condition, there exists one or more system component failures (generation units or one of the transmission lines) and some loads are curtailed. In this condition, system is in the Risk state and risk indexes should be accordingly updated. The lack of generation and transmission lines overloads both may direct the system to load interruption.

Condition two: There exists one or more system component failures, but load curtailment has not occurred. It is obvious that the system is not in the risk mode of operation neither be inferred as health state. If for any extra failure (means fully N-2 criterion), all constraints are satisfied and the loads are supplied, the state is accounted as health state, otherwise it is in the margin state.

Condition three: There is no system contingency and no load curtailment. In this case, 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 cannot 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 Figure 3.

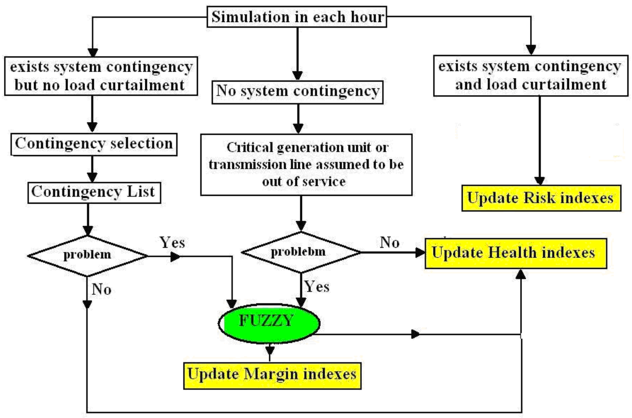

Figure 3. Well-being indices calculation using Fuzzy algorithm

5. Simulation Results

The proposed method for composite 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 Figure 4. The RBTS is an educational test system that 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 are given in [13]. The upper part of the RBTS, including busses 1 and 2, are named the "Generation Center" and the bottom part is called "Load Center". In this paper, one small modification has been made on the RBTS such that one transmission line is added between buses 5 and 6 named line 10.

The proposed model was coded in MATLAB environment and the Power Station/ETAP software was implemented for AC load flow and power system analysis. The RBTS well-being indices are calculated using the developed MATLAB software.

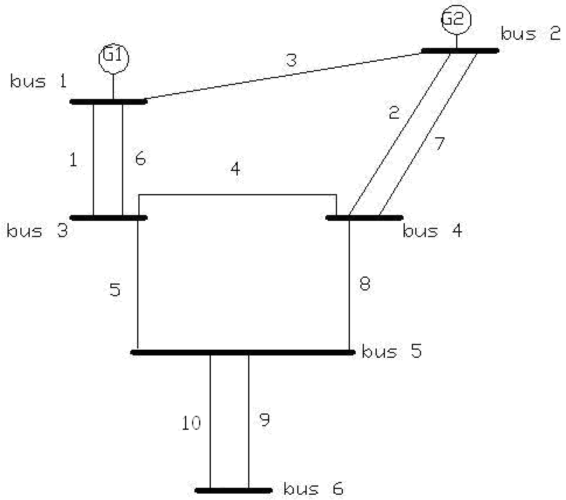

Figure 4. Single line diagram of the RBTS

Table 1 presents the calculated well-being indices for the delivery points and for the whole RBTS. It can be seen in this table that the risk index of bus 2 is much smaller than those of other buses. This is due to the fact that bus 2 is located at the generation center of the system. However, the other buses are connected to the generating units through transmission lines which their failures increases the risk index of these buses. Besides, the delivery point indices are directly affected by load shedding philosophy utilized in the simulation analysis. In this study, for simplification purposes, same priority values inserted for all loads in the RBTS. 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 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 transmission lines overloads and bus voltage drops in the simulation. As mentioned in section 4, selecting various membership functions and considering different load constrains and specification in the algorithm will result another health and margin indices.

Table 1. 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)	0.98976	0.90087	0.89919	0.900011	0.899452	0.90502
Prob(M)	0.01018	0.09877	0.10051	0.099953	0.100545	0.09455
Prob(R)	0.00006	0.00036	0.00029	0.000008	0.000003	0.00043

6. Conclusions

Power system well-being analysis combined with MCS and Fuzzy algorithm is described in this paper. The aim of implementing the fuzzy is to consider the amount of the curtailed load in health and margin calculation. The AC load flow is used to estimate the operational violations in power system constraints and the necessary loads that should be curtailed in each contingency. The results presented reveal that considering the practical operational constraints of transmission network could affect the health and margin indices of the system. One of the main important points that directly affect the results is the contingency selection algorithm. This paper implements a simplified contingency selection according to N-2 criteria. Other contingency selection methods can be also utilized in the proposed method.

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