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J. Electrical Systems 7-2 (2011): 206-224

Regular paper

REAST: Renewable energy analysis and sizing tool

Journal of Electrical Systems

This paper reports the development of a computer model 'Renewable Energy Analysis and Sizing Tool (REAST)'. Aim of the model is to find an optimal configuration of photovoltaic-wind hybrid energy system comprising battery and generator as a back up. The optimal configuration with least cost and high reliability is obtained on the basis of loss of power supply probability method. New mathematical models are used to asses the performance of solar and wind systems.Net present cost method is used to determine the cost of system configuration. A novel penalty function is employed for low reliability level in the cost calculation. The model is very useful for analyzing the performance of the system and gaining a better insight in the components sizes before they are really built. Usefulness of the model is illustrated by means of a case study. Program is developed in MATLAB environment.

Keywords: Hybrid photovoltaic-wind system, optimization, net present cost, simulation model, loss of power supply probability

1. Introduction

Steadily increasing demand of electricity and social interest for global environmental concern has necessitated an urgent search for alternative energy sources to meet the energy requirements. This fact makes renewable energy resources very attractive for many applications. Wind and solar energy sources are considered as viable option for future electricity need, particularly for rural area electrification. Besides being free, the energy coming from these sources is available at no cost. However, a demerit of such sources is that their outputs are fluctuating by weather. Initial cost of facilities is also very expensive and needs maintenance costs.

Normally the photovoltaic-wind hybrid system is operated in parallel with diesel generator in order to reduce the average load on generator and hence to save the fuel .This mode of operation is beneficial particularly when the renewable energy penetration is small. However, a small amount of energy is always wasted. Another mode of operation of operating the generator is to operate the generator as and when required to meet the load. This mode is unattractive because numbers of start-stop cycles are more. This problem is alleviated by adding battery bank storage to the system. Addition of battery bank increases reliability of the system and decreases the start-stop cycles of generator.

In fact, photovoltaic system alone is incapable to protect the battery against deep discharge. Adding a dynamic source of energy such as wind turbine or diesel generator protects the battery bank against deep discharges and thus extends its life [1].Thus, photovoltaic (PV) and wind hybrid system comprising battery bank storage and diesel generator is considered as perfect solution to meet the electricity need of the remote area consumers. The application of such systems also reduces the probability of energy shortage taking the advantage of their complementary nature.

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Many studies have been carried in the area of renewable energy systems [1], [3], [9-12], [14], [21-22]. Most of these works reported so far use the hourly average resource data over a few year for simulation[10],[14].It has been reported that small-to-medium-size(10-100KW)hybrid energy system based on wind and solar sources may electrify the villages, small health clinics and community centers[2],[23].

This paper describes the development of a computer model using iterative technique for the design of an autonomous PV/wind hybrid energy system as shown in Fig 1.Loss of probability method is used as the key parameter to asses the reliability of the system. Energy balance calculation approach with time step of one hour is adopted for optimization.

2. Hybrid system configuration

Proposed hybrid system configuration is depicted in Fig.1. This configuration is used to design an autonomous photovoltaic-wind hybrid energy system. When the load demand exceeds the sum of renewable and battery bank storage power, diesel generator is started to meet the load. On the contrary, when renewable power exceeds the load demand, and battery bank is full, the excess power is dumped to an external resistor called dump load. The function of this 'dump load' is to preserve the stability of system and dissipate the energy deliberately, when the load on the diesel generator is below a certain minimum load limit specified by manufacturer. This load limit on generator is specified to avoid the incomplete combustion and carbon deposits (glazing) on the cylinder walls, causing premature engine ware [3].Converters and diesel generator are selected on the basis of peak load demand. Optimal system configuration is determined using annual hourly average resource data. In this resource data, period of time (days) with no wind and/or solar radiation which do occur in real-life situation, are ignored. A backup diesel generator is included in the system configuration to account for these real life situations. This backup generator supplies power to the load during emergency when renewable power and stored energy in battery bank is found insufficient to cope up with the load demand.

The reliability measures in terms of loss of power supply probability (LPSP) and the total life cycle cost are used as the indices for evaluation of different system configurations. The system that contains the diesel generator and battery storage essentially requires the dispatch strategy. Dispatch strategy is a set of rules used to control the operation of generator and battery bank whenever there is insufficient renewable power to meet the load demand.

For fix number of wind turbines, the annual LPSP values of hybrid systems with different number of solar photovoltaic module and battery combinations are calculated first. Then all possible combinations satisfying desired reliability level are extracted for life cycle cost calculation. Finally the least cost (optimal) system is found from these extracted combinations.

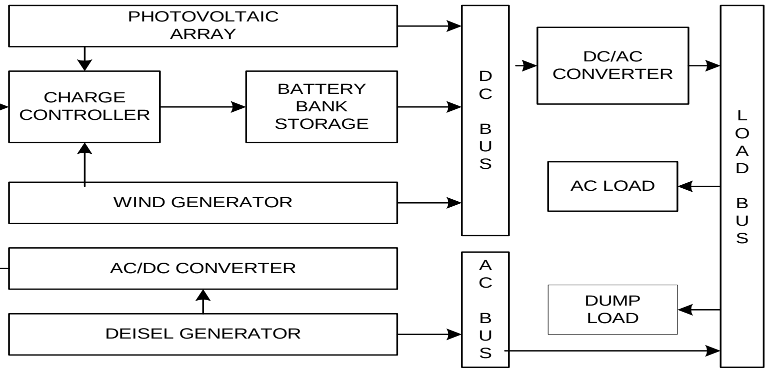

Fig.1: Block diagram of a typical PV-wind hybrid energy system

3. System components models

Hybrid system components mathematical modeling is a first mandatory step before any phase of optimal system sizing is carried out. In the proposed hybrid system configuration, there are five principal components which need mathematical modeling. These components are photovoltaic array, wind generator, battery storage, dc to ac converter and diesel generator. Sizing and performance evaluation of system is highly dependent on accuracy of the mathematical models used for its components. Mathematical modeling of each system component is described in the subsequent sections:

3.1 PV generator

There are many photovoltaic models developed so far, ranging from simple idealized model to detailed models that reflect the details of the physical processes occurring in the cells. They are either single diode model or double diode model. The double diode model is more accurate compared to single diode model but it requires many parameters which are not mentioned in the data sheet of module supplied by manufactures. On the contrary, single diode model requires only four/five parameters which are invariably available in the data sheet, and the accuracy of the model is also very good. Due to this reason only, single diode model has always been very popular amongst the researchers [1], [4], [14].Double diode model is only suitable when detailed PV cell and module experiments are to be performed in advance. The detailed description of these models can be found in [5] and [6].

Unlike to solar cell models used by researchers, a new model called effective solar cell model is used in this study. The beauty of this model is its capability to find an explicit solution for voltage, in contrast to single diode and double diode models. This model requires only four parameters to solve the current and voltage equation. Thus, calculation work is reduced .The novelty of the effective solar cell model is that both resistances of single/double diode models are combined into a virtual photovoltaic resistance (R_{pv}). This Photovoltaic resistance can take both positive and negative values. Therefore, it is not a simple ohmic resistance. The equivalent diagram of effective solar cell is depicted in Fig.2.

All points on photovoltaic module characteristic curve are calculated using equation (1)-(7) with very good accuracy [7]:

$$M=\frac{Voc}{Isc}\left(K1\frac{Imax\,Vmax}{Isc\,Voc}+K2\frac{Vmax}{Voc}+K3\frac{Imax}{Isc}+K4\right) \quad (1)$$

$$R_{pv}=-M\frac{Isc}{Imax}+\frac{Vmax}{Imax}+\left(1-\frac{Isc}{Imax}\right) \quad (2)$$

$$V_T=-\left(M+R_{pv}\right)Isc \quad (3)$$

$$I_o=Isc\,\exp^{-\left(\frac{Voc}{V_T}\right)} \quad (4)$$

$$I_{ph}=I_{sc} \quad (5)$$

$$I=I_{ph}-Io\,\exp^{\left(\frac{V+IR_{pv}}{V_T}-1\right)} \quad (6)$$

$$V=V_T.\ln\left[\left(\frac{I_{ph}-I+Io}{Io}\right)\right]-IR_{pv} \quad (7)$$

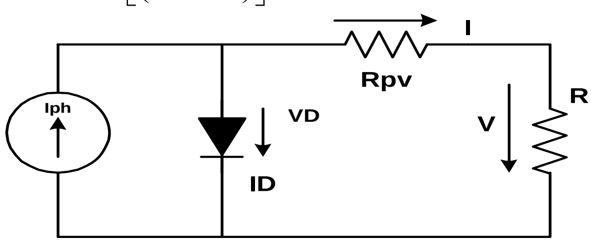

Fig.2: Equivalent diagram of effective solar cell

Where, M is Gradient, V_{oc} is open circuit voltage, I_{sc} is short circuit current, V_{max} is maximum power point voltage, I_{max} is the maximum power point current, R_{pv} is the virtual resistance, V_T is thermal voltage, I_o is reverse biased saturation current of diode, ID and VD are the diode current and voltage respectively and I_{ph} is photocurrent. This photocurrent is dependent upon solar incidence radiation. Incidence radiations falling on the surface of the solar module are calculated using HDKR model [5]. Gradient M is the function of cell parameters. K_1, K_2, K_3, and K_4 are constants. These constants are calculated using least square method. The typical values of these constants for crystalline silicon cells are:

$K_1 = -5.411$ $K_2 = 6.450$ $K_3 = 3.417$ $K_4 = -4.422$

It is assumed that maximum power point tracker is used for adjusting the impedance seen by panel to match the optimum point on I-V curve. The generated maximum power output of the photovoltaic module during time step t is calculated as:

$$P_v(t)=NpvV(t)I(t) \quad (8)$$

Where, $P_v(t)$ is power generated by solar system, Npv is the number of modules used in solar system, V(t) and I(t) are the values of maximum voltage and current of module respectively.

3.2 Wind turbine generator

It is unfair to use a mathematical model for all the wind turbine generators (WTG) of same capacity designed by different manufacturers. This is true because the power output performance curves of these wind turbine generators are never found same. In some papers [8-10] researchers have assumed that the turbine power curve has a linear, quadratic or cubic form. In other papers [11,12] the power curve is approximated with a piecewise linear function with a few nodes. Where as in some other case studies, a model which has a similar form is applied taking into account the Weibull parameters[1],[13].All theses models are often used for the simulation and evaluation of WTG performance particularly for field applications. However, the most accurate calculation of hourly wind power produced by a wind turbine generator is possible only by using its own performance curve supplied by manufacturers.

In this work, mathematical model used to realize the performance curves of wind turbine generators is developed using MATLAB function POLYFIT. This function fits an nth-order polynomial to data using a least square minimization technique. In order to guarantee the fitting accuracy, number of polynomial expressions are used in the model for example, second order polynomial used for the curve fitting equation of the power curves of any wind generator can be expressed as –

$$P_w(t) = \begin{cases} 0 & (v < v_{in}) \\ a_1 v^2 + b_1 v + c_1 & (v_{in} \le v < v_1) \\ a_2 v^2 + b_2 v + c_2 & (v_1 \le v < v_2) \\ a_3 v^2 + b_3 v + c_3 & (v_2 \le v \le v_{out}) \\ 0 & (v > v_{out}) \end{cases} \tag{9}$$

Where $P_w(t)$ is output of wind generator at wind speed v, v is the wind speed at hub height; v_{in} and v_{out} are cut- in and cut-out wind speed of WTG respectively. The hourly output of WTG can be obtained by using equation (9) that describes the physics of actual power curve of wind generator and average hourly wind speed at the hub height.

It has been observed that with five data points, the fifth –order polynomial fit goes through all the data points, which demonstrates a general characteristic of curve fitting polynomials: For ‘n’ data points, an nth-order polynomial fit will go through all the data points. However, for large amount of data, it is not usually a good idea to use a higher-order polynomial that goes through all the points because it will have large oscillation. Hence, lower order polynomials are preferred for curve fitting in equation (9).The applicability of this technique is demonstrated in Fig.3 for BWC XL1 Type one Kilowatt wind turbine generator.

The variation of wind speed with the elevation influences both the assessment of wind resources and the design of wind turbine. A widely used power law model with one-seventh ratio is applied in this study to account the wind variation with the height [14].

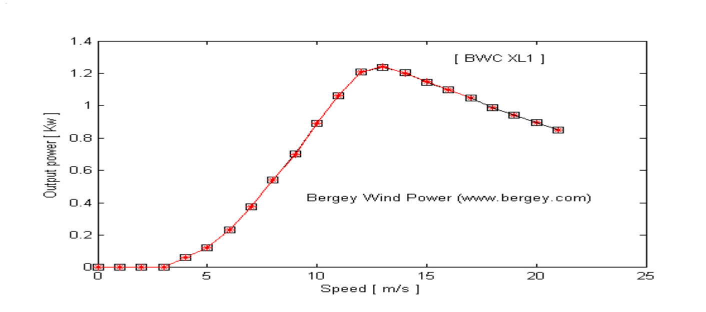

Fig.3: Application of curve fitting technique

3.3 Battery bank storage

A mathematical model of battery bank storage is necessary to predict the state of charge (SOC) of battery at each hour of simulation period. It is difficult to predict the exact SOC of battery for uncontrolled charge /discharge cycles in stand alone systems. Load will not be satisfied when the power generated by both the wind turbine and PV system is insufficient and storage is depleted and its state of charge has fallen below a predetermined minimum value. Energy is stored in battery bank when power generated by wind turbine and PV system exceeds the load. On the contrary, energy is taken from the battery bank when power generated is less than the load demand. The SOC of battery bank at any time t_1 depends upon state of charge in the previous moment t_0 and the sequence of generated power and load demand levels in the time interval t_1- t_0. System controller (not shown in block diagram) starts/stops charging batteries when SOC of battery bank reaches to its predefined minimum/maximum charge quantity. System controller disconnects the load when SOC falls below a minimum charge quantity.

The SOC of battery bank storage at any hour t can be obtained by monitoring the charge/discharge energy to/ from the battery as given by following expressions:

$$E_{batt}(t) = \min\left[\text{ChargeLim}, \left(El(t)/\eta_{inv} - Eg(t)\right)/\eta_{batt}\right] \tag{10}$$

$$E_{batt,in}(t) = \min\left[\text{ChargeLim}, \left(Eg(t) - El(t)/\eta_{inv}\right)\eta_{batt}\right] \tag{11}$$

$$Eb(t)=Eb(t-1)\,(1-\delta)-E_{batt}(t)+E_{batt,in}(t) \tag{12}$$

where $Eb(t)$ and $Eb(t-1)$) are SOC of battery at the time t and $(t-1)$ respectively; δ is the hourly self discharge rate of bank taken as 0.009 for this study; $E_{batt,in}(t)$ and $E_{batt}(t)$ are the charge and discharge quantities of battery storage; $El(t)$ is load demand; $Eg(t)$ is the total energy produced by both PV and WTG systems at time t; η_{inv} and η_{batt} are the efficiency of inverter and charge/discharge efficiency of battery storage respectively; ChargeLim is the maximum allowable charge/discharge energy to/from the battery, assumed to be equal to 10/20 percentage of total battery bank storage capacity. In this paper, the charge/ discharge efficiency of battery is assumed to be the same and equal to the round trip efficiency of battery storage.

At any time (t), the charge/discharge energy of battery bank is subject to the following constraints:

$$E_{batt,in}(t) \leq 0.10 C_b N_b \quad (13)$$

$$E_{batt}(t) \leq 0.20\, C_b N_b \quad (14)$$

$$Ebmin \leq Eb(t) \leq Ebmax \quad (15)$$

Where, C_b is the capacity of the battery, N_b is number of batteries used. At the beginning of simulation, maximum charge quantity of battery bank Ebmax takes the value of nominal capacity of battery bank storage. Minimum charge quantity of battery bank storage (Ebmin) is calculated by maximum depth of discharge (DOD) allowed:

$$Ebmin = (1 - DOD) CbNb \quad (16)$$

Where, DOD is equal to 70% of battery bank capacity. Detailed modeling of battery requires many parameters which are difficult to obtain without a sophisticated lab facility. Hence, the use of a complex battery model is ignored, the reason being that our objective is to design a hybrid system and not to simulate in detail, the working of the said system.

3.4 Diesel generator

In this study, diesel generator (DG) has two decision variables, first related to the selection of diesel generator (whether to select the DG or not) another related to power generation from DG. The generation characteristics of DG can be described by the equation:

$$E_{dg(t)} = E_{dgload(t)} \leq DG_{KW}.X_G \quad (17)$$

$$E_{dg(t)} = E_{dgload(t)} = 0 \quad \text{or} \quad = [TPL,\ DG_{KW}.X_G] \quad (18)$$

Where, $E_{dg(t)}$ is energy produced, $E_{dgload(t)}$ is energy produced and routed to load in hour t by DG. DG_{KW} and X_G are the rating and number of units of DG respectively. The equation (18) states that the power generation from DG at any hour t can take the value of zero or any value between 'threshold power level' (TPL) and nominal capacity of DG system, provided the DG option is opted in the program. Threshold power level is load on DG (expressed in terms of percentage of nominal capacity of DG) below which generator operation becomes uneconomical.

3.5 DC to AC converter

DC to AC converter (i.e. inverter) used in hybrid systems is selected on the basis of peak load demand so that it is capable to supply the reactive power to the load as and when needed. The efficiency of inverter is a function of the ratio of the actual load (i.e. output of inverter P_{out} to the inverter input P_{in}) .Thus; an accurate inverter model is needed. The efficiency of inverter is defined as [15]:

$$\eta_{inv} = \frac{P_{out}}{P_{in}} \tag{19}$$

The input power is written in terms of out put power as:

$$P_{in} = P_{out} + P_L \tag{20}$$

Where, P_L is the power loss in the converter approximated by two constants K_1 and K_2 as:

$$P_L = K_1 + K_2 p \tag{21}$$

Where p is the ratio of converter output put power (P_{out}) and nominal power (P_n). The constant K_1 is independent of load and constant K_2 includes load dependent loss. These constants are evaluated as [16]:

$$K_1 = \frac{1}{99}\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9\right)^2, K_2 = \frac{1}{\eta_{10}} - K_1 - 1 \tag{22}$$

Where, η_{10} and η_{100} are the efficiencies of inverter at 10% and 100% of inverter nominal power respectively. The inverters designed by standard manufacturers normally provide the values of these efficiencies.

4 System design criteria

The techno-economic design of hybrid system has been done using the concept of loss of power supply and life cycle cost calculation as technical and economical criteria.

4.1 Technical criteria

Reliability parameter is very important in case of autonomous hybrid power system design. In this paper, concept of loss of power supply probability (LPSP) is used to express the reliability of system. The LPSP is defined as the ratio of all energy deficits to the total load demand during the considered period. A LPSP of zero means the load will be always satisfied, and LPSP of one means that the load will never be satisfied [14].

$$LPSP = \sum_{t=1}^{T} LPS(t) \Big/ \sum_{t=1}^{T} El(t) \tag{23}$$

$$LPS(t) = El(t) - (Eg(t) - Eb(t-1) - Ebmin)\eta_{inv} \tag{24}$$

Where, $LPS(t)$ is the loss of power supply during hour t and T is the total number of hours within one year. The loss of power supply as defined here does not include the energy deficit due to component breakdown or maintenance down time. It is only related with the capacities of energy sources and load demand.

4.2 Economical criteria

Economics plays an integral role in both, in simulation process wherein it operates the system so as to minimize the total life cycle cost, and in its optimization process, wherein it searches for system configuration with the lowest total life cycle cost. The life cycle cost calculation includes the initial cost of construction, component replacement, maintenance and fuel cost and miscellaneous cost such as emission /penalty cost resulting from pollutant emission / load unmet.

In this study, the life cycle cost (LCC) calculation is done only for those system configurations that satisfy customer desired reliability criteria. Therefore, initially the unit sizing program is run to get these combinations, and thereafter the program is extended to evaluate the LCC of such combinations. The LCC of system without any other miscellaneous cost is calculated as [17]:

$$LCC=\frac{ACC}{CRF} \tag{25}$$

$$ACC=CC+OMC+RC+FC \tag{26}$$

Where, ACC is the annual cost of configuration, CRF is the capital recovery factor, ACC is the sum of annual capital costs (CC), operation & maintenance (OMC), replacement cost (RC), and fuel cost (FC) of all system components. The annual cost can be found by multiplying the initial cost by the capital recovery factor (CRF).The CRF is defined as:

$$CRF\left(i_{r,}ny\right)=\frac{\left[i_r\left(1+i_r\right)^{ny}\right]}{\left[\left(1+i_r\right)^{ny}-1\right]} \tag{27}$$

Where $i_{r,}$ is the annual interest rate, ny is the life of the system. Following expressions are used for the calculation of annual fuel cost (FC) and replacement cost (RC) in equation (26).

$$FC=\left(DG_{KW}F_o+F_iP_{DG}\right)N_{DGH}\ C_{fuel} \tag{28}$$

$$RC_k=C_{REP}F_{REP.}SFF\left(i_r,nc\right)-SFF\left(i_r\ ,\ ny\right)\ SVC \tag{29}$$

Where, DG_{KW} is the rating of generator, F_o is no load fuel consumption of DG, F_i is the incremental fuel consumption rate (liter/hour), P_{DG} is DG output (KW), N_{DGH} is the number of operating hours, and C_{fuel} is the cost of fuel (USA \$/liter). RC_k is the annual replacement cost of system component 'k', C_{REP} is the replacement cost, F_{REP} is the replacement factor, SFF is sinking fund factor, nc is life of component, and SVC is the salvage value of component. The detailed description of the parameters used in equation (28) and (29) can be found in [18]:

4.2.1 Low reliability penalty cost

A new penalty function is used to measure the system reliability in terms of either loss/gain of revenue. An appropriate weight is introduced in the cost function that is inversely proportional to the level of system reliability using the equation:

$$P_c = 5.LCC\left[1\text{-}R\right]^{1.75} \tag{30}$$

$$R=\left[1\text{-}LPSP\right] \tag{31}$$

Where, P_c is the penalty cost, R is reliability level of system. This penalty cost representing reliability level of system is added in the LCC of system, to find optimal system configuration.

4.2.2 Pollutant emission cost

When the fuel combustion takes place in diesel generator, numbers of emission (gases) are produced. Percentage of carbon dioxide (CO_2) is largest amongst these emissions. Due to this reason the amount of carbon dioxide production only is considered to find emission cost in this study. The CO_2 emission cost is calculated on the basis of price of tradable renewable certificate using following equations:

$$CO_{2weight} = \left(C_{content} \cdot P_{DG}\right) / 1016.04 \tag{32}$$

$$CO_{2tax} = \left(PTRC / C_{content}\right).1016.04 \tag{33}$$

$$E_c = CO_{2weight}.CO_{2tax} \tag{34}$$

Where, E_c is the cost of emission, $C_{content}$ is the carbon content taken as 0.6078 Kg per KWh, PTRC is the price of tradable renewable certificate (US$/KWh). $CO_{2weight}$ is taken in tons, and CO_{2tax} has been calculated in terms of US dollars per ton. Finally this cost of emission is also added in the annual cost to the customer (ACC) to calculate LCC of system in equation (35).

5 Simulation

The mathematical models of different system components developed in the preceding sections are used for simulating the hybrid power system. The whole simulation process is broadly divided in to three parts:

(1) Inputs-
- System Configuration Specifications: PV module, wind and diesel generators, battery bank, balance of system (BOS).
- Power converting equipments rating and their efficiencies.
- Load Data : Appliances and their daily use
- Resource Data : Wind speed, solar insolation data

(2) Supporting data-
- System capital cost, Installation cost, O&M cost, fuel cost, system replacement cost, system salvage value, discount rate, project life time and environmental costs values.

(3) Output-
- Life cycle cost (LCC), reliability(R), per unit cost of energy (COE), battery bank life (BBL), excess energy, diesel generator operating hours.

5.1 Objective function

The major concern in the design of any energy system using renewable energy sources is the accurate selection of system components that can economically satisfy the load demand. Hence, system's components are found subject to:

1. Minimizing an objective function representing life cycle cost (LCC) of hybrid system.
2. Ensuring that the load is served according to a certain desired reliability criteria.

The objective function to find the optimal configuration to satisfy the demand of customer at desired reliability level with minimum cost is defined as:

Minimize:

$$ACC=\sum_{k}(CC_k+OMC_k+RC_k+FC_k)X_k+E_c+P_c \tag{35}$$

Where, the index ' k ' is made to account for wind, photovoltaic, diesel generator, and battery. X_k is the decision variable representing the number of generating units of k , E_c is cost of emission, and P_c is penalty cost for load unmet.

5.2 Constrains

The load must be satisfied according to a certain reliability criteria. Hence, for an autonomous system:

$$E_{g(t)}+N_{DGH}DG_{KW}+FC_bN_bC_b+LPS(t)\geq El(t) \tag{36}$$

$$Eg(t)+N_{DGH}DG_{KW}+FC_bN_bC_b \leq El(t) \tag{37}$$

$$[1\text{-}LPSP]\geq R \tag{38}$$

Where, N_{DGH} is the number of operating hours of DG, DG_{KW} is the rating of DG, FC_b is the fraction of the battery capacity expected to discharge in each period, N_b is the number of battery used, C_b is the capacity of each battery, $LPS(t)$ is the deficit of power during hour t .

5.3 Selection of wind turbine generator

A new approach for automatic wind turbine generator (WTG) selection has been introduced in this work. Computational model automatically selects the most appropriate WTG to be used with system for a particular site. It does so by matching the rated wind speed of all WTG available in the data bank; with optimum wind speed calculated using the equation given below [13]:

$$V_{opt}=c\left[\frac{1-k}{k}\right]^{1/k} \text{m/s} \tag{39}$$

Where, V_{opt} is the optimum wind speed, c and k are the weibull parameters. For the annual energy output, WTG so selected essentially has highest capacity factor.

5.4 Power dispatch strategies

The power dispatch strategies used in this work are based on the strategies reported by C.D. Barley in [19] and used in [18] with certain minor modifications. These strategies are categorized as load following strategy and cycle charging strategy. The main difference between these two strategies is that in case of load following strategy the DG is used only to cover the net load (i.e. load minus energy produced by renewable generators)where as in case of cycle charging strategy the DG covers the net load and recharge the battery bank also. Thus, in load following strategy, the battery bank is supposed to be recharged by renewable generators. This would be possible during those hours only, when net load is negative. In that case battery cycling will be less intensive. Therefore, with this strategy the controller used in the hybrid power system must be able to prevent the battery bank from being a longer period on a low state of charge.

The goal of each dispatch strategy is to minimize the operating cost of system. In both kinds of strategies, frugal option and SOC set point option can be chosen. Using frugal option, the 'threshold power level' below which it is more economical to use stored energy than diesel power can be calculated as:

$$P_F=F_0\Big/\left[\left(C_{BW}\big/C_{fuel}\right)-F_i\right] \tag{40}$$

Where, P_F is the frugal discharge threshold power, F_0 is diesel generator fuel consumption at no load (liters/hour/KW), C_{BW} is the battery wear cost (US$/kWh), C_{fuel} is diesel fuel cost ($/liter), and F_i is the incremental fuel consumption rate (liters/hour/KW).The dispatch controller ensures that the stored energy in battery bank is used only to meet net load below this 'threshold power level'. Hence, frugal option never allows the battery storage to meet the load, when it would be cheaper to use DG power instead. The detail description of these strategies can be found in [20].

5.5 Optimization procedure

An iterative optimization technique is used to find the optimal design of hybrid renewable power system in this work. The programming has been done in MALAB7.0 using M-files. Energy balance calculation method using deterministic approach with one hour time step is employed for simulation. This procedure presents the following major steps to be adopted for calculation in each time step:

1. Read the input data and supporting economical data as mentioned in the section
2. Select the most appropriate WTG for the site using wind data and equation (39).
3. Calculate the power produced by PV and WTG system using equations (8) and (9) respectively for every hour of the year.
4. Select first the diesel generator option (YES/NO) 'NO' in hybrid system algorithm.
5. Calculate the SOC level of battery bank storage using the equations (10)-(12).
6. Enter the maximum and minimum number of PV modules and battery to be used for simulation and calculate the reliability levels to be achieved with all the possible combinations of number of batteries, PV modules, with fixed capacity of wind system using equation (23) and (31).
7. Choose the reliability level desired by customer amongst all found in previous step.
8. Extract all the combinations satisfying the desired reliability level of the customer.
9. Calculate the penalty costs of all extracted combinations using equation(30)
10. Find the life cycle cost (LCC) of combinations using economic parameters given in Table I and equations (25)-(27) Note that, cost of emission (E_c) in objective function will be zero because option chosen in step 4 is 'NO'
11. Find the optimal configuration satisfying reliability level of customer with minimum cost.

In case diesel generator option 'YES' is chosen in step 4, design procedure will require certain modification as given below:

- Calculate the net load as load demand minus combined PV and WTG power.
- If net load is less than zero, battery bank will start charging through renewable power. In case, battery bank is full excess energy is either utilized by second priority load or consumed in dump load.
- If net load is greater than zero but lesser than critical charging load, diesel generator will operate in cycle charging mode otherwise in load following model [20].
- Follow the steps 5-6 and ignore the steps 7-9 as the reliability level and penalty cost with diesel generator will always be hundred percent and zero respectively.
- Follow the steps 10-11 with modifications in the calculation of LCC, as cost of emission will now be included in objective function. Obtain the optimal combination having minimum cost found in step 11.It is to note that, the value of P_c in this case will be zero.

6. Case study

This case study utilizes resource data of a typical Indian site (Bondhina) located in Ratlam district at the altitude of 560 meters above sea level. The latitude and longitude of the site are 23° 12' north and 77° 24' east respectively .This site has a good wind régime for the design of renewable hybrid system. Metrological data used in this study were taken during July 2001 to June 2002. The annual hourly average data of solar insolation and wind speed at 25 meters, of above site are depicted in Fig. 2. Typical load demand profile of a residential building situated in Bondhina is shown in Fig. 3. Energy balance calculation method using one hour time step is employed for optimization. It is assumed that during this time step of one hour the energy produced by solar and wind system and the load demand of consumer will not change. Energy produced by each renewable power generator is shown in Fig. 4. It is observed that the solar and wind energy are complementary to each other in this site.

The energy output of PV and WTG systems are obtained using annual hourly average metrological data. Specifications of system components, and other input parameters used in the case study are given in Table 1.

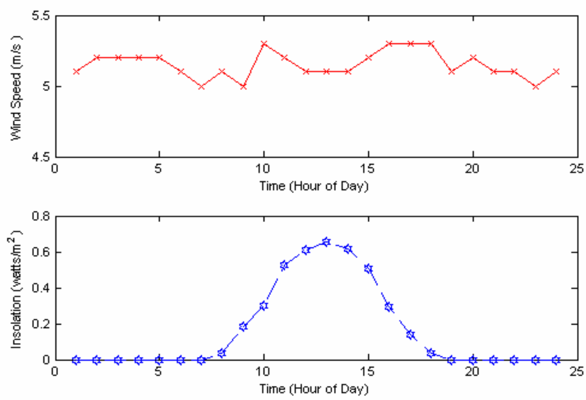

Fig.2 : Resource input data of typical Indian site (Bondhina)

Optimization results obtained for 95% reliability level in each type of system are presented in Table 2. Pure wind system has been found most cost effective for the site. This is due to good wind regime prevailing in this site. The LCC of other two (Pure PV and PV-wind hybrid) systems are unjustified. Nevertheless, the PV-wind system LCC is acceptable in case of autonomous system. Energy balance calculation result of optimal PV-wind system is shown in Fig. 5. Fig. 6 shows the application of novel penalty function in cost calculation. It is to note that penalty cost decreases with increase in reliability level of hybrid system.

The contribution of each renewable power generator, battery bank and DG using cycle charging and load following strategy is shown in Fig.7 and Fig.8.The optimization results with these strategies are given in Table 3. It is observed that load following strategy is cheaper than cycle charging strategy.

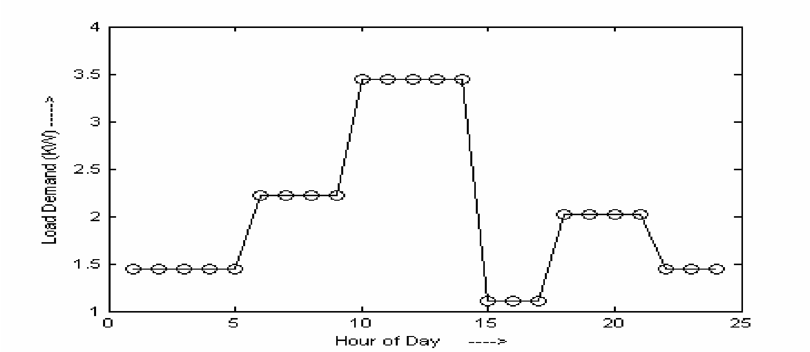

Fig. 3 : Typical load demand profile of a residential building

It is interesting to note that weight of CO_2 produced in case of load following strategy is 6.98 tones only despite of more than double number of diesel operating hours in contrast to cycle charging strategy. This is true because CO_2 production is based on actual load shared by the generator during an hour. It is to reiterate that during cycle charging operation diesel generator always runs at rated power as shown in Fig. 7.

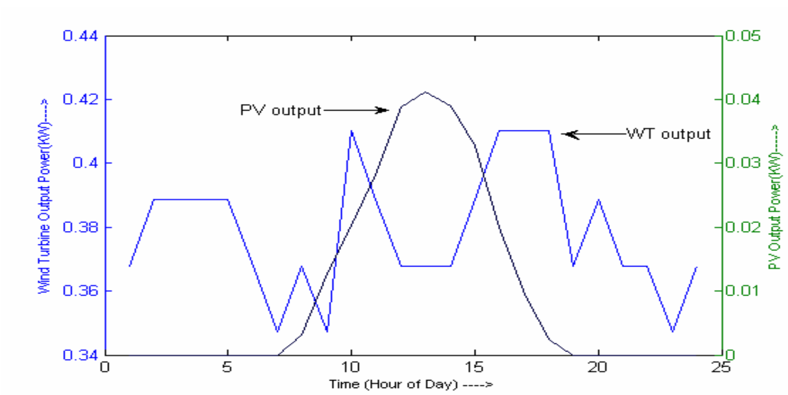

Fig. 4 : Power output of a wind turbine and PV module

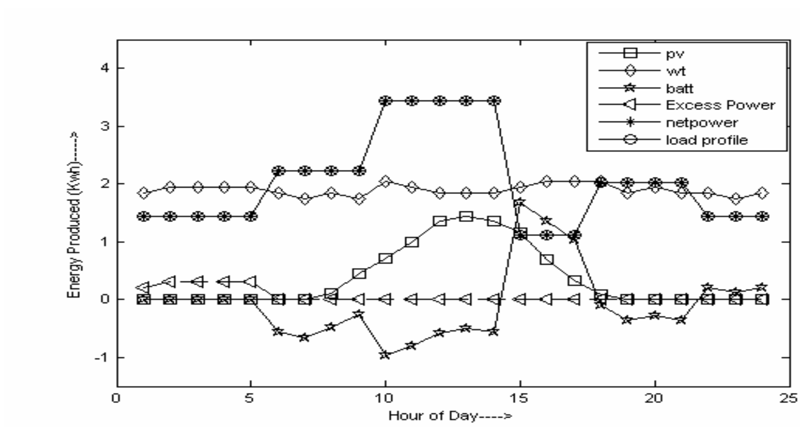

Fig. 5 : Energy balance calculation results of PV-wind system

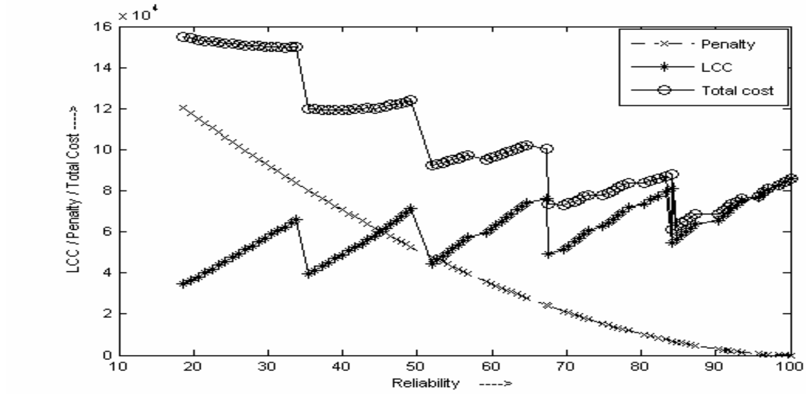

Fig. 6 : Reliability verses cost relationship with penalty function

Table 1 **:** Input data /other parameters used in case study

Wind Turbine (BWC XL1) Specifications: Rated output =1 KW, Cut-in speed = 2.5 m/s, Rated speed =11 m/s, Cut-out speed = 13 m/s, Rotor diameter = 2.5 m/s, Air Density = 1.225 kg/m^3. Five numbers (fixed capacity 5KW) of wind turbines are considered to design the system. Capital cost of each wind turbine is calculated @ \$ 2.59 per watt. The other costs in terms of percentage of wind turbine cost are : Tower cost 20%, installation and civil work 10%, annual operation and maintenance cost 3% and replacement cost (optional) equal to cost of wind turbine. Turbine hub height and life span are 30 meters and 25 years respectively.
Battery (Deep cycle Type) Specifications: Nominal Voltage = 6V, Nominal capacity=225 Ah (1.35 KWh) Life time throughput = 815 KWh Floating life of battery = 5 years Efficiency = 92% Depth of discharge allowed =70% Capital cost of battery is calculated @ \$200 per KWh. Other costs in terms of its percentage cost are: Shelter cost 1%, yearly O&M cost 2%, whereas replacement cost equates to its capital cost.

Diesel Generator Specifications: Nominal capacity = 5 KW No load Fuel consumption = 0.071 Incremental fuel consumption = 0.410 Life time operating hours (LTOH) =15000 Minimum load on generator to run = 30% of generator capacity Capital cost of diesel generator is calculated @ $ 0.550 per watt. Other costs in terms of its capital cost are: installation plus shelter cost 10%, O&M cost $0.148 per hour fuel cost $ 0.70 per litre and replacement cost equal to generator capital cost.
Converter & other parameters Specifications: Size = 5 KW Life span = 10 years Efficiency (10/100) percent of load = 92% and 96% Project life =25 years Real rate of interest = 8% Price of PTRC= $ 0.050 per KWh Carbon content =0.6078 Kg per KWh Capital cost of converter is calculated as $1.76 per watt out of which $ 0.96 per watt is meant for system controller (which has not been considered separately).Replacement cost of converter is $0.8 per watt. Yearly O&M cost of converter is 1.5% of its capital cost.

Table 2 **:** Optimization results without generator#

Sr. No	System type	Configuration			LCC (US$)	COE (US$)	BBL. (YRS)
		N_b	N_{PV}	N_{WT}			
1	Pure-Wind	09	00	06	42581.7	0.23	3.1
2	Pure -PV	38	144	00	144207.6	0.56	3.5
3	PV-Wind	18	34	5	79248.80	0.41	2.3

Reliability level 95%

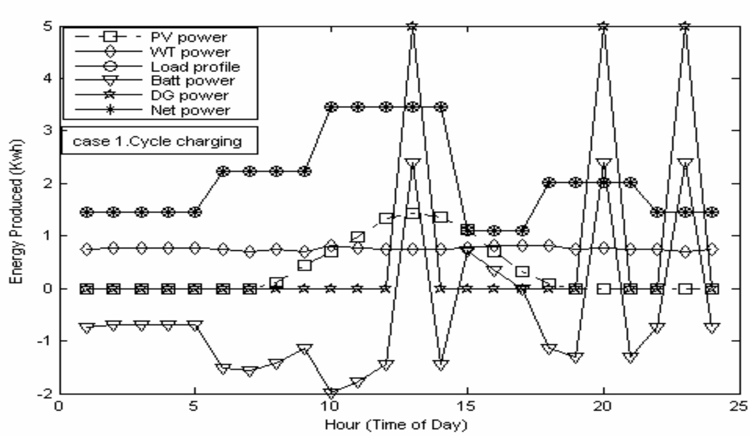

Fig. 7 : Energy balance calculation results with load cycle charging strategy

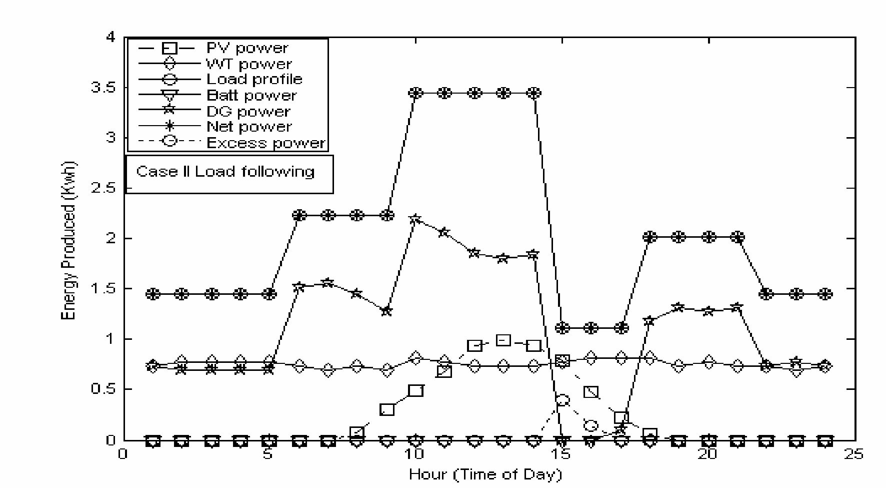

Fig. 8 : Energy balance calculation results with load following strategy

Table 3 : Optimization results with generator strategies#

Number of:			LCC (US$)	COE (US$)	Generator Operating Hours	CO_2 Emission	Strategy Type
BATT.	PV	WTG					
17	23	2	108242.2	0.47	2424	7.30	Cycle Charging
00	16	2	88696.72	0.42	6629.00	6.98	Load following

#Reliability level 100%

8.0 Conclusion

In this paper, an optimization model named as renewable energy analysis and sizing tool (REAST) is developed. REAST utilizes the new mathematical models to asses the solar and wind energy. A novel penalty function is employed to account the low penalty cost for high reliability level and vice versa. Selection of suitable wind turbine for the site under consideration is automatic. The cost of energy for any hybrid system configuration satisfying a desired reliability level depends on renewable energy potential quality and strategy used for its operation. REAST has been found very useful to find the optimal components sizes and to evaluate the performance of a renewable hybrid energy system.

9.0 Acknowledgement

Authors gratefully acknowledge the support of Dr. Siraj Ahmed, Associate Professor Mechanical Engg. Department, MANIT, Bhopal (India) for providing resource input data of the site.

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