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Technical Note

Assessing and Evaluating Reliability of Single-Stage PV Inverters

Aryan Tabrizi, Mehdi Rahmani*

Department of Electrical Engineering, Imam Khomeini International University, Qazvin, Qazvin, Iran.

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ABSTRACT

Reliability is an essential factor in Photovoltaic (PV) systems. Solar power has become one of the most popular renewable power resources in recent years. Solar power has drawn attention because it is free and almost available worldwide. Moreover, the price of maintenance is lower than other power resources. Since there are no moving parts in PV systems, their reliability is relatively high. It is assumed that a typical PV system can operate 20–25 years with minimum possible interruptions. However, solar power systems may fail, the same as any other systems. It is indicated by several studies that the PV inverters are responsible for major failures in PV systems, as other components are almost passive. Hence, the reliability of the inverter has maximum impact on the reliability of the whole PV system. Thus, not only assessing and calculating the reliability value of inverter is highly crucial, but also increasing its value is essential, as well. This paper calculates and evaluates the reliability of PV single-stage inverters exclusively. Furthermore, there are suggestions that improve their reliability value.

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1. INTRODUCTION

The level of energy consumption is growing due to population growth and progress in the industry. Therefore, sustainable energy systems with effective cost methods are required to meet the growing demand of energy [1]. Solar power is known as one of the most common renewable energy resources all over the world as it is pollution-free, is available in almost every region, and requires low maintenance effort. Solar power can be transformed into electricity directly utilizing PV panels. The output of a PV panel is Direct Current (DC); however, most of the electronic devices require Alternating Current (AC). Hence, the output voltage of a PV panel/array must be transformed into AC voltage by an inverter. PV panel(s)/array(s) and inverter(s) alongside some optional elements form a typical PV system. PV inverters are the most important parts of PV systems. They are the brain of the system and their main function is to convert the DC power produced by the PV array to AC power [2]. Inverters can be categorized in various ways; however, in this paper, inverters are categorized into Single-Stage Inverters (SSIs) and Multi-Stage Inverters (MSIs) [3-8]. SSIs have advantages including low cost, low weight, less bulkiness, and fewer elements, which lead to better efficiency and minor loss. Increasing the input DC voltage and converting it into AC voltage with the desired amplitude and frequency are done in separate steps in MSIs; however, they are done in a single step in SSIs. With a proper design in structure and appropriate switching method, SSIs can have higher efficiency, greater reliability, and lower cost due to the smaller number of elements [9-11]. The rate of operating safe and on schedule is called reliability. The assessment of reliability is one of the most important issues to be studied in distribution systems. Even sometimes these studies may recommend some new elements to improve the reliability value in the system [12, 13]. The reliability of a PV system is highly dependent on the inverter, as most of failures are caused by the inverter. Hence, the main part of assessing reliability in PV systems is to calculate the reliability value of their inverter.

According to the above discussion, the calculation of reliability value of a PV system is highly necessary and the main step is to evaluate the reliability of its inverter. Various studies have been done on evaluating the reliability of renewable energy resources, especially in the case of PV systems. F. Blaabjerg studied reliability of both wind turbines and PV applications [14]. The effect of PV array sizing on reliability was investigated in [15]. One of the main approaches to reliability is using the Markov method. This method was used to study the reliability in PV systems [16] and PV inverters [17]. The solutions to enhancing the PV inverter reliability through the control of the battery system (three different control strategies for self-consumption operation) were explored in [18] and their impact on the PV inverter loading was investigated.

The first purpose of this paper is to propose a method to evaluate the reliability of PV SSIs by their containing elements. The second purpose is to use the proposed method to study and compare the reliability values in some of the PV SSIs' structures to discover the characteristics of the structures with higher and lower reliability values. Hence, it can be help figure out how to increase reliability value in PV SSIs.

*Corresponding Author's Email: mrahmani@eng.ikiu.ac.ir (M. Rahmani)
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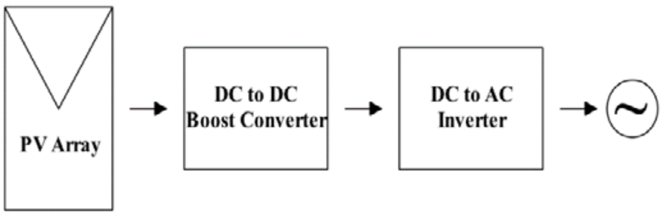
There are some methods for evaluating the reliability of these systems; however, they have some limitations and are not adequately accurate. This paper proposes a new simulation-based method to evaluate the reliability of SSIs. This method can be used for any desired period of time. Its accuracy is extremely high and it is determined by the number of iterations defined by the user (any desired value). Another advantage of this method is that if any new element is added to the structure of the inverter or be removed from it, still the reliability can be evaluated. Moreover, this method can consider the impact of using the same elements that are obtained from different manufacturers with different identical specifications. The reliability value of some of the SSIs [19-24] is evaluated. Moreover, there are some suggestions for increasing reliability values which are deduced by comparing and studying the output results.

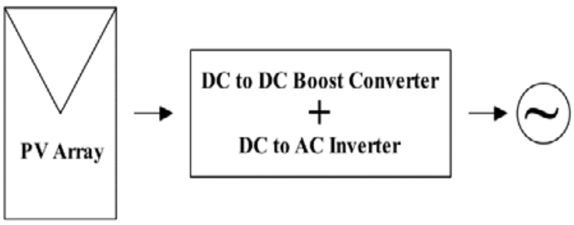
The reliability of PV single-stage inverters has been exclusively studied in this paper. Hence, Section 2 includes a brief explanation of SSI, reliability in systems, and main different approaches to evaluating its value. Section 3 explains the reliability evaluation method which is used in this paper step by step. In Section 4, the simulation results by the proposed method for some of the most well-known SSIs in MATLAB are presented in different conditions. Finally, the conclusion is presented in Section 5 alongside some suggestions to improve the value of reliability in SSIs.

2. RELIABILITY CONCEPT IN SSI

Figure 1 represents a brief and general preview of SSI and MSI. SSI is studied in this paper.



(a)



(b)

Figure 1. On-grid PV system with (a) multi-stage inverter and (b) single-stage inverter

The system reliability is defined as “the probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment” [25]. Reliability is an intrinsic quality in every system. Trying to increase reliability after design and manufacturing is impractical and even if possible, it is extremely expensive.

In the PV systems, inverters are highly important. Table 1 includes data from [26] and indicates that the major failures and energy losses in a typical PV system are caused by the inverter. Therefore, assessing the reliability of the inverter is essential.

Reliability can be calculated by various methods in different periods of time. Generally, reliability assessment methods are divided into two main groups:

- Analytical
- Simulation

In this paper, the reliability of single-stage PV inverters in different structures in PV systems is simulated, calculated, and assessed by the Monte Carlo method at the design and manufacturing phase (Figure 2).

For this simulation and calculation, the design layout of elements (series or parallel), quality of used elements (elements failure rate), and quality of elements are needed.

Table 1. Data from 3500 reports of 350 commercial PV systems with an approximate capacity of 150 kW from January 2010 to March 2012 [26]

Failure area	% of Tickets	% of kWh lost
Inverter	43	36
AC subsystem	14	20
External	12	20
Other	9	7
Support structure	6	3
DC subsystem	6	4
Planned outage	5	8
Module	2	1
Weather station	2	0
Meter	1	0

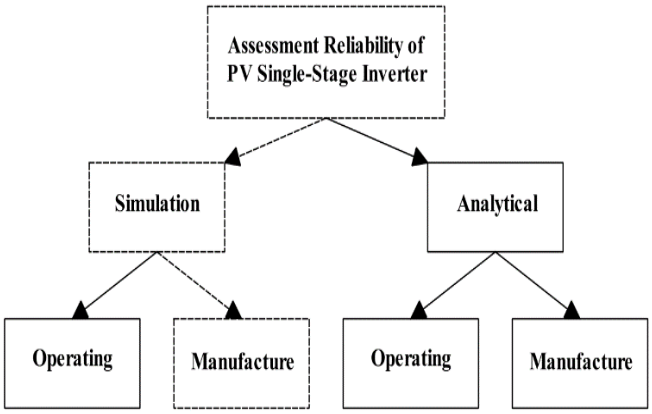


Figure 2. Assessment methods of reliability in the single-stage PV inverter in different phases

3. PROPOSED METHOD FOR RELIABILITY EVALUATION IN PV SSIS

If a component or a system be intact at time t=0, the probability of failure at time t=0 is equal to “zero”. The failure probability of the system will be increased through time and it will reach “one/unity”, and the system will surely fail in a long period of operation. This property is equivalent to the Cumulative Distribution Function. It is designated by Q(t) and is shown in Figure 3. Moreover, Survivor Function is designated by R(t) and is calculated as follows [16, 27]:

$$R(t)=1-Q(t) \quad (1)$$

where

$$Q(t)=\frac{N_f(t_0)}{N_0} \quad (2)$$

$$R(t)=\frac{N_s(t_0)}{N_0} \quad (3)$$

where N_0 is the total number of studied elements, $N_S(t)$ is the number of intact elements until $t=t_0$, and $N_f(t)$ is the number of defective elements until $t=t_0$.

In calculating the reliability value for a single-stage PV inverter in the proposed topology, it is assumed that all equipment and elements must operate properly so that the inverter operates properly. Otherwise, the inverter may continue to operate, but not in the predicted way and with desired quality. Moreover, the proposed topology can assess the reliability even if:

- Extra elements are added to the structure of inverter for increasing the reliability or other purposes;
- Some elements are removed due to modifying the structure of inverter or other purposes;
- Some elements are changed due to maintenance or other purposes.

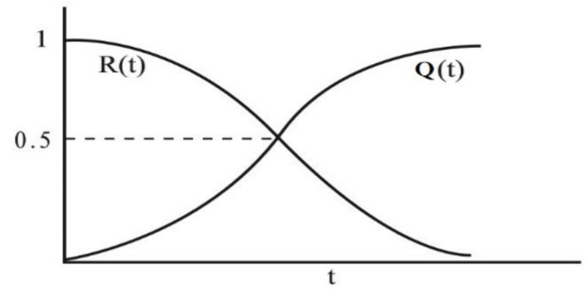


Figure 3. The relation between Q(t) and R(t)

The commonly used elements in inverters are inductors, capacitors, resistors, diodes, MOSFETs (or IGBTs), switches, wires, maybe transformer, and other optional elements. For assessing the reliability, the number of each element in the structure must be determined and the Hazard Rate Function (λ) of each element must be attained of its datasheet or handbook.

$$\lambda_p=\lambda_b\times\pi_T\times\pi_A\times\pi_R\times\pi_S\times\pi_C\times\pi_Q\times\pi_E \quad (4)$$

where λ_P is the part failure rate, λ_b is the base failure rate (usually expressed by a model relating to the influence of electrical and temperature stresses on the part), π_T is temperature sensitivity factor (it is usually changed for MOSFET), π_Q is a quality factor (quality of structure phase of elements), π_E is an environmental factor (including humidity, vibration, noise, dust, pressure, shock, etc.), and other factors (π_A, π_R, π_S, π_C) are just determined if they are necessary [28].

In this paper, λ_P is used to calculate the reliability of single-stage inverters:

$$\lambda_p(t)=\frac{\text{number of failure per unit time}}{\text{number of components exposed failure}} \quad (5)$$

The inputs for the proposed simulation method are:

- Number of each element in the structure of the single-stage PV inverter
- Hazard rate for each component
- Number of iterations
- Time period (years)

Moreover, the main steps of the proposed simulation method are as follows:

1. Create random numbers with uniform distribution.
2. Convert random numbers to time values using an equation or system data and by the conversion methods such as inverse conversion method.
3. Whenever the calculated time is equal to or greater than the mission time, it is considered as the success of the system. Likely, whenever this value is shorter than the mission time, it is regarded as a failure.
4. Repeating Steps 1 to 3 leads to a cumulative number of successes and a number of failures (for the desired number of iterations).
5. The system reliability is obtained by dividing the number of successes by the number of simulations (iterations).

To compare the reliability values of different inverters, it is assumed that the same components in different inverters are supplied from similar manufacturers with identical λ values. Table 2 shows the λ used in calculations.

Table 2. λ values for some used components in single-stage PV inverters [29]

No.	Description	λ (Failures/10^6 Hours)
1	Diodes, High frequency	0.22
2	Transistor, High frequency, MOSFET	0.060
3	Resistor, Fixed, Wire-wound (Power type)	0.0024
4	Capacitor, Fixed, Electrolytic	0.00040
5	Inductive devices, Coils	0.000030
6	Low power transformer (<300W)	0.022
7	High power transformer (≥300W)	0.049
8	Connectors, General	0.0010
9	Printed wiring assembly/ Printed circuit board	0.000017
10	Thyristor	0.0022

Several methods are used for reliability prediction. Some methods have their statistical data, others depend on additional data from other sources, and the rest are the updated versions of older methods. Some data is only appropriate for special systems, while other data can be used for any system. The reliability prediction of the methods cannot be compared because each analysis method is dependent on different data and each focuses on different factors and assumptions [30]. However, the authors claim that the proposed method has advantages over the previous methods including:

- Reliability of inverter can be evaluated accurately by the proposed method even if some elements are added, removed, or changed.
- Reliability can be calculated not just for a specific period of time, but for any desired period of time.

- The accuracy of the reliability investigation can be changed. As it is studied in the next section, the accuracy of reliability for iteration of 100,000 is acceptable. However, for critical consumption, the number of iterations can be increased. Hence, the accuracy will be increased to a greater extent.
- The proposed method is capable of evaluating reliability in SSIs even if its element is provided by different manufacturers (for instance, 3 inductors with 3 different λ's).

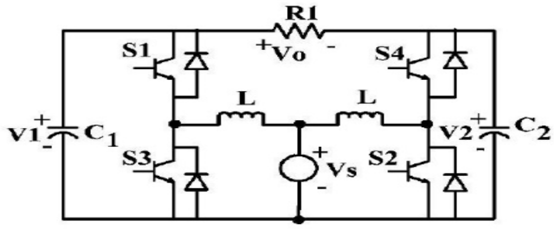
By comparing reliability values of different structures using the proposed method, it can be observed that the failure is caused more by which elements, then consumers have two options: first, try to modify the structure which is hard and not practical, or use the same element with a lower λ value from different manufacturers. Although it costs more, it leads to a higher reliability value in the long run.

4. SIMULATION RESULTS

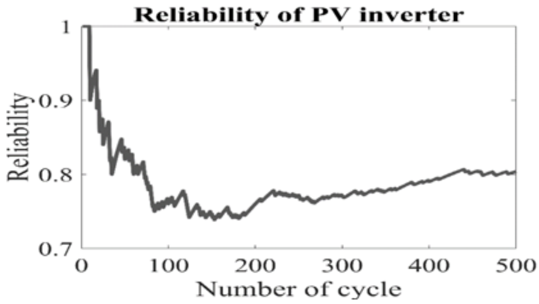
In this section, first, the simulation results of the proposed method in different situations (different numbers of iterations and different periods of time) are studied for Barbi and Caceres topology [19]. Then, the reliability evaluation of some other PV SSIs is studied and compared in the most realistic and optimum conditions with the proposed method.

The proposed single-stage inverter by Barbi and Caceres [19] and its output result for 500 iterations (which is 0.8360) are represented in Figure 4. However, the result is not stabilized and valid as it is shown. Hence, the number of iterations must be increased. Figure 5 and Table 3 shows the reliability values for different iterations in this topology.

Given that probability functions are used in this computation and simulation proposed method, it is not expected that the output results remain constant in every run as it is not in any other probability function. However, the results of multiple attempts must be in an acceptable range. This goal is achieved by increasing the number of iterations. Table 4 shows the results for two more runs.



(a)



(b)

Figure 4. (a) The proposed single-stage inverter topology by Barbi and Caceres [19] and (b) its output result in 500 iterations and 20 years

As the reliability value of a single-stage inverter varies in time, the assessment of reliability must be maintained for a specific period of time. The reliability decreases with increasing the computational time. The results of the reliability calculation over a period of 1 year to 35 years with 100,000 iterations for Barbi and Caceres proposed topology are shown in Table 5 and Figure 6. it can be deduced that the reliability of the single-stage inverter varies relatively linearly in relation with the duration of the evaluation.

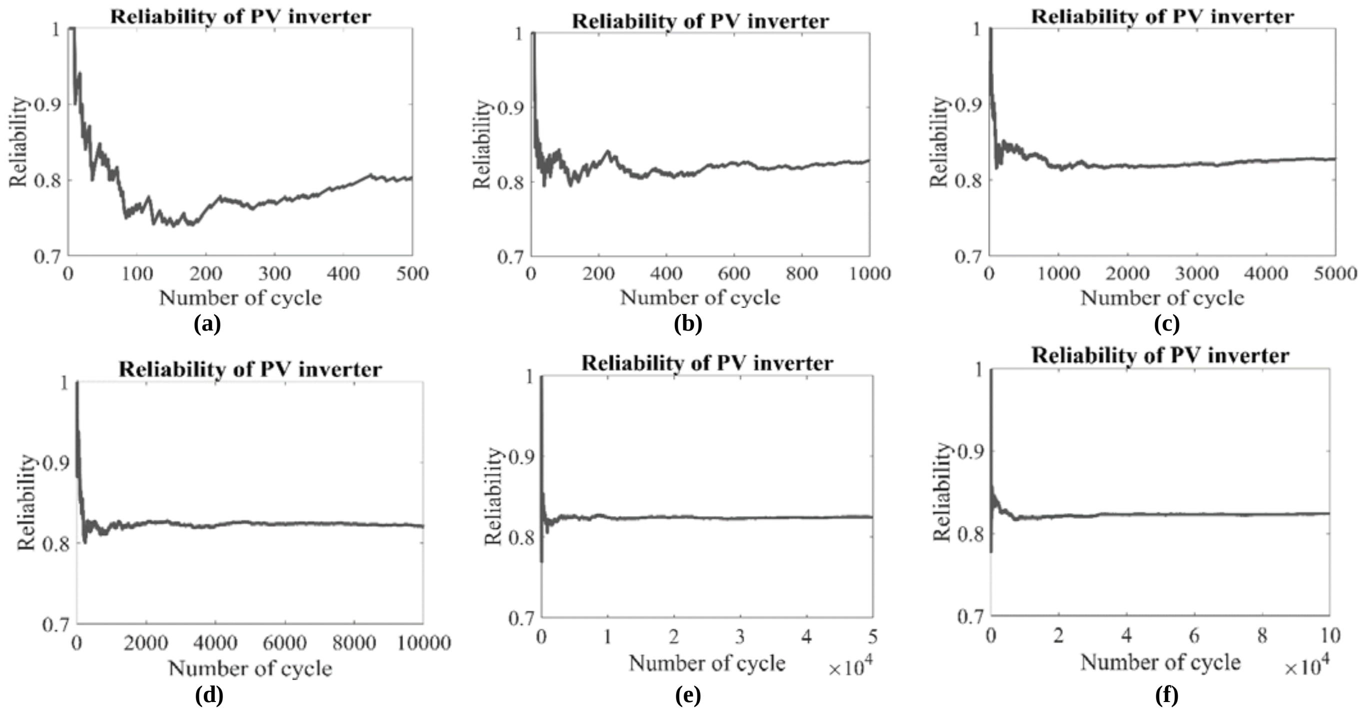


Figure 5. The reliability values of Barbi and Caceres proposed topology for iteration of (a) 500, (b) 1,000, (c) 5,000, (d) 10,000, (e) 50,000, and (f) 100,000

Table 3. The reliability values for different iterations

Number of iterations	500	1,000	5,000	10,000	50,000	100,000
Reliability	0.8380	0.8280	0.8256	0.8212	0.8222	0.8225

Table 4. Comparing the output result deviation of Barbi and Caceres proposed topology in the iterations of 100,000 and 500 for 20 years

Number of iterations	**First run**	**Second run**	**Third run**	$\frac{\textbf{Max}-\textbf{Min}}{\textbf{Max}}\times\textbf{100}$
500	0.8440	0.8280	0.8380	1.8957 (%)
100,000	0.8225	0.8213	0.8216	0.1458 (%)

Table 5. The results of the reliability calculation over a period of 1 year to 35 years with 100,000 iterations for Barbi and Caceres proposed topology

Duration of evaluation	1	5	10	15	20	25	30	35
Reliability value	0.9902	0.9537	0.9060	0.8624	0.8221	0.7837	0.7442	0.7063

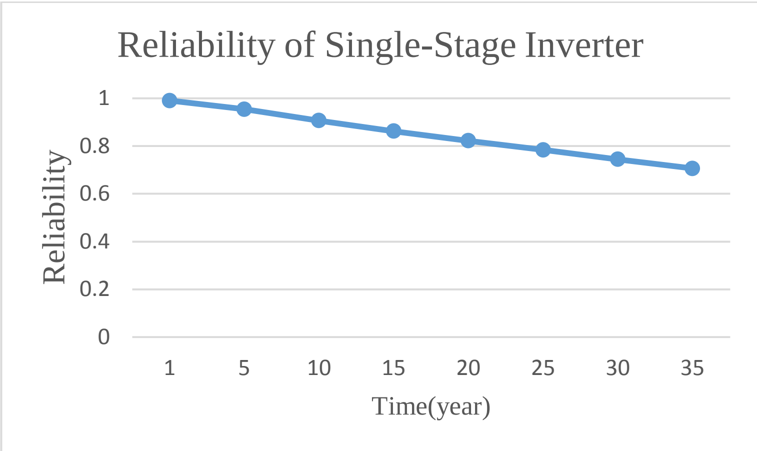
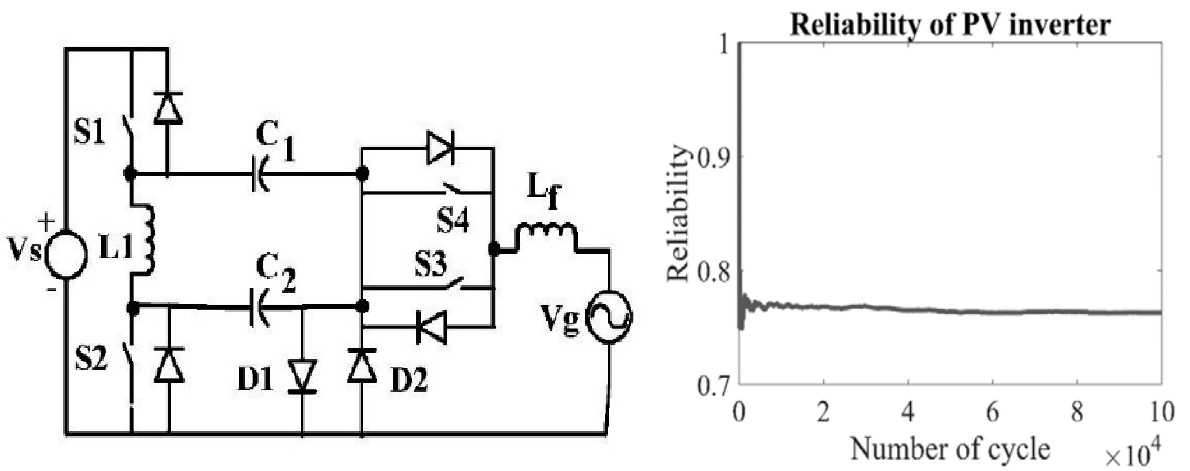


Figure 6. The results of the reliability calculation over a period of 1 year to 35 years with 100,000 iterations for Barbi and Caceres proposed topology

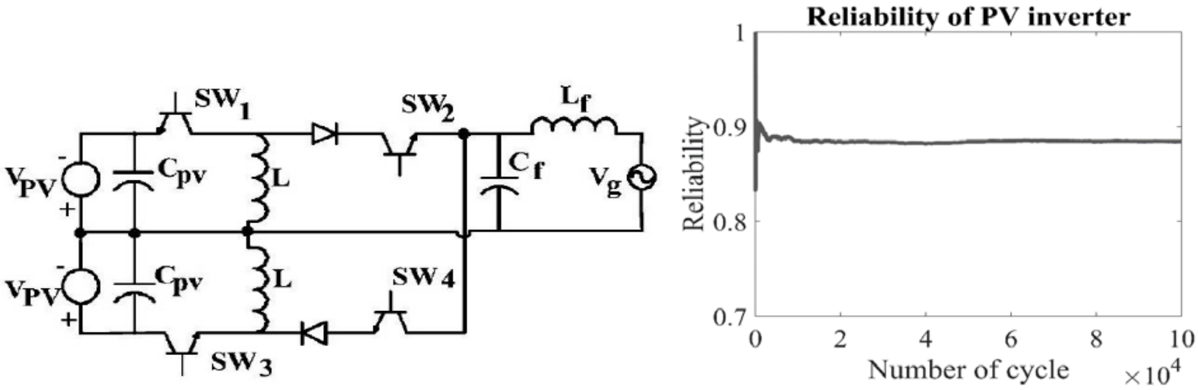
In the following, calculations and evaluation of the reliability of some single-stage inverters with the iteration of 100,000 for 20 years of operation are represented.

Figures 7 to 12 indicate the proposed single-stage inverter topologies by Schekulin [20], Kasa topologies without and with transformer [21] (two topologies), Wang [22, 23] (two topologies) and Sachin [24] alongside their paper results with the iteration of 100,000 in 20 years, respectively. Moreover, the final results of all the mentioned topologies are represented in Table 4.



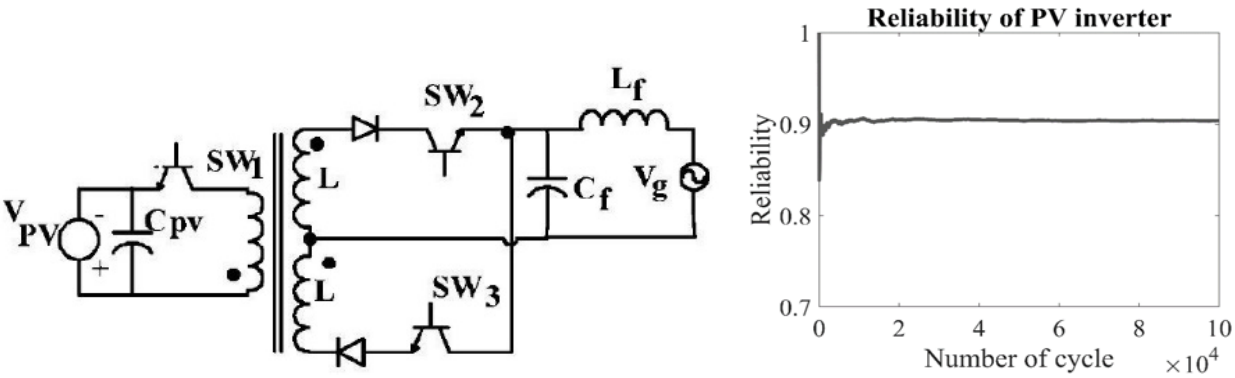
(a) (b)

Figure 7. (a) The proposed single-stage inverter topology by Schekulin [20] and (b) its output result



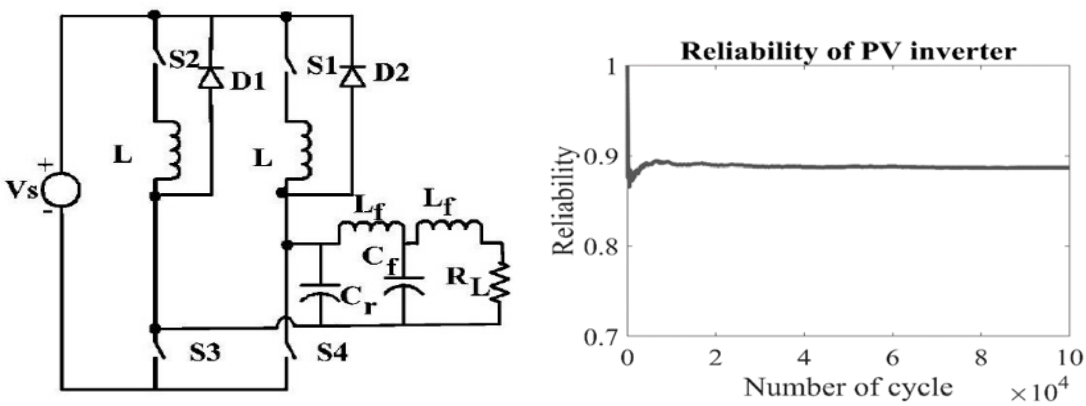
(a) (b)

Figure 8. (a) The proposed single-stage inverter topology without transformer by Kasa [21] and (b) its output result



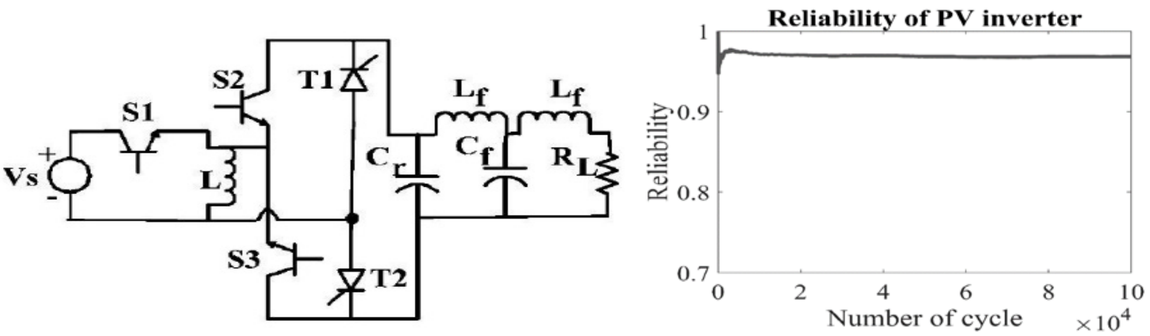
(a) (b)

Figure 9. (a) The proposed single-stage inverter topology with transformer by Kasa [21] and (b) its output result



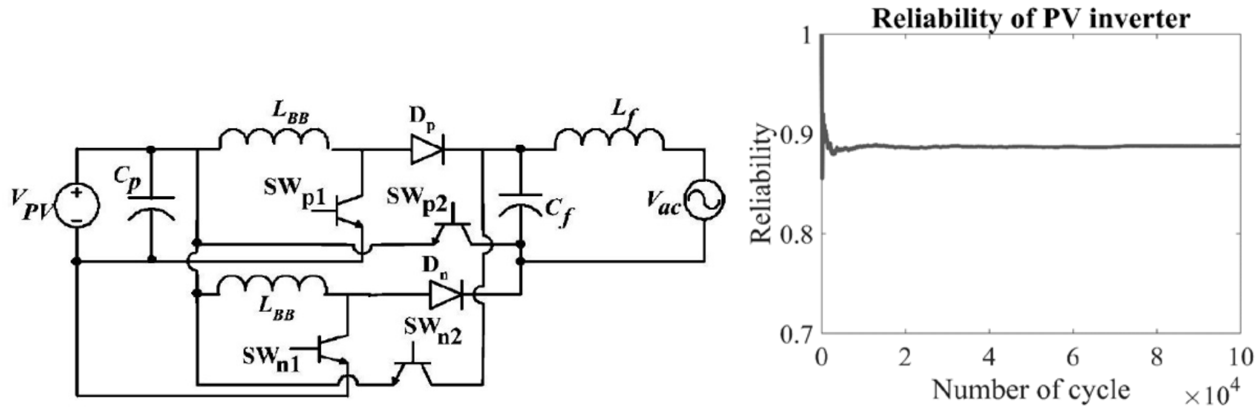
(a) (b)

Figure 10. (a) The first proposed single-stage inverter topology by Wang [22] and (b) its output result



(a) (b)

Figure 11. (a) The second proposed single-stage inverter topology by Wang [23] and (b) its output result



(a) **(b)**

Figure 12. (a) The second proposed single-stage inverter topology by Sachin [24] and (b) its output result

Table 6. Reliability values for the mentioned single-stage inverter topologies

Topologies	Number(s) of								Reliability (20 Years & 100000 Iterations)
	Capacitors	**inductive**	**Transistors**	**Diodes**	**SCR**	**Boards**	**Connectors**	**Transformer**	
Barbi & Caceres [19]	2	2	4	4	0	1	4	0	0.8225
Schekulin [20]	2	2	4	6	0	1	4	0	0.7607
Kasa (without transformers) [21]	3	3	4	2	0	1	6	0	0.8836
Kasa (with transformers) [21]	2	1	2	2	0	1	4	1	0.9029
Wang (First) [22]	2	4	4	2	0	1	4	0	0.8889
Wang (Second) [23]	2	3	3	0	2	1	4	0	0.9676
Sachin [24]	2	3	4	2	0	1	4	0	0.8878

It was mentioned earlier that the evaluated reliability value would be increased by increasing the number of iterations; however, it has been experimentally proven in this paper that 100,000 is a proper value for the number of iterations (Table 4).

According to Figure 6, the reliability value in SSIs will be decreased relevantly in a linear pattern.

Moreover, according to Table 6:

- The reliability value of inverters with SCR is higher than that of inverters with diodes due to lower λ value.
- The reliability value of inverters with a transformer is higher than that of inverters without transformer due to the fewer components; on the other hand, this can lead to higher costs and losses.

5. CONCLUSIONS

This paper proposed a method for evaluating reliability values by simulation of inverters, single-stage inverters, or any scheme containing different elements with different λ. As it is mentioned before in Section 3, the reliability prediction by different methods cannot be compared because each analysis method is dependent on different data and each focuses on different factors and assumptions. The proposed method has some privileges over other methods. For instance, this method can evaluate the reliability of inverter accurately even if some elements are added, removed, or changed for any desired period of time and for the desired number of iterations determining the accuracy and convergence. The impact of different λ values for different elements (for instance, inductor and capacitor have different λ values) and even different λ values for different types of a single element (for instance, two different inductors with different λ values) can be calculated by this proposed method. The impact of the intended operation time was also considered. Furthermore, the number of iterations was optional and varied as the operator desired. Given that the reliability calculation by the proposed method was obtained by simulating the actual process and studying the random behavior of the system (inverter in this case), the reliability calculations were performed repeatedly for a particular inverter. The values may not be the same, but these values are quite close to each other. The calculated value of reliability was influenced by the intended operation time so that the reliability would be decreased relevantly in a linear pattern in single-stage inverters.

6. ACKNOWLEDGEMENT

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