Reliability and Economic Analysis of Power Generation System with Inclusion of Photovoltaic and Wind Energy Sources

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Abstract—This paper presents a method for Reliability and Economic Analysis of power generation system with inclusion of Photovoltaic and Wind energy sources. This is done by evaluating the reliability index, loss of load expectation (LOLE), for the power generation system with and without integration of PV and wind system in the overall electric power generation system. Economic analysis with inclusion of PV and wind sources in the overall generation system is done in terms of conventional fuel savings due to the use of these non-conventional energy sources.

Index Terms—Generation System, Loss of load expectation, Photovoltaic, Reliability analysis, Wind.

I. INTRODUCTION

With the ever increasing demand for electrical power, every nation is looking to non-conventional energy sources as the alternative source of power generation. This is very important for future keeping the continuous depletion of the conventional energy sources in consideration as well as pollution and many other adverse environmental impacts due to them. New technologies for electrical power from sun and wind have been developed and considerable research is being done to improve them. The installed capacity of wind power generation units in commercial operation was nearly 7000 MW by the end of year 2000 [1], [2]. With the technological advancement, photovoltaic (PV) systems are also being used now days for commercial power generation from solar energy. By their very nature these power generation sources are small, modular, and geographically distributed, which clearly identify them as Distributed Generation (DG) sources.

As the PV and wind units are being included in the commercial power systems, the fluctuating nature of energy produced by these units has different effect on the overall system reliability than the energy produced by conventional energy sources. These units also have different effect on system economics, as there is no fuel cost involved in case of power generation from PV and wind [3].

This paper presents a method for Reliability and Economic Analysis of power generation system with inclusion of Photovoltaic and Wind energy sources. This is done by evaluating the reliability index, loss of load expectation (LOLE), for the power generation system with and without inclusion of PV and wind system in the overall electric power generation system. Economic analysis with inclusion of PV and wind sources in the overall generation system is done by assessing the conventional fuel savings realized by replacing the conventional fuel units with PV and wind power generation units.

II. RELIABILITY ANALYSIS OF POWER GENERATION SYSTEM WITH INCLUSION OF PV AND WIND ENERGY SOURCES

A. Probabilistic Model of Power Generation System

The availability or random outages of power generation units is calculated as probability density function on the bases of the historic data. The graphical representation of the availability of the generating capacity of a given unit on the bases of historical data is represented as shown in Fig.1.

![Fig. 1. Random unit performance record ignoring schedule outage.](image-url)
The long-term average of power 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).

The probability values $p$ and $q$ are probability of the unit being in the up-state at any time $t$ and the probability of the unit in the downstate at any time $t$ respectively [4], [5]. The forced outage capacity probability density function of the unit is depicted in Fig. 2.

![Fig. 2. Forced outage capacity probability density function.](image)

The reliability analysis for power generation system uses a capacity outage probability table, which is an array of capacity levels and the associate probabilities of existence. This is obtained by combining the generating units availability and unavailability using basic probability concepts. From the individual probability table, we prepare cumulative probability table [6]. The cumulative probability is the probability of finding a quantity of capacity outage equal to or greater than the indicated amount. In this paper we are using a generation system for the two state units and a recursive algorithm, which adds the units sequentially, is used to build the capacity model of the generation system that is represented as the cumulative probability table.

**B. Recursive Algorithm for the Probabilistic Capacity Model of the Power 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

$$P'(X) = (1-U_i)P'(X) + U_i P'(X - C_i)$$  \hspace{1cm} (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 $P'(X) = 0.0$ otherwise.

$P'(X - C_i)$ = Outage capacity $(X - C_i)$ probability before the $i^{th}$ unit is added.

**C. Loss of Load Expectation**

The technique used to determine whether a power generation system 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 power 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; therefore, individual hourly load values are used.

$$LOLE = P(C_i < L_i)$$ \hspace{1cm} (2)

where

$C_i$ = available capacity on hour $i$

$L_i$ = forecast peak load on hour $i$

$P(C_i < L_i)$ = probability of loss of load on hour $i$

After computing the hourly value of LOLE for all the hours under study, the index for the entire period is computed by:

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

where

$LOLE$ = loss of load expectation for period under study.

$nhs$ = number of hours under study

The value of LOLE is in hours.

**D. Loss of Load Expectation for Power Generation System with Inclusion of PV and Wind Energy Sources**

The overall power generation system is divided into three subsystems, containing the conventional, photovoltaic and wind units respectively, and capacity outage probability models are built using a Recursive Algorithm for each of these three subsystems. Each of the generation system models is described by two m-dimensional vectors as follows:

$C_i$ = $i^{th}$ element of the $C$ vector

= one of the possible discrete capacity states

$P_i$ = $i^{th}$ element of $P$ vector

= $P(C \geq C_i)$

= probability of capacity on outage being equal to or greater than $C_i$

$m$ = number of generation states
These three generation subsystem probability models are represented by the vectors

- \( CC \) = capacity vector of conventional subsystem
- \( PC \) = probability vector of conventional subsystem
- \( CPV \) = capacity vector of PV subsystem
- \( PPV \) = probability vector of PV subsystem
- \( CWIND \) = capacity vector of wind subsystem
- \( PWIND \) = probability vector of wind subsystem

The power output of the PV and wind subsystems are calculated for each hour under study and vectors containing the hourly output of the PV and wind power generation unit subsystems are created as:

- \( POPV_k \) = power output of the PV system during the \( k^{th} \) hour of the period under study
- \( POWIND_k \) = power output of the wind system during the \( k^{th} \) hour of the period under study

The probability model of PV and wind generation subsystems are modified to take into account the effect of the fluctuating energy generation by creating two m-dimensional vectors \( MPV_k \) and \( MWIND_k \) such that:

\[
PRPV_k = \frac{POPV_k}{CPV} \text{ and } PRWIND_k = \frac{POWIND_k}{CWIND}
\]

where

- \( MPV_{k,i} \) = \( i^{th} \) element of \( MPV_k \)
- \( CPV_i \) = \( i^{th} \) element of \( CPV \)
- \( PRPV \) = rated power of PV subsystem
- \( MWIND_{k,i} \) = \( i^{th} \) 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:

\[
C_{ijn} = CC_i + CPV_j + CWIND_n
\]

where \( i, j, n \) refer to the states in the first, second and third subsystems respectively and \( C_{ijn} \) represent an element in three-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 \( LOLE_k = 0.0 \)
2. \( n = 1 \)
3. \( j = 1 \)
4. \( CT = CC_{nc} + CPV_{npv} + CWIND_{nwind} \)

where

- \( CT \) = total capacity
- \( nc \) = number of states in conventional subsystem
- \( npv \) = number of states in PV subsystem
- \( nwind \) = number of states in wind subsystem
- \( CC_{nc} \) = total capacity in conventional subsystem
- \( CPV_{npv} \) = total capacity in PV subsystem
- \( CWIND_{nwind} \) = total capacity in wind subsystem

(5) \( i = 1 \)

6. \( C_{ij} = CC_i + CPV_j + CWIND_n \)

If \( C_{ij} \) is equal to or more than \( (CT - \text{load}) \) for the hour, go to (9).

7. \( i = i + 1 \)

If \( i \) is less than or equal to \( nc \), go to (6).

8. If \( i \) is more than \( nc \), go to (11)

9. \( b = i \)

where

- \( b \) = boundary state defining the loss of load.

10. \( LOLE_k = LOLE_k + PC_b (PPV_j - PPV_{j+1}) (PWIND_n - PWIND_{n+1}) \)

12. \( n = n + 1 \)

If \( n \) is less than or equal to \( nwind \), go to (5).

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

III. ECONOMIC ANALYSIS OF POWER GENERATION SYSTEM WITH INCLUSION OF PV AND WIND ENERGY SOURCES

As PV and wind units replace some conventional generation units, the fuel that would have been used for power generation is saved due to the use of these renewable energy sources. In the present economic analysis study, this conventional fuel saving is evaluated. For this, total energy generated by the PV and wind units in entire period under study (\( nhs \) hours) is calculated by using the hourly-modified PV and wind generation capacities. Then the conventional fuel saving that has been achieved because of the utilization
of these renewable energy sources is evaluated, in terms of quantity and money, by using formulae:

\[
\text{Quantity of fuel saved} = \frac{X_{\text{ren}} \sum_{i=1}^{nhs} 360000(Y_{i,\text{pv}} + Y_{i,\text{wind}})}{2\eta} \text{ Kg} \quad (9)
\]

\[
\text{Cost of fuel saved} = \frac{CF \cdot X_{\text{ren}} \sum_{i=1}^{nhs} 360000(Y_{i,\text{pv}} + Y_{i,\text{wind}})}{LCV \cdot 2\eta} \text{ Rs.} \quad (10)
\]

where

\( X_{\text{ren}} \) = power in MW which is replaced by PV and wind units
\( \eta \) = efficiency of conventional generation unit
\( Y_{i,\text{pv}} \) = percentage of full rated capacity that is generated by PV unit for a particular hour
\( Y_{i,\text{wind}} \) = 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; Rs./Kg

IV. SIMULATION RESULTS FOR CASE STUDY

The reliability evaluation method and economic analysis method has been applied on a test system with a total capacity of 176 MW shown in table 1 [7]. For the present study, a system with conventional subsystem and photovoltaic and wind subsystems was used. For the simulation purpose some conventional units were replaced by the non-conventional energy generation units and this is represented as the penetration level of the non-conventional power in the overall power generation system. The replaced conventional power generation was equally divided between PV and wind units. The details about the PV and wind units are given in Appendices I and II [8]. All the units contained in wind system are taken to be identical and same is the case with all PV units.

### TABLE I

<table>
<thead>
<tr>
<th>Unit capacity (MW)</th>
<th>No. of units</th>
<th>Total capacity (MW)</th>
<th>Forced outage rate (FOR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>40</td>
<td>0.08</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>36</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Then for different penetration levels of non-conventional energy sources; the reliability indices, energy generated, fuel and money saved by PV and wind units have been simulated for four different months of the year for the study system. The results obtained are presented in table 2.

Historic data is taken for wind velocity, solar radiation, and ambient temperature [9]. Hourly load data using daily load cycle was used. This simulation study is based on the tacit assumption that during one-month period under consideration, wind speed, solar radiation, ambient temperature and load patterns do not vary significantly from day-to-day and same daily statistics is used for the entire month [10].

### TABLE II

<table>
<thead>
<tr>
<th>Penetration level (%)</th>
<th>March</th>
<th>June</th>
<th>September</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLE (hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>65.29</td>
<td>11.20</td>
<td>17.32</td>
<td>32.73</td>
</tr>
<tr>
<td>13.6</td>
<td>69.26</td>
<td>15.17</td>
<td>30.81</td>
<td>69.67</td>
</tr>
<tr>
<td>20.5</td>
<td>92.14</td>
<td>27.9</td>
<td>52.92</td>
<td>90.74</td>
</tr>
</tbody>
</table>

| Energy Generated (KJ×10^9) |       |      |           |          |
| 6.8                        | 7.3   | 10.8 | 7.29      | 5.38     |
| 13.6                       | 14.6  | 21.5 | 14.6      | 16.8     |
| 20.5                       | 21.9  | 32.3 | 21.9      | 16.1     |

| Fuel Saved (10^3 Kg)       |       |      |           |          |
| 6.8                        | 684.3 | 1007 | 683.2     | 503.8    |
| 13.6                       | 1369  | 2014 | 1366      | 1008     |
| 20.5                       | 2053  | 3021 | 2050      | 1511     |

| Fuel Saved (Million Rs.)   |       |      |           |          |
| 6.8                        | 2.5   | 3.6  | 2.5       | 1.8      |
| 13.6                       | 4.9   | 7.3  | 4.9       | 3.6      |
| 20.5                       | 7.4   | 11   | 7.4       | 5.4      |

V. CONCLUSIONS

A method for reliability and economic analysis of power generation system with inclusion of photovoltaic and wind energy sources has been presented in this paper. The probabilistic capacity generation models of photovoltaic and wind energy systems are modified hourly to incorporate the fluctuating nature of these energy systems 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 photovoltaic and 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 photovoltaic and wind energy system.

The simulation study has been done on a sample power system for four months, characterizing different weather condition of the years, and reliability index (LOLE), energy generated, fuel and money saved with increasing penetration level of photovoltaic and wind energy sources are presented. The effect of including the photovoltaic and wind system on
power generation system reliability is moderate at lower penetration level but increases rapidly with the increase of non-conventional power penetration in generation system because the effects of fluctuating energy from these energy sources become more dominant. Therefore, the level of PV and wind energy integration in the conventional generation system at present level of technology should not be very high when considering their effect on the overall generation system reliability though their inclusion provide the savings in operating cost and also result in the savings of fast depleting conventional fuel deposits.

VI. APPENDIX

A. Appendix I

Photovoltaic units of 1 MW capacity with FOR = 0.09 were used in this paper. These units were modeled by a two state model, and the power output of these units was calculated using the following equations:

\[ W = \eta_{\text{at}} A H_{\text{tilt}} \eta_m \eta_{\text{pc}} \] (11)

\[ \eta_{\text{at}} = F_m \left[ 1 - \beta(T_{\text{cell}} - 28) \right] \eta_p \] (12)

\[ T_{\text{cell}} = 0.032 H_{\text{tilt}} + T_a \] (13)

\[ H_{\text{tilt}} = H_{\text{horizontal}} R \] (14)

where

- \( W \): power output at plant
- \( \eta_{\text{at}} \): module efficiency at ambient temperature for the particular hour
- \( A \): surface area of the total modules
- \( \eta_m \): wiring efficiency
- \( \eta_{\text{pc}} \): efficiency of power conditioning system
- \( H_{\text{tilt}} \): radiation on the tilted surface
- \( H_{\text{horizontal}} \): radiation on the horizontal surface
- \( R \): factor to correct horizontal incident radiation to that on a tilted surface
- \( \eta_p \): standard efficiency of module
- \( F_m \): matching factor
- \( \beta \): temperature coefficient for the change in module efficiency
- \( T_{\text{cell}} \): temperature of cell
- \( T_a \): ambient temperature.

These equations are for a fixed tilt plant. For optimum power generation in a whole year, the tilt is taken as the latitude of the place.

B. Appendix II

Wind turbine system units of 500 KW capacity with FOR = 0.03 were used in this paper. The wind speed data for these units is:

- \( V_{ci} \): Cut-in velocity = 12.6 kmph
- \( V_c \): Rated velocity = 32.4 kmph
- \( V_{co} \): Cut-off velocity = 69.0 kmph

The power output of these units was calculated using the following equations:

\[
POW = \begin{cases} 
0.0 & 0 < V < V_{ci} \\
A + BV + CV^2 & V_{ci} < V < V_r \\
PRW & V_r < V < V_{co} \\
0.0 & V > V_{co} 
\end{cases}
\] (15)

\[
A = \frac{1}{(V_{ci} - V_r)^2} \left[ V_{ci} (V_{ci} + V_r) - 4 (V_{ci} V_r + V_{co} V_r) \right]^3 
\] (16)

\[
B = \frac{1}{(V_{ci} - V_r)^2} \left[ 4 (V_{ci} + V_r) \left( V_{ci} + V_r \right)^3 - (V_{ci} + V_r) \right] 
\] (17)

\[
C = \frac{1}{(V_{ci} - V_r)^2} \left[ 2 - 4 \left( V_{ci} + V_r \right)^3 \right] 
\] (18)

where

- \( V \): wind velocity for the hour in question
- \( PRW \): rated power of the unit

VII. REFERENCES