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Markov process reliability model of PV inverter

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Abstract **– Since Photovoltaic (PV) systems have penetrated generation networks, their failures started to have a detrimental effect on the economics of power generation and risk of power interruptions. The dominant failure causes behind these failures is the Photovoltaic Inverter (PVI). In this respect, reliability prediction of PVI has been of great concerns, nowadays, to designers and manufacturers during the design phase. In this paper, Markov process is chosen to estimate the reliability of PVI based on the recent failure data of Siemens norm SN-29500 handbook. Both the reliability and MTTF are evaluated. Results show that the estimated life span of PVI is significantly different compared with the results from similar studies based on MIL-HDBK-217F, which was last updated in 1995.**

I. INTRODUCTION

Designers are always seeking for high reliable Photovoltaic Inverter (PVI) that remains operational and keeps its objectives without failure during its expected life. However, this view is idealistic due to the operational and economic constrains associated with the PVI's operation. In fact, PVI face many challenges in the field that contrast the high expectations of PV systems reliability; due to the technical specification variability of its system components, power losses, temperature, and high electrical stresses. In addition, relative high-risk factors exist due to the network grid conditions such as over voltages and reverse power flow due to switching in/off of system equipment and the operation of on-load tap changer. Consequently, PVI contributes significantly in the failures of PV systems.

In the German 1000 PV roof program, 2056 grid-connected PV systems were installed on the roofs of private houses in the period 1990 to 1995. The reported failures show around 65% of total number failures are caused by the inverter defects followed by other components of Balance of System (BoS) during the observed period 1992-1997 [1]. A further investigation, conducted on 126 PV system by Sandia National Laboratories in [2], shows that 76% of the 196 observed failures occur by the PV inverter. In the period January 2010 to March 2012, an intensive survey was conducted by SunEdison [3] to analyze 3500 failure tickets issued for 350 PV systems. The results show that 43% of the collected tickets are assigned to the failures of the inverter followed by the AC subsystem.

Since PV systems have penetrated generation networks, their failures start to have a detrimental effect upon the economics of power generation and risk of power interruptions. The dominant failure cause in these failures is assigned to PVI. Therefore, reliability prediction of PVI has been of great concerns, nowadays, to designers and manufacturers during the design phase; because its functional elements in this life cycle phase, may be repeatedly, rearranged or its capability may be changed.

In literature, many efforts are exerted towards reliability estimation of PVI, For instance, Harb et al. [4] discussed the reliability of PVI based on the stress-factor methodology, Koutroulis et al. [5] focused on reliability improvement of PVI during the design phase through the estimation of the useful life time of inverter's critical components, and Pregeij et al. [6] showed the impact of inverter configuration on the PV system reliability and energy production. Fife et al. [7] presented the necessary field reliability indices to be estimated for PVIs. Another study [8] proposed Bayesian inference methodology to model the uncertainty hazard and repair rate of fielded PVIs. An approach based on Monte Carlo simulation is presented in [9] to assess the expected availability of a particular inverter design and make qualitative assessments of several potential approaches to increasing inverter reliability.

In general, a successful reliability predication generally requires developing a reliability model of the system considering its function and structure. In this study, PVI is assumed to be a non-repairable system.

Non-repairable systems can be modelled through several techniques (e.g. reliability block diagram, fault tree diagram, space states, etc.). In this work, Markov process is chosen to predict the reliability of PVI, because it is suitable to model the random progress through discrete states in which the future state is determined only by the present variable and independent on the way in which the present state arose from its predecessors [10].

So far, the military handbook of electronic equipment MIL-HDBK-217F [11] is the most widely used source when it concerns reliability prediction. However, it has several drawbacks; it was last updated in 1995; the range of temperature for electronic components is quite limited, and no considerations were given to the stress profile factor on the failures of these electronic components, although they are not continuously stressed during the operating time .

The novelty of this work stems from the calculation of the failure rates for Markov process based on an up-to-date source, Siemens norm SN-29500 handbook [12], that includes a recent failure rate database on IGBT modules and other electronic components, and introduces the stress profile factor to the estimation of predicted failure rates.

This paper is organized as follows: section II shows the main components of PVI, section III presents Markov process modelling of PVI, section IV shows the failure rate calculations based on Siemens norm SN-29500 handbook, and section V shows the impact of the operating temperature on the reliability of the whole PVI. Finally, Section VI comprises conclusion.

II. STRUCTURE OF PVI

The reliable operation of PVI is based on its main components. From reliability point of view, the PVI inverter can be modeled as a chain of functional blocks connected in series, each corresponding to one of its components; Since the PVI inverter cannot function without any of its components, the failure of one of these blocks constitutes in the failure of the whole inverter [13]. Therefore, it is necessary to evaluate the failure modes of each component. The typical three-phase PVI 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 consists of both IGBT and FreeWheeling Diode (FWD) that are connected to a ceramic substrate through wire bonds. Capacitors are widely used for dc links to balance the instantaneous power difference between the input source and output load, and minimize voltage variation in the dc link.

The DC and AC contactor connect the PV inverter to the PV module and the grid in the morning and disconnect the PV inverter from the PV module and the grid in the evening or when the inverter has a fault, fans usage aims to cool power devices on heat sinks the most efficient way, and PCB mechanically supports and electrically connects electronic components using conductive tracks. It can be single sided, double sided or multi-layer. The design and the proper selection of PCB are essential for a better reliability and an improved performance.

The control software should be designed to adapt the operating voltage range, output power level, operating hours, and change in temperature, health monitoring facility, and the most proper actions for the different PV panels and grid faults. In PVI, the control software is stored in implemented inside the microcontroller. Hence, the failure of microcontroller results in the failure of PVI itself. A block diagram of PVI components is illustrated in Fig. 1.

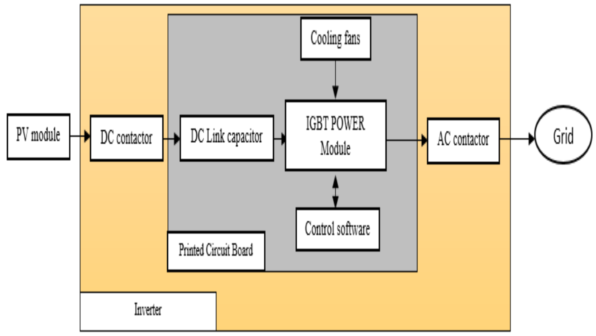

Fig.1 . PV inverter components

III. MARKOV PROCESS

Markov Process models the system's behavior with respect to time by considering different states for the system and the transition in between these states. If the stochastic process is continuous, it is called continuous time Markov chain or Markov process; otherwise, the stochastic process is discrete and called discrete time Markov chain.

The random variable X(t) denotes the state of the system at time t and the collection of all possible states is called state space denoted by X. Accordingly, for a stochastic process { X(t), t ⩾ 0} with a state space {X= 0,1,..,r}, and the state of the process is assumed to be X(s)=i at time s, the conditional probability of this process to be at state j at time t+s is;

$$P\{X(t+s)=j\,|X(s)=\mathrm{i},X(u)=\ x(u),0\le \mathrm{u}\ \le \mathrm{s}\}\qquad(1)$$

Equation (1) shows that the future probability of the system is dependent on the past history of the process. However, the Markovian process considers only the present state of the system regardless past history of the system,

$$P\{X(t+s)=j\,|X(s)=\mathrm{i}\ \}\qquad(2)$$

Markov process can be presented graphically by a state transition diagram where the system states are presented by circles or rectangles and the directed arcs are the transition between the states. The transition from one state to another depends on the time interval available for the transition regardless the global time, time-homogeneous process, or it can be dependent on the global time, inhomogeneous time-process. For Markov process, the rate of the change from one state to another follows Kolmogorov forward equations.

Kolmogorov forward equations are set of differential equations that describe the probability distribution of the system's state. For a process of probability state vector P(t) =[P0(t), P1(t),….Pr(t)], the distribution P(t) can be estimated from Kolmogorov forward equation as follows,

$$\dot{P}_j(t)=\sum_{k=o}^{r} a_{kj}\,P_k(t)\qquad(3)$$

Where a_{kj} is the transition rate from state k to j. In matrix terms, this can be written in a compact form as;

$$\frac{d\,p(t)}{dt} = p(t).\mathbf{A} \qquad (4)$$

For a finite possible number of states,

$$\sum_{j=0}^{n} P(t) = 1 \qquad (5)$$

In systems modelling without repairs, IEC-61165 [14] considers three possible states for the system up, degraded and absorbing state, as shown in Fig. 2. 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.

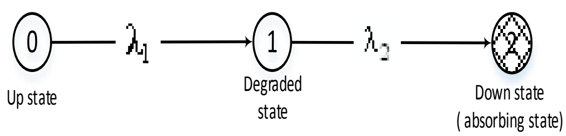

Fig. 2. State transition diagram with three states [14]

Because of the criticality functions of PVI components, Markov modelling will be represented by up and absorbing states only as shown in Fig. 3, where each state represents a scenario of failure. These scenarios are listed in Table 1. It is worth stating that the control software failure is expressed by the failure of microcontroller circuit.

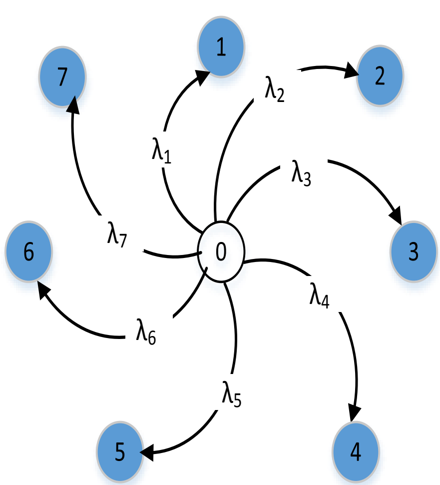

Fig. 3. State transition diagram of PVI failures

Table1. System states

State	Scenario
0	All components works
1	Six packs IGBT module fails
2	DC link capacitor fails
3	Microcontroller fails (control software)
4	AC contactor fails
5	DC contactor fails
6	Cooling fan fails
7	PCB fails

Based on (4), (5) and Fig. 3,

$$P_0^{\bullet}(t) = -(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7)\,P_0(t) \qquad (6)$$

IV. FAILURE RATE ESTIMATION

According to Siemens Norm SN-29500 handbook, the predicted failure rate of PVI components are shown in table II, where λ_{ref} is the reference failure rate; $\theta_{j,1}$ is the reference junction temperature, V_s is the operating voltage and θ_1 is capacitor temperature. π_v , π_I , π_s , π_E ,π_Q and π_T are the voltage, current, switching rate, environmental , quality and thermal factors respectively. Regarding cooling fans, IEEE-493 declared a failure rate 0.01041 failure/year based on a field survey of propeller fans [9], meanwhile the failure rate of PCB is obtained from the generic database introduced by MIL-HDBK-217F.

It is worth to mentioning that thermal design is a critical issue and thermal stress factor has a significant impact on the PVI and power electronic. Therefore, the failure rate predication is evaluated in terms of the thermal stress to highlight its impact.

It should be taken into account that IGBT module, DC-link capacitor and microcontrollers are not continuously stressed during the day and there are breaks without electrical stress. Therefore, Siemens Norm SN-29500 introduces a stress profile factor π_w for each of these components. π_w is calculated using this equation;

$$\pi_w = W + R\frac{\lambda_0}{\lambda}(1 - W) \quad \text{For } 0 \le W \le 1,\ R \ge 0 \qquad (7)$$

Where λ is the predicted failure rate in Table 1; R is constant and equals 0.5 for DC link capacitor and 0.08 for both IGBT module and microcontroller. W is a ratio, that represents the duration of the component stress to operating time of PVI and it equals to 0.25 assuming that PVI is subjected to electrical stress for 6 hours per day. λ_0 is the failure rate at wait temperature, which is the component or junction temperature during the non-stress phase ($\lambda_0 = \lambda_{ref}.\pi_T(\theta_0)$) and λ is the failure rate under actual operating conditions. θ_0 is assumed to be 25 °C , thus π_T (θ_0) equals to 0.044, 0.26 and 0.07 for IGBT module, DC-link capacitor and microcontroller respectively.

V. RELIABILITY EVALUATION OF PVI

PVI reliability is the probability to perform its required function without any failures, under given conditions and for a stated period of time. Therefore, the PVI reliability is equal to probability of state 0, $P_0(t)$. By substituting the values of components failure rates in Table 2 and considering the stress profile factor as well presented in (8),(9) and (10) , the solution of (6) is shown in (11).

It is obvious from (11) that PVI reliability is a function of thermal factors of IGBT module, DC-link capacitor and microcontroller. Siemens norm-29500 introduces the values of thermal factors for different temperatures as shown in Table 3. These values are inserted into (11) and Fig. 4 is illustrated.

It is depicted from Fig. 4 that the reliability of PVI decrease as the operating temperature increases.

Systems analysts give a lot of attentions to MTTF; because it is difficult, in some cases, to have an access to the component/equipment or maintenance resources is not sufficient. In fact, MTTF is considered a basic measure of reliability for non-repairable systems. It represents the time to first failure under specified conditions. MTTF is given by,

$$MTTF = \int_0^{\infty} R(t)\, dt \qquad (12)$$

Table 2. Predicted failure rates equations

Component	Predicted failure rates (Failure per year)	
IGBT module (Six packs)	$\lambda_1 = \lambda_{ref1} \cdot \pi_{T1}(\theta)$	$\lambda_{ref1} = 6.1361 \times 10^{-4}$ $(\theta_{j,1} = 100\ °C)$
Dc-link Capacitor	$\lambda_2 = \lambda_{ref2} .\pi_v .\pi_Q .\pi_{T2}(\theta)$	$\lambda_{ref2} = 0.4383 \times 10^{-4}$ $(\theta_1 = 40°C)$ $\pi_Q = 2$; π_v=1
Microcontroller (CMOS)	$\lambda_3 = \lambda_{ref3} \cdot \pi_v .\pi_{T3}(\theta)$	$\lambda_{ref3} = 7.0126 \times 10^{-4}$ $(\theta_j = 90°C)$ $\pi_v = 1$ (V_s= 5 V)
AC contactor	$\lambda_4 = \lambda_{ref4} .\pi_v \cdot \pi_I . \pi_s . \pi_T \cdot \pi_E$	$\lambda_{ref4} = 0.0022$ $\pi_v = 1.4$ (Vs = 690 V); $\pi_I = 1$ $\pi_s = 10$; $\pi_E = 1$; $\pi_T = 1$,
DC contactor (2 poles)	$\lambda_5 = \lambda_{ref5} .\pi_v \cdot \pi_I . \pi_s . \pi_T . \pi_E$	$\lambda_{ref5} = 8.7658 \times 10^{-4}$ $\pi_v = 1.4$ and $\pi_I = 2.1$ (V_s= 600 V) $\pi_s = 10$; $\pi_E = 1$; $\pi_T = 1$
Cooling fans	λ_6 =0.01041	
PCB	λ_7 =0.0156	

The equations of λ_1 , λ_2 and λ_3 in terms of π_T will be written after applying the stress profile factors as follows,

$$\lambda_1 = W.\lambda_{ref1} \cdot \pi_{T1}(\theta) + R.\lambda_{ref1}.\ \pi_{T1}(\theta_0)\,[1–W] \qquad (8)$$

$$\lambda_2 = W.\lambda_{ref2} .\pi_v .\pi_Q .\pi_{T2}(\theta) + R.\lambda_{ref2}.\ \pi_{T2}(\theta_0)\,[1–W] \qquad (9)$$

$$\lambda_3 = W.\lambda_{ref3} .\pi_v .\ \pi_{T3}(\theta) + R.\lambda_{ref3}.\pi_{T3}(\theta_0)\,[1–W] \qquad (10)$$

Table 3. Thermal factors of IGBT module, DC-link capacitor and microcontroller

Theta	20	30	40	50	60	70	80	90	100	110	120
$\pi_{T1}(\theta)$	0.044	0.056	0.092	0.15	0.22	0.34	0.49	0.71	1	1.4	1.9
$\pi_{T2}(\theta)$	0.26	0.51	1	1.9	3.7	7.2	14	28	55	107	206
$\pi_{T3}(\theta)$	0.07	0.086	0.13	0.19	0.29	0.43	0.66	1	1.5	2.4	3.7

$$R(t) = P_0(t) = \exp(-[0.0826 + 10^{-4} \times (1.534\,\pi_{T1}(\theta) + 0.219\,\pi_{T2}(\theta) + 1.753\,\pi_{T3}(\theta))]\,t) \qquad (11)$$

Table 4 shows the MTTF for different operating temperature. It is depicted that the MTTF of PVI decreases, as well, as the operating temperature increases. For instance, the MTTF for operating temperatures 20 °C and 120 °C is 12.1 and 11.35 years respectively.

Table 4. MTTF for different operating temperature

Operating temperature	20	40	60	80	100	120
MTTF (years)	12.10	12.09	12.08	12.03	11.87	11.35

It should be noted that the prediction equation (11) does not yield the exact estimate of MTTF, but it shows the expected values based on the reference values of components failure rates and clarifies the impact of temperature on the whole lifetime of PVI.

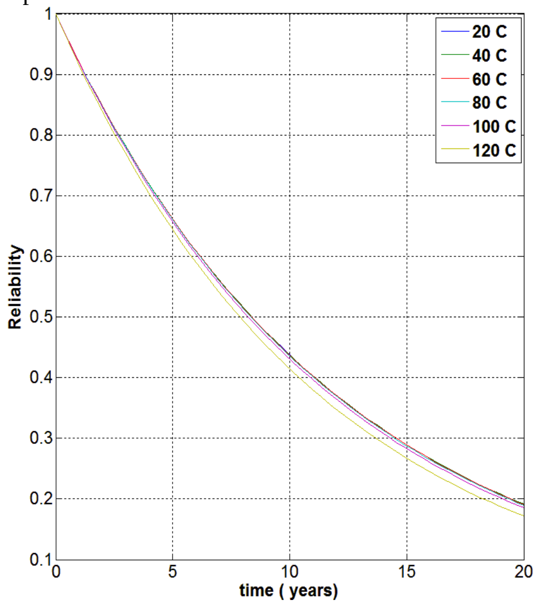

Fig. 4. Reliability of PVI

In fact, the life span of PVI has been significantly improved compared with the values declared in literature, around 4.7 years [9, 15,16]. In the IEA PVPS studies, the failure rate of inverter dropped from 0.7 failure per year in 1995 to 0.4 failure per year in 1996 [1]. In Switzerland, Data from EPFL shows a significant improvement of the mean failure rate one failure in seven years for 133 inverter-years during 1992-2001 and one failure in 24 inverter-years during 1996-2001. Task & survey inverter indicates a clear improvement with MTTF around 10 years [1].

This controversy may be due to MIL-HDBK-217F, which was a base for the previous prediction of failure rates, although it was last updated in 1995. It doesn't introduce base failure rates for IGBTs , consequently the failure rate of IGBT module was not predicted previously in the reliability assessment of PVI. Furthermore, PVI inverter is not subjected to continued electrical and thermal stresses, however previous studies did not give attention to stress profile factor in their estimation.

VI. CONCLUSION

PV inverter is an expensive and complex equipment in the PV systems. Consequently, the existing literature focuses on the reliability of the inverter. However, the majority of the existing studies investigates the reliability of inverter using military handbook, MIL-HDBK-217, although it does not reflect the current progress in the technology of PVI and the reliability enhancement of its components.

In this work, a reliability prediction is conducted by Markov Process based on Siemens norm SN-29500 handbook. The predicted failures rates are estimated in terms of thermal stress in order to highlight its impact. The aforementioned results in section V explain why the current warranty periods declared by a number of manufacturers have reached ten years instead of the typical three-five-year warranty.

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