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Reliability Cost/Worth Assessment of Generating Systems Incorporating Solar PV / Wind Energy

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Abstract: Today's world needs uninterrupted qualitative electrical power with high reliability. Since the renewable sources such as wind and solar energy provide stochastic power output, it is crucial to predict and control absolutely. Energy storage is expected to be correlative with them to maintain stability and reliability of system. The reliability evaluation models of wind power, solar photovoltaic power and energy storage which can be used in sequential Monte Carlo simulation are developed. The inherent characteristics that are deterministic to chronological variation of power output are incorporated during modelling. It includes wind speed, solar radiation, energy conversion performance and charge/discharge constraints of energy storage. Reliability evaluation methods are preferred for assessment of dependable capacities associated with system reliability indices to determine specific information for the long-term planning purposes. In this paper Evaluation techniques for performing reliability cost/worth studies on a power system using wind energy, solar energy and energy storage systems are presented. Two major methods designated as the optimal utility cost method and the reliability cost/worth method are developed and discussed.

Keywords: *Renewable , Reliability, Solar PV, Wind*

1. Introduction:

Since the fuel cost with conventional generation is continuously escalating , the utilization of renewable energy resources such as wind and solar energy for electric power supply has received considerable attention in recent years. Wind and solar energy will become major sources for power generation in the future because of their environmental, social and economic benefits, together with public support and government incentives.

The wind and sunlight are, however, unstable and variable energy sources, and behave far distinctly than conventional sources. Energy storage systems are often required to smoothen the fluctuating nature of the energy conversion system especially in small isolated applications. This paper is focused on the development and application of reliability and economic benefits assessment associated with incorporating wind energy, solar energy and energy storage in power generating systems. A probabilistic strategic approach using sequential Monte Carlo simulation was employed in this paper and a number of analyses were conducted with regards to the adequacy and economic assessment of generation systems having solar energy , wind energy, and energy storage. The evaluation models and techniques incorporate risk index distributions and different operating strategies associated with diesel generation in small isolated systems. Deterministic and probabilistic techniques are combined to provide useful adequacy indices for small isolated systems that include renewable energy and energy storage.

1.1 Power System Reliability Evaluation

The Objective function of a modern power system is to deliver its customers with electrical energy as economically as possible and with an acceptable level of reliability [1]. Electric power utilities therefore must provide a reasonable assurance of quality and continuity of supply to their customers. The level of assurance depends on the needs of the customer and the associated cost of providing the service. In general, high reliable systems involve large financial investment. In practice it is unrealistic to try to design a power system with a hundred percent reliability and hence, power system planners and engineers always try to achieve a reasonable level of reliability at an affordable cost. It is evident that reliability and related cost/worth evaluation are important aspects in power system design, planning and operation.

The reliability of a power system is a measure of the overall ability of the system to perform its basic adequate function. The concept of adequacy is generally treated to be the existence of sufficient facilities within the system to satisfy the load demand. Hence Adequacy is considered to be associated with static conditions which do not include system disturbances.

2. Reliability Cost/Worth Modelling and the Effects of Wind Energy, Solar Energy and Energy Storage Utilization in Electric Power Systems

The major focus in Electrical power system planning in general is directed to the areas of reliability and the investment/operation alternatives associated with determining a desired level of reliability.

This paper is directed towards the development of models and techniques for the economic assessment of power systems containing wind energy, solar energy and/or energy storage.

The various cost factors associated with the power system planning are considered and modeled. These factors include the costs associated with the required investments and the operation of the system together with the customer unsupplied energy costs due to power interruptions. Two different approaches for evaluating reliability cost and reliability worth are developed and discussed. These approaches are then applied to conduct a range of economic studies using the system data.

2.1 Reliability Cost/Worth Evaluation Models

Reliability cost/worth assessment is a crucial phase in electric power system planning, operation and optimization. Each investment incorporating non conventional energy sources and storage facilities should be evaluated in terms of both the reliability and costs of the system and the reliability worth to the customers. There are different costs associated with a power system containing wind energy, solar energy and energy storage. These costs can be generally divided in the two different categories of utility costs and customer interruption costs (CIC). The utility costs include the costs associated with the operation and the required investments of the system . The utility costs can be further divided into fixed costs and variable costs. The fixed costs include such factors as generating unit, storage system, installation and design costs etc. The variable costs mainly consist of fuel costs and the maintenance costs of the generating units and energy storage system. The customer interruption costs are the customer unsupplied energy costs due to electric supply interruptions. The sum of the utility costs and the customer interruption costs is designated as the total cost.

2.2 Utility Costs:

The overall utility cost can be represented in a single function and designated as the utility cost function (UCF) shown in Equation (2.1). This UCF can be used in a wide range of economic analyses in power system planning.

$$UCF=\sum_{i=1}^{Nt}(\alpha_i P_i + C_i^0+C_i^M) + \sum_{j=1}^{Nc} C_i+ \beta W_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

where:

α_i- The installed generating unit cost in \$/kW or \$/MW of the ith generating unit .

P_i- The power rating of the i^{th} generating unit in kW or MW .

C_i^0- Other constant costs such as design and installation costs associated with the i^{th} generating unit .

C_i^M- The maintenance cost of ith generating unit.

C_i^F- The fuel cost of ith conventional generating unit

β - The combined unit cost of the installed energy storage system in \$/kWh or \$/MWh [2] .

W_S- The installed capacity of the energy storage system in kWh or MWh.

N_t - The total number of generating units.

N_c - The total number of conventional generating units.

Energy storage systems need replacement during the life period of the system. In order to consider this fact in the evaluation, the combined cost of the storage system is used instead of the installed energy capacity unit cost. The combined cost is the sum of the present value of the purchase and replacement cost of the storage system. Typical fixed costs and variable costs associated with different generating unit types and energy storage for small isolated systems are presented in Table 2.1. It is assumed that the maintenance costs are a fixed percent of the unit costs in Table 2.1. It should be noted that the values in Table 2.1 are general indications only and may not reflect specific market or local site installation conditions

Table 2.1: Typical cost data for different generating units and storage in small isolated applications

Unit or Storage	Unit or Combined Cost Of Storage ($/ KW or $/KWh)	Other Constant Costs ($/KW)	Maintenance Costs (Percentage Of unit Costs)
Diesel	300	600	2%
WTG	1,200	450	2%
PV	1100		0%
Storage	450		0%

Table 2.2: Sector interruption cost estimates expressed in $/kW

	Interruption Durations				
User Sector	1 minute	20 minutes	1 hour	4 hour	8 hour
Large Users	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.163	55.808
Commercial	0.381	2.969	8.552	31.317	83.008
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.690
Government & Institute	0.044	0.369	1.492	6.558	26.040
Office & Buildings	4.778	9.878	21.065	68.830	119.16

2.3 Customer Interruption Costs:

Customer interruption costs (CIC) are directly depend on the type of customer and the duration of interruptions. The evaluation of customer interruption costs is usually done using sector customer damage functions (SCDF) or composite customer damage functions (CCDF) depending on the customer groups involved [1]. The interruption costs for various outage durations can be obtained through customer surveys of the different customer groups [1]. Sector interruption cost estimates are expressed in $/kW and shown in Table 2.2 [1].

The CCDF can be obtained from the system SCDF using Equation (2.2) [1].

$$CCDF = \sum_{k=1}^{n} k_i SCDF_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

where:

k_i - The per unit energy consumption of customer sector i

$SCDF_i$ -The sector customer damage function of customer i

n- The number of customer sectors

The CCDF is a measure of the cost associated with power interruptions as a function of the interruption duration for the customer mix in the given system.

The system CCDF, which is calculated from the SCDF shown in Table 2.2 for the IEEE-RTS [3] is shown graphically in Figure 1

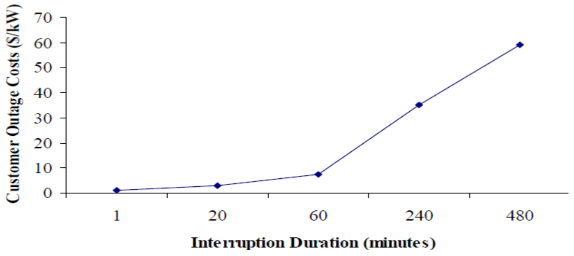

Figure 1 Composite customer damage function for the IEEE-RTS

2.4 Reliability Cost/Worth Evaluation Techniques

In General, as the reliability level increases, the utility costs increase and the customer interruption costs decrease. This is illustrated in Figure 2 Conventionally, electric utilities have been keen interested in utility costs in their planning and customer interruption costs were not extensively considered. The objective of the conventional approach is to find an optimal utility cost (point A) while ensuring that the supply reliability is equal to a pre-established objective (Point R). This approach is designated as the Optimal Utility Cost Method (OUCM) . An alternative approach to incorporating both factors is to use a reliability cost and reliability worth philosophy in the evaluation. This approach is designated as the Reliability Cost/Worth Method (RCWM) . The basic objective of the RCWM is to determine an optimal reliability level (R_{opt}) at which the total costs become minimum [1]. Both the techniques have their own merits and demerits. The OUCM is quite simple and easy to implement. The major disadvantage with OUCM is that it requires a pre-specified reliability target in the planning process, Whereas in the RCWM, the system reliability level is not a pre-determined value, but is an outcome of an optimization process.

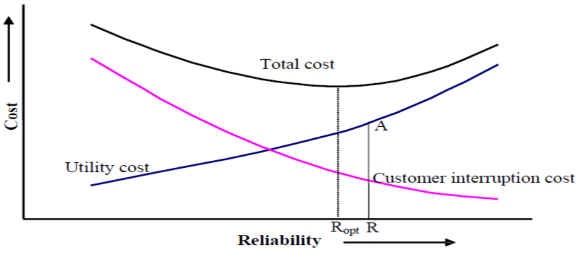

Figure 2 System reliability and costs

2.4.1 Optimal Utility Cost Method (OUCM)

In the OUCM either deterministic or probabilistic is opted to evaluate the costs associated with different alternatives. The most often used probabilistic criterion in the OUCM is the LOLE (Loss of Load Expectation). In order to maintain a certain reliability level with increasing system load, it may be necessary to add extra generating unit and/or energy storage capacity. The method is tested for the two cases of without and with energy storage.

a) Systems without energy storage

If a system has no energy storage, the benefits of different generating unit additions to the system can be evaluated in terms of the utility costs at a particular risk level for a given site location. Figure 3 illustrates the relationship between a risk index and non-conventional unit capacity additions to a given system for two different test locations. In Figure 3, R_c is the reliability criterion, C_1 and C_2 are the additional renewable capacities needed to keep the expanded generating system at risk level R_c for Locations 1 and 2 respectively. The system costs associated with different system expansions can be calculated and compared using Equation (2.1). The important planning task is the selection of the most beneficial option in terms of the reliability and costs. This kind of analysis is presented in detailed in [4] using the RBTS as an example.

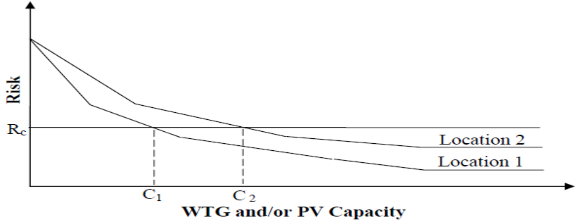

Figure 3 Variation of reliability indices with WTG and/or PV capacity

b) Systems with energy storage If the system has energy storage, it is mandatory to find the optimal sizes of the non-conventional generating unit and the storage system capacity so that the total utility cost is minimized at a given risk level. The process presented in [2] is extended and modified to evaluate the utility costs for power systems utilizing conventional units, WTG, PV and energy storage.

The objective function of the cost optimization problem is to minimize the UCF as defined in Equation (2.1) subjected to the constraints of a pre-determined reliability criterion. This is evaluated under the assumption that the total capacity of conventional units are known and fixed for a given system, if the system contains any conventional generating units. The additions of WTG, PV and/or energy storage to a given system improve the system reliability. Utilization of these non-conventional energy sources also has positive economic impacts such as fuel savings in a given system. The utility costs can be determined for a range of alternatives including all possible combinations of WTG and/or PV and the storage system capacities subjected to the following inequality constraints:

$$W_{Smin} \ll W_S \ll W_{Smax}$$

$$P_{min} \ll P \ll P_{max} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.3)$$

Where W_S and P are the energy storage capacity and the total non-conventional unit capacity respectively in Equation (2.3). The variables W_S and P are discontinuous and usually vary in well defined discrete steps. The change in W_S is mainly due to the addition of more storage capacity and the change of P is due to the addition of more WTG and/or PV units to the system. Therefore, the number of combinations of energy storage and non-conventional unit capacities is restricted.

Figure 4 describes the relationship between a reliability index and renewable energy capacity additions to a given system for three energy storage capabilities designated as W_{B1}, W_{B2} and W_{B3}. The curves in Figure 4 are designated as equal energy storage capacity curves (EESCC) and R_c is the reliability criterion. This reliability level can be justified by several alternatives. The optimum solution is the one which results in the lowest system cost as defined in Equation (2.1).

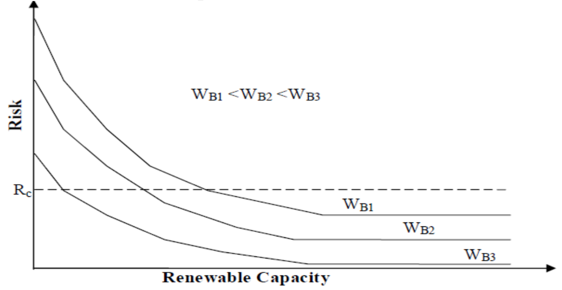

Figure 4 Equal energy storage capacity curves

Another alternative is to use equal renewable energy capacity curves (ERECC). An ERECC gives the relationship between a reliability index and energy storage capacity for a fixed non-conventional unit capacity condition. Three curves designated as P_1, P_2 and P_3 and the reliability criterion R_c are shown in Figure 5 The reliability level can be satisfied by several alternatives. The lowest cost of these options can also be determined using Equation (2.1).

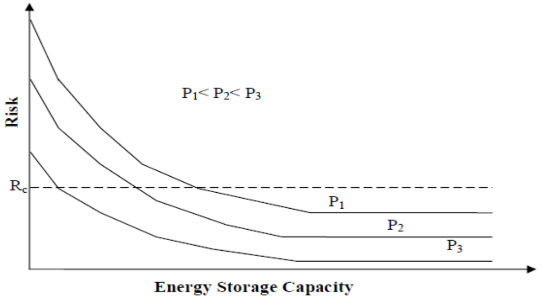

Figure 5 Equal Renewable Energy Capacity Curves

The EESCC and ERECC approaches can be combined to obtain the relationship between the renewable energy capacity and the energy storage capacity with the risk levels as parameters. Figure 6 illustrates this relationship using the LOLE index as a parameter. The curves shown in Figure 6 are designated as equal risk curves (ERC) . Figure 6 can be used to determined the minimum cost combination of non-conventional unit capacity and energy storage capacity for a given reliability level. The objective of this approach is to find an optimal utility cost as indicated by points A, B and C for different risk levels represented by LOLE 1, LOLE 2 and LOLE 3 respectively. This approach is an effective tool for designing and planning small isolated systems containing energy storage. Customer interruption costs are not directly considered in this approach as they would be basically constant for each of the designated risk levels. Customer unsupplied energy costs due to electric supply interruptions are directly considered in the evaluation using the RCWM technique presented in the following subsection.

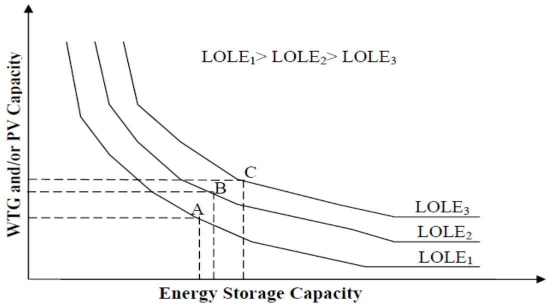

Figure 6 Equal risk curves

2.4.2 Reliability Cost/Worth Method (RCWM)

The basic objective of the reliability cost/worth approach is to determine an optimal reliability level at which the total costs (sum of the utility costs and customer interruption costs) are minimized [1]. The probabilistic criterion most often used in the RCWM is the LOEE. The utility costs can be calculated using Equation (2.1) and the customer interruption costs can be calculated as follows using Monte Carlo simulation:

1. Calculate the duration and the expected energy not supplied at each interruption.
2. The average load loss during the i^{th} interruption is then calculated by dividing the expected energy not supplied during that interruption by the duration of outage.

$$L_i = \frac{EENS}{di} \text{..............................(2.4)}$$

Where:

$EENS_i$ - Expected energy not supplied in kWh or MWh in the i^{th} interruption

d_i - Outage duration (hour) of the i^{th} interruption

L_i - Average load loss in kW or MW in the i^{th} interruption

3. The interruption cost per kW or MW for the outage is obtained from the system SCDF or CCDF and multiplied by the load loss to get the customer outage cost in dollars for the i^{th} outage.

$$CIC_i = C(\,d_i\,)\,L_i \text{....................(2.5)}$$

Where:

d_i - Outage duration (hour) of the i^{th} interruption

$C(d_i)$ - Interruption cost in i^{th} interruption from CDF ($/kW)

L_i - Average load loss in kW or MW in the i^{th} interruption

4. The system customer outage cost in dollars is finally calculated by adding cost associated with each interruption.

$$CIC = \sum_{i=1}^{N} CIC_i \text{ ………………………..(2.6)}$$

Where: N is the total number of interruptions.

The basic customer outage cost data are not always available for every outage duration. Logarithmic interpolation, therefore, was used to evaluate the costs between the existing data points and extrapolation was used to calculate the other costs. The interpolation and extrapolation techniques are given respectively in Appendices E and F.

The customer outage costs decrease and the utility costs increase as additional generating and/or energy storage capacity are added to a system as shown in Figure 7

The RCWM can be used to determine an optimum adequacy level incorporating both the costs of providing reliability and the worth of having that reliability. This approach is often used to evaluate the optimum reserve margin in conventional generation planning. Once the optimal generating reserve is determined, the target adequacy level is also determined. The RCWM also can be used to determine the optimum addition of non-conventional generating capacity and/or storage capacity to a small isolated system.

2.5 System Studies

The described reliability cost/worth evaluation models and techniques are applied to examine the economic impact of power systems utilizing wind energy, solar energy and energy storage in this section. Different system configurations are investigated and analyzed. The economic assessment of systems containing wind energy and/or solar energy and energy storage is conducted using small isolated example systems considering different operating strategies. The fixed and variable costs associated with small isolated systems shown in Table 2.1 are used in following analyses. All of the fixed costs expended during the life time of a project or equipment are converted to a series of consecutive equal payments occurring in each year as presented in Equation (2.7) [5].

$$A = P\,\frac{[i\,(1+i)^n]}{(1+i)^n - 1} \text{ ………………………..(2.7)}$$

Where:

P - Present sum of money at time zero

i - Annual interest rate

N - Total number of interest periods

A - A uniform series of payments.

The lifetime of WTG and PV units is assumed to be 20 years and the annual interest rate is assumed to be 12% in following analysis. The combined costs associated with energy storage are also considered on a 20 year base. The economic benefits due to fuel savings are also incorporated. A fuel cost of $1.1/liter and a heat rate of 3.2 kWh/liter are used for the diesel units. Other annual fixed charges such as taxes, insurances and depreciation are not included in the studies.

2.5.1 Application of the OUCM

In order to illustrate the use of the previously developed methods, studies have been conducted on various alternatives using the small isolated system cases. All of the diesel units are assumed to be continuously operated and the wind regime is assumed to be represented by the Regina site. The system annual peak load is 40 kW. The selected risk level is a LOLE of 30 h/year as shown in Figure 7.

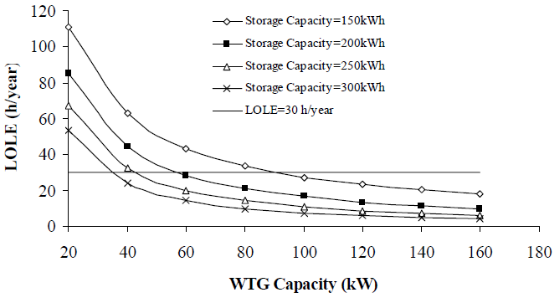

Figure 7 Equal energy storage capacity curves

The utility costs associated with the four different storage capacity levels at a LOLE of 30 h/year are compared in Table 2.5.1 The annual fixed costs and production costs associated with the diesel generating units are not included in Table 2.5.1. It can be seen from Table 2.5.1 that although the system load can be satisfied by all of the four different alternatives at a LOLE of 30 h/year, the annual utility costs associated with these system configurations are different. The minimum cost alternative in this case requires a total WTG capacity of 44 kW and a 250 kWh energy storage system in addition to the two diesel units. The total WTG capacity and energy storage capacity are 91 kW and 150 kWh respectively for the maximum cost alternative. The difference between the maximum and the minimum cost is approximately $3, 810.00/year.

Table 2.5.1: Annual utility costs for the different alternatives shown in Figure 8 at a LOLE of 30 h/year

Alternative	1	2	3	4
WTG Capacity (kwh)	36	44	58	91
Storage Capacity (kwh)	300	250	200	150
Unit Costs ($k)	43.20	52.80	69.60	109.20
Storage Costs ($k)	135.00	112.50	90.00	67.50
Other Constant Costs ($k)	16.20	19.80	26.10	40.95
Total Capital Costs ($k)	194.40	185.10	185.10	217.65
Annualized Capital Costs ($k/ year)	23.95	22.80	22.88	26.81
Savings due to reduced Fuel ($k/ year)	15.78	15.52	15.28	15.72
Annual Utility Costs ($k/ year)	8.17	7.28	7.60	11.09

3. Conclusions:

Evaluation techniques for performing reliability cost/worth studies on a power system using wind energy, solar energy and energy storage systems are presented. Two major methods designated as the optimal utility cost method and the reliability cost/worth method are developed and discussed. These approaches are then used to conduct a range of economic analyses on various example systems. Different diesel unit operating strategies are also incorporated in the evaluation

In the OUCM, the minimum cost for a given system at a specified reliability level is determined using three different curves. These curves are the equal energy storage capacity curves, equal renewable energy capacity curves and the equal risk curves. The results obtained using these curves show that a particular system load can be satisfied at specified risk levels by a number of alternatives with different costs. The optimum combination of the total non-conventional generating unit capacity and the energy storage can be determined for a given level of reliability. The annualized capital costs and the savings due to reduced fuel usage decrease with increase in the LOLE criterion. The savings due to reduced fuel usage can offset the capital costs and this effect becomes more significant with increase in the LOLE criterion. Intermittent diesel operation is superior to continuous diesel operation when the savings due to reduced fuel usage is significant.

When different alternatives are compared at a specified reliability level, the utility costs for all the alternatives can be quite different. The customer interruption costs for these alternatives may be similar due to the specified reliability requirement. In this case, the differences in the total utility cost between the individual alternatives are dominated by the fixed and the variable utility costs. The optimum alternative can be selected using the OUCM when the reliability criterion is fixed at a specified level.

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