Reliability Assessment of Battery-Assisted and Electrolyser-Battery Integrated PV Systems for Off-Grid Applications*

¹J. K. Annan, ²F. B. Effah and ³J. E. Quaicoe

¹University of Mines and Technology (UMaT), P. O. Box 237, Tarkwa, 00233, Ghana ²Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana ³Memorial University of Newfoundland and Labrador (MUN), Engineering Faculty, St. John's, Canada

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Abstract

Solar Photovoltaic (PV) systems are usually the most obvious choice of renewable electrical energy installations for electrical energy supply. PV systems are generally categorised as grid-connected or standalone systems. In many applications, the most common type of storage used in solar PV systems is chemical storage, in the form of battery units. This paper considers the use of an electrolyser as an alternative storage system to convert excess PV electrical output into hydrogen gas for later utilisation by Proton Exchange Membrane Fuel Cell (PEMFC). In this paper, PV system involving battery storage units are assessed along with PV system having electrolyser-battery integration in terms of their reliabilities. The assessment involves review of the schematics of the proposed PV configurations, the determination of component failure rates and the reliability modelling of the system. Reconfiguring the system into power delivery mode with power delivery routes and storage mode with storage routes, the reliabilities of the systems were obtained. Applying probabilistic approach, the reliability for the combined power delivery route was given as 0.853013 whereas the direct PV supply route, the battery supply route and the fuel cell supply route gave reliabilities of 0.802564, 0.81723 and 0.827821, respectively, for one year of the system life. The combined system reliability of the storage mode gave a value of 0.997483 whereas the battery storage route and the electrolyser storage route gave reliability estimates of 0.948448 and 0.930736, respectively. Further system analysis showed that the electrolyser-battery integrated system is more reliable but had some setbacks which included the fact that the battery had to charge after which the electrolyser could work. Again, the PV output should be greater than the load demand to enable the electrolyser work effectively. The electrolyser-battery integrated system is more applicable for large PV output system feeding varying loads at different periods.

Keywords: Reliability, Fuel Cell, Photovoltaic System, Fault Tree Analysis, Functional Block Diagram

1 Introduction

A typical photovoltaic system employs solar panels, each comprising several solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted or wall mounted. The mount may be fixed, or use a solar tracker to follow the sun across the sky (Anon., 2017a). Solar PV systems can be configured as grid-tie battery-free system or grid-tie batterybackup system. The grid-tie (intertied or utilityinteractive) battery-free PV system is simple, and does not provide effective backup power during power outage; even if the sun is shining and there is substantial power output from the PV panel. On the other hand, the grid-tie system, provided with battery backup, may be complex and relatively expensive but beneficial in powering some selected loads when the grid is down. Other configurations of the solar PV system include the off-grid or stand-alone PV System which incorporates large amounts of battery storage to provide power for certain number of hours or days and the direct PV system which, as simple as it is, directly connects the photovoltaic panel to a load such as motor or pump (Anon., 2017a). Storage in the PV system is usually a battery bank, typically lead-acid batteries; but other storage devices exist including fuel cell via an electrolyser (Anon., 2017c). In related articles, Golnas (2012) investigated into PV system reliability and realised that module failures represent a small fraction of identified issues while outages of mission-critical subsystems comprised 69% of identified service issues. He finally concluded that most of the issues manifest at the inverter. Srisaen (2006) also analysed the effects of PV grid-connected system location on power quality of both radial and loop operated distribution systems and concluded that the implementation of the PV grid-connected system could improve the power quality of a distribution feeder. Jahn (2004), the other hand, presented operational on performance results of grid-connected PV systems, as collected and elaborated from 334 PV installations in 14 different countries for the photovoltaic power systems programme of the International Energy Agency (IEA). Harb and Balog (2013) proposed a new methodology for calculating the mean time between failure (MTBF) of a photovoltaic module-integrated inverter (PV-MII). Using stress-factor reliability methodology Harb and Balog (2013) applied a usage model for the inverter to determine the statistical distribution of thermal and electrical stresses for the electrical

components and hence determined that the electrolytic capacitor is the most vulnerable component with the lowest MTBF. Giovanni et al. (2008) also provided an overview of the open problems related to PV power processing systems to ensure high efficiency and high reliability, thereby focusing attention of researchers on present and future challenges. Chan (2011) finally presented the reliability estimation of the power stages in three grid-connected photovoltaic systems namely integrated topology, two-stage configuration and a three-stage configuration. The researchers reviewed above, in one way or another, performed reliability analysis on certain parts of the PV system. This research is geared towards reliability estimation for two specific configurations of PV system based on storage devices employed.

2 Resources and Methods Used

This paper addresses means of reliably storing PV energy using either batteries or a combination of battery and electrolyser. Using fault tree analysis and failure analysis, the reliability of these two systems are estimated. Using MATLAB, predictive reliability estimates are assessed for specific applications. The aim is to ensure the most reliable configuration to be adopted for certain applications.

2.1 PV Configurations

The schematic diagrams of Fig. 1 and Fig. 2 show the PV configurations under consideration. In Fig. 1, battery is employed in the PV system to store excess energy with the help of the charge controller. In the circuit, the charge controller diverts excess electricity to the DC busbar when batteries are fully charged. In addition, the charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from batteries. It prevents overcharging and may protect against overvoltage, which can reduce battery performance or lifespan. It also prevents complete draining of battery, or performs controlled discharges to protect battery life. The inverter converts the DC output into AC and then distributed to specific AC loads (Anon, 2017d). In Fig. 1, the battery, representing battery bank, stores the required amount of energy for later use by specific load(s) when the there is no sunshine to ensure continuous PV panel output.

Fig. 2 shows another configuration which employs the use of battery bank together with electrolyser to store energy in the form of DC and in the form of H_2 gas respectively. This system is usually applicable in systems where power is used intermittently and where there is long period of idleness of power delivery by the PV system. A typical example is solar street lighting where the solar power is only required throughout the night. For such a system, power needs to be stored for the entire period of the day. If by any chance, the batteries get charges quickly, the electrolyser takes over to convert excess power into H_2 gas which is then utilised locally or remotely by fuel cell to produce power to feed other loads.

2.2 Reliability

Reliability describes the ability of a system or component to function under stated conditions for a specified period. Reliability is theoretically defined as the probability of success or as the frequency of failures (Anon, 2017e). Mathematically, reliability R(t) is a function of time and it is given by:

$$R(t) = 1 - F(t) \tag{1}$$

For a Constant Failure Rate (CFR) model, R(t) is given by:

$$R(t) = \exp\left[-\int_{0}^{t} \lambda dt\right] = e^{-\lambda t}, \quad t > 0 \quad (2)$$



Fig. 1 Schematic Diagram of PV System with Battery Storage Unit



Fig. 2 Schematic Diagram for PV System Integrating Battery – Electrolyser Storage Units

where F(t) is the Cumulative Distribution Function (CDF) or failure probability and λ (lambda) is the failure rate with the assumption that λ (t) = λ , at $t \ge 0$ for a CFR model. The Mean Time to Failure (MTTF) which is the average time that an item will function before it fails, is given by the expression:

$$MTTF = \int_{0}^{\infty} e^{-\lambda t} dt = \frac{1}{\lambda}$$
(3)

Design lifetime for a defined reliability function t_r is given as:

$$R(t_r) = e^{-\lambda t_r} = R \implies t_r = -\frac{1}{\lambda} \ln R \qquad (4)$$

2.2.1 Reliability of Systems

One approach to analyse a complex system is to apply a particular failure law to the entire system. An alternate approach is to determine an appropriate reliability model for each component of the system and by applying the rules of probability according to the configuration of the components within the system, compute the system reliability (Khan and Yang, 2015a). System reliability can be assessed by the following models as given by Ebeling (1997). Components within the system may be related to one another in two primary ways: in either serial or a parallel configuration. In serial configuration, all components are critical. If either of two components fails, the system fails. Its reliability block diagram is shown in Fig. 3.



a) Serial Configuration



b) Parallel Configuration

Fig. 3 Reliability System Configurations

For a serial configuration, the system reliability R_s is given as:

$$R_s(t) = R_1(t) \cdot R_2(t) \cdot R_3(t) \cdot \dots \cdot R_N(t)$$
 (5)

For parallel configuration, system reliability R_s is given in general as:

$$R_{s}(t) = 1 - \prod_{i=1,n} [1 - R_{i}(t)]$$
(6)

2.3 Reliability Block Model of the PV Configurations

The reliability block diagram focuses on the actual routes or possibilities taken for successful operation of a system. Considering the PV system configurations, successful operation on one hand, involves the satisfaction of DC or AC load demand. Using functional block models obtained from block diagrams, Annan (2017) developed the reliability block model of Fig. 4. From Fig. 4, various routes considered to successfully deliver AC power to load demand include:

- (i) Direct feeding of PV panel output to the inverter though a control unit,
- (ii) Stored energy in the battery feeding the inverter through a charge controller, and
- (iii) Stored H₂ gas used by Proton Exchange Membrane (PEM) Fuel Cell (FC) to deliver DC to the inverter.

Applying Equations 5 and 6, the resultant reliability of power fed to the distribution board is given as:

$$R_{AC} = \left(1 - \left(1 - R_{cu}R_{pv}\right)\left(1 - R_{b}R_{cc}\right)\left(1 - R_{cv}R_{cc}\right)\right)$$

$$RtRcvRfc \times Ri \times Rdb$$
(7)

The reliability expressions for the individual routes regarding the battery supply, direct PV panel supply and FC supply are given by Equations 8, 9 and 10 respectively.

$$R_{ACb} = R_b \times R_{cc} \times R_i \times R_{db} \tag{8}$$

$$R_{ACpv} = R_{cu} \times R_{pv} \times R_i \times R_{db} \tag{9}$$

$$R_{ACfc} = R_t \times R_{cv} \times R_{fc} \times R_i \times R_{db}$$
(10)

Successful operation of the PV system on another hand, involves the storage of the PV output power for future use. Fig. 5 highlights the various routes considered by the PV system configurations to successfully store power; which includes:

- (i) PV panel output used to charge battery bank via a charge controller and
- (ii) PV panel output feeding an electrolyser to produce hydrogen gas stored in a tank.

Applying Equations 5 and 6, resultant reliability of storage units is given as:

$$R_{storage} = R_{pv} \times \left(1 - (1 - R_{cc}R_b)\left(1 - R_{fs}ReRcvRt\right)\right)$$
(11)

where the individual storage paths R_{SB} (battery path) and R_{SE} (electrolyser path) have reliabilities given as follows:

$$R_{SB} = R_{pv} \times R_{cc} \times R_b \tag{12}$$

$$R_{SE} = R_{pv} \times R_{fs} \times R_e \times R_{cv} \times R_t \tag{13}$$

2.4 Reliability Estimates Using Fault Tree Analysis

Estimating the reliabilities of the block diagrams of Figs. 4 and 5 require the determination of failure rates of each component within the system configurations. In his thesis, Annan (2017) obtained failure rates of the system components using MIL-217F-2 handbook, International Atomic Energy Agency (IAEA) handbook and MTBF calculator. A summary of the failure rates is given by Table 1.



Fig. 4 Reliability Block Model (RBM) to Supply AC Load Demand by the PV System



Fig. 5 Reliability Block Model (RBM) to Store PV Output

Table 1 Summary of Component Fandre Rates					
Component	Related Expression	Failure Rate (Failures per Item Year)			
Electrolyser	R_e	1×10^{-5}			
H ₂ Tank	R_t	2×10^{-6}			
Fuel Cell	R_{fc}	5×10^{-5}			
Fused Switch	R_{fs}	0.031767656			
Gas Control Valve	R_{v}	3×10^{-2}			
Charge Controller	R_{cc}	0.042924			
Battery	R_b	4.6e-6			
Inverter	R_i	0.09636			
Distribution Board	R_{db}	0.0625464			
Control Panel	R_{cu}	0.051037512			
PV Panel	R_{pv}	0.01			

 Table 1 Summary of Component Failure Rates

(Source: Annan, 2017)

2.4.1 Fault Tree Analysis of the PV System Configurations

Some symbols employed in Fault Tree Analysis (FTA) are shown in Fig. 6 (Anon., 2017b). The fault tree diagrams for the power delivery RBM (Fig. 4) and the storage RBM (Fig. 5) are respectively given by Fig. 7 and Fig. 8.



Fig. 6 Basic Symbols Used in FTA

In the FTDs of Fig. 7 and Fig. 8, an 'R' represents reliability and 'P' represents failure probability. For an 'or' gate with inputs 1 and 2, the reliability is given by $R(t) = R_1 \times R_2$ while, the failure probability, P is given by $P(t) = P_1 + P_2 - P_1P_1$. For an 'or' gate with inputs 3 and 4, the failure probability P is given by $P(t) = P_3 \times P_4$. For the basic events (denoted by bubbles or circles), the failure rates of the corresponding components are applied to equation 2 to obtain their respective reliabilities for the first year. The reliabilities and failure probabilities of the intermediate events represented by the 'or' gate and the 'and' gate are obtained by using equations 1 and 2 together with the 'or' gate and 'and' gate expressions given in this paragraph.

3 Results and Discussion

In the fault tree diagram for power delivery paths of Fig. 7, the reliability for the combined power delivery paths is given as 0.853013 whereas the direct PV supply, the battery supply and the fuel cell supply routes gave reliabilities of 0.802564, 0.81723 and 0.827821, respectively, for the first year of the system life. For a 10-year period, the reliability trends are given by Table 2. The plot shown in Fig. 9 shows the reliabilities of the three routes considered, where the reliabilities of the various routes sunk to 0.2 or less after the 10-year period.



Fig. 7 Fault Tree Diagram (FTD) for PV Power Delivery Paths of Fig. 4



Fig. 8 Fault Tree Diagram (FTD) for PV Storage Paths of Fig. 5



Fig. 9 Power Delivery Routes for the PV System Configurations

Year	Combined Power Delivery Route	Direct PV Supply Route	Battery Supply Route	Fuel Cell Supply Route
1	0.853013	0.802564	0.81723	0.827821
2	0.727338	0.644109	0.667864	0.685288
3	0.619735	0.516938	0.545799	0.567295
4	0.527554	0.414876	0.446043	0.469619
5	0.44859	0.332964	0.36452	0.38876
6	0.380986	0.267225	0.297896	0.321824
7	0.323158	0.214465	0.24345	0.266413
8	0.27375	0.172122	0.198954	0.220542
9	0.231591	0.138139	0.162591	0.182569
10	0.195668	0.110865	0.132875	0.151135

Fable 2 Results of Reliabili	ty Estimation for	r PV Power	Delivery	Configuration
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The reliability assessment of the PV power delivery system indicates that the reliability of the fuel cell path is the highest while the battery supply route follows next. On the contrary, the period within which the system operates differs since the direct PV power delivery route is established right after construction of the system. The battery supply route is then developed after the direct supply route is established but takes time to effectively supply power since charging of the battery takes time. Usually, the PV system is designed in such a way that the battery is charged after which excess power feeds auxiliary systems like the electrolyser. If such a design is considered, then it will take a longer time for the electrolyser to be fed to produce the required gas. This implies that the fuel cell supply route is comparatively less efficient which is in line with research conducted by Yilanciab et al. (2009) who assessed three different energy demand paths and identified the hydrogen path to be the least efficient. With a load in place, the system may be alternatively designed to produce more output than the load demand. The excess power hence charges the battery to completion while the electrolyser is

fed to produce gas in smaller quantities while feeding the load at the same time. In this case, the production of gas may not be consistent. When the load is disconnected and the batteries are fully charged, operation of the electrolyser becomes swift. For the system to deliver power considering the power delivery routes of Fig. 9, the following assumptions are considered.

- (i) The PV output is greater than the load demand.
- (ii) The cost in establishing the system is worth the power produced by the system.
- (iii) The system is designed to feed several load demands at varying consumption periods.

With these assumptions in place, the PV system configuration during full load demand may see the electrolyser not enjoying requisite power to produce gas but considering varying load demand periods, the system may be effective to feed the electrolyser. In the reliability block model of Fig. 5, the system is configured to store PV output power by means of a battery in the form of DC or an electrolyser in the form of gas. The system indicates that, the battery charging route is more reliable with reliability estimate of 0.948448 as compared to the electrolyser storage route which has a reliability of 0.930736. For a 10-year period, the reliability of the battery storage route is more promising than the electrolyser route as shown in Fig. 10. The reliability values of the complete storage routes for a 10-year period is shown in Table 3. It could also be seen from Fig. 10 that the combined storage reliability is very high i.e. 0.997483 within a 1-year period. To attain this reliability, the system should be designed to produce high PV output to feed many loads. Since all the loads may not be engaged at the same time, the downtime of the load and all other excess power developed could be used to generate the gas from the electrolyser. Wang and Nehrir (2008) proposed and simulated an electrolyser-fuel cell system to serve as back up for long-term storage system. The reliability assessment indicates that the electrolyser route is relatively less reliable, but according to Wang and Nehrir (2008), the electrolyser route of PV power storage can be very useful as long-term and portable storage system.



Fig. 10 Storage Routes for the PV System Configurations

Table 3 Results of Reliability	'Estimation for P'	V Storage	Configuration
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Year	Combined Storage Route	Battery Storage Route	Electrolyser Storage Route
1	0.997483	0.948448	0.930736
2	0.990437	0.899553	0.866269
3	0.979557	0.853179	0.806268
4	0.965454	0.809196	0.750423
5	0.948666	0.76748	0.698445
6	0.929668	0.727915	0.650068
7	0.908874	0.690389	0.605042
8	0.886651	0.654798	0.563134
9	0.863315	0.621041	0.524129
10	0.839145	0.589025	0.487826

4 Conclusions and Recommendations

The PV system configuration shown in Fig. 2 is more effective for high PV output system feeding several loads, where excess power produced as a result of better solar insolation or downtime of one or more loads will never be wasted but effectively stored for future or remote load consumptions. The system reliability estimation has shown that the system incorporating the electrolyser is reliable in supplying load demand and in storing power for later use. In general, the electrolyser-battery integrated PV system is more reliable in supplying power to load demands than the battery-assisted PV system. For long-term storage and portability of the storage system, the electrolyser-battery integrated system is a preferred choice. The electrolyser units would be more appropriately configured into large solar PV systems to manage excess power production.

This research gives prior knowledge in the detailed reliability assessment of an operational hybrid energy system where the building blocks of the reliability block model may expand to include additional components (such as valves, tachogenerators, instrumentation devices and control circuitry) and exact failure rates of components measured over a period and under certain specified conditions. Aside reliability assessment, sensitivity analysis and power delivery estimates for pilot projects may be required to conclude on the establishment of hybrid renewable energy system. Finally, event tree analysis could be performed on the system and then integrated with the fault tree analysis to obtain detailed reliability assessment of the hybrid renewable energy system.

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Authors



J. K. Annan holds a PhD degree and an MPhil degree in Electrical and Electronic Engineering both from the University of Mines and Technology (UMaT), Tarkwa. He also holds a BSc degree in Electrical and Electronic Engineering from the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi. His

research interests are in Renewable Energy Systems, Reliability in Power Generation and Supply, Computer Applications and Control Systems. He presently lectures at the Electrical and Electronic Engineering Department of the University of Mines and Technology, Tarkwa, Ghana.



F. B. Effah received the BSc degree in Electrical/Electronic Engineering from the Kwame Nkrumah University of Science and Technology, Kumasi, in 2001. He received the MSc degree in Electrical Engineering and PhD degree in

Electrical and Electronic Engineering from the University of Nottingham, U.K., in 2009 and 2014, respectively. He is currently an academic at the Kwame Nkrumah University of Science and Technology, Kumasi. His research interests include Z-source converters, multilevel converters, matrix converters, solid-state/hybrid circuit breakers, renewable energy systems and advanced power converter control.



J. E. Quaicoe obtained his MSc and PhD degrees in Electrical Engineering from the University of Toronto in power electronics. He also holds an undergraduate degree in Electrical Engineering from the University of Science and Technology, Kumasi, Ghana. He is currently a Professor in the Engineering Faculty of the Memorial University of

Newfoundland and Labrador, St. John's, Canada. His current research activities focus on the development of control/switching strategies and topologies for renewable energy systems, including fuel-cell, wind energy, and tidal energy generation systems.

