2002년도 대한전기학회 하계학술대회 논문집 2002.7.10-12

풍력을 포함하는 전력 시스템의 신뢰성과 경제성 해석 방법

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A Methodology for Reliability and Economic Analysis of Wind Energy Embedded Electric Power System

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Abstract - A methodology for reliability and economic analysis of wind embedded electric power system is presented in this paper. This is done by evaluating the reliability index, loss of load expectation (LOLE), for the power system with and without integration of wind system in the overall electric power system. Economic analysis of the wind energy embedded electric system is done in terms of conventional fuel saving assessment due to the use of wind power generation units.

1. INTRODUCTION

The wind energy, a very important source of power in human civilization since hundreds of years, is being used for electric power generation in many countries since many years and about 7000 MW wind power generation was in commercial operation by the end of year 2000. As the wind generation units are being embedded in the commercial power system, the fluctuating nature of the energy produced by these units has different effect on the overall system reliability than the energy produced by conventional units. Wind units also have different effect on system economics, as there is no fuel cost involved in case of wind power generation. A methodology for reliability and economic analysis of wind embedded electric power system is presented in this paper. A reliability index, loss of load expectation (LOLE), is evaluated with and without inclusion of wind system in the overall electric power generation system and the conventional fuel savings, realized by replacing the conventional fuel units with wind power generation units, is assessed.

2. RELIABILITY ANALYSIS OF WIND ENERGY EMBEDDED ELECTRIC POWER SYSTEM

2.1 Probability Model of Generation System

The availability or random outages of generation units is calculated as probability density function on the bases of the historic data. The long-term average of generation unit up-time expressed as a fraction of the average cycle time gives the probability that the generation capacity of the unit will be available, also called the unit availability (denoted as p). In the same way, the long-term average of the down time gives the probability that the generating capacity of the unit will be unavailable (denoted by q), also called as the unit forced outage rate (FOR).

In this paper we are using a generating system for the two state units and a recursive algorithm, in which units are added sequentially, is used to build the capacity model of the generating system that is represented as the cumulative probability table [1]. The reliability analysis for power system uses this table where cumulative probability is the probability of finding a quantity of capacity outage equal to or greater than the indicated amount.

2.1.1 Recursive Algorithm for the Probabilistic Capacity Model of the Generation System

The cumulative probability of a particular capacity outage state of X MW, after the i^{th} unit of capacity C_i MW and forced outage rate U_i are added, is given by

$$P(X) = (1-U_i)P'(X) + U_i P'(X-C_i) \qquad (1)$$

Where $P'(X)$ and $P(X)$ denote the cumulative probabilities of the capacity outage state of X MW before and after the i^{th} unit is used.

The above expression is initialized by setting
$P'(X) = 1.0$ for $X \le 0$
and
$P'(X) = 0.0$ otherwise.
$P'(X-C_i)$ = Outage capacity $(X-C_i)$ probability before the i^{th} unit is added.

2.2 Loss of Load Expectation

The technique used to determine whether a generation expansion plan satisfies a desired level of reliability is defined by a reliability index, loss of load expectation (LOLE). A loss of load will occur only when the system load level exceeds the capability of the generating capacity remaining in service. Loss of load expectation is the probability of the power generating units of a system being inadequate to meet the load demand. The capacity outage probability table of the generation system is convolved with system load characteristics for calculating the loss of load expectation. An hourly peak load variation model is used where its hourly peak load represents each hour.

$$LOLE_i = P_i(C_i < L_i) \quad (2)$$

Where
C_i = available capacity on hour i
L_i = forecast peak load on hour i
$P_i(C_i < L_i)$ = probability of loss of load on hour i

$$LOLE = \sum_{k=1}^{nhs} LOLE_k \quad (3)$$

Where
LOLE = loss of load expectation for the period under study. The value of LOLE is in hours.
nhs = total number of hours under study

2.3 Loss of Load Expectation evaluation of Wind Energy Embedded Electric Power System

For reliability evaluation, the overall system is divided into two subsystems, containing the conventional and wind units respectively, and a generation system model is built using a Recursive Algorithm for each of these two subsystems. Each of the generation system models is described by two m-dimensional vectors as follows:

C_i = i^{th} element of the Capacity vector C
= one of the possible discrete capacity states
P_i = i^{th} element of Probability vector P
= $P(C \geq C_i)$
= probability of capacity on outage being equal to or greater than C_i
m = number of generation states

These two generation system capacity models are represented by:

CC = capacity vector of conventional subsystem
PC = probability vector of conventional subsystem
CWIND = capacity vector of wind subsystem
PWIND = probability vector of wind subsystem

Now, for each hour under study, the power output of the wind subsystem is calculated and a vector containing the hourly outputs of the wind unit subsystem is created as:

$POWIND_k$ = power output of the wind system during the k^{th} hour of the period under study

Wind generation subsystem capacity model is modified to account for the effect of the fluctuating energy by creating an m-dimensional vector $MWIND_k$ such that:

$$MWIND_{k,i} = \frac{CWIND_i POWIND_k}{PRWIND} \quad (4)$$

where
$MWIND_{k,i}$ = i^{th} element of $MWIND_k$
$CWIND_i$ = i^{th} element of CWIND
PRWIND = rated power of wind subsystem

Each subsystem is treated as multi-state unit and these subsystems are combined to calculate the LOLE for the hour in question. The combination of these multi-state units results in states with capacities given by the equation:

$$C_{ij} = CC_i + CWIND_j \quad (5)$$

Where i and j refer to the states in the first and second subsystems respectively and C_{ij} represent an element in two-dimensional array C that constitutes all possible capacity states of the combined system. A Discrete State Algorithm is used for evaluating the LOLE of the system for the hour under study, which is as follows:

① Initialize by setting
$LOLE_k = 0.0$
where
$LOLE_k$ = loss of load expectation for k hour of study
② j = 1
③ $CT = CC_{nc} + CWIND_{nwind}$ (6)
where
CT = total capacity
nc = number of states in conventional subsystem
nwind = number of states in wind subsystem
CC_{nc} = total capacity in conventional subsystem
$CWIND_{nwind}$ = total capacity in wind subsystem
④ i = 1
⑤ $C_{ij} = CC_i + CWIND_j$ (7)
If C_{ij} is equal to or more than (CT-load) for the hour, go to (8).
⑥ i = i + 1
If i is less than nc, go to (5).
⑦ If i is more than nc, go to (10)
⑧ b = i
where
b = boundary state defining the loss of load.
⑨ $LOLE_k = LOLE_k + PC_b(PWIND_j - PWIND_{j+1})$ (8)
⑩ j = j + 1
If j is less than or equal to nwind, go to (4).

The reliability index for the entire period is computed by the summation of all hourly values of LOLE.

3. ECONOMIC ANALYSIS OF WIND ENERGY EMBEDDED ELECTRIC POWER SYSTEM

The total energy generated by the wind units in entire period under study (nhs hours) is calculated by using the hourly modified wind generation capacity. Then the conventional fuel saving, achieved by replacing the conventional fuel units with wind power generation units, is assessed by using a formula:

$$\text{Quantity of Fuel saved} = \frac{1}{LCV}\sum_{i=1}^{nhs}\frac{3600000XY_i}{\eta} \text{ Kg} \quad (9)$$

$$\text{Cost of Fuel saved} = \frac{CF}{LCV}\sum_{i=1}^{nhs}\frac{3600000XY_i}{\eta} \text{ Won} \quad (10)$$

Where

X=power in MW which is replaced by wind units

η = efficiency of conventional generation unit

Y_i=percentage of full rated capacity that is generated by wind unit for a particular hour

LCV=lower calorific value of fuel used at the input of conventional unit; KJ/Kg

CF=cost of fuel used; Won/Kg

4. SIMULATION RESULTS

The reliability and economic analysis methodology have been applied on a sample test system with a total capacity of 176 MW shown in table 1. The simulation study was done using the load characteristics of one province in India. The 12 MW conventional units were replaced one after one with wind units, which is represented as the penetration level of the wind power in the overall electric generation system. The details about the wind units are given in Appendix I [2]. For different penetration levels of the wind sources; reliability indices, energy generated and fuel & money saved by embedding the wind units have been simulated for four different months of the year. The results obtained are presented in table 2.

Table 1: Data for the test system used for simulation study

Unit capacity [MW]	No. of Unit	Total Capacity [MW]	Forced outage rate [FOR]
50	2	100	0.05
20	2	40	0.08
12	3	36	0.08

Table 2: LOLE, energy generated and fuel saved for four different months of a year

Penetration level[%]	March	June	September	December
LOLE(hours)				
6.8	68.70	10.87	17.34	65.92
13.6	80.54	12.24	30.81	79.21
20.5	94.61	21.94	59.02	107.13
Energy generated[KJ×10^9]				
6.8	6.71	14.8	7.76	3.48
13.6	13.4	29.5	15.5	6.97
20.5	20.1	44.3	23.3	10.5
Fuel quantity saved [10^3 Kg]				
6.8	629	1384	726.7	326.4
13.6	1258	2768	1453	652.7
20.5	1887	5142	2180	979.1
Money saved [Million Won]				
6.8	62.1	135	70.2	32.4
13.6	121.5	270	140.4	62.1
20.5	183.6	405	210.6	94.5

5. CONCLUSIONS

A methodology for reliability evaluation for wind energy embedded electric power system has been presented in this paper. The probabilistic capacity generation model of wind energy system is modified hourly to incorporate the fluctuating nature of the wind energy system and then the system reliability, which is represented as loss of load expectation (LOLE), is evaluated using the discrete state algorithm. Finally the energy generated by the wind energy system is calculated and the conventional fuel saving is assessed as an indication of economic saving in system operation due to the use of wind energy system. This methodology has been applied on an Indian test system and results obtained are presented for four different months of the year.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by BK21 program.

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APPENDIX I

Wind turbine system units of 500 KW capacity with FOR = 0.03 were used in this paper and power output of these units was calculated using the following equations:

$$POW = \begin{cases} 0.0 & 0 < V < V_{ci} \\ A + BV + CV^2 & V_{ci} < V < V_r \\ PRW & V_r < V < V_{co} \\ 0.0 & V > V_{co} \end{cases} \tag{11}$$

$$A = \frac{1}{(V_{ci} - V_r)^2}\left[V_{ci}(V_{ci} + V_r) - 4(V_{ci}V_r)\left(\frac{V_{ci} + V_r}{2V_r}\right)^3\right] \tag{12}$$

$$B = \frac{1}{(V_{ci} - V_r)^2}\left[4(V_{ci} + V_r)\left(\frac{V_{ci} + V_r}{2V_r}\right)^3 - (3V_{ci} + V_r)\right] \tag{13}$$

$$C = \frac{1}{(V_{ci} - V_r)^2}\left[2 - 4\left(\frac{V_{ci} + V_r}{2V_r}\right)^3\right] \tag{14}$$

where

V = wind velocity for the hour in question

PRW = rated power of the unit

V_{ci} = Cut-in velocity

V_r = Rated velocity

V_{co} = Cut-off velocity