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Reliability assessment of photovoltaic balance of system

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***Abstract* – The Photovoltaic (PV) system is divided mainly into two subsystems; PV modules and balance of system (BoS) subsystems. This work shows two approaches for a reliability analysis on the subsystem level of BoS; Failure mode effects criticality analysis (FMECA) and Markov Process. FMECA concerns the root causes of failures and introduces prioritization numbers to highlight critical components of BoS. Meanwhile, Markov process is a reliability methodology that aims to predict the probability of success and failure of BoS. In this way, Markov process is a supportive tool for helping decision-makers to judge the criticality of failures associated with the operation of PV systems. The Novelty of the proposed methodologies stems from analyzing the roots of failure causes of BoS components and estimating the probability of failure of these components in order to improve the early development of BoS, enhance maintenance management, and satisfy the demanding reliability by electric utilities.**

I. INTRODUCTION

Balance of System (BoS) comprises all the non-module components of Photovoltaic (PV) power plants. Failures of BoS components are the major reason behind the presence of non-producing modules in PV field. Ten years survey [1] was carried out by Sandia National Laboratories on 35 PV systems, and results showed that failure of BoS components such as switches, fuses, dc contactors and surge arrestors were responsible for 54% of the non-producing modules that were found, around 10,000 non-working modules. The DC and AC wires in addition to connectors of modules junction boxes contributed in 6.2 % of 68,739 non- working modules [1]. The layout of the PV system varies according to the architecture design; it can be a single- inverter system where all the strings are connected to central inverter, string-inverter system where each string has its own inverter, or multi inverter system where the PV field is divided into groups of strings connected to an inverter. Accordingly, BoS varies in design according to the layout of the PV systems. The most optimized BoS whose components are the basic for any design is presented in Fig.1. The failure of any of its components contributes significantly in the failures of PV system. It is worth mentioning that protection equipment are excluded since the utility switchgear is sufficient for the protection proposes of an optimum BoS.

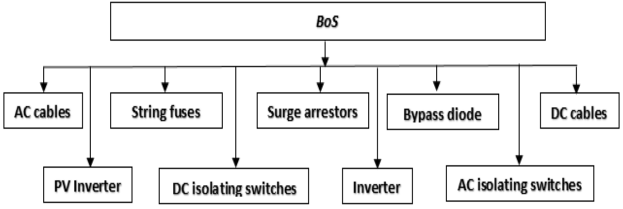

Fig. 1. BoS Components

In literature, most of the studies focus on PV modules reliability evaluation and only very limited publications consider the reliability of BoS. Among these publications, a qualitative reliability analysis is presented in [2] using fault tree analysis and other efforts in [3] investigated the reliability of both PV modules and BoS using Petri's networks in order to estimate the lifetime, reliability, and availability.

In general, the first step towards enhancing a system's reliability is to detect the root causes of systems' failures. In this respect, Failure Mode Effect Criticality Analysis (FMECA), a well-known methodology, is used in order to analyze the failure causes of systems. It focuses mainly on identifying the possible failure causes. In addition, it is one among several methods used for risk assessment and management by selecting the most proper maintenance strategies to enhance the system performance.

A recent research [4] applied FMECA on a PV system designed by Brookhaven National Laboratory and results show that inverter and ground system of PV system have the highest RPN. It provides a strong investigation of the FMECA on the whole PV system components; however [4] considered a specific design and did not list recommended action to limit the failure causes, and the potential failure modes were listed without highlighting the contribution of each system component in the failure of the whole PV system.

On the other hand, FMECA methodology, in this work, is limited with more details to BoS only whose components are more optimized. The failure causes of each component are studied in details, and recommended actions are listed. In addition, a prioritization number is assigned to each failure, based on IEC-60182, to improve the maintenance activities. Moreover, a further reliability investigation is carried out by Markov Process to be a supportive tool along with FMECA in case of any confusion on judging the priority number by maintenance management. More details on the confusion of judging RPN is available in [5].

Both techniques illustrate results that can be utilized during the design phase in order to reduce the major field problems and improve the reliability of the systems. Also, they can be used during the operation phase by improving the maintenance management and reducing the failure probability of occurrence.

This paper is organized as follows; section 2 provides a general overview on the failure causes of BoS components; section 3 presents FMECA results; section 4 shows the Markov process conducted on BoS. Finally, section 5 includes conclusion.

II. BALANCE OF SYSTEM FAILURE CAUSES

Mapping the failure causes is the first step towards the reliability analysis for determining the underlying failures and enhancing failure prediction methods. Fig. 2 shows a schematic diagram of optimized BoS that consists of the necessary components needed to be installed on a PV string. In this section, the failure cause of each BoS's component is described in details.

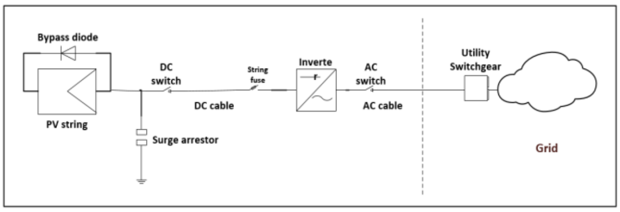

Fig. 2. BoS of PV string

A. AC and DC cables

AC and DC cables represent the veins of PV systems and their failures results in partial or complete shutting down of PV plant. In addition, cables problems at the module levels can lead to a severe mismatch for other modules cabled in the same parallel block [6] and results in the drop of output power. Loose cables by poor workmanship due to excess torque and pressure during installation, undersized cables, overvoltage and over current, insufficient protection are the main causes for PV cabling.

B. Bypass diode

Bypass diodes are usually supplied inside module junction box or manufactured only inside PV modules for sophisticated module types only [7]. A study was carried out in [8] on 1272 modules showed that 47 % of the modules have defective bypass diodes and 3% of the defective bypass diode caused burn mark on the modules. Generally, the main function of a bypass diode is to allow the current to pass around the shaded or cracked cells and thereby reduces the power losses within the module itself. Hence, the hot spots will be avoided and a long lifetime of the system will be guaranteed [9]. Bypass diodes have a junction temperature reaching upwards 150-200 °C and they possess a significant self-heating [10], however the main reason of their failures is the applicable thermal stress during their operation because they are not exposed to sufficient air flow for cooling.

C. String fuse

Depending on the necessary capacity of PV system, there might be several strings which are connected in parallel for higher currents and more power. Only PV systems that have at least three strings require a fuse to be placed on each string. PV systems which have less than three strings will not generate sufficient fault current and do not present a safety hazard [11]. In general, a fuse can be considered as a conductor with a relatively low melting temperature surrounded by a dielectric insulator. String fuses have different failure modes that can be summarized into false operation, design factor, cracks of dielectric packaging and shift in fuse resistance; the resistance is increased during the normal operation, or it becomes relatively low during tripping [12-13]. Moreover, the fatigue factor contributes in these failure modes; string fuses are subjected to wear out since switching on and off would heat up and cool down the fuses. Consequently, fuse fatigue is developed by time.

D. DC and AC isolating switches

IEEE Std C37.100-1992 [14] defines the isolating switch as a mechanical switching device used for changing the connection in circuit or for isolating a circuit or equipment from the source of power. In PV systems, the installation of DC switch on each string is necessary for the maintenance purposes of strings in order to avoid shutting down the inverter and consequently disconnecting the whole strings.

On the AC side, since the cable connecting the inverter to grid is usually dimensioned to carry current higher than the maximum current which the inverter can deliver. A protection against overload is not necessary and a circuit breaker at the utility switchgear is sufficient to protect against faults from the grid. However, an AC switch is still necessary and should be installed for maintenance purposes of the inverter [15].

The most common failure mode of isolating switches is a failure in mechanical mechanism; thus the switch fails to open or close, and contacts carbonization; that results in local temperature rise and reduction of contact quality.

E. Inverter

In a grid-connected *PV* plant, inverter represents an expensive and complex key component. A typical three-phase *PV* inverter includes: IGBT Power modules, cooling fans, control software and DC link capacitors implemented on Printed Circuit Board (*PCB*) in addition to AC & DC contactors. IGBT power module fails as a result of thermal runaway [16], ceramic substrate to base plate solder fatigue [17], partial discharge [18], and FWD if short circuited [19]. AC and DC contactors fail to open or close due to design defects, mechanical locks, failure of tripping coil, arcs and overheating that cause degradation of the electric contacts. Solder fracture and cracks are the main failure causes of *PCB* and results in overheating and gradual resistance increase of the solder joints [20]. The control software fails in case of improper design, absence of health monitoring facility and incapability to adapt the change in electrical and environmental parameters.

F. Surge arrestors

Surge arrestors are designed to isolate the PV circuit from the grounding during the normal voltage operating and conducting to the ground when the voltage of the line exceeds the threshold value. In PV systems, they are installed to provide a complete protection against lightning and induced over voltages. On the DC side, a surge protection device is always placed on the supply side of the inverter's isolating device in order to provide a complete protection when the isolating device is opened. In service, Surge arrestors are exposed to frequent lightening that result in excessive overheating and lead to degradation of its characteristics. Also, moisture ingress can find its way inside the surge arrestor in case of sealing defects and contribute in dielectric degradation.

III. FAILURE MODE EFFECT CRITICALITY ANALYSIS

FMECA consists of two separate parts, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA). FMEA includes a list of possible equipment failure modes, reason of these failures, local and final effects that refer to the impact of each failure on the system element and the whole system respectively, and the alternative recommended corrective actions to avoid each failure.

On the other hand, Criticality Analysis plans and focuses the maintenance activities according to a set of priorities by giving failures with the highest risk the highest priority[2a].

A) FMEA on BoS

The analysis starts with gathering information on the functions and failures of BoS components. The impact of each failure cause for each component is investigated on the component itself and the PV modules and strings, stated in the local effect. Afterwards, the impact of each component failure on the whole PV system is considered in final effect. Finally, the most proper recommendations are given to reduce the failure of each BoS component. The working of FMEA on BoS is listed in Table 1.

B) *CA on BoS*

The criticality is a manner to quantify how much attention is necessary to pay about determined component failure or event; this is carried out either through qualitative means based on experience and field background or quantitative means if previous failure data are available. Currently, field data are not available for BoS, therefore, a qualitative CA is the most relevant means to evaluate CA. This is managed by assigning each failure mode to a Risk Priority Number (RPN), defined by RPN = O × S × D, where S represents a scale for the failure severity and the risks behind the failure occurrence, O denotes the probability of failure mode occurrence, and D means detection, and represents the possibility to recognize the failure before the system or the customers are affected. For the expectation purposes of components' failures, IEC evaluation criterion is selected as shown in Table 2.

TABLE 2. IEC-60182 EVALUATION CRITERIA FOR OCCURRENCE, SEVERITY, DETECTION

Occurrence (*O*)	Severity (*S*)	Detection (*D*)	Ranking
Failure is unlikely	No discernible effect	Almost certain	1
Low: Relatively few failures	Very minor	Very high	2
	Minor	High	3
Moderate: Occasional failures	Very low	Moderately high	4
	Low	Moderate	5
	Moderate	Low	6
High: Repeated Failures	High	Very low	7
	Very high	Remote	8
Very high: Failure is almost unavoidable	Hazardous with warning	Very remote	9

In CA evaluation, the occurrence is evaluated in accordance to the failure rate of the BoS components stated in Table 3; the severity is based on the expected interruption of power and possible damages to PV modules, and detection considers the fault detection tools and equipment in the field. The evaluated RPN is presented in Fig. 3.

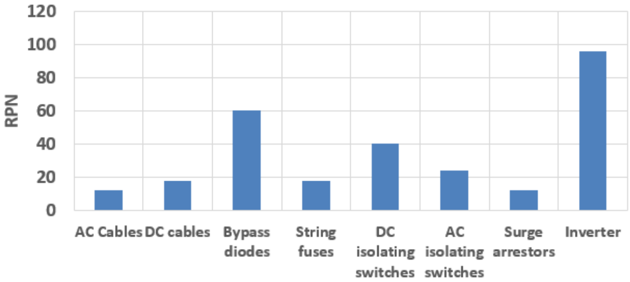

Fig. 3. RPN of BoS components

It is depicted from Fig. 3 that inverter has the highest RPN because of the complexity of its components. Bypass diode follows the inverter since its rate of occurrence is quite high compared to the rest of other components, its failure results in burned marks on PV modules and reduction of power. In the field, the failure detection of the bypass diode is done by infrared camera and signal transmitter devices. Both the inverter and bypass diode are the key elements for a safe system operation; therefore, it is recommended to conduct the aforementioned detection procedures of the bypass diodes along with the routine maintenance of PV inverter in time. On the other hand, Surge arrestor has the lowest RPN; since it is very rarely when it fails in short circuit mode, and it is not opening the circuit in case of open circuit mode.

IV. MARKOV PROCESS ON *BOS*

Markov process is a sequences of random variables in which the future variable is determined by the present variable and independent on the way in which the present state arose from its predecessors. The analysis looks at a sequence of events and analyzes the tendency of one event to be followed by another [22]. This tendency is the probability evaluation of transition from one state to another until the system has reached the final state. Thus, a Markov process is defined by a process {p(t), t⩾0} with state space X={0,1,2,3,….r} and stationary transition probabilities:

$$Pij = Pr(p(t) = j \mid p(0) = i)\ for\ all\ i,j\ \in X \quad (1)$$

Where, p(t) is a random variable denotes the state and belongs to state space X. The rate of the change from one state to another is estimated based on the transient analysis point of view, through Kolmogorov forward equations,

$$\frac{d\,p(t)}{dt} = p(t).\mathbf{A} \quad (2)$$

And,

$$\sum_{j=0}^{n} P(t) = 1 \quad (3)$$

Where Where $\frac{d\,p(t)}{dt}$ is a vector that represents the state probability p (t) at time t, and A is a matrix of failure rates between states. As the number of possible states are finite, Equation (3) is necessary because the probabilities of all states at any time t should equal one and system can be in one and only one of these states. In case of zero repair rates, i.e. Poisson birth-death process, Equation (2) can be rewritten as,

$$\frac{dp_i(t)}{dt} = - \sum_{i\neq j} \lambda_{i,j}\, P_i(t) + \sum_{i\neq j} \lambda_{j,i}\, P_j(t) \quad (4)$$

Although Markov process, from the theoretical viewpoint, is flexible and versatile, special precaution are necessary to deal about the difficulties of practical applications. The main problem is that the number of system states and possible transitions increases rapidly with the number of events in the system [23] therefore, assumptions become a necessity. The usual assumptions considered by current standards and references, i.e. IEC-61165 [23], IEC 61508[24], and [22], can be summarized as follows: i) failure and repair rate are constant, ii) failure and repair events are independent, iii) the transition probability from one state to another state occurs within a very small time interval, iv) only one event occurs at the same time.

In systems modelling without repairs, IEC-61165 [23] considered three possible states for the system up, degraded and absorbing state. The up state represents that the system which is free of any failure. Degraded state is related to system state whose performance meets the warranty limits although its operation is associated with failures. Absorbing states are the final states for the system when it falls. In Markov process, states are absorbing if they are once reached by the system, the system will remain there forever.

The term BoS is a very general term since it includes all the non PV module components and it depends as well on the design of the PV system, whether it is central inverter, string-inverter system or multi inverter PV system. Therefore, the reliability analysis is carried out on the BoS components of installed on PV string shown in Fig. 2. It is assumed that surge arrestor never fail in short circuit mode and it is not opening the circuit in case of failure, therefore it will be excluded from the Markov process analysis.

The major problem that always appears on any reliability study concerning the PV system is the lack of PV components failure information and absence of reliability, therefore the components failure rate of BoS are gathered from literature [26-28] in Table 3. It is worth to mention that the inverter failure rate is calculated by considering one failure in 8 years [25] so the failure rate is 0.125 failure/year.

Table 3. Component adopted failure rates

Component	Failure rate
Bypass diode	0.027 f/ year [26]
DC switch	0.0018 f/year [27]
AC wire	0.00011 f/year. [28]
DC wire	0.00042 f/year. [28]
AC Switch	0.0003 f/year [27]
String fuse	0.00017 f/yr [26]
Photovoltaic inverter	0.125 f/ year [25]

According to the string configuration, shown in Fig. 2, once any component fails the whole PV string fails; therefore, each components is assumed to have two states up and down. All the possible scenarios for the failures of the string BoS components are listed in table 4. Accordingly, the state transition diagram is illustrated in Fig. 4. Consequently, the state equations of string BoS can be estimated from (4) as follows;

$$P_0^{\prime}(t) = -(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7)\, P_0(t) \quad (5)$$

From the definition, reliability is the probability to perform its required function without any failures, under given conditions and for a stated period of time. Therefore, the string BoS reliability is equal to probability of state 0, $P_0(t)$. Hence $R(t)$ is presented in Fig. 5.

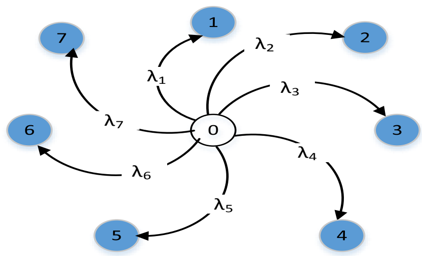

Fig.4. State transition diagram of string BoS failures

Table 4. System states

State	Scenario
0	All components works
1	Bypass diode fails
2	DC switch fails
3	AC wire fails
4	DC wire fails
5	AC Switch fails
6	String fuse fails
7	Photovoltaic inverter fails

Based on Fig. 5, the MTTF of string BoS is around 6 years which is close to the MTTF of the inverter. In order to highlight the impact of the inverter on the reliability of string BoS, Fig.6 is illustrated. The MTTF of string BoS without the inverter is around 33 years.

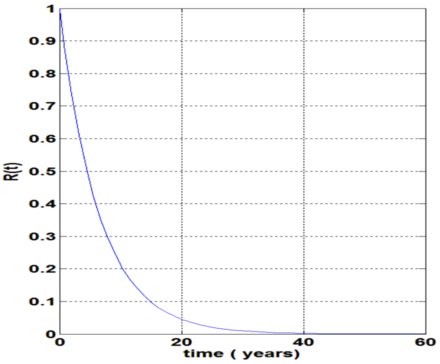

Figure 5. Reliability of string BoS

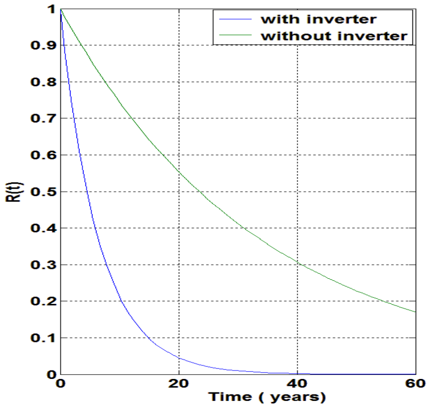

Figure 6. Comparison of string BoS reliability w and w/o inverter

V. CA OF PV INVERTER

VI. CONCLUSION

The root failure causes of PV string BoS are studied in details through FMEA approach, and a qualitative CA was conducted in order to prioritize these failure causes, to enhance BoS maintenance activities and decision-making. CA shows that PV inverter has a high RPN compared to other failure causes and this result was supported by Markov Process. In Markov analysis, the MTTF of string BoS is significantly low, around six years, due to the high failure rate of the inverter. The estimated MTTF of string BoS excluding the inverter impact is around 33 years; this can be an accepted value compared to the lifetime of PV module.

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Table 1. FMECA on BoS

Item	Outage mode	Possible outage cause	Local effect	Final effect	Compensating provision against failure	S	O	D	*RPN*
BoS	AC Cables	Thermal expansion and contraction. Loose cables. Undersized cables. Overvoltage and over current.	Slow output power degradation and increased power losses	Shutdown of one or more PV strings. Arcs and fire risk	Minimizing electrical cables wiring, proper design, sufficient protection, using cable ducts, routine visual inspection	3	2	2	12
	DC cables					3	3	2	18
	Bypass diodes	Thermal stress, insufficient cooling. Over voltages and high currents. Insufficient rating	Hot spots and burn marks on PV module	Bypass diode is open circuited: no change in output power. Bypass diode short circuited: Significant drop of power.	proper design, installing surge arrestors	5	6	2	60
	String fuses	False operation. Improper design, cracks of dielectric packaging. Shift in fuse resistance, Thermal wear out.	In closed circuit mode: Slow output degradation and increase of power losses. In open circuit mode: isolation of the one or more strings	Significant reduction of output power	Proper design, installing surge arrestors. Regular visual inspection	3	2	3	18
	DC isolating switches	Mechanical mechanism Failure, improper design, carbonized contacts	Increase in contact resistance and power losses	Partial or complete shutdown of the PV system	Enhance periodic maintenance and proper inspection of operating mechanism	4	5	2	40
	AC isolating switches					4	3	2	24
	Surge arrestors	Excessive overheating Sealing defects and environmental contamination	Characteristics degradation. leakage current increases and dielectric integrity fails to discharge over voltages.	Partial discharge arching, induced over voltages and lightning strikes on PV equipment	Regular testing (leakage current and Meggar) Visual inspection to avoid dust accumulation and sealing defects. Maintaining and ensuring proper grounding systems.	2	2	3	12

	Inverter	- High operating Temperature and long power cycle of IGBT - Failure of cooling fans and contactors. - Cracks and delaminated layers in PCB - Poor performance by the control software	- Damage of IGBT, reversed Air flow. - Fan failure. - Board integrity is reduced - Unreliable MPPT scheme - Power losses & degradation of contactor.	Inverter outage and interruption of the Photovoltaic output power	- Lowering thermal resistance between IGBT and heat sink, - improve chip thickness and bonding technology, - Preventive maintenance to carry out contactor electrical tests - Improving inverter data acquisition level. - Temperature sensors for cooling monitoring & protection	6	8	2	96