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Reliability, availability, and condition monitoring of inverters of grid-connected solar photovoltaic systems

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Abstract

Reliability, Availability and Condition Monitoring (RACM) evaluation has become a critical area of interest for researchers as the output power quality of a Photo-Voltaic (PV) system depend on the reliability of its components. In this paper, the RACM of grid-connected PV systems is presented. For this, the Reliability Block Diagram (RBD) technique along with the exponential probability distribution function is used. The main objective of this work is to identify the weakest subsystem of a system in order to enhance system reliability. The condition monitoring system will be helpful in avoiding the sudden breakdown and unexpected maintenance of the system. An elaborate analysis is presented for PV system beginning from the sub-assemblies to the subsystems and then to the overall system. In addition, the subsystems are ranked based on their impact on the overall availability of the system. This is decided based on the availability importance measures. It is observed that the inverter forms the weakest subsystem in the solar system. The novelty of the proposed RACM method is that one can monitor the health status or useful life of the system regularly which is not yet explored in the literature. Most of the papers have considered that the components of PV systems are non-repairable but in this paper, the redundancy concept is explored which helps in increasing the reliability and availability of the system. When the proposed method and the results obtained are compared to existing methods, it is discovered that the proposed work outperforms them.

1 | INTRODUCTION

Solar PV systems are being implemented in many places to provide electricity to buildings, organisations, society, and industries too. This significant growth rate of PV systems has attracted the attention of researchers towards its development. The electricity generation from solar PV systems depends on the availability of sunlight with good irradiation. The availability of PV-generated electricity affects the grid power supply and distribution either in a direct or indirect way. Therefore, the connection between grid supply and PV system generation should be given attention so that power can be utilized properly. This will help in achieving a good generation-supply management system from the utility grid with the cooperation of solar PV systems. Along with the reliability and availability of grid-connected PV systems, the condition monitoring of its components is also crucial. Hence, RACM is focused in this paper on a grid-connected PV system. This helps to produce an accurate prediction of grid-connected PV-based energy generation systems and to plan for a scheduled maintenance [1, 2]. It aids in the identification of components that can have a significant influence on overall availability and also the cause of failure of the complete system. It may also be used to plan and operate PV systems according to the health status of the system and its components. In case of any fault, the proposed system will warn much earlier so that one can schedule the maintenance date and time rather than sudden shutdown. The research works done in solar PV modules [3–6], Balance of System (BOS) [7, 8], and inverters [9] are constrained since reliable data on the failure and repair rates of PV systems is not accessible. Therefore, most of the works available in the literature have considered either one subsystem or subsystems with a larger number of components of the PV system.

The repair time of components of PV system affects its availability which needs to be considered. In literature, some of the researchers have discussed the dependability and availability of PV systems and its component with simple assumptions considered. The authors in [10, 11] have discussed it in detail. The authors have also mentioned the discrepancies coming from the assumptions made while doing simulation and actual experiment with a PV system.

For adequate functioning of the grid-connected PV system, the availability and dependability are important parameters as discussed in [12–14]. In literature, the most commonly used techniques for reliability analysis including availability and dependability of large systems involve RBD and Fault Tree Analysis (FTA) [15]. As discussed by the authors in [12], in FTA, a logical diagram is formed which represents the system and each block of the logical diagram represents its failure rate. Most of the research papers have discussed the system dependability involving failures of each sub-system which concludes that any single failure is going to be critical for that system. In some research works, the dynamic FTA technique is used which involves the calculation of failure rates using a time-dependent probability density function as discussed in [16]. This method is also having one demerit of not using optimal probability density functions for each sub-system.

An exponential distribution-based RBD approach is used in this paper to analyse the dependability of a grid-connected solar-PV system. Despite the fact that most of the components of a PV system are considered non-repairable equipment, the restoration of a lifetime will have an impact on the device function and should not be overlooked. Thus, the input data for various subsystem failures and repair rates that are necessary for this research are gathered from worldwide databases. The condition monitoring system is very crucial in knowing the current health status of PV system components. This is also helpful in showing the effect of maintenance on the life cycle of the component [17]. There are various methods available in the literature for condition monitoring of any equipment like supervised, unsupervised type machine learning techniques and deep learning techniques such as artificial neural network (ANN) and convolution neural network (CNN). In this paper, an unsupervised type machine learning technique is used for the monitoring of inverter of the PV system. Although it is used when one does not have the historical data or failure data it is a quite simple technique to be applied even if one has the data. The name of the technique is Principal Component Analysis (PCA) which is a well-known data dimension reduction technique and unsupervised machine learning technique as well. This technique is used to reduce the dimension of higher dimensional data sets and to do statistical analysis of the data for feature extraction. In literature, it has been used for feature extraction also with other machine learning techniques such as Support Vector Machine (SVM) and k- nearest neighbour (KNN). Therefore, looking at the simplicity and flexibility of the PCA technique, it is implemented in this paper for condition monitoring. The second aim of this paper is to list the components of PV system according to its criticality so that the weakest component is recognised which fails most frequently. The main contributions of this paper are as follows:

- Reliability, availability, maintainability, and condition monitoring of PV system.
- Reliability and availability analysis using RBD method with exponential probability distribution function.
- Listing of components of a PV system based on the need for maintenance.
- Condition monitoring of inverters of PV system for failure prediction using PCA technique.

The various configurations of solar-PV systems are detailed in Section 2 of this paper. Section 3 explores broad ideas of dependability, system decomposition, reliability modelling, data collecting, and case studies, whereas Section 4 discusses availability importance measurements, reliability, and availability of PV system. The condition monitoring of inverters of a PV system is discussed in Section 5 results and an explanation of the acquired outcomes is discussed in Section 6. Finally, Section 7 summarizes the findings of this research work.

2 | LAYOUTS OF SOLAR-PV SYSTEMS

Basically, PV systems are classified into two different systems namely, grid-connected and stand-alone systems. The grid ensures the reliability of the system by serving as an ideal component for storage in a grid-connected PV system, while a battery is required for a stand-alone PV system for storage. Figure 1 depicts the arrangement of components in a PV system connected with the grid. The primary source of generation of electricity for a grid-connected solar system is a PV array. The operation of a grid-connected system is intended in parallel and synchronously with the utility network. If more power is obtained than needed during the day, the PV arrays from commercial and residential can sell the excess amount of power to the grid [18]. The power can be bought from the grid during the night times or when more power is needed by the sites. Thus, for PV arrays the grid serves as a means of storage during the day. Sometimes batteries can also be present for these PV arrays and they can choose whether to sell the excess power to the grid or store it in the batteries. Stand-alone PV systems are generally sized and designed to supply certain AC and/or DC loads and operation is not dependent on the electric grid. For energy storage, a battery is needed by a stand-alone PV system. The battery gets charged when energy is produced in excess or at times of low or no loads. The battery will discharge to meet the load when there is low radiation from the sun. In order to ensure a longer lifetime for the battery, this charging and discharging process is supervised by a charge controller [19–22].

The choice of the precise type of system has a large effect on reliability [23, 24]. The PV systems are labelled according to their reliability level having lower or higher reliability. There are two types of PV systems: grid-connected and standalone. The grid-connected solar system is preferably positioned near the grid, which without delay is fed through its output power. In this type of system, battery storage is not needed. In case more power is needed, it is fulfilled by the grid. This helps the

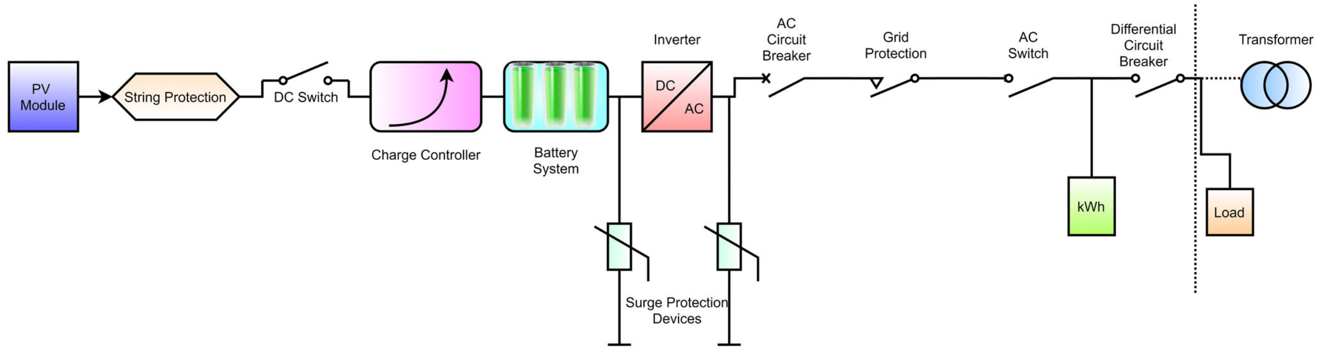

FIGURE 1 Arrangement of components in PV system connected with the grid.

grid-connected PV system to have high reliability as it can fulfil the demand of the local loads. The loads are also categorized based on the interruption level that can be tolerated by the loads. Based on this, there are three types of loads: non-essential (high interruption is allowed), essential (very small interruption is acceptable), and critical (no interruption is acceptable). Energy storage requirement comes only when the grid is unreliable, in this case for supplying critical loads, the storage system is useful then the total system becomes an uninterruptible power system. The loads which are placed far away from the grid-connected PV system, the standalone PV system and grid can be a good solution to fulfil those loads. The battery storage system plays an important role in this case to balance the energy demand. The loads are further divided into two types based on the requirement of the battery storage. The non-deferrable is the first kind of load which needs a continuous power supply and the second one is a deferrable load where the interruption of supply is acceptable and based on the availability of PV power and grid supply, the demand is supplied. Therefore, battery storage is a must in non-deferrable loads whereas, it can be neglected for deferrable loads. In this type of load, battery storage is not recommended. The water irrigation pumping system comes under the deferrable loads [2].

In the PV system which is connected with a less reliable grid, an Automatic Static Transfer Switch (ASTS) is used for instantaneous response to the islanding condition of the PV system. In this condition, a power outage problems or power quality problem arise as the grid gets disconnected. The PV system under islanding conditions provides power to the essential and critical loads which need a continuous power supply. The non-essential loads can compromise the power supply so these loads are disconnected under islanding conditions. The main focus of this paper is on the PV system connected with low-reliability gird.

3 | RELIABILITY AND AVAILABILITY ANALYSIS

Reliability is defined as the probability of a system or device performing its function adequately for the period of time intended under the operating conditions intended. The intention is to get a better knowledge of device failure so that product designs may be changed to extend product life and reduce the negative effects of failure [25]. Electric power systems are a prime example of a system that requires a high level of reliability. According to the basic definition, the key quality of reliability is the probability of the system completing its function adequately. As a result, probability calculations are required for system dependability evaluations. Probability gives an idea of how likely an event will occur. The reliability function ($R_{PV}(t)$) can be written in term of probability ($P_{PV}(t)$) as Equation (1) [11, 26].

$$R_{PV}(t) = P_{PV}(T > t). \tag{1}$$

The failure probability $F_{PV}(t)$ is a cumulative distribution function (CDF) is given as Equation (2) [11, 26].

$$F_{PV}(t) = 1 - R_{PV}(t) = P_{PV}(T \leq t). \tag{2}$$

The reliability and unreliability expressed in Equations (1) and (2) can further written in terms of probability density function ($f_{pdf}(t)$) as given in Equations (3) and (4), respectively.

$$R_{PV}(t) = \int_{t}^{\infty} f_{pdf}(t)dt, \tag{3}$$

$$F_{PV}(t) = \int_{-\infty}^{t} f_{pdf}(t)dt. \tag{4}$$

By using the reliability function or probability density function, the mean time to failure of component 'c' ($MTTF_c$) of the PV system can be calculated by the expression given in Equation (5).

$$MTTF_c = \int_{0}^{\infty} (t \times f_{pdf}(t))dt = \int_{0}^{\infty} R_{PV}(t)dt. \tag{5}$$

As the PV system components are considered to be of the non-repairable type so they can be connected in series in the reliability block diagram and the overall reliability of such system will be given by Equation (6) where R_{si} is the reliability of sub-assembly 'si'. For 'm' number of sub-assemblies 'si', the total reliability of the sub-assembly 'si' is given by Equation (7)

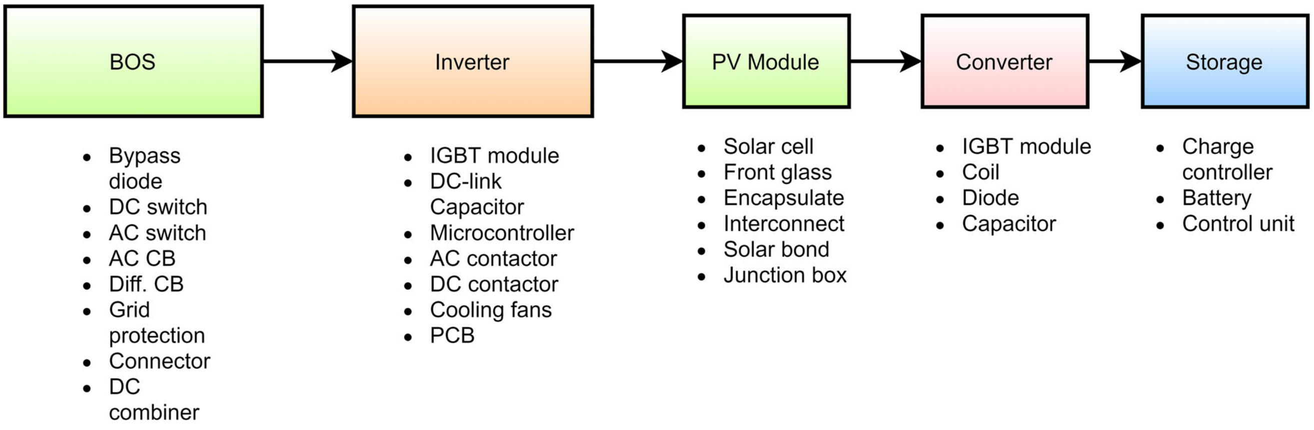

FIGURE 2 Division of PV system into its components and sub-components and reliability block diagram.

where λ_{si} is the failure rate of sub-assembly 'si'. For the 's' number of series connected components with 'P' parallel sub-assemblies, the overall reliability of the system is given by Equation (8).

$$R_{overall} = \sum_{si=1}^{n} R_{si}, \tag{6}$$

$$R_{msi} = exp\left(-\sum_{si=1}^{n}(m_{si}\lambda_{si}t)\right), \tag{7}$$

$$R_{overall} = 1 - (1 - R^{s})^{P}. \tag{8}$$

3.1 | System decomposition

In reliability analysis, the first step is system decomposition. Based on the working function of each sub-system, the complete PV system is decomposed into its sub-systems during this phase. Each sub-system is further decomposed into its assemblies which is a very complicated task for reliability analysis. Therefore, most of the works done in literature are focused on major systems or components but not the sub-assemblies. Another reason for this is the unavailability of the failure, repair and maintenance-related information of the sub-assemblies of the larger PV systems. The PV system can be divided into five major components as discussed in [15]. The five major components are BOS, PV module, DC converter system, DC-AC inverter, and battery system. These five major components are further divided into sub-components as shown in Figure 2. The major drawback observed from the literature is the non-involvement of the BOS sub-component of a PV system while doing reliability and availability analysis of PV systems. There are only limited works that have considered the reliability and availability of BOS along with the PV modules while doing reliability analysis of the PV system as discussed in [15]. The authors have also discussed the fault tree technique for the reliability analysis of PV modules.

3.2 | Reliability evaluation of inverter system

The layout of the solar power system depends on the architectural design. Based on the number of inverters present in the PV system and the structure of the inverter connection with other components, the reliability block diagram of the inverter is decided. There may be the case when all components are connected to the inverter which is present singly as a central inverter or there may be a single inverter present in each line connecting to other components [27]. This affects the overall reliability and availability of the PV system. In case, if only one central inverter is present, the reliability level depends on the availability and reliability of that single inverter. If multiple inverters are present in the system then, groups of strings are counted as per the number of inverters available for each component.

To do a better analysis of the RACM of PV system, a layout has been proposed in this paper containing a typical three-phase PV system. The sub-systems are the IGBT power module, cooling fan, software, DC link capacitors along with Printed Circuit Board (PCB), and AC and DC contactors. In the PV module, the 36 cells are connected in series. The inverter part is the most crucial in the RACM analysis of the PV system.

3.3 | Reliability modeling using RBD method

The data needed for RACM of each component is collected from various resources as mentioned in this paper wherever needed. The PV module can be further divided into a large number of sub-components but due to the lack of data and to avoid the complication of the system, the whole PV module is considered as a single system for RACM analysis. RACM evaluation of large PV systems connected with the grid is carried out by the usage of a number of reliability methods. Among them, FTA and RBD are considered in most of the reliability-related works done in the literature. In FTA, the system configuration is represented by a logical sketch and components are represented by each block and are defined by failure rates. On the opposite hand, RBD is preferred when the failure and repair rates are

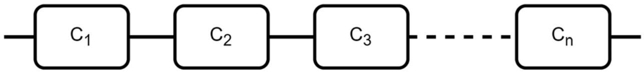

FIGURE 3 The 'n' components of the system are connected in series.

taken into consideration. Components of an RBD system are understood as series or parallel blocks that are interconnected depending on their impact on the system as a whole. Component failure and repair rates are described by the blocks. From a reliability point of view, the entire system appears to be of sub-assemblies which are in series, in parallel, in a grid or a series-parallel combined structure of sub-assemblies. This paper only considers series and parallel processing. The overall failure rate and repair rate of a series connected system are given by Equations (9) and (10), respectively, and also, the overall failure rate and repair rate of two parallel connected systems are given by Equations (11) and (12), respectively [26].

$$\lambda_{sys} = \sum_{si=1}^{n} \lambda_{si}, \tag{9}$$

where 'si' is representing the sub-system and 'sys' is representing the overall system.

$$\mu_{sys} = \frac{\sum_{si=1}^{n} \lambda_{si}}{\sum_{si=1}^{n} \frac{\lambda_{si}}{\mu_{si}}}, \tag{10}$$

$$\lambda_p = \frac{\lambda_1 \lambda_2 (\mu_1 + \mu_2)}{\mu_1 \mu_2}, \tag{11}$$

$$\mu_p = \mu_1 + \mu_2. \tag{12}$$

In the series connected system as shown in Figure 2, for the successful operation of the system, all the sub-assemblies have to work. If any of one of the sub-assemblies fails then that can result in the failure of the whole system. On the other side, the parallel connected system failure takes place if all sub-assemblies linked in the parallel path failed and if at least any one of the sub-assembly workings is enough to result in the successful operation of the entire system. Therefore, the series connected system is considered a non-redundant system and the parallel connected system is considered a totally redundant system. In a system of two components, when the failure rate and repair rate of each component is known, the overall failure rate and repair rate are given by Equations (11) and (12), respectively.

If there are n independent components of a system and are connected in cascade as shown in Figure 3 and if all the components are under working conditions for the successful operation of the system then, according to the simple probability principal, the overall reliability of the system is given by Equation (13).

$$R_{sys} = \sum_{c=1}^{n} R_c = R_1 + R_2 + R_3 + \cdots + R_n, \tag{13}$$

where R_c is representing the reliability of component c of the system. The reliability of the system can be calculated using the failure rate of the system. If the failure rate of each component of the system is known then, the overall reliability of the system can be found using Equation (14).

$$R_{sys} = \sum_{c=1}^{n} e^{\sum_{c=1}^{n} -\lambda_c t}. \tag{14}$$

For one component, if the failure rates of its sub-components are known then, the reliability of that component is found using Equations (15) and (16).

$$R_c = e^{-\lambda_c t}, \tag{15}$$

$$\lambda_c = \sum_{i=1}^{m} \lambda_i, \tag{16}$$

where i=1,2,…,m is representing the number of sub-components of the component following exponential probability distribution function and connected in series. It is noticed that the summation of failure rates of each sub-components connected in series gives the failure rate of the component and the summation of failure rates of each component gives the failure rate of the system.

3.4 | Data collection

Collecting data on system reliability is one of the main challenging and the most important step in RA analysis. A huge amount of data including failure rate and repair rate of different components of PV systems is gathered from the literature in which different technologies and layouts of a PV system are used. In this paper, an exponential distribution based on the RBD approach is used to give a strategy for RA analysis of a grid-connected PV system. The needed input statistics are derived from literature such as failure rates of various subsystems, as indicated in Table A.1. The gathering of relevant data is a key stage in reliability and availability analysis. For system reliability and availability analysis, the gathering of strong failure and repair rates data is highly required for more reliable and accurate findings. As a result, one of the key issues in this paper is gathering a large quantity of reliability and performance data for each sub-assembly from numerous systems in order to get an accurate number for each sub-assembly's failure rate and repair rate. These figures were taken from a number of valid research studies that utilised them to estimate the dependability of grid-connected solar PV systems. The obtained data is first sorted and then the median value is calculated for each of the sub-assemblies. The middle figure in the sorted list of the collected data is the median failure or repair rate. This is because when compared to the calculation of average values, the median values give the least uncertainties in the analysis of the data. The resulting median values of the failure rates of specific sub-assemblies are compared with the failure rates of the same sub-assemblies acquired from real field data in [28] to confirm the validity of the gathered data. The computed median values are fairly near to the genuine field data, according to the results. The obtained data is first sorted and then the median value is calculated for each of the subassembly. This is because when compared to the calculation of average values, the median values give the least uncertainties in the analysis of the data. The Table A.1 in the Appendix shows the collected data of each sub-assembly failure and repair rates of the solar PV system. As mentioned in Table A.1, in some of the literature which is used to collect the reliability data, some data are indicated as NA which means not available. The main objective of this paper is to collect a huge amount of data including repair and failure rates of large PV systems. This is done to find the sub-assemblies' accurate failure and repair rate values. It can be observed from Table A.1, that the data gathered is varying a lot and is very inconsistent. This is mainly because the data is collected from systems with various configurations and located at various locations, in addition to having different climatic conditions. If we consider one reference as the input then so many doubts will be raised like what if the reference that we considered is having an unexpected value which may be occurred when an assumption is made to avoid the absence of data of a few sub-assemblies. Therefore, this type of error and unexpected values in the collected data are avoided by calculating the median of the data after sorting. When compared to the calculation of the average values the median value will decrease the uncertainties that occurred from the unexpected values.

For the evaluation of RA of each sub-assembly, the nominal power of the considered PV systems ranges from 100 kW to 2500 kW. Each sub-assembly of the PV system contains an identical battery (12 CS 11P, 475 Ah, 12 V) and is analysed twice for the operation over 1 year and over 20 years with 8.5 h of operation per day. Detailed information on the PV system components have been provided in Table A.2 in the Appendix. There can be different structures of battery connection based on the requirement of the storage capacity [29]. In this paper, each battery used has a reserve capacity of two days. The power output of the PV system can not be considered complete for reservation. Only a part of it can be kept as reserved capacity. In this paper, it is assumed that 5% of the power generated from PV is reserved. The battery storage used for this is having two batteries connected in series where each battery is 12 V. After connecting 30 such battery structures, a 200 kW rating storage system is prepared. If two batteries of 12 V are used then, a 24 V capacity battery will be prepared and the parallel combinations required is 15. For high output power PV systems, the sub-assemblies are increased as shown in Table 1 and discussed in detail in [30].

Tables 2 and 3 show the failure rate and repair rate, respectively, of 7 PV systems of different ratings. These rates are calculated based on the data shown in Tables A.1 and 1 using RBD method as mentioned in Equations (9) and (10) for series connection and Equations (11) and (12) for parallel connection.

TABLE 1 Details of sub-assemblies of each component of the PV system [30].

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	437	874	2166	4351	6517	8702	10868
Converter	3	6	15	27	42	57	72
Bypass diode	23	46	114	229	343	458	572
AC circuit breaker	1	2	5	9	14	19	24
AC Switch	1	1	1	1	1	1	1
DC switch	3	6	15	27	42	57	72
Differential C. B.	1	1	1	1	1	1	1
Grid protection	1	1	1	1	1	1	1
Connector (coupler)	874	1748	4332	8702	13,034	17,404	21,736
Inverter	1	2	5	9	14	19	24
Charge controller	1	1	1	1	1	1	1
Battery system	16	30	76	150	224	298	372

4 | AVAILABILITY ESTIMATION

The authors in [31] have considered the availability importance measures for enhancing the system reliability. These are important as they help to know the weakest component of the system and one can work on that component to improve the overall reliability and availability of the system.

Availability importance measure depends on the failure and repair rates and also on the system structure. For every subsystem, it is given a value between 0 and 1. Among them, 1 indicates the best level of importance and on the other hand 0 value indicates the low level of importance. For a system containing n subsystems, the availability importance of subsystem 'si' is given by $I_A^i = A_{sys}/A_{si}$ where A_{sys} is representing the availability of the system and A_{si} is representing the availability of each sub-system. The impact of the availability of the subsystem 'si' on the overall system's availability can be obtained with the aid of using the availability importance measures. With the help of availability importance measures, the availability of each sub-system can be calculated and the impact of the availability of each sub-system on the overall availability can also be analysed. The availability analysis of each sub-system helps to know the weakest sub-component of the system and helps in improving the overall availability of the system.

In availability importance measures, the first motive is to find the sub-system which is affecting the availability of the system most. There are two types of importance measures. One is based on the failure rate and another one is based on the repair rate. As per the name of these importance measures from the failure rate-based availability measure, the effect of the failure of each sub-system on the overall availability of the system can be observed. On the other hand, the repair rate-based availability measure helps in knowing the effect of repair of any sub-system or component of system on the overall availability of the system as given in Equation (17) [26].

$$A_{si} = \frac{\mu_{si}}{\lambda_{si} + \mu_{si}}, \tag{17}$$

where λ_{si} is the failure rate of subsystem 'si' and μ_{si} is the repair rate of the subsystem 'si'. When n sub-systems which are independent of each other are connected in series then, the

TABLE 2 Subsystem failure rate (YR^{-1}) estimated from Table A.1.

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	0.020337	0.040674	0.100800	0.20248	0.30328	0.40497	0.50577
Converter	0.065153	0.130305	0.325763	0.58637	0.91214	1.23790	1.56366
Inverter	0.124100	0.248200	0.620500	1.11690	1.73740	2.35790	2.97840
BOS	0.077680	0.119890	0.245500	0.43700	0.64710	0.85810	1.06820
Storage system	0.019856	0.019856	0.019856	0.01986	0.01986	0.01986	0.01986

TABLE 3 Subsystem repair rate (YR^{-1}) estimated from Table A.1.

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	11.790	11.790	11.790	11.790	11.790	11.790	11.790
Converter	310.250	310.250	310.250	310.250	310.250	310.250	310.250
Inverter	6.515	6.515	6.515	6.515	6.515	6.515	6.515
BOS	59.207	57.806	56.554	55.676	55.593	55.541	55.520
Storage system	49.950	49.950	49.950	49.950	49.950	49.950	49.950

availability of the overall system is as given in Equation (18) [11, 32]. For a subsystem 'si' of a series connected system, the availability importance measure is defined as in Equation (19) [11, 32].

$$A_{sys} = \prod_{si=1}^{n} A_{si} = \prod_{si=1}^{n} \frac{\mu_{si}}{\lambda_{si} + \mu_{si}}, \tag{18}$$

$$I_A^{si} = \frac{\partial A_{sys}}{\partial A_{si}} = \prod_{k=1,\neq si}^{n} A_k = \frac{A_{sys}}{A_{si}}. \tag{19}$$

From Equation (18), it can be concluded that the availability of subsystem 'si' is not affected importance measure of that particular sub-system. For the subsystem which is having less availability estimate that subsystem must be given the highest priority for the increased availability. The two types of availability importance measures are given by Equations (20) and (21) [11, 32].

$$I_{A,\lambda_{si}}^{si} = A_{si} \times \frac{1}{\lambda_{si} + \mu_{si}}, \tag{20}$$

$$I_{A,\mu_{si}}^{si} = A_{sys} \times \frac{\lambda_{si}}{\mu_{si}(\lambda_{si} + \mu_{si})}. \tag{21}$$

When system is having constant failure rate and constant repair rate, then the easiest way to determine the availability of a system with operating time t is exponential availability model which is given by Equation (22) [11, 32].

$$A_{sys}(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}. \tag{22}$$

5 | CONDITION MONITORING OF INVERTERS OF PV SYSTEMS

Condition monitoring refers to the process in which the system or its components are checked regularly to know whether it is functioning properly or not. It can be an online or offline process. Due to advancements in digital technology, the industries are moving towards the industry 4.0 revolution and automation of the processes. Each piece of equipment and its components are monitored from a single monitoring screen which is the visualization of the results obtained from reliability, availability, maintainability and maintenance process. Once any system or equipment is given maintenance either as per the scheduled maintenance or predictive maintenance, the reliability and availability of that system must be updated. This system is possible only when there is an integral condition monitoring system which keeps a record of each failure and maintenance [18, 25]. Being the weakest component of the PV system, the inverter is mainly focused in this paper for condition monitoring. In a similar way, other components can also be monitored. The authors in [17] have discussed the PCA technique in detail. The data set including the current and voltage can be handled separately. In this paper, the current and voltage of the inverter are used for the condition monitoring of the inverter. The complete methodology proposed in this paper is shown in Figure 4. The reliability, availability, and maintainability of the system are already discussed in the earlier sections of this paper. Now, this section is focused on the condition monitoring of the inverter of PV systems. The first step in monitoring is data pre-processing in which data is normalized or any other statistical method is applied to make the data useful. The most important factor to be taken care of in condition monitoring is that the selected data or parameter must be a good predictor of the health of that system or component. In this case, current and voltage data are found to be good predictors of the inverter's health. After

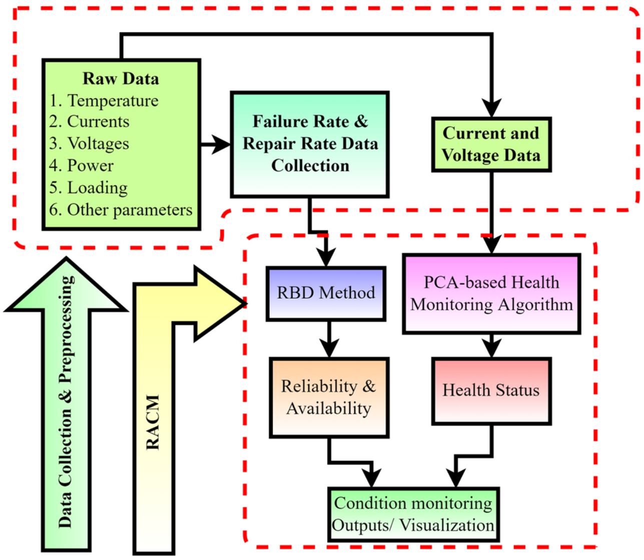

FIGURE 4 The proposed methodology for RACM in PV systems.

pre-processing of the data set, the smoothed data is sent to the PCA-based monitoring algorithm. The PCA technique gives the current health status of the inverter and helps in knowing the degradation in health by a visualization output. The PCA-based monitoring algorithm is shown in Figure 5. The collected data set is smoothed or normalized to get the accuracy of the results. The loading matrix is formed using the covariance matrix of the data set $D_{n\times m}$ where n and m indicate the number of rows and columns of the data set matrix A, respectively, as discussed in [17]. The first step in the PCA algorithm is to subtract the mean from each dimension as shown in Equation (23).

$$D_{modified} = [D]_m - [\bar{D}]_m. \tag{23}$$

Now, the covariance matrix is to be formed using the formula given in Equation (24) [17].

$$[C] = \sum_{i=1}^{p} \frac{(d_i - \bar{d}) \times (d_i - \bar{d})^T}{n}, \tag{24}$$

where $\bar{d}$ is the mean value of d_i. The eigenvalues and eigenvectors are calculated, and eigenvectors are stored in a matrix [B], which contains the loading vectors shown in Equations (25) and (26) [17].

$$([C]_{m\times m} - [I]_{m\times m}\lambda)\{D\}_{m\times 1} = \{0\}, \tag{25}$$

where 'I' is representing the identity matrix.

$$[B]_{(m\times m)} = [\{D_1\}\{D_2\}\{D_3\}\dots\dots\dots\{D_m\}]. \tag{26}$$

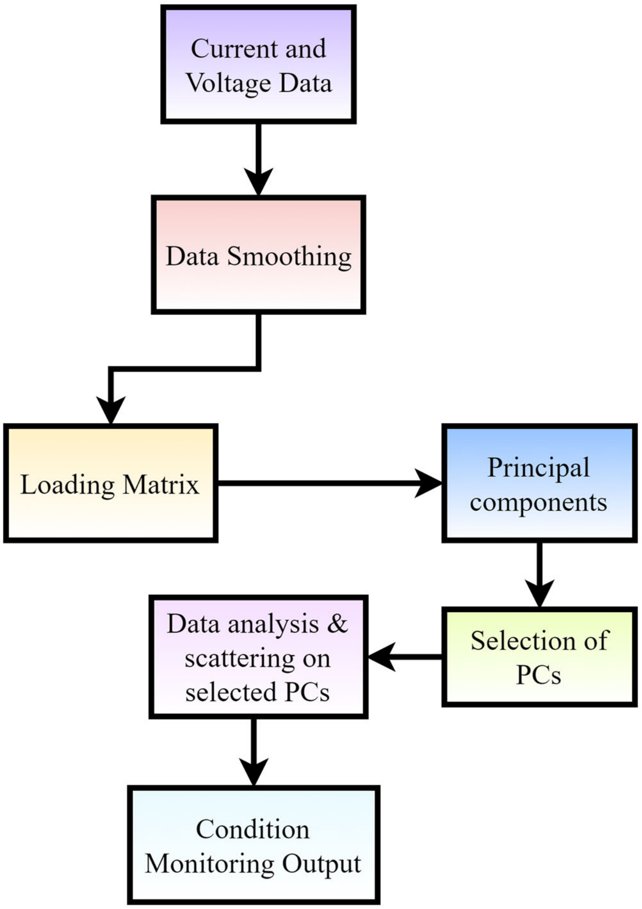

FIGURE 5 Flow chart of PCA-based condition monitoring algorithm.

The eigenvalues are put in a diagonal matrix $[eig]_{(m\times m)}$ which contains the eigenvalues corresponding to the PCs. Then, eigenvalues are ranked in decreasing order and top 'a' vectors are chosen $[eig]_{(a\times a)}$, to get the required PCs. The eigenvectors corresponding to the chosen eigenvalues are retained as given in Equation (27) [17]:

$$[B]_{(m\times a)} = [\{A_1\}\{A_2\}\{A_3\}\dots\dots\dots..\{A_a\}]. \tag{27}$$

Finally, the PCs [P] are calculated, and then these are projected in the data set matrix [D] as given in Equation (28) [17]:

$$[D]_{(n\times m)}[B]_{(m\times a)} = [P]_{(n\times a)}. \tag{28}$$

For the current and voltage matrix, $D_{(n \times m)}$ which contains n observations of m variables (n > m), the PCA explains the variance of data matrix D in terms of a new set of independent variables (PCs). When the PCA method is applied, the matrix D is written as the linear combination of orthogonal vectors, and these orthogonal vectors are in the direction of the PCs as given in Equation (29).

$$D = S \times B^T + R = s_1 b_1^T + s_2 b_2^T + \cdots.. + s_k b_k^T + R, \tag{29}$$

where S is the matrix formed by the scores of the PCs, B is the matrix of loading for PCA, and R is the residual matrix which is also called random error.

The Principal Components (PCs) are assessed using the loading matrix that has been created. The number of PCs used in the reliability data set is the same as the number of attributes used in the data set. Effective PCs are chosen from among the

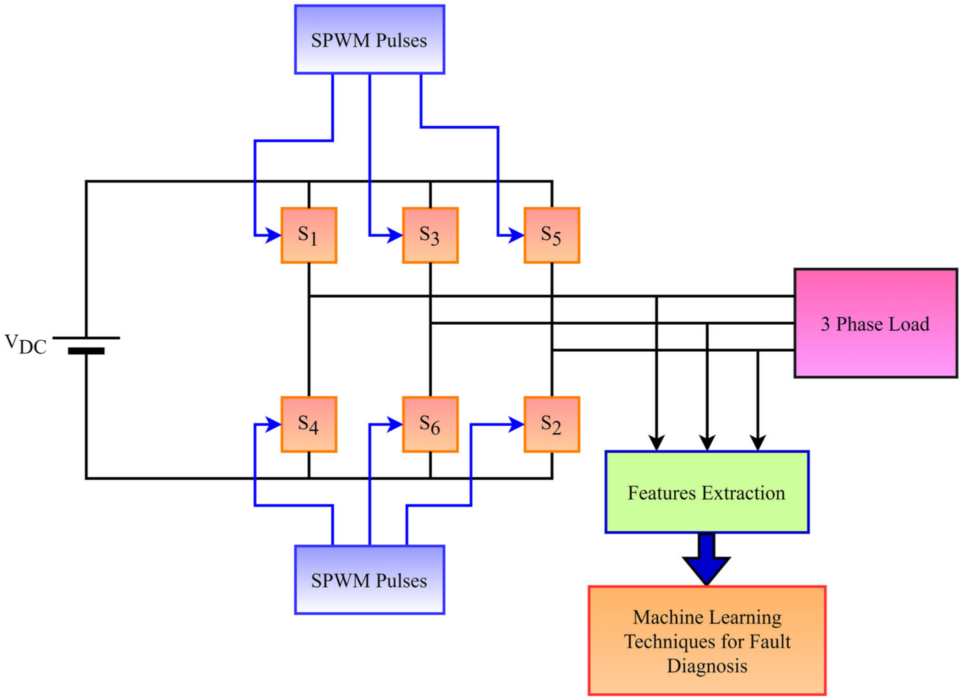

FIGURE 6 Unsupervised machine learning (PCA) based fault detection method of a three-phase inverter.

PCs. The first two PCs are determined to be useful in this scenario, covering 100% of the data variation. Using the PCs which are covering most of the data set and the normalized data set, the mean, standard deviation and the average path followed by the data, starting and ending points of data, and range of PCs in the scale of the score are determined for the further analysis. A boundary is set, based on the nature and coverage of score values by the data set, to monitor the movement direction of data which indicates the degradation in case the data moves away from the centroid. Once maintenance is done for the component, it regains its life cycle and hence, the data again starts from the centroid. PCA technique is useful to detect the fault condition of inverters using the features extracted from three-phase current and voltages. In this work, three-phase line voltages are used for fault detection as it is giving better results than three-phase currents. The block diagram of PCA-based fault detection of IGBT-based three-phase inverter is shown in Figure 6.

The line voltages $V_{ab}, V_{bc}, and V_{ca}$ of three-phase inverter under normal operating condition are shown in Figure 7.

When the three-phase voltage data is analysed using the PCA algorithm developed, it is observed that 100% of the data is covered by the first two principal components as shown in Figure 8.

Hence, the first two principal components are enough to be used as predictors for fault detection. When the data points are scattered over these two principal components, it forms an elliptical shape under normal conditions. This shape is distorted when there is any fault condition occurring in the inverter. The shape formed under normal conditions is shown in Figure 9. The two data points are found outside the ellipse due to the transient effect on the voltage waveforms. These outliers can be neglected in the fault detection algorithm. The boundary of the normal dataset is set in the region of two PCs as shown in Figure 10.

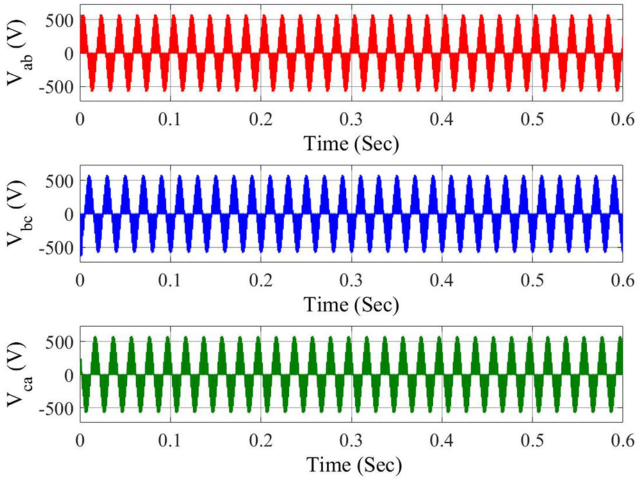

FIGURE 7 Line voltages of three-phase inverter under normal condition.

The normal operating region under two PCs is formed by two concentric ellipses. Under normal operating conditions, the data points lie inside the outer ellipse and outside the inner ellipse. When the next coming data point from the PCA algorithm is found to lie inside the lower ellipse, the algorithm detects the fault condition. This way the fault condition of the three-phase inverter is detected using the PCA algorithm.

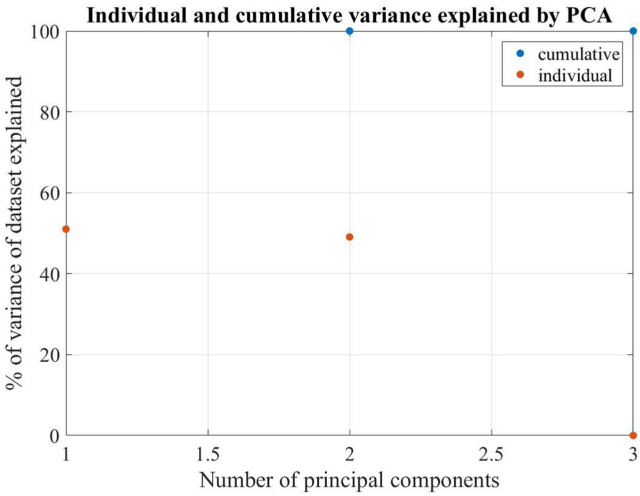

FIGURE 8 Percentage variance of three-phase voltages under particular principal component.

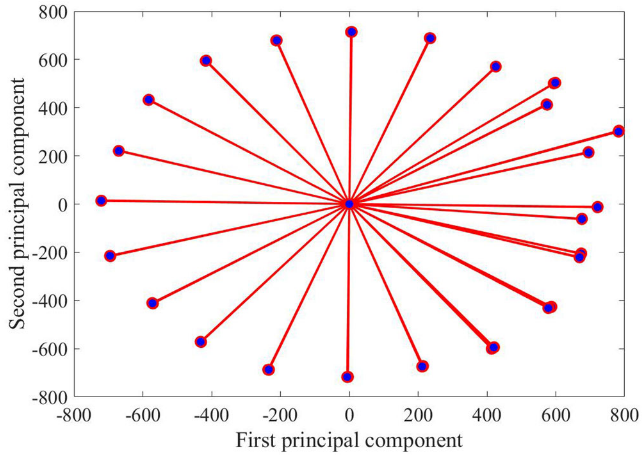

FIGURE 9 Elliptical shape formed by the data points under normal conditions over two PCs.

6 | RESULTS AND DISCUSSION

In this paper, the RACM of PV systems of seven different ratings and with an average of 8.5 h of operation per day is presented. Reliability for a non-repairable system which contains n independent sub-assemblies which are connected in series can be calculated by Equation (30) [32].

$$R_{system} = \prod_{si=1}^{n} R_{si}, \tag{30}$$

where R_{si} is representing the sub-assembly 'si' reliability. The overall reliability of sub-assembly in the case of the exponential distribution is given by Equation (31) [11, 32] where, m_{si} is representing the total number of 'si' sub-assembly, and λ_{si} is representing the failure rate of 'si' sub-assembly.

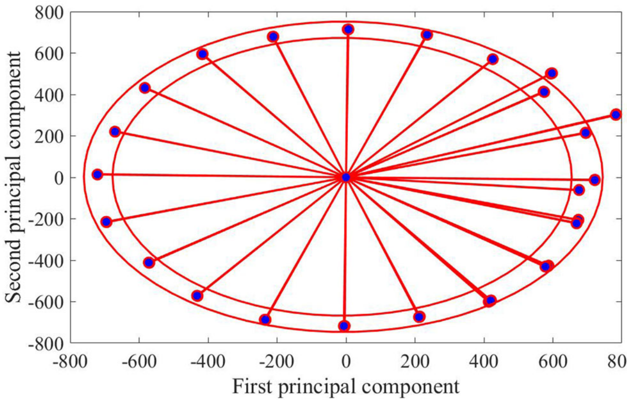

FIGURE 10 Region formed by the normal data set under two PCs.

$$R_{sub-assembly,Tot} = exp(\sum_{si=1}^{n} m_{si}\lambda_{si}t). \tag{31}$$

By using Equations (30) and (31) and Table 2, the reliability of the sub-systems is calculated for two different duration of operation: 1 year and 20 years and given in Tables 4 and 5, respectively. It is observed that with the increase in the PV power output, the reliability of the sub-assemblies and subsystems is decreased. It is observed that after 1 year of operation for a 200 kW system, the PV module has a 96.014% reliability measure which means the probability of operating adequately, whereas the inverter subsystem has 78.024% reliability percentage. For a 2 MW system, the PV module has a 66.69% probability of operating without failures, whereas the inverter has only a probability of 9.46% as tabulated in Table 4. On the other hand, for 20 years of operation, there is a noticeable quick decline. For an instance, for a 200 kW system, the PV module has a 44.33% reliability percentage, whereas the inverter has only 0.6985% reliability percentage. For a 2 MW system, the PV module has only 0.0304% probability of operating correctly, whereas the inverter is having 0% of the probability of operating without failure means it is not reliable as shown in Table 5.

When any one of the subsystems or sub-assemblies of the PV system fails then the reliability will be zero per cent, the 0% reliability does not mean the entire PV system failure. The entire system reliability for 1 year of operation is illustrated in Figure 11 and the reliability for 20 years of operation is illustrated in Figure 12.

For estimating each sub-system availability of the PV system, the failure rates in Table 2 and repair rates in Table 3 are substituted into Equation (17) and the obtained values are listed in Table 6. From Table 6, it is clear that the storage system is having a higher availability whereas the inverter system is having a lower availability when compared to the remaining five subsystems. The impact of the availability of each subsystem on the entire system availability can be understood with the help of the availability importance measure. The availability importance measures for all the subsystems can be calculated by using Equations (19)–(21) and then listed in Tables 7–9.

TABLE 4 Subsystem reliability of PV system for 1 year of operation (in %) (using Equation 30).

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	97.9869	96.0142	90.4114	81.6699	73.8389	66.6997	60.3041
Converter	93.6925	87.7828	72.1977	55.6342	40.1666	28.9993	20.9368
Inverter	88.3292	78.0204	53.7676	32.7293	17.5977	9.4619	5.0874
BOS	92.5260	88.7018	78.2313	64.5971	52.3562	42.3967	34.3626
Storage system	98.0340	98.0340	98.0340	98.0340	98.0340	98.0340	98.0340

TABLE 5 Subsystem reliability of PV system for 20 years of operations (in %) (using Equation 31).

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	66.5819	44.3315	13.3187	1.7428	0.2321	0.0304	0.0040
Converter	27.1702	7.3822	0.1481	0.0008	0.0000	0.0000	0.0000
Inverter	8.3576	0.6985	0.0004	0.0000	0.0000	0.0000	0.0000
BOS	21.1485	9.0918	0.7372	0.0160	0.0002	0.0000	0.0000
Storage System	67.2253	67.2253	67.2253	67.2253	67.2253	67.2253	67.2253

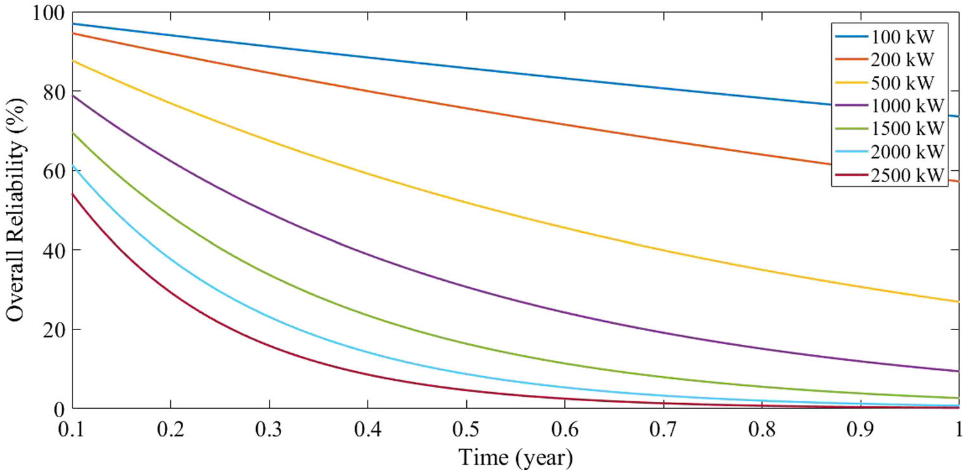

FIGURE 11 Percentage reliability of PV systems for 1 year of operation.

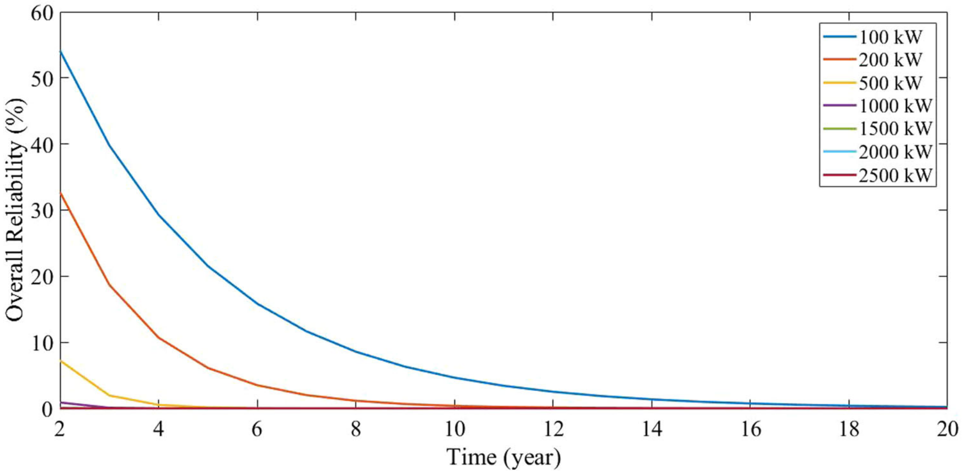

FIGURE 12 Percentage reliability of PV systems for 20 years of operation.

TABLE 6 Subsystem availability (in %).

Power (in kW)	100	200	500	1000	1500	2000	2500
PV modules	99.8278	99.6562	99.1522	98.3115	97.4920	96.6791	95.8865
Converter	99.9790	99.9580	99.8951	99.8114	99.7069	99.6026	99.4985
Inverter	98.1308	96.3303	91.3043	85.3659	78.9474	73.4266	68.6275
BOS	99.8690	99.7930	99.5678	99.2212	98.8494	98.4785	98.1123
System storage	99.9603	99.9603	99.9603	99.9603	99.9603	99.9603	99.9603

TABLE 7 Availability importance measures.

Power (in kW)	100	200	500	1000	1500	2000	2500
PV module	0.979428	0.960524	0.907783	0.845077	0.777793	0.719934	0.669677
Converter	0.977946	0.957623	0.901032	0.832378	0.760516	0.698803	0.645366
Inverter	0.996365	0.993687	0.985810	0.973232	0.960496	0.947921	0.935675
BOS	0.979024	0.959206	0.903994	0.837328	0.767113	0.706779	0.654484
System storage	0.978130	0.957602	0.900445	0.831138	0.758588	0.696302	0.642385

TABLE 8 Importance measures based on failure rates.

Power (in kW)	100	200	500	1000	1500	2000	2500
PV Module	0.082790	0.080914	0.075699	0.069280	0.0627057	0.0570772	0.0522258
Converter	0.003151	0.003084	0.002898	0.002673	0.0024369	0.0022345	0.0020593
Inverter	0.147265	0.141529	0.126138	0.108856	0.0918840	0.0784418	0.0676378
BOS	0.016492	0.016525	0.015847	0.014806	0.0134831	0.0123412	0.0113475
System storage	0.019567	0.019156	0.018013	0.016626	0.0151748	0.0139288	0.0128503

From Table 7, it can be observed that the components which are affecting the availability of solar PV systems are PV module and inverter. Hence, it is clear that the overall availability of the system can be increased by improving the availability of the PV module and inverter of PV systems. From Tables 8 and 9, it is clear that the availability of each sub-system or component affects the overall availability of the system. This is possible to know using failure rate-based and repair rate-based availability importance measure method. From the results shown in Figures 13, 14, and 15, it is clear that the inverter and PV module is the weakest components of the PV system. Therefore, these need to be given special attention for enhancing the overall availability of the PV system. Among the failure rate-based and repair rate-based availability measures techniques, the failure rate-based availability measure method is more effective. Hence, it is given more focus to calculating the overall availability of PV system using failure rates of inverter and PV module.

To get the improved availability of the PV system, a few solutions can be suggested as follows: preventive and predictive maintenance of the weakest components, reactive maintenance which involve the periodic inspection of the system components, and addition of redundant systems.

By using the redundancy approach for the weakest component of the PV system which is an inverter, the availability of the entire system can be increased. Redundancy is nothing but adding new parallel paths. Redundant elements are energized

TABLE 9 Importance measures based on repair rates.

Power (in kW)	100	200	500	1000	1500	2000	2500
PV module	0.0001428	0.0002792	0.0006472	0.0011899	0.0016131	0.0019606	0.0022405
Converter	0.0000007	0.0000013	0.0000030	0.0000051	0.0000072	0.0000089	0.0000104
Inverter	0.0028050	0.0053916	0.0120131	0.0186611	0.0245024	0.0283885	0.0309201
BOS	0.0000216	0.0000343	0.0000688	0.0001162	0.0001569	0.0001907	0.0002183
System storage	0.0000078	0.0000076	0.0000072	0.0000066	0.0000060	0.0000055	0.0000051

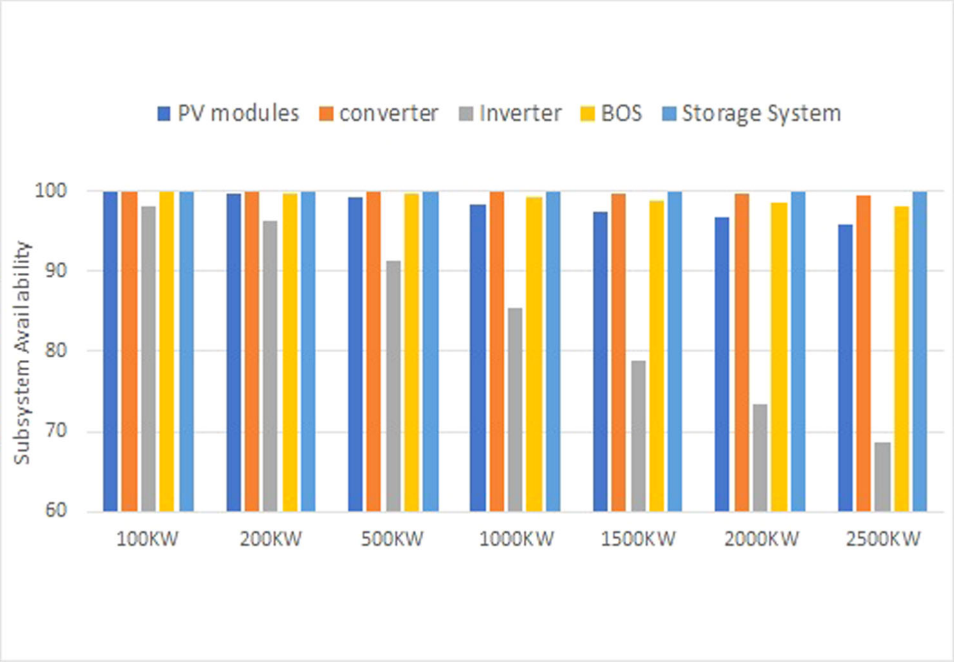

FIGURE 13 Sub-systems availability for the studied systems.

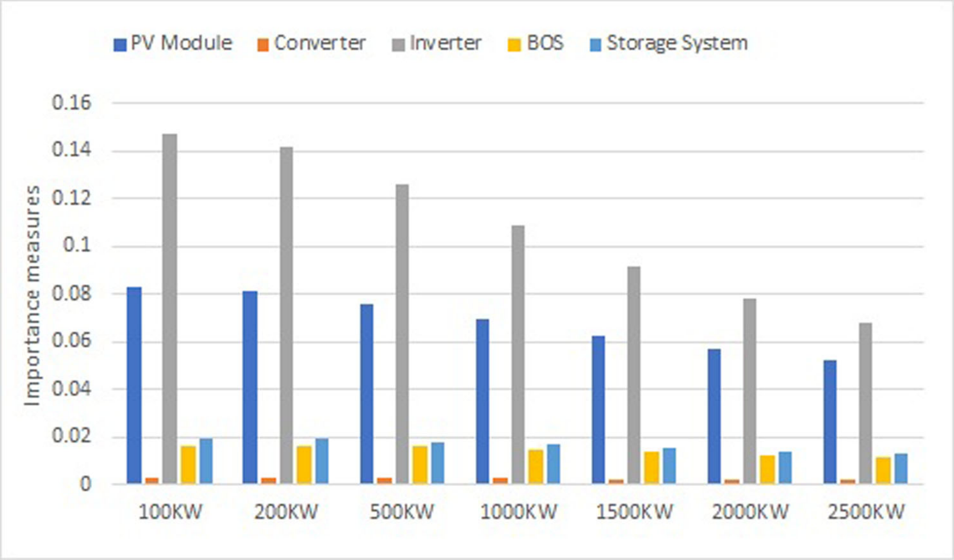

FIGURE 14 Importance measures for PV module, converter and inverter.

continuously in a hot standby redundant system and made to perform the circuit function, whereas redundant elements perform if and only if the primary circuit elements fail in the cold standby redundancy. For a hot standby system, the failure rates and repair rates are given by Equations (11) and (12) because redundancy means adding new parallel paths. In this paper, N+1 technique of redundancy is used. With the help of Equation (22), and Tables 2 and 3, the overall system availability is presented without redundancy and with the redundancy of the inverter is presented in Figures 16 and 17. It can be observed that the entire system availability increases when inverter redundancy is considered as shown in Figures 16 and 17.

In this paper, only permanent faults that occur due to manufacturing defects, which can be repaired manually if they occur, are considered. Because of this, after 1 year the availability will not be affected by these faults that is it remains constant. From Figures 16 and 17, it can be observed that the availability is constant after 1 year. Whereas there are other faults like intermittent which are not considered. If these faults are

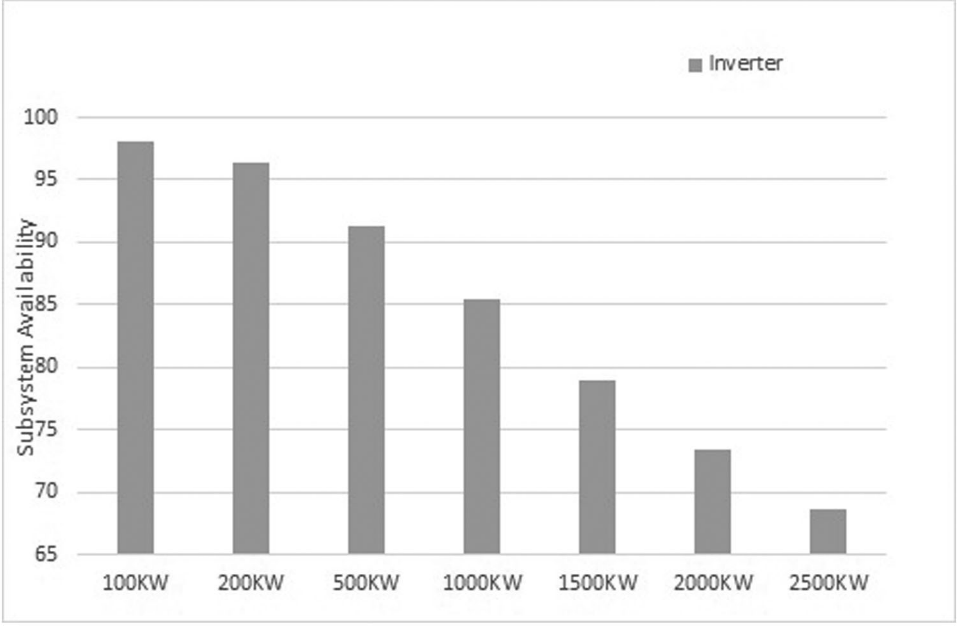

FIGURE 15 Sub-system availability for inverter.

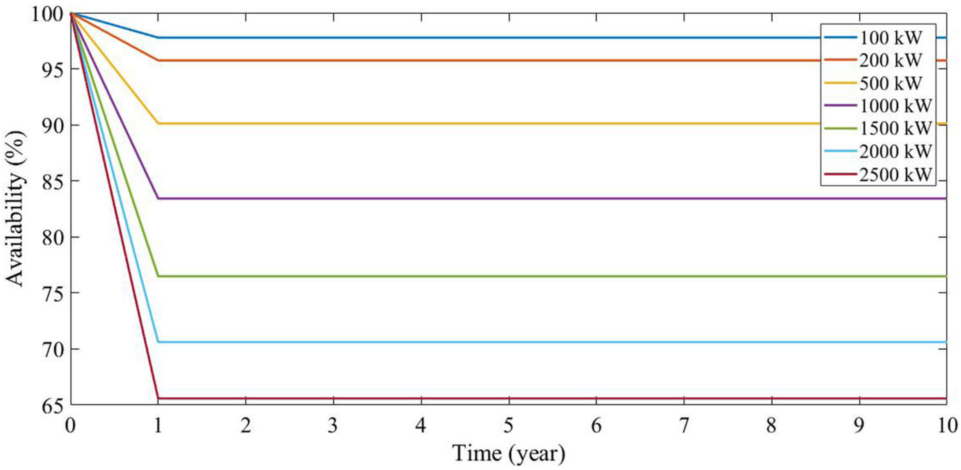

FIGURE 16 Overall system availability before inverter redundancy.

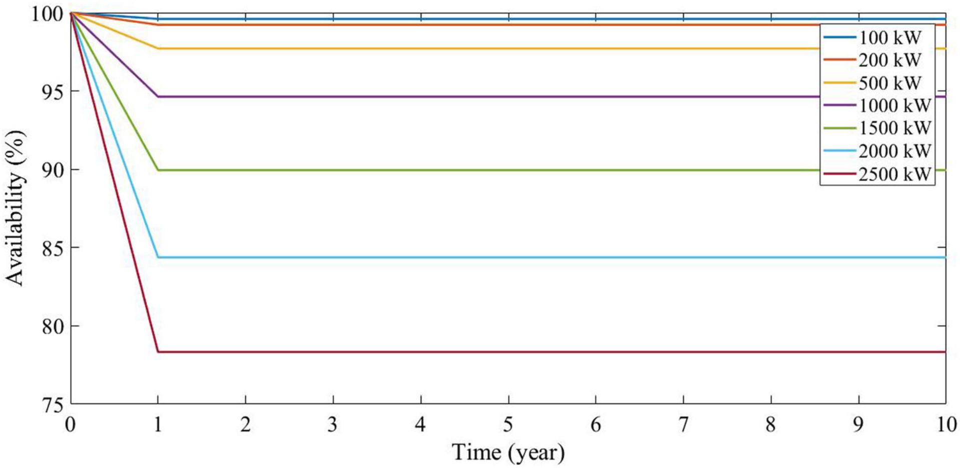

FIGURE 17 Overall system availability after inverter redundancy.

TABLE 10 Ranking of components of PV system affecting the availability.

Subsystems of PV system	Ranking
Inverters	1
PV modules	2
BOS	3
Converters	4
System storage	5

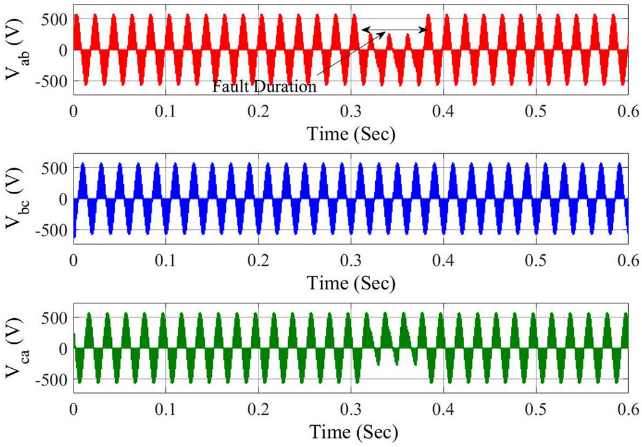

FIGURE 18 Three-phase voltages under open-circuit fault at switch S1.

also considered then the availability of the system may decrease continuously.

The results obtained from availability importance measures are tabulated in Table 7 which shows that the availability importance measure of the inverter is highest for the PV system. The weakest component of the PV system is the inverter having the least reliability. The ranking of the subsystems based on their effect on the system availability is presented in Table 10.

The proposed algorithm helps in getting the health monitoring of the inverter. The three-phase voltages under fault condition (open circuit fault at switch S1) are shown in Figure 18. The waveform is distorted under fault conditions from 3.2 s to 3.8 s. To detect the occurrence of fault conditions at the earliest, the PCA algorithm is used. It gives the alarm when the next coming sample lies outside the normal region under two PCs. If the data points are lying in the region formed inside the outer ellipse and outside the inner ellipse, the inverter is operating normally; if the data points are lying inside the inner ellipse, there is a problem with the inverter and it is degrading, and the system will automatically raise an alarm. The coverage and boundary of distinct operating conditions are computed using the PCA technique and the score coefficients of the PCs, rather than being chosen at random. PC score coefficients are key factors for inverter health monitoring. When the maintenance crew and the operator get an automated health status update via an alarm system, email, and text message, the condition monitoring system will be reliable. When a fault scenario is detected, the system sends an email to the maintenance team members as well as an appropriate alarm. For the open circuit fault at switch S1, the detection output of the PCA algorithm is shown in Figure 19.

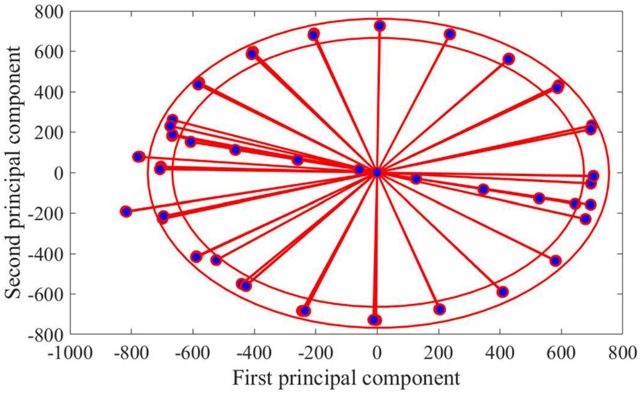

FIGURE 19 Detection output under open-circuit fault at switch S1 using PCA.

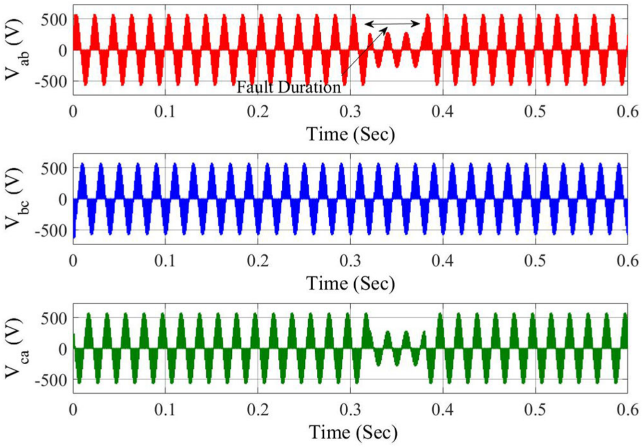

FIGURE 20 Three-phase voltages under open-circuit faults at switches S1 and S2.

When the open-circuit fault occurs at multiple switches, the algorithm is able to detect the faults. When open-circuit faults are created at switches S1 and S2, the voltage waveforms and corresponding detection output of the PCA algorithm are shown in Figures 20 and 21, respectively.

The comparison of the proposed method with the existing methods is shown in Table 11. The reliability values of the PV system found using the proposed method and existing methods after 1 and 20 years of operation are shown in Tables 12 and 13, respectively. The PV system considered in [26] is the same as in this paper. The authors have calculated the failure rate and reliability of each component. The calculated values of reliability are found to be close to that found in the arithmetic formula. Therefore, in the literature, the work done in [26] is found to give approximately correct reliability calculation of the PV components. It can be seen from Tables 12 and 13 that the reliability values of PV components in this paper are close to the values found in [26]. Hence, it can be concluded that the proposed method of reliability calculation is correct and gives better

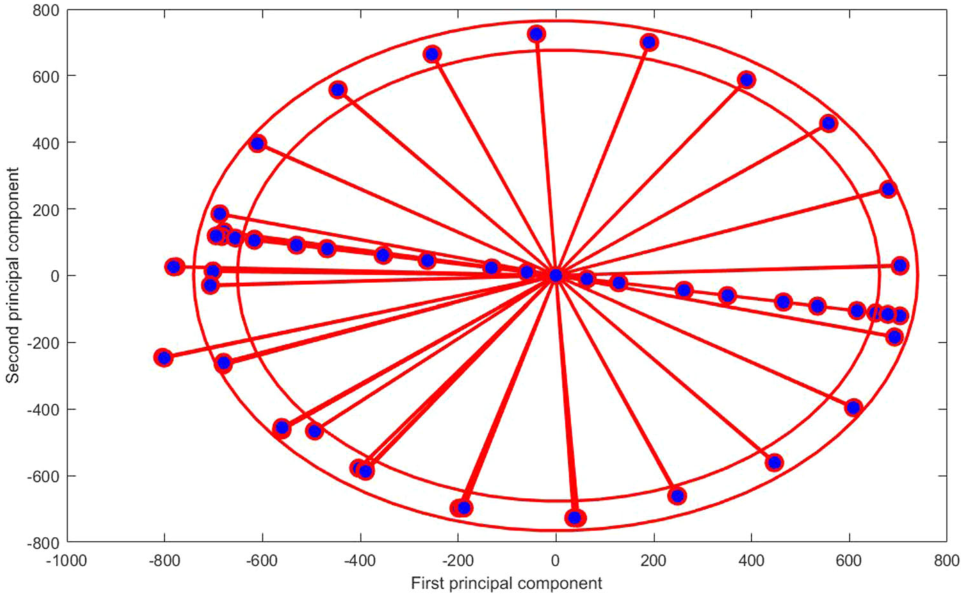

FIGURE 21 Detection output under open-circuit faults at switches S1 and S2 using PCA.

TABLE 11 Comparison of the proposed method with existing methods.

Parameter	[15]	[30]	[26]	Proposed method
Method used	FTA	FTA	RBD	RBD-PCA
Focused on	Reliability	Reliability	Reliability, availability, and maintainability (RAM)	RACM
Data used	Failure	Failure	Failure and repair	Failure, repair, and monitoring data
Health prediction	No	No	No	Yes

TABLE 12 Comparison of the reliability values of PV system found from proposed method and existing methods after 1 year of operation.

PV Systems (kW)	[15]	[30]	[26]	Proposed method
100	78.9735	78.3716	71.7895	71.6708
200	66.5429	65.2364	54.2866	52.3450
500	36.9867	36.3520	22.9058	22.0675
1000	16.0560	16.0188	7.0235	7.0083
1500	6.5542	6.3991	1.9056	1.8197
2000	2.2507	2.001	0.4663	0.41
2500	1.002	0.96	0.089	0.077

and more accurate results than [15, 30]. The proposed algorithm is good for deciding the priority list of components needing maintenance and monitoring. After listing the components, the weakest component is given an appropriate monitoring system.

TABLE 13 Comparison of the reliability values of PV system found from proposed method and existing methods after 20 years of operation.

PV Systems (kW)	[15]	[30]	[26]	Proposed method
100	1.5192	0.6820	0.2800	0.1995
200	0.05	0.01	0.0008	0.0004
500	0	0	0	0
1000	0	0	0	0
1500	0	0	0	0
2000	0	0	0	0
2500	0	0	0	0

7 | CONCLUSION

The RACM of large PV systems is presented in this paper. The RBD method based on exponential probability distribution has been used for reliability and availability analysis. The findings can be concluded as follows.

- The five key PV system components are presented in order of their impact on total system availability.
- The inverter is at the top of the list, indicating that it is the weakest component of the PV system. The inverter needs maintenance to avoid any sudden breakdown because the availability of PV system is mostly affected by the inverter.
- The redundancy strategy has been shown to improve system reliability and availability by allowing operations to continue even when main components are unavailable.
- Using the inverter's voltage and current data, the PCA-based condition monitoring system is effective in monitoring the inverter's health.

- This monitoring technique may be used in various subassemblies of a PV system to improve overall system reliability and availability, which is a future goal of this work.

NOMENCLATURE

AC	Alternating Current
ANN	Artificial Neural Network
ASTS	Automatic Static Transfer Switch
BOS	Balance of System
CB	Circuit Breaker
CDF	Cumulative Distribution Function
CNN	Convolution Neural Network
DC	Direct Current
FTA	Fault Tree Analysis
KNN	k-Nearest Neighbor
kW	Kilo Watt
NA	Not Available
PCA	Principal Component Analysis
PV	Photo-Voltaic
RA	Reliability and Availability
RACM	Reliability, Availability, and Condition Monitoring
RBD	Reliability Block Diagram
SVM	Support Vector Machine

AUTHOR CONTRIBUTIONS

Kumari Sarita: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft. R.K. Saket: Methodology, project administration, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Baseem Khan: Methodology, project administration, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest statement.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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APPENDIX

For designing the sub-assembly of the PV module of 'P' kW, the following calculations will be helpful.

1. For PV modules:
   - Find the total power of load using Equation (A.1) where, $n = 1, 2, 3, .., \mathrm{N}$, indicating total number of loads.

$$P = \sum_{n=1}^{N} P = P_1 + P_2 + \cdots + P_N. \tag{A.1}$$

   - Find the operating time per day for each load T_n.
   - Find the total energy per day using Equation (A.2)

$$E = \sum_{n=1}^{N} P_n \times T_n. \tag{A.2}$$

   - Find the energy required from the PV system using Equation (A.3). It is needed to take this 20–30% more than the actual load demand.

$$E_{neededperday} = 1.3 \times E. \tag{A.3}$$

   - Find the panel generation factor (PGF). Let it is to be X.
   - Find the total Watt-peak rating of the PV array using Equation (A.4).

$$P_{Peakratingo\,fPV} = \frac{E_{neededperday}}{X}. \tag{A.4}$$

   - Find the number of modules using the formula given in Equation (A.5).

$$\text{Number of modules} = \frac{P_{Peakratingo\,fPV}}{\text{Rated power of PV module}}. \tag{A.5}$$

2. For inverter: the number of inverters is found using Equation (A.6).

$$\text{Number of inverters} = \frac{\text{Rated power of the system}}{\text{Rated power of the selected inverter}}. \tag{A.6}$$

TABLE A.1 Gathered data of failure rate and repair rate from literature.

Components of PV system	Failure rate*10^{-6} (h^{-1})	Repair rate (h^{-1})	References
PV modules	26.000	NA	[33]
	3.2000	0.0667	[34]
	4.6000	0.0057	[35]
	0.0150	0.0037	[15, 30, 36, 37]
	0.0150	0.0037	[38]
	1.4000	NA	[39]
	0.0046	0.0250	[40]
	24.000	0.0039	[41]
	NA	0.0083	[32]
Converter	5.9000	NA	[33]
	8.1000	0.13	[34]
	27.000	0.1000	[42]
	0.4600	0.0250	[40]
Bypass diode	5.4000	0.1667	[34]
	0.3100	0.0208	[15, 30, 36, 37]
	0.3100	0.0208	[38]
	3.5000	NA	[32]
	0.6800	NA	[39]
	0.3100	0.0208	[41]
DC switch	0.2000	0.0208	[15, 30, 36, 37]
	0.2000	0.0207	[38]
	0.7000	NA	[39]
	0.2000	0.0208	[41]
AC Switch	0.0340	0.0208	[15, 30, 36, 37]
	0.0340	0.0207	[38]
	0.7000	NA	[39]
	0.0340	0.0208	[41]
AC C. B	5.7000	0.0208	[15, 30, 36, 37]
	5.7000	0.0207	[38]
	0.4000	NA	[39]
	5.7000	0.0208	[41]
Differential C. B	5.7000	0.0208	[15, 30, 36, 37]
	5.7000	0.0207	[38]
	0.2300	NA	[39]
	5.7000	0.0208	[41]
Grid Protection	5.7000	0.0208	[15, 30, 36, 37]
	5.6000	0.0207	[38]
	5.7000	0.0208	[41]
Connector	0.0002	0.0015	[15, 30, 36, 37]
	0.0002	0.0016	[38]
	0.4500	NA	[39]
	0.0002	0.0015	[41]
Inverter	20.000	NA	[33]
	13.000	0.0833	[34]
	11.000	0.0057	[35]
	40.000	0.0021	[15, 30, 36, 37]
	27.000	0.1000	[42]
	40.000	0.0021	[38]
	7.6000	0.0025	[32]
	180.00	NA	[39]
	57.000	0.0057	[40]
	NA	0.0021	[41]
Charge controller	44.000	NA	[33]
	14.000	NA	[35]
	6.4000	0.0161	[15, 30, 36, 37]
	6.4000	0.0006	[38]
Battery system	19.000	NA	[33]
	11.000	0.0057	[34]
	13.000	0.0060	[38]

TABLE A.2 Information regarding the PV system considered in this work [26].

Rating of the PV module	230 W
Short circuit current of PV module	8.24 A
Open circuit voltage of module	37.2 V
Inverter rating	100 kW
Maximum DC current of the inverter	235 A
Maximum voltage of the inverter	1000 V
Battery	12 CS 11P, 475 Ah and 12 V
DC-DC converter	D = 0.531 to .493, L = 8.31 mH, C = 255 micro-F, and s=10 KHz.

3. For bypass diode: the number of bypass diodes can be found using Equation (A.7).

$$\text{Number of bypass diode} = \frac{\text{Number of PV modules}}{\text{Number of PV arrays}}. \tag{A.7}$$

4. AC CB: It is equal to the number of inverters.
5. AC Switch: As per the requirement of connecting to AC.
6. Differential CB: As per the requirement.
7. Connectors or couplers: It is double of a number of PV modules.