

Photovoltaic Hybrid Systems Reliability and Availability

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ABSTRACT

Reliability, availability, and cost have been the major concerns for photovoltaic hybrid systems since their beginning as primary sources for much critical applications like communication units and repeaters. This paper describes the performance of two hybrid systems; photovoltaic-battery, wind-turbine coupled with the public-grid (PVBWG) hybrid system and photovoltaic-battery, wind-turbine coupled with the diesel generator (PVBWD) hybrid system. The systems are sized to power a typical 300W/48V dc telecommunication load continuously throughout the year. Such hybrid systems consist of subsystems, which in turn consist of components. Failure of any one of these components may cause failure of the entire system. The reliability and availability basics, and estimation procedure for the two proposals are introduced also in this paper. The PVBWG and PVBWD system configurations are shown with the relevant mean-time-between-failure (MTBF) and failure rate (λ) of each component. The characteristics equations of the two systems are deduced as a function of operating hours and the percentage of sun and wind availabilities per day. The system probability failure as well as the reliability is estimated based on the fault tree analysis technique. The results show that, by using standard or normal components MTBF, the PVBWG is more reliable and the time of periodic maintenance period is more than one year especially in the rich sites of both sun and wind, but PVBWD competes else. Also, in the first five years from the system installation, the system is quit reliable and may not require any maintenance. The results show also, as the sun and wind are available, as the system reliable and available.

Keywords: PV, Wind, Reliability, Hybrid Systems, Fault Tree

1. Introduction

The telecommunication systems are considered one of the most critical loads in the application of the PV systems, and should have absolute reliability. Loss of load for such systems may contribute a great operation problem. For this reason such a PV-hybrid complex systems are used to

assure the required degree of reliability. The renewable energy sub-systems PV array and wind turbine could supply the load requirements alone while the public grid terminal or the Diesel generator unit is present as a back-up sub-system to power the load and charge the storage battery in the case of insufficient or neither sun nor wind are available.

The size of the system components are estimated as shown in the following data:

- The PV array consists of 18 modules with 110 W_p each (1980W_p total) at standard test conditions (STC),

1000W/m² and 25 °C. The PV array is divided into 9 strings, each string compose two series modules to reach the system bus voltage 48V.

- The wind turbine has a 750W_P at 9.5 m/s wind speed (nominal value) attached with a mechanical system to control the rotor speed, and hence the output voltage and frequency. The generator is connected by a power conditioning circuit, which compose an AC/DC converter followed by a DC/DC converter to regulate the output voltage from the wind generator.

- A storage battery sub-system consists of 4 batteries with 230 Ah each at 12V rating, with a total capacity 11.04 kWh,

- A redundant, local and remote system controller controls the system. The local controller is used to manage the system operation while the remote controller can interact in the case of local controller failure or missing the power supply^{[1][2]}.

2. System Operation Algorithm

The system configuration is shown in Figure 1. The PV array and the wind generator are connected in parallel with the battery bank, which can be charged in emergency cases from the public grid. The output power from the PV array is controlled by the digital shunt regulator connected in parallel with the PV array. Inserting a fast schotcky diode between them prevents the reverse operation between the PV array and the wind generator. A microcontroller board controls all the system components and the system operation is monitoring remotely by another controller through a modem and a telephone cable. The remote controller can shutdown or restart the local system as well as control the switches between the different system components. It is also able to change the system mode of operation. The remote control has the ability to sense and record the different system variables as well as to get a database from the renewable sources, sun and wind.

3. System Reliability Study

To study the system reliability, the system functional block diagram is created from the general one to show the

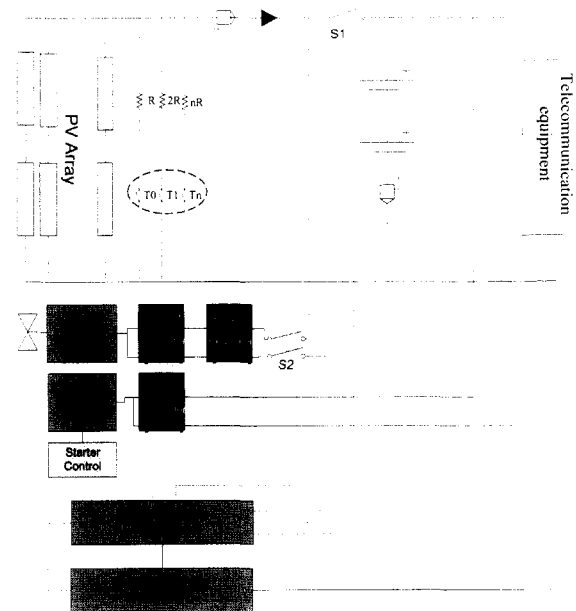


Fig. 1. The general hybrid system block diagram.

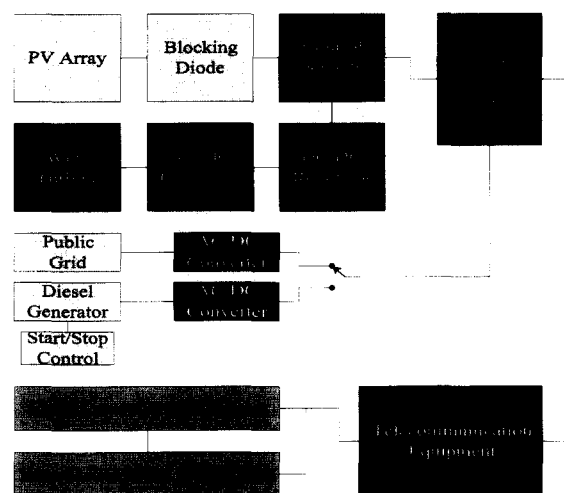


Fig. 2. PVBWD and PVBWG systems functional block diagram.

weight and the actual position of each component in the system. Figure 2 shows the functional system block diagram where each component is present in the relevant place and takes a sequence number, which will be used to deal about it in the fault tree diagram. In this diagram, the transfer switch configure the either the PVBWD or the PVBWG hybrid system. The list of the system components and their mean time between failure (MTBF) and failure rate are present in Table 1.

Table 1. the system components list with its MTBF's and λ 's.

Item Nr	Item Description	MTBF's (hrs)	Failure rate $\lambda(*10^{-6})$
1	PV array	87600	11.416
2	Blocking Diode	40000	25.000
3	Wind Turbine	8760	114.160
4	AC/DC Con.1	20000	50.000
5	DC/DC Con.	10000	100.000
6	Power Switch	30000	33.333
7	Starter control	25000	40.000
7'	Public grid	1000000	1.0
8	Diesel Gen.	20000	50.000
9	AC/DC Converter.	25000	80.000
10	Storage Battery	30000	33.333
11	Local Controller	17520	57.078
12	Remote Cont.	17520	57.078

The MTBF's data are obtained from different sources; pilot plants data, PV components manufactures data sheets and field experience^{[3]-[6]}.

4. Fault Tree Analysis of the PVB Hybrid System

The fault tree analysis is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event. A fault tree thus depicts the logical inter-relationships of basic events that lead to the undesired event to the fault tree. The reliability logic diagram of fault tree represents the effect of subsystem failure (at the bottom of the tree) on overall system failure to deliver power to the load (at the top of the tree)^[7]. The fault tree diagram of the proposed PVBWD hybrid system is shown in Figure 3. It should be noted that the existence of the PV array or the wind turbine generator depends on the availability of the renewable energy sources sun and wind, so the fault tree analysis should include the different modes of the system operation^{[8][9]}.

5. System Reliability Calculation

In this section, the PVBWD characteristic equation will be estimated depends on the following modes of operation:

List of the System Components:

- 1- PV Array,
- 2- Blocking Diode,
- 3- Wind Turbine,
- 4- AC/DC Converter [1],
- 5- DC/DC Converter,
- 6- Control Switch S1,
- 7- Starter Control,
- 8- Diesel Generator,
- 7'- Public Grid Terminal,
- 9- AC/DC Converter [2],
- 10- Storage Battery Bank,
- 11- Local System Controller,
- 12- Remote System Controller.

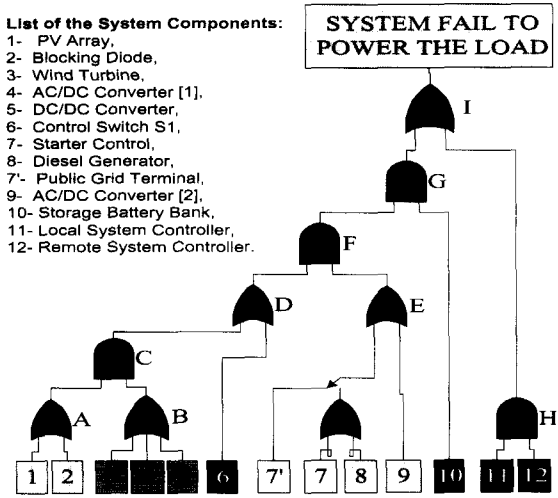


Fig. 3. The fault tree diagram of the proposed PVB hybrid system.

1. Sun as well as wind is available,
2. Sun available but wind is not available,
3. No sun but wind is available, and
4. Neither sun nor wind is available.

In this study, the parameter σ is used to deal with the sun-available percentage as the parameter ω is used to deal with the wind-available percentage. The partial time, which used to calculate the partial reliability part can be deduced from the following state Table 2. The summation of the different partial times should be equal to the overall period of operation time t .

The probability that item of equipment will work successfully (item reliability $R(t)$) is described by:

$$R(t) = e^{-\lambda t} \quad (1)$$

where, λ is the failure rate, and

t is the time of successful operation.

Table 2. The partial time of the different operating states.

Sun	Wind	Partial Time
1	1	$\sigma.\omega.t$
1	0	$\sigma.(1-\omega).t$
0	1	$(1-\sigma).\omega.t$
0	0	$(1-\sigma).(1-\omega).t$

The item of equipment reliability can be expressed as a polynomial as follows:

$$R(t) = 1 - \lambda t + (\lambda t)^2/2! - \dots + \dots \cong 1 - \lambda t$$

The complement of the item of equipment reliability is the probability failure of such item which defined as $F(t)$, where,

$$F(t) = 1 - R(t), \text{ then } F(t) = \lambda t$$

The sub-systems probability failure can be estimated as follows:

- For the series components, the sub-system probability failure is:

$$F(s)_S = \sum_{i=1}^n \lambda_i * t, \text{ while}$$

- For the redundant components, the sub-system probability failure is:

$$F(s)_R = \prod_{i=1}^n \lambda_i * t.$$

where, i is the item number, $i = 1 : n$,

n is the number of sub-system items.

In the following, the system probability of failure at different modes of operation will be introduced based the fault tree diagram shown in Figure 3.

6.1 Mode 1, Both-Sun and-Wind are available

$$F(A) = K1 \sigma \omega t$$

$$F(B) = K2 \sigma \omega t$$

$$F(C) = K1 K2 (\sigma \omega t)^2$$

$$F(D) = K1 K2 (\sigma \omega t)^2 + \lambda_6 \sigma \omega t$$

$$F(E) = K3 \sigma \omega t$$

$$F(F) = K1 K2 K3 (\sigma \omega t)^3 + K4 (\sigma \omega t)^2$$

$$F(G) = K5 (\sigma \omega t)^4 + K6 (\sigma \omega t)^3$$

$$F(H) = K7 \sigma \omega t$$

$$F(I1) = K5 (\sigma \omega t)^4 + K6 (\sigma \omega t)^3 + K7 \sigma \omega t$$

6.2 Mode 2, Sun-Available but no Wind

$$F(A) = K1 \sigma (1-\omega) t$$

$$F(B) = 1$$

$$F(C) = K1 \sigma (1-\omega) t$$

$$F(D) = K8 \sigma (1-\omega) t$$

$$F(E) = K3 \sigma (1-\omega) t$$

$$F(F) = K9 (\sigma (1-\omega) t)^2$$

$$F(G) = K10 (\sigma (1-\omega) t)^3$$

$$F(H) = K7 \sigma (1-\omega) t$$

$$F(M2) = K10 (\sigma (1-\omega) t)^3 + K7 \sigma (1-\omega) t$$

6.3 Mode 3, No-Sun but Wind-Available

$$F(A) = 1$$

$$F(B) = K2 (1-\sigma) \omega t$$

$$F(C) = K2 (1-\sigma) \omega t$$

$$F(D) = K11 (1-\sigma) \omega t$$

$$F(E) = K3 (1-\sigma) \omega t$$

$$F(F) = K12 ((1-\sigma) \omega t)^2$$

$$F(G) = K13 ((1-\sigma) \omega t)^3$$

$$F(H) = K7 (1-\sigma) \omega t$$

$$F(I3) = K13 ((1-\sigma) \omega t)^3 + K7 (1-\sigma) \omega t$$

6.4 Mode 4, Neither-Sun Nor-Wind is Available

$$F(A) = F(B) = F(C) = F(D) = 1$$

$$F(E) = K3 (1-\sigma) (1-\omega) t$$

$$F(F) = K3 (1-\sigma) (1-\omega) t$$

$$F(G) = K14 ((1-\sigma) (1-\omega) t)^2$$

$$F(H) = K7 (1-\sigma) (1-\omega) t$$

$$F(I4) = K14 ((1-\sigma) (1-\omega) t)^2 + K7 (1-\sigma) (1-\omega) t$$

6.5 System probability failure and characteristics equation

The overall system probability failure is the summation of partial system probability failures, so the system probability failure can be expressed as follows:

$$\begin{aligned} F(S) &= F(I1) + F(I2) + F(I3) + F(I4) \\ F(S)_{PVBWD} &= K5 (\sigma \omega t)^4 + K6 (\sigma \omega t)^3 + K7 \sigma \omega t \\ &\quad + K10 (\sigma (1-\omega) t)^3 + K7 \sigma (1-\omega) t \\ &\quad + K13 ((1-\sigma) \omega t)^3 + K7 (1-\sigma) \omega t \\ &\quad + K14 ((1-\sigma) (1-\omega) t)^2 + K7 (1-\sigma) (1-\omega) t \end{aligned}$$

By the similar way, the PVBWG hybrid system can be expressed as follows:

$$\begin{aligned}
F(S)_{PVBWG} = & K10(\sigma.\omega)^6 * t^6 + [K11(\sigma.\omega)^5 + K17(\sigma.(1-\omega))^5 \\
& + K21((1-\sigma).\omega)^5] * t^5 + K23((1-\sigma).(1-\omega))^4 * t^4 \\
& + K12[(\sigma.\omega)^3 + (\sigma.(1-\omega))^3 + ((1-\sigma).\omega)^3 \\
& + ((1-\sigma).(1-\omega))^3] * t^3 + K13 * t.
\end{aligned}$$

where, K's are a coefficient related to the components MTBF's.

6. Conclusion

The PVBWD & PVBWG hybrid systems reliability and availability are examined. The characteristics equation of each system is deduced and expressed as a function of the operating hours, sun and wind availabilities. The results are shown in the following six Figures (4-9) based on the percentage availability of both sun and wind. Three modes of operation are included; 0 % sun & 60 % wind (Figures 4, 7), 60 % sun & 0 % wind (Figures 5, 8), and 60 % sun & wind (Figures 6, 9).

The results show that PVBWD system is the most relevant choice in the poor regions of the renewable sources, since the system reliability and the expected MTBF's are larger compared to the other system. While the PVBWG is the best choice in the rich regions of any of the renewable source, solar or wind.

The results show also that the worst MTBF is about 5000 hrs while the best MTBF is about 11000 hrs of operation; this means that minimum periodic maintenance time is 5000 hrs.

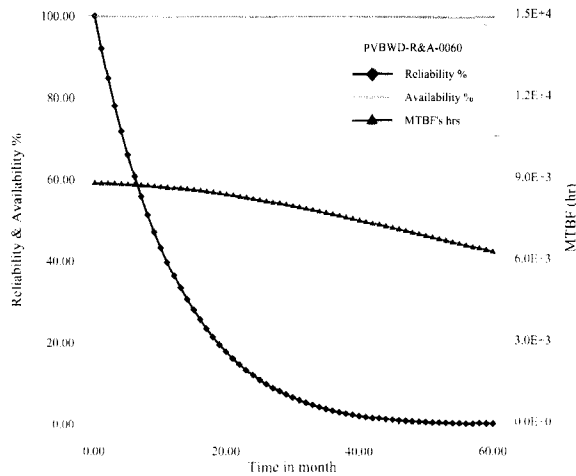


Fig. 4. PVBWD system's reliability, availability and MTBF in windy regions.

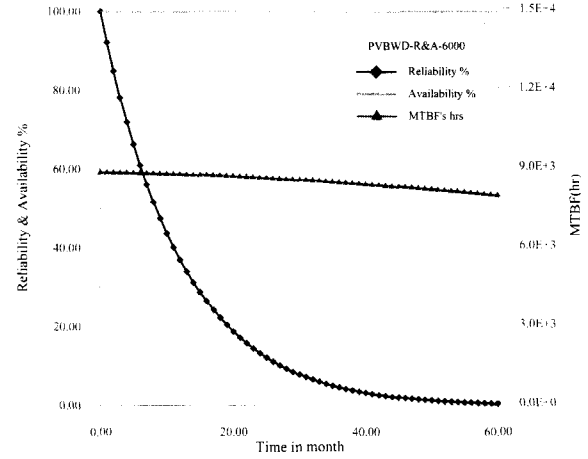


Fig. 5. PVBWD system's reliability, availability and MTBF in sunny regions.

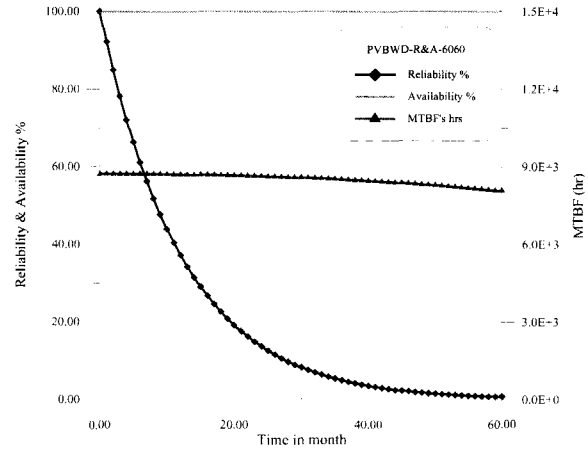


Fig. 6. PVBWD system's reliability, availability and MTBF in sunny and windy regions.

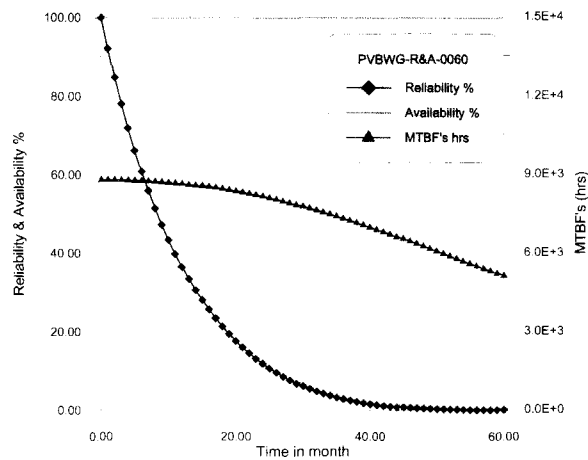


Fig. 7. PVBWG system's reliability, availability and MTBF in windy regions.

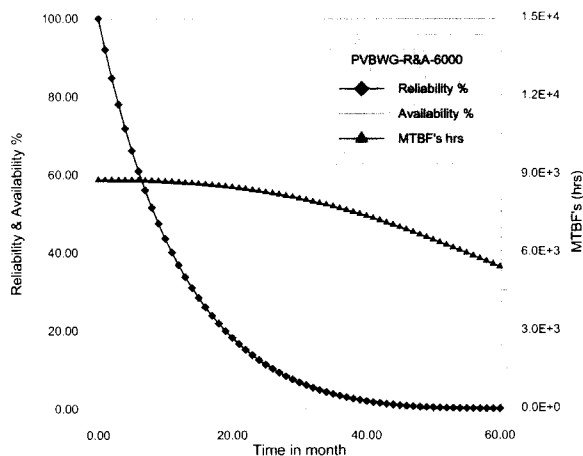


Fig. 8. PVBWG system's reliability, availability and MTBF at sunny regions.

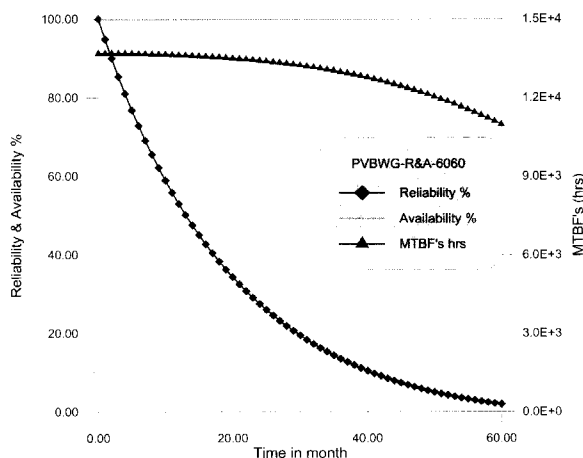


Fig. 9. PVBWG system's reliability, availability and MTBF at sunny and windy regions.

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