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Reliability Analysis usingRenewable Energy Sources

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Abstract: This paper reviews some of the analytical methods developed in our laboratory for reliability evaluation of large-scale power systems including renewable energy sources like photovoltaic units and wind farms. The methods presented here successfully reflect the correlations existing between the hourly load and the fluctuating energy outputs of unconventional generating units.Three different approaches, each an improvement over its predecessor, are presented for computing reliability indices like Loss of Load Expectation (LOLE) and Expected Unserved Energy (EUE). In the first approach, all the generation system models are combined hourly by means of an efficient algorithm for calculating the relevant reliability indices. The second approach uses a clustering algorithm for identifying a set of system states, such that the reliability indices are calculated for each state and then aggregated to yield overall values. The third approach introduces the concept of mean capacity outage tables for efficiently calculating EUE,
Keywords: Renewable energy sources, loss of load expectation, expected unserved energy, clustering, mean capacity outage tables.

1.INTRODUCTION : The escalation in prices of energy derived from fossil fuels like coal, oil and gas over the last few decades has led to an increased interest in developing newer and cleaner ways of energy generation. A substantial increase in global population and rising concerns about environmental pollution has given a further impetus to the ongoing research efforts. Though the concept of electrical power generation from alternative energy sources like the sun and wind is well established today, continuous research is being done for improving the current technologies. The total installed capacity of wind generation in the world has increased by about 8.5 times over the last decade alone [1]. A study of the energy mix in the European Union nations also reveals that the percent contribution to the power pool as derived from alternative energy sources like wind and biomass has steadily increased over the last decade [1]. The 2009 long term reliability assessment report published by the North American Electric Reliability Corporation (NERC) projects an additional 260000 MW of new renewable “nameplate” capacity to be coming into effect in US over the next ten years (2009-2018). It further estimates that

Though renewable energy generation is cheaper and cleaner as compared to conventional methods, the power outputs of these unconventional units are intermittent by nature due to variations in their basic energy source. As a result, these units have a different impact on overall system reliability from that of conventional units. For planning purposes, it is thus important to develop models of such time-dependent energy sources and incorporate them into traditional reliability studies. For this to be done successfully, the following factors have to be taken into consideration: scheduled outage, failure and repair characteristics of both conventional and unconventional units, the fluctuating nature of energy output from the unconventional units, and the correlation between this intermittent energy supply and the hourly load demand.

2SINGH AND GONZALEZ APPROACH.:

The Singh and Gonzalez approach was therefore proposed in [4] for accurately modeling the impact of renewable energy sources on the overall system reliability. In this approach, the entire power system is divided into several subsystems containing the conventional and unconventional generating units. A generation system model is then built for each subsystem. Using an efficient algorithm, the models corresponding to the unconventional subsystems are modified hourly in order to reflect the fluctuating nature of energy produced by such units. All the generation system models are then combined hourly in order to calculate the Loss of Load Expectation (LOLE) and Expected Unserved Energy (EUE) indices for the given hour. To further improve the computational efficiency for calculating the different reliability indices, an alternative clustering approach was proposed in [6]. In this approach, the correlation between the hourly load and the intermittent energy outputs of the unconventional subsystems is modeled by defining a set of states or clusters. Each state is identified by a given value of load and the corresponding mean values of the outputs of the different unconventional subsystems. Reliability analysis is performed by combining the conventional subsystem with the unconventional subsystems belonging to each cluster, and the outputs are then aggregated to yield overall indices. The indices calculated using this approach, however, are not as accurate as those obtained in [4] owing to the inherent approximations associated with clustering. A third method was therefore proposed in [7] for accurate determination of the reliability indices (especially EUE) with minimal computational effort. In this new approach, the hourly computation of a system negative margin table for calculating EUE is replaced by the hourly application of a mean capacity outage table, thereby saving considerable CPU time. The remainder of this paper has been structured in the following fashion.

Section 2 gives an overview of the LOLE and EUE reliability indices used in generation adequacy studies. Sections 3 to 5 give a detailed description of the Singh and Gonzalez approach, the clustering approach and the mean capacity outage table approach respectively. While Section 6 presents the various case studies performed using the proposed approaches, Section 7 discusses the important results. Finally, Section 8 summarizes the conclusions.

2.1 LOSS OF LOAD EXPECTATION:

LOLE, or more commonly HLOLE (Hourly Loss of Load Expectation) is the expected number of hours during the period of observation of the system load cycle when insufficient generating capacity is available to serve the load [8]. The system load is described as a chronological sequence of „Nt" discrete load values „Li" for successive time steps k = 1, 2, 3… Nt. Each time step has equal duration ΔT = (T/Nt) hours, where „T" represents the total duration of the period of observation of the system load cycle [7]. For a given time step „k", the probability of the system margin (capacity - load) being less than or equal to „M" MW can be computed as:

$Pk(M) = P\ j(C \leq Cj)$ (1)

In equation (1), „j" is the smallest integer representing a particular discrete capacity state such that the expression (Cj – Lk) ≤ M is satisfied, „Cj" is the generation capacity associated with state „j", „Lk" is the system load level during time step „k", and „P j(C≤Cj)" is the cumulative probability that the generation capacity „C" is less than or equal to „Cj". Note that the various generation capacity states (Cj"s) are arranged in descending order, i.e., Cj+1 is less than Cj. The Loss of Load Expectation for the time step „k" can then be calculated using equation (2) as:

LOLEk = Pk(0)*(ΔT)

. **2.2 Expected Unserved Energy (EUE)**

The EUE index measures the expected amount of energy which will fail to be supplied during the period of observation of the system load cycle due to generating capacity differences and/or shortages of basic energy supplies [8]. A general expression for the computation of the Expected Unserved Energy is [7]:

$EUE = \Delta T * UkNtk$=1 (4)

In equation (4), the term „Uk" represents the expected unserved load during the time step „k", and is calculated using the following equation [7]:

$Uk = (\Delta M)*[\ P(M) - GkM$=0 - 0.5*{P(0) + P(-Gk)}] (5)

For practical cases, a system negative margin table is built for each time step „k", and „P(M)" is then computed at discrete negative margins M = 0, -ΔM, -2ΔM,…, -Gk. Here, „-Gk" represents the smallest possible negative margin during time step „k", and „ΔM" is a fixed positive increment value. An example demonstrating how to construct a system negative margin table for a given time step „k", and then calculate „Uk", is given in [7].:

3.1 Discrete State Method

We shall explain this method [4] using our sample system consisting of a conventional and two unconventional subsystems. Let us now define the following vectors associated with the three generation system models as:

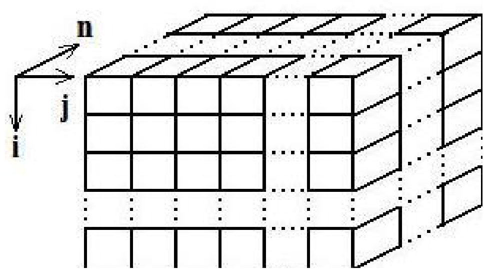
CC, PC = Generation capacity and cumulative probability vectors associated with the model corresponding to the conventional subsystem.

CUl, PUl = Generation capacity and cumulative probability vectors associated with the model corresponding to the lth unconventional subsystem, where l ϵ [1, 2].

Since each of these subsystems is treated as a multistate unit, the combination of their generation system models for the kth hour of study results in distinct states with capacities given by [4]:

$Cijn,k = CCi + A1,k*CU1,j + A2,k*CU2,n$ (7)

In equation (7), the subscripts „i", „j" and „n" refer to the different states in the first, second and third subsystem respectively. The state space diagram for this combination can be represented by a cuboid as shown in fig



In equation (8), the term „th" denotes a threshold and is valid only for given values of „j" and „n". It is numerically equal to the smallest value of „i" such that the expression (CCth + A1,k*CU1,j + A2,k*CU2,n) ≤ Lk is satisfied for the kth hour of study. „Lk" is the system load level for the kth hour and „nu1" represents the total number of states in the first unconventional subsystem. It may be noted that equation (8) is basically a generalization of equation (1) with „M" being set to 0. The LOLP for the given hour in question can then be calculated by summing up equation (8) over all values of „n". Thus:

$LOLPk = LOLPk,n$

In equation (9), the term „nu2" refers to the total number of states in the second unconventional subsystem. The Loss of Load Expectation for the kth hour of study, LOLEk, can be computed using

equation (2) by replacing „Pk(0)‟ with „LOLPk‟ and „ΔT‟ with 1 hour. Thus, „LOLEk‟ is numerically equal to „LOLPk‟ for our case. Finally, the LOLE for the entire period of study is obtained as:
$LOLE = LOLEk$

CLUSTERING METHOD:
The Singh and Gonzalez approach described in Section 3 yields accurate values of the system reliability indices, but is computationally inefficient owing to the hourly calculations involved. It is particularly unsuitable for calculating EUE, as the hourly construction of a system negative margin table and the subsequent computations of „Uk‟ (see equation (5)) drastically increases the CPU time. The clustering approach was therefore proposed in [6] for efficiently calculating the reliability indices with minimum computational effort.
Clustering, or grouping, is done on the basis of similarities or distances between data points. The inputs required are similarity measures or data from which Referring to our sample system, the Loss of Load Probability for the cth cluster (LOLPc) can be calculated using equations (8) and (9). One should note that the subscript „k‟ denoting a given hour in those two equations will now be replaced by the superscript „c‟ denoting a given cluster. Using the concept of conditional probability, the LOLP for the entire system can then be obtained as:
$LOLP = LOLPc*P(dc)Ncc=1$ (14)
In equation (14), the term „P(dc)‟ refers to the probability of occurrence of the cth cluster and is obtained by dividing the cluster‟s frequency by „Nt‟. Finally, the LOLE for the entire period of study is obtained as:
$LOLE = LOLP*Nt$ (15)
The expected unserved load for the cth cluster, Uc, can be calculated using equation (5) by constructing a system negative margin table for the given cluster and by noting that the subscript „k‟ in the equation will now be replaced by the superscript „c‟. The Expected Unserved Energy for the cth cluster, EUEc, can then be obtained by multiplying „Uc‟ with „Nt‟. Using the concept of conditional probability, the EUE for the entire system is finally obtained as:
$EUE = EUEc*P(dc)Ncc=1$ (16)
A close look at the approaches I and II reveals that while in the former, the modifications of the generation capacity vectors of the unconventional subsystems and the combination of the generation system models were carried out every hour; these operations are performed on a cluster-by-cluster basis in the latter. Since the number of clusters is typically much smaller than the number of hours under study, the clustering method is much more efficient. It should however be noted that the indices calculated using this approach are not as accurate as those obtained in [4], as the contents of the „**dc**‟ vectors based on which the computations are performed for each cluster are obtained by averaging the corresponding values over a number of hours. This gives rise to some approximations in the calculations. It will be shown in later sections that the accuracy of the indices calculated using this method is a function of the number of clusters chosen for a given simulation. The Cubic Clustering Criterion [12] can however be used for choosing the optimum number of clusters. One should also note that if the number of clusters is equal to the number of hours in the study period, i.e. if „Nc‟ is equal to „Nt‟, the approaches I and II become identical to each other

MEAN CAPACITY OUTAGE TABLES

The first few steps of this approach are again similar to those of Approach I, in the sense that the entire system is divided into several subsystems corresponding to the conventional and the different types of unconventional units. A generation system model is then built for each such subsystem. To incorporate the effect of fluctuating energy, the generation system models of the unconventional subsystems are modified hourly depending on their energy output levels. The models corresponding to all the subsystems are then combined hourly in order to calculate the LOLE and EUE indices.
Referring to our sample system described in Section 3, let us now define the following vectors in addition to those (**CC, PC , CUl, PUl**) already presented in Section 3.1:
XC = Capacity outage vector associated with the generation system model corresponding to the conventional subsystem.
XUl = Capacity outage vector associated with the generation system model corresponding to the lth unconventional subsystem, where l ϵ [1, 2].
We shall now rewrite equation (7) in terms of the system capacity outages as follows:
$Xijn,k = XCi + A1,k*XU1,j + A2,k*XU2,n$ (17)
Let us also define the term „critical capacity outage‟ for the kth hour of study, Xk, as [7]:
$Xk = CC1 + (Al,k*CUl,1)2$
$l=1 – Lk$ (18)
All terms used in equation (18) are as described in Section 3. It may be noted that the expression (CC1 + (Al,k∗CUl,1)2l=1) represents the effective total generation capacity of the system during the kth hour of study. For a given hour, say „k‟, a loss of load situation occurs when Xijn,k > Xk for given values of „i‟, „j‟ and „n‟. The expected unserved load during the kth hour of study, Uk, can now be expressed as follows [7]:
$Uk = (Xijn,k-Xk *P(Xijn,k))Xijn,k>Xk$ (19)
In equation (19), the term „P(Xijn,k)‟ is used to represent the probability that a system capacity outage occurs exactly equal to „Xijn,k‟ MW. We shall now demonstrate how the hourly computation of the system negative margin table for calculating

„Uk‟ can be avoided by the application of a mean capacity outage table. The Loss of Load Probability for the kth hour of study, „LOLPk‟ can be expressed as [7]:

$LOLPk = P(Xijn,k)Xijn,k>Xk$ (20)

Let „Hk‟ represent the expected (mean) value of all system capacity outages which would cause capacity deficiency during hour „k‟ [7]. Thus:

$Hk = (Xijn,k*P(Xijn,k))Xijn,k>Xk$ (21)

Using equations (20) and (21), we can rewrite equation (19) as [7]:

$Uk = Hk – Xk*LOLPk$ (22)

While the term „Xk‟ in equation (22) can be calculated using equation (18) for a given hour „k‟, „LOLPk‟ can be computed using equations (8) and (9). Let us now expand equation (21) by using relevant terms from equations (8), (9) and (17).

$Hk = [XCi+A1,k*XU1,j+A2,k*XU2,n$

equation (8). „nc‟ represents the total number of states in the conventional subsystem. The term „th in equation (23) can now be redefined in terms of the system capacity outages as the smallest value of „i for which the expression (XCi + A1,k*XU1,j + A2,k*XU2,n) > Xk is satisfied for given values of „j and „n. Using the relevant notation for cumulative probability (refer to equation (8)), equation (23) can be rearranged as:

$Hk = \{PU1,j\ PU2,n\ [A1,k\ XU1,j\ PC\ t+nu1j=1nu2n=1A2,k\ XU2,n\ PC\ t+ XCi\ PCi\ nci=t]\}$ (24)

In order to simplify equation (24), we define [7]:

$HC\ q = (XCi\ PCinci=q)$ (25)

Substitution of equation (25), with q = th, in equation (24) yields:

$Hk = \{PU1,j\ PU2,n\ [A1,k\ XU1,j\ PC\ t+nu1j=1nu2n=1A2,k\ XU2,n\ PC\ t+HC(t)]\}$ (26)

We refer to the term „**HC(q)** for q = 1, 2, 3, … nc, as the Mean Capacity Outage Table of the conventional subsystem. This table is the key concept proposed in [7] for efficiently computing EUE. Once the cumulative probability vector „**PC** associated with the generation system model of the conventional subsystem is computed, the construction of the mean capacity outage table „**HC(q)** requires little additional computational effort as one can use a simple recurrence relation [13]. The expected unserved load during hour „k (Uk), as expressed in equation (22), can therefore be calculated using equations (8), (9), (18) and (26). The EUE for the entire period of study is then finally calculated using equation (4).

The advantage of using equation (22) over equation (5) for calculating „Uk can be realized by observing that the use of the mean capacity outage table essentially eliminates the need for carrying out hourly computations

Approach I vs. Approach II

Reduced synthetic system E [5] was used for this case study, which was performed using Approaches I and II for two different load cycle shapes, January and July, representing winter and summer peak respectively. The reliability indices calculated using both the approaches were then compared to each other for analyzing the efficiency and accuracy of the individual methods. The synthetic system E consists of the units shown in Table I.

Approach II vs. Approach III

It may be noted from Tables V and VI that the values of the reliability indices computed using Approaches II and III decrease with increasing levels of unconventional generation capacity. Regarding the computation of EUE using Approach II, the accuracy of the values obtained depends on the number of clusters chosen, the choice of initial seeds in the clustering algorithm and the correlation between hourly load and the wind energy supply [7]. It may be observed from Table VI that the accuracy of the EUE values increases with an increase in the number of clusters chosen for a given simulation.

CONCLUSION

This paper gives a detailed description of the approaches used for performing quantitative reliability analysis of large-scale power systems incorporating renewable energy sources. Three different approaches are presented along with relevant equations and diagrams. The results obtained from simulation runs performed using the individual approaches are then compared for analyzing their efficiency and accuracy. Approach III turns out to be the most efficient, as it is conceptually simple, accurate and the least time consuming.

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