Reliability Analysis Of Different Capacities Solar PV Power Plant

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Abstract
Solar Photovoltaic (PV) Plant converts solar irradiance into electricity directly, thereby helping to reduce the requirement of fossil fuels and pollution substantially. They provide a continuous and reliable renewable source of energy. However, Solar PV plants are continuously exposed to diverse and changing environmental conditions, such as temperature, humidity, dust, and rain. Exposure to such conditions creates electrical and visible faults in the PV Plant components. These faults may impact the PV plants' lifetime, performance, and reliability.

In this regard, this research study aims to propose a methodology for reliability modelling and analysis of large-scale grid-connected PV plants using a Fault Tree Analysis (FTA) approach. Specifically, an exhaustive literature survey is carried out to acquire the failure/repair rates of different components/faults existing on both AC and DC side of the PV Plant. Component-wise, Subsystems-wise, and overall PV plant reliability analysis has to be carried out and predicted its failure probability with years of Operation. Then, the Fussel-Vesely (F-V) importance measure is employed to identify critical component in solar PV plant. Results showed that reliability of large-scale PV Plants is higher as compared with small capacity solar plants. Similarly, analyzed different topology inverter sub-systems reliability of solar plant and predicted that string inverter configuration is more reliable as compared with central inverters. The recommendations and scope for further study are provided to optimize operations and maintenance costs of solar PV Plant.

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I.   Introduction

The history of humankind is the history of energy. Electricity is a clean and relatively safe form of energy. The consumption of electrical energy is increasing daily as urbanization and industrial development is happening rapidly

First, there are many large industries which are dependent on legacy power generation sources. The mining of coal, for instance, is a massive industry that gives opportunity to millions of people. These jobs can't be easily wished away. Further the workers are usually semi-skilled and semi-literate and can't be put to work in other jobs.

Second, massive investment is already made in existing generation sources and these assets are reliable for the next twenty-five to thirty years. Investors and lenders have funded all these projects and need returns and capital protection on their investments.

Third, the rapid growth which is required in renewable energy capacity is quite daunting. The current total capacity of all electricity generation sources globally 7,100 gigawatts (GW), of which renewables are now reaching 1,000 GW and coal is almost half or 3,000 GW. With the assumption of global demand growth rate of 3 percent in electricity, required 200 GW of new capacity per year to meet the demand. Due to the low plant-load factor (PLF) of renewables (usually one-third of conventional plants), required three times of this capacity in renewables to meet the growth demand (approximately 500 GW) per year. But now the addition of 150GW of new renewable capacity is happening every year globally. At the current pace of renewable energy installations yearly, that would require 50 years of capacity growth with the assumption that new installations (to add renewable capacity) grow at 10 percent per year, it would still require 20 years of capacity growth.

Grid-connected PV power plants' combined capacity increased dramatically from 300 MW in 2000 to around 21 GW in 2010 and 843 GW in 2019. With 63 GW of installed grid-connected solar power capacity as of March 31, 2022, solar power in India is a rapidly growing industry.

The Challenges mentioned above while transitioning from fossil fuels to renewable sources, power generation sources (solar, wind, hydro etc.) must be reliable to provide continuous power supply to grid. Since the technology of renewable energy systems is in evolving state, a reliability study is required for all renewable

energy generation sources to predict and cross verify the lifetime of different components and system whether it's performing as per required trends or not.

As the growth rate of PV systems continues to increase, the main worry for investors, owners, and stakeholders is making sure that a PV system supplies energy as anticipated. Unanticipated failures that prolong downtime periods are bad for the investment's financial performance. Reliability evaluation is done as part of any PV system planning's due diligence to evaluate the risks brought on by component failures.

The Solar photovoltaic (PV) power plants market has grown significantly over the past few years and is now acting a crucial part in limiting the use of conventional, finite energy sources (such as coal, oil, natural gas, or nuclear energy, etc.), thereby minimizing the greenhouse gases emission and air pollutionand by 2030, it could reach up to 1500 GW **(International Renewable Energy Agency, 2022).**

Theoretical Background

A solar utility's primary goal is to provide the end consumer with affordable, reliable, and high-quality power. Failure in a solar power plant can occur suddenly and sometimes without warning, leading to the shutdown of grid or the failure of several components inside or outside the plants.

Reliability

Reliability is an essential tool for long-term operation and system planning of solar plant which allows facilitating risk assessment and significant reduction in revenue losses. The ability to function as required, without interruption, for a certain time interval t, under specified circumstances, is known as reliability R(t). It influences the system's availability to produce the (ideal) energy yield, specifically the absence of failures. It can be mathematically stated as:

$$R(t) = \exp\left[-\int_0^t \lambda(u)du\right] = \exp(-\lambda t)$$

where λ is the failure rate (constant). Indicators like failure rates or the Mean Time Between Failures (MTBFs) are typically used to highlight the reliability characteristics of PV system components.

Reliability Networks for different Configurations

When performingreliability study on a solar PV plant, several configurations/designs can be formed. Here, in this part, particularlyimpact of the system reliability analysis of such often occurring different networks in physical systems, and it suggests assessing the dependability of various networks utilized in solar plant reliability analysis**(Dhillon, 2006).**

Series Network

This is most likely the most prevalent design in engineering systems, and the block diagram for it is given in Figure 1.1. The diagram depicts N-unit system, with each block representing a unit. For the series system to function properly, all units must be operational.
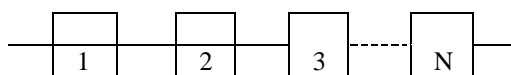

Fig 1.1:N-unit series connected component system.

Series connected component's reliability (as shown in figure 1.1) is expressed by:

$$R_s, Series = R1 \times R2 \times \dots\dots\dots \times Rn = \prod_{i=1}^{n} Ri$$

Parallel Network

In Parallel connected component, the success of the system depends on at least one of the N concurrently running units, where N is the number of units in the system.
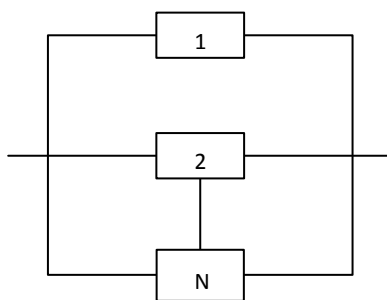
Fig 1.2: N-unit parallel connected component system

Parallel connected component's reliability (as shown in figure 1.2) is expressed by:

$$Rp, Parallel = 1 - (1 - R1)X(1 - R2)\ldots\ldots\ldots\times (1 - Rn)$$

With the help of these formulas, Series and parallel connected component's reliability can be calculated and analyzed.

The probability mass function of the binomial distribution is represented by.

$$P(x) = P[X = x] = {}^{n}C_x p^x q^{n-x}$$

n = number of failures in the random Operation,

x = number of successful operations against n trials.

p = probability of successful operation in each trial.

q = 1 − p = probability of breakdown in each trail

The binomial coefficient shows how many ways there are for x successes to happen after n trials. The k-out-of-n system of similar and independent components therefore satisfies all requirements for employing the binomial distribution. Therefore, if RS represents a k-of-n system's reliability during a specific time period, then.

RS = Successful operation probability of at least k components in the system

$$Rs = \sum_{x=k}^{n} P(x)$$

Reliability can be analyzed for M-out-of-network system with the help of above formula.

As reliability enhances risk assessment and reduces revenue losses, reliability analysis of various engineering systems has grown to be a crucial concern for planning and longer operation. Additionally, it makes it possible to forecast system behavior over time and adjust maintenance plans accordingly. However, a typical constraint is the absence of trustworthy data from the field to conduct in-depth research. Reliability research provides an up-to-date dataset of field reliability and its impact on overall systems' performance, with a focus on large scale PV systems (LSPVSs), or systems with more than 1 MWp installed capacity.

The required reliability of engineering systems is typically specified in the design specification, and during the design phase, every effort is taken to successfully achieve this need. The importance of reliability in designed systems is significantly increased by factors like the rising number of quality- and reliability-related lawsuits, competition, public pressure, high acquisition costs, previously well-publicized system failures, loss of prestige, and complex and sophisticated systems. **(Dhillon, 2006).**

Bathtub Hazard Rate Concept

The failure rate of any component/items is a function of time (i.e., it changes with time), this well-known notion which is utilized to depict failure behavior of numerous engineering items**(Dhillon, 2006)**. In Figure 1.4, a bathtub failure rate curve is displayed. It is split up into three areas, namely Regions I, II, and III.

Due to failures happening for reasons like those indicated in Table 3.1, the item rate (i.e., time-dependent failure rate) decreases during this time or region.
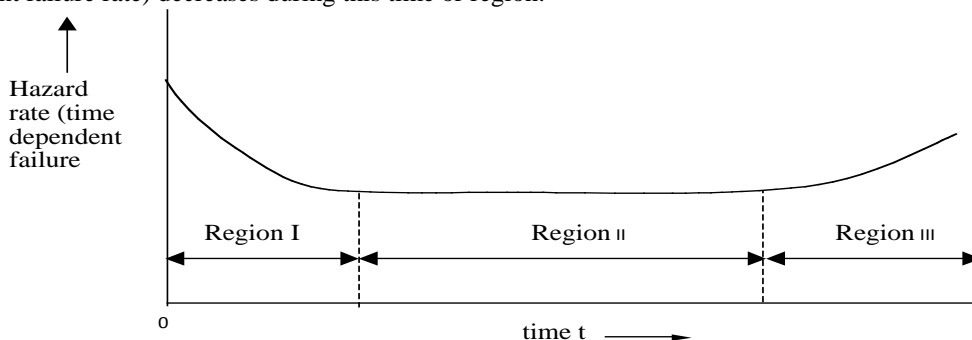
Fig 1.4: Bathtub hazard rate curve.

Table1.1:Different Regions of the Bathtub Hazard Rate Curve along with Reasons for the Occurrence of Failures

Region	Reason
I: Burn-in period	Poor manufacturing methods
	Poor processes
	Poor quality control
	Poor debugging
	Human error
	Substandard materials and workmanship
II: Useful life period	Low safety factors
	Undetectable defects
	Human errors
	Abuse
	Higher random stress than expected.
	Natural failures
III: Wear-out period	Wear caused by friction
	Poor maintenance
	Incorrect overhaul practices
	Corrosion and creep
	Short designed-in life of the item
	Wear caused by aging.

Importance of Reliability Analysis for PV Plant:

The importance of reliability engineering is greatest in the field of engineering products. British Standards define reliability as an object's capacity to carry out a needed function under specified circumstances for a specified amount of time. According to NASA, reliability is the possibility that a technology will function correctly under the given operational conditions.

Because solar PV systems have long payback periods, remote installations, and new, developing technologies, reliability analysis has a greater impact on them. The PV solar plant is moving from pilot demonstration projects to large-scale installation.
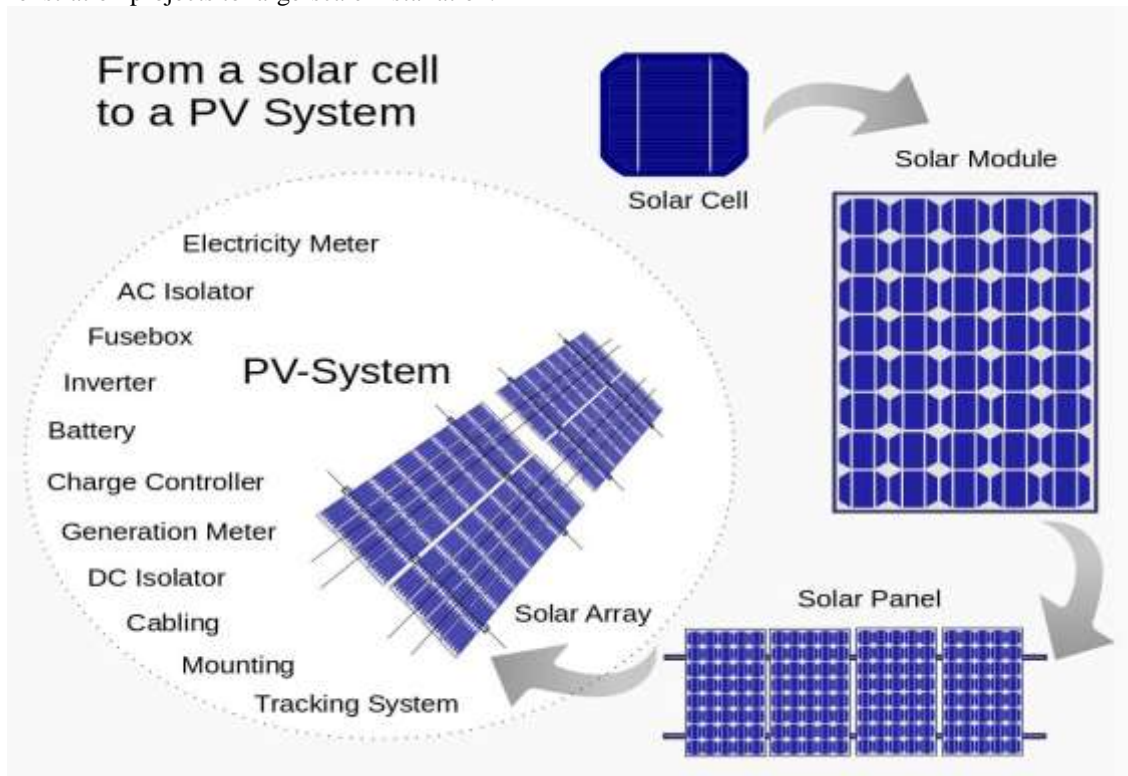

Fig. 1.5: Different parts of solar PV Plant

In other words, the reliability of a solar power plant refers to its ability to operate successfully for a predetermined period. Reliable Solar PV power plants increase renewable energy output, provide a higher return on investment, and help lower global carbon emissions. In addition to PV solar panels, a PV solar plant also consists of several other components, as shown in Fig. 1.5.

System reliability is lower than it would be with conventional generation sources due to the PV system's highly variable and uncontrollable solar insolation and power input, which can lead to high electrical stress in the panels and potentially shorten their operational lifetimes and power electronic interfaces. Second, the power distribution system will suffer from a high proportion of PV generation.

Solar PV Power Plant:
Major Components of SPV Power Plant

Solar PV power plant consists of three major parts that are PV panels or modules, inverter andBalance of System (BOS) components. Inverters are very crucial component of solar PV plant, and they have Maximum Power Point Tracker (MPPT) controllers to maximize the power output of the solar Plant.Fuses, Miniature Circuit Breakers (MCBs), overcurrent safety devices, cables, AC switchgears, transformers and storage devices are all part of the BOS element. A solar PV array is made up of the parallel strings of PV modules, each of which contains several PV modules. It transforms solar power into electric power. Blocking diode are used for unidirectional current flow from the PV panel to the inverter and also provide the protection for PV modules to act as load.
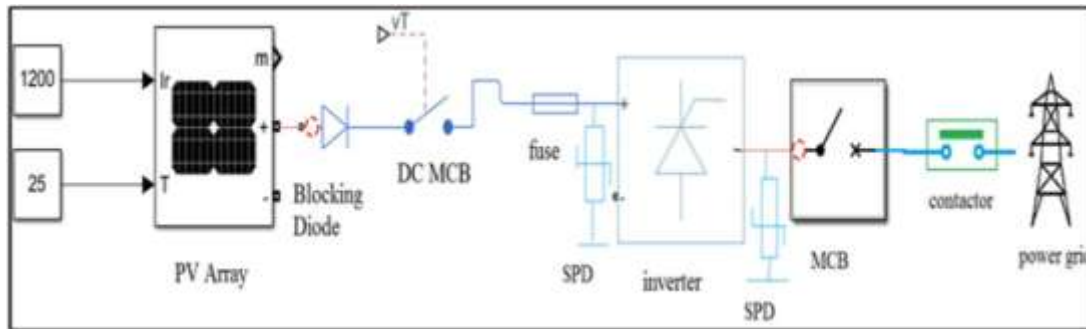
Fig 1.11: Single line diagram of a solar PV Plant.

Large scale solar PV power plant consists of following major Components:

1. Solar PV Modules
2. Modules Mounting Structures (Fixed/Seasonal Tilt/Tracker)
3. DC Cables
4. DC Connectors
5. DC String Combiner Box
6. Inverters (Central and String)
7. Inverter Duty Transformer
8. AC Cables
9. Field Lightening Arrestors
10. ICOG Panels
11. Control and Relay Panel
12. HT Panels
13. ACBD for Auxiliary system
14. SCADA for Monitoring and Control
15. UPS and Batteries for Auxiliary Supply
16. Switchyard
17. Metering Panels
18. Transmission Line
19. PPC (Power Plant Controller)
20. ABT Meters

Fault Tree Analysis

Creating a fault tree for a Solar PV power plant involves identifying potential failure events and their causes, and then organizing them in a logical and hierarchical structure. Fault trees help in analyzing the system's reliability and identifying critical points that may lead to failures. Below are the steps to create a fault tree for a Solar PV power plant:

Define the Top Event:

Start by identifying the top-level event, which represents the main failure you want to analyze or prevent. For a Solar PV power plant, the top event could be something like "Total power output failure" or "Complete shutdown of the power plant."

II.   Methodology

A solar power plant's reliability analysis evaluates the system's capacity to consistently provide electricity over a specific time frame. It assists in forecasting downtime, identifying probable faults, and assessing the plant's overall reliability and availability.

Electrical Architecture LSSPV Power Plant

The electrical architecture of a generic PV solar plant from solar PV Modules to point of common coupling with grid is shown in below figure 3.1. Electrical architecture shows that most of the electrical components are connected in series. For enhancement of Power plant capacity up to MW level, Parallel combination of the same architecture is carried out.
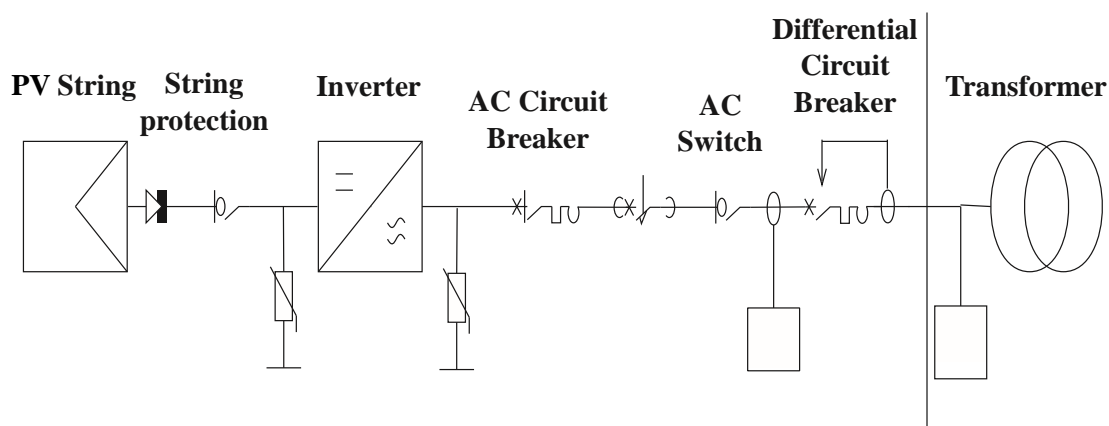
Fig 3.1: Electrical architecture for the PV Power Plant.

A large-scale solar power plant's electrical architecture typically consists of several interconnected systems and components that work together to generate electricity from solar energy and transmit it to the grid or consumers.

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Reliability Modelling of Solar PV Plant
General reliability concepts and functions
The following principles are required to describe the fundamentals of PV system reliability probability analysis.

The **probability density function (pdf)** f(t) indicates the component population's failure distribution over the whole-time range; the bigger its value in t, the more failures will occur in an infinitesimal interval around t.

The **failure probability function** f(t) f(t) is the likelihood that a component will fail within a given time t; it is defined as the pdf's cumulative distribution function (cdf):

$$\mathbf{F(t)} = \mathbf{Pr(T \le t)} = \int_{-\infty}^{t} \mathbf{f(t)} \, \mathbf{dt} \tag{3.1}$$

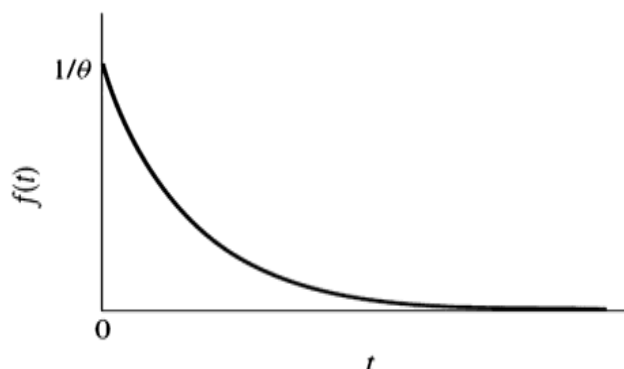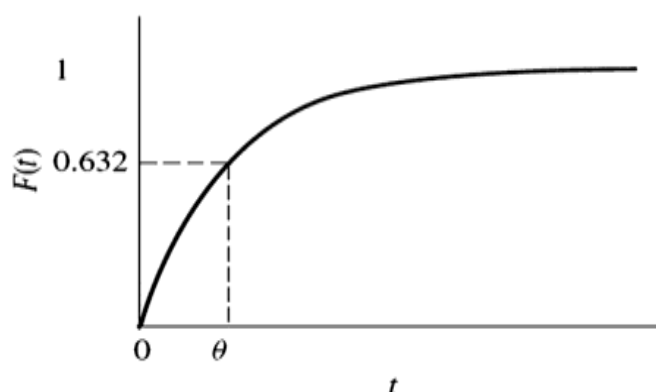It can alternatively be understood as the population proportion failing prior to or at t.

Fig 3.3: The exponential distribution's probability density function (where $\theta = \lambda$)

Fig. 3.4 Exponential distribution failure probability (where $\theta = \lambda$).
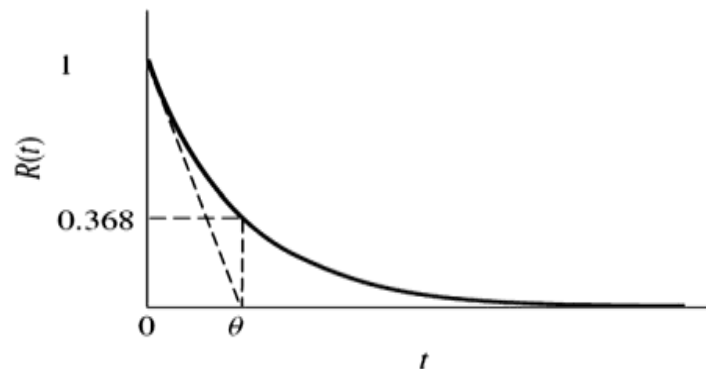**When t = θ, F(t) = 0.632.**

Fig 3.5: Failure probability for the exponential distribution (where θ = λ).
When t = θ, R(t) = 0.368

The **reliability probability function R(t)** represents the population percentage surviving time t and is obtained from Equation (3.1) by knowing that it is the complement to 1 of the F(t) (the probability of success being one minus the probability of failure):

$$R(t) = 1 - F(t) = \Pr(T \le t) = \int_t^{\infty} f(t)\, dt \qquad (3.2)$$

The **failure rate h(t)** (also known as the hazard rate) is the rate of change in the risk that a surviving product would fail in the next small interval of time, calculated as follows.

$$h(t) = \frac{f(t)}{R(t)} \qquad (3.3)$$

The most popular way for defining reliability of non-repairable objects is the **mean time to failure (MTTF)** for the sub-assembly, which quantifies the expected life for the sub-assembly. It can be determined using:

$$MTTF = \int_0^{\infty} R(t)\, dt \qquad (3.4)$$

It is assumed that the defects' time distributions are exponentially distributed. The *pdf* for the exponential distribution is

$$f(t) = \lambda e^{-\lambda t} \qquad (3.5)$$

And from equations (3.1), (3.2), (3.3), (3.4) (see figure 3.4 and 3.5):

$$F(t) = 1 - e^{-\lambda t} \qquad (3.6)$$
$$R(t) = 1 - F(t) = e^{-\lambda t} \qquad (3.7)$$
$$h(t) = \lambda \qquad (3.8)$$
$$MTTF = 1/\lambda \qquad (3.9)$$

For analysis of Solar PV Plant and Subsystems reliability, Equations (3.6), (3.7), (3.8) and (3.9) will be used (**Zini** *et al.***, 2011).**

III.   Results And Discussion

The reliability analysis of solar PV power plant has been predicted for individual component, sub-systems and overall solar plant using Microsoft excel software.

Determination of Solar PV Plant Components and Parameters

To predict the reliability results of each sub-assembly, eight large scale grid-tied solar-PV plants were designed and considered for test results based on practical plant designs. The nominal power of these plants ranges from 1 MW, 2 MW, 5MW, 10 MW, 20 MW, 50 MW, 100 MW and 250 MW. The total number of sub-assemblies also increased as with the PV plant power output capacity increased. The resulting number of sub-assemblies for each system is listed in Table 4.1.

In this research work, 1000 V system is utilized to analyze the reliability of the solar PV plant with different capacities. The Modules are used for 330 Wp each and central Inverters are of 500 KW each. Table 4.2 shows the basic details of the Solar PV Modules and Inverters.

Table 3.1 Number of sub-assembly for each PV Plant.

AC Power (MW)	1	2	5	10	20	50	100	250
DC Power (MWp)	**1.2**	**2.4**	**6**	**12**	**24**	**60**	**120**	**300**
PV modules	3636	7273	18182	36364	72727	181818	363636	909091
Strings Fuses	182	364	909	1818	3636	9091	18182	45455

DC cables	24	48	121	242	485	1212	2424	6061
DC Box switch	12	24	61	121	242	606	1212	3030
Inverter	2	4	10	20	40	100	200	500
AC Switch	2	4	10	20	40	100	200	500
AC circuit breaker	1	2	5	10	20	50	100	250
IDT	1	1	2	5	10	13	25	31
Power Transformer	0	0	1	1	1	1	2	2
Differential CB	1	1	1	2	4	8	10	25
Grid Protection	1	1	1	1	1	1	2	2

Table 3.2: The PV Module and Inverters characteristics

Inverter(500kW)	PV Modules (330W)
Vmpp,min = 450 V	Isc= 9.25 A
Vmpp,max = 820 V	Vmpp= 42.5
Vmax = 1000V	Voc = 46.5
Idc Max = 1175A	Impp = 8.57

Inverters ratings which have been installed till now in different solar PV plants are from 50 KW to 3.5 MW. Based on the size and design considerations, inverter selection was carried out. Presently CI and SI both configurations are utilized for power generation. The plants which are less than 1 MW, mostly SI are installed and the plant having capacity of 5 MW or above, mostly CI are installed to make system easy to operate and maintain. CI configuration, all inverters are placed at single location and dedicated rooms are provided for the same but for SI inverters, they are installed near to solar modules array and completely exposed to environment and scattered placement in the field.

The method which is used to design/select each sub-assembly for different capacity PV plant is presented in Appendix I. The scale-up configuration for large-scale capacity is shown in Appendix II.

Reliability and Availability for various component of solar plant

MTTR and MTBF are estimated based on the failure rate and repair rates shown in Table 3.1 and Table 3.2 in chapter 3. Reliability analysis was also done for 1st, 5th, 10th, and 20th year of operation of individual components. Individual component reliability is above 88% for all the installed components is solar PV plant. In case of central inverter, 1st year operational reliability predicted as 88.24% and 20th Year reliability estimated 8.20% and its availability during first year operation analyzed as 94.95%. All the mechanical components such as module mounting structure, screw, stud, and sleeves has almost 100% reliability and availability respectively.

Mainly the components associated with inverters and power switching components like IGBT, cooling fan, Breakers etc. have less reliability and availability as compared with other solar PV plant components. Power electronics components in the solar inverters play vital role in the PV plants frequent breakdown. Spares needs to be maintained properly in advance to reduce the MTTR value and continuous maintenance has been carried out to minimize the MTBF.

Table 3.3: Component reliability and availability for Solar PV Plant components

Component	R (1yr)	R (5yr)	R (10yr)	R(20Yr)	MTBF	MTTR	Availability
	%	%	%	%	hrs.	hrs.	%
PV module	99.995	99.977	99.953	99.906	21345.7	1.4	99.99
Thin Film	99.957	99.788	99.576	99.153	2351.0	1.7	99.93
PV Connector	99.998	99.991	99.983	99.966	58603.8	5.2	99.99
PV string cable	99.999	99.996	99.992	99.984	128928.3	0.8	99.999
Terminal (lug)	100.000	100.000	100.000	99.999	3223207.1	0.2	100.000
-(metal sleeve)	100.000	99.999	99.998	99.995	424106.2	0.2	100.000
-(screw)	99.813	99.069	98.146	96.327	534.4	0.2	99.97
-(stud)	100.000	99.999	99.998	99.996	453972.8	0.2	100.00
-(block)	99.995	99.977	99.955	99.910	22137.4	0.2	100.00
-(strip)	99.999	99.996	99.992	99.984	128414.6	0.2	100.00
Fuses	99.993	99.967	99.935	99.870	15348.6	0.1	100.00
String Fuse	99.980	99.898	99.795	99.591	4883.6	0.4	99.99
SMU	99.486	97.458	94.980	90.212	194.2	1.2	99.38
DC switch	99.935	99.675	99.351	98.705	1534.9	1.2	99.92
DC main cable	99.985	99.925	99.850	99.700	6659.5	1.2	99.98
AC cable	99.996	99.978	99.957	99.913	23022.9	1.2	99.99
Disconnector	99.966	99.830	99.659	99.320	2930.2	0.8	99.97

String Inverter	95.394	78.995	62.402	38.940	21.2	0.4	98.04
CI	88.244	53.510	28.633	8.198	8.0	0.4	94.95
DC Capacitor	96.855	85.233	72.647	52.776	31.3	0.8	97.36
DC main breaker	98.132	91.002	82.814	68.582	53.0	0.8	98.42
IGBT module	96.495	83.661	69.992	48.989	28.0	0.4	98.51
AC filter Caps	99.351	96.795	93.692	87.783	153.5	0.8	99.45
AC circuit breaker	98.132	91.002	82.814	68.582	53.0	0.8	98.42
CCB	92.563	67.949	46.170	21.317	12.9	0.8	93.84
Cooling fan	92.039	66.047	43.622	19.029	12.1	0.6	95.51
Transformer	91.848	65.364	42.725	18.254	11.8	0.8	93.26
Power switchgear	99.366	96.870	93.838	88.056	157.2	2.8	98.23

Overall individual plant reliability of different capacity solar plants

By utilizing conclusion of FTA and simulating the failure rates of different components with all components details of different capacity solar plants, following trend achieved for the reliability of one year of operation. The highest reliable solar plant is of smallest capacity 1 MW as 60.56% and 100% reliability achieved by all solar plants having capacities more than 10 MW. It is suggested that the plant with higher AC capacity is more reliable as compared with lower capacity solar PV plants.
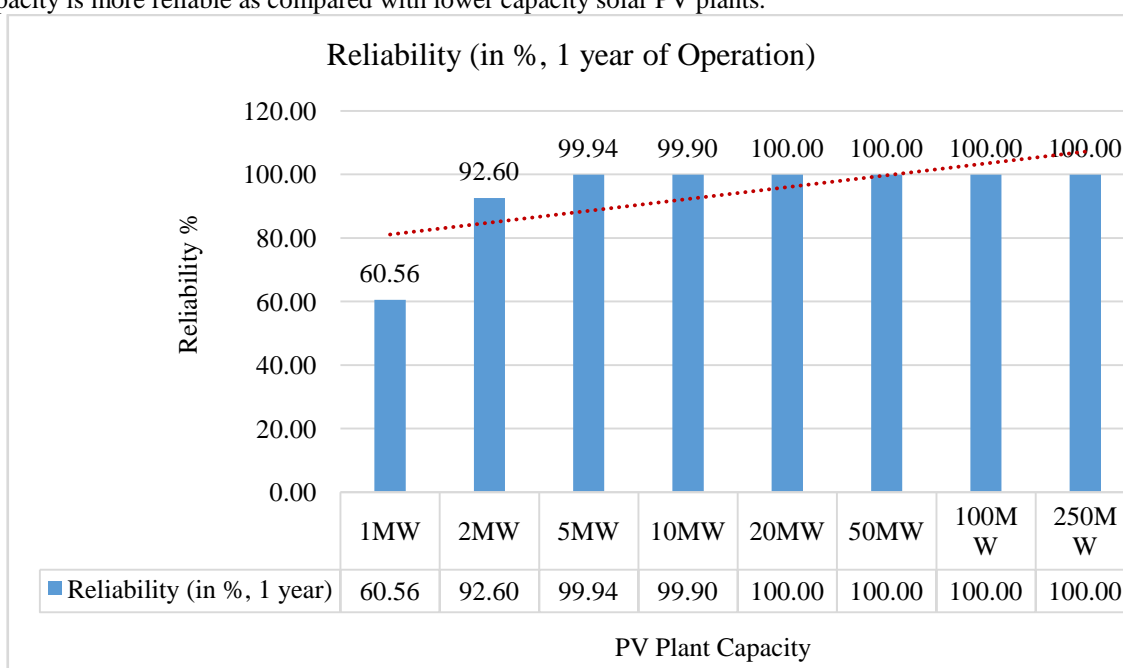

Fig 3.1: Overall plant reliability with different Capacities (for one year operation)

Similarly, for twenty years of operation, different PV plants reliabilities were analyzed. Smallest capacity plant of 1 MW achieved lowest reliability as 0.08% and rest all PV plants achieved reliability index as 77.65% for 20 MW and 99.94% for both 100MW and 250 MW, means that for bigger capacity solar PV plants will have at least one circuit continuously in operation, because of which the reliability is coming as above 99.94% for all the plants greater than 50 MW.

Now most of the solar plant construction carried more than 50 MW at single location and connected with reliable grid on 66KV or above so that grid failure or tripping's occurs low. Moderate capacity plant like 10 MW and 20 MW having reliability index in between 52.72% to 77.65%.
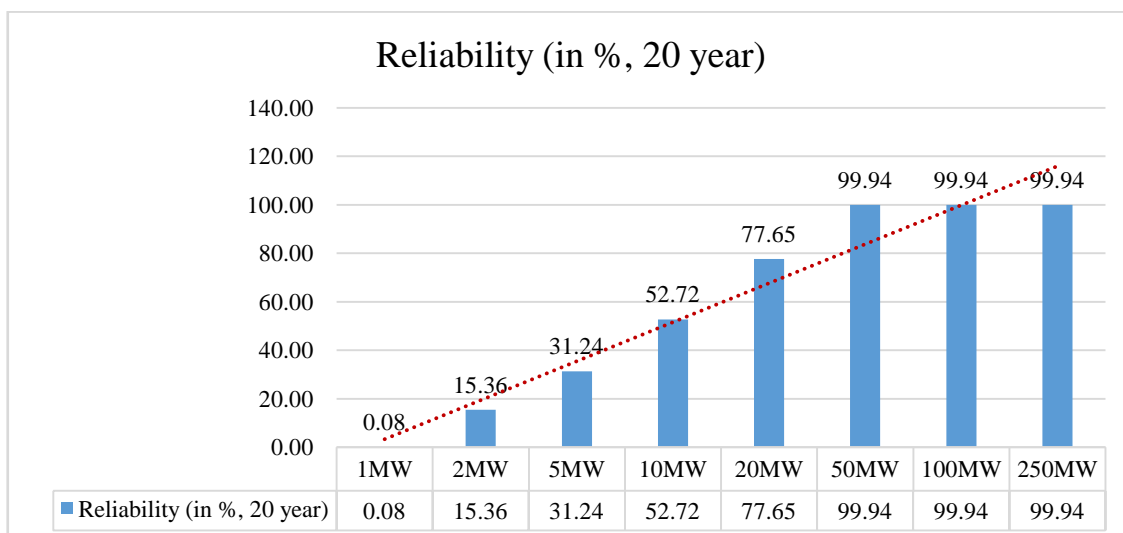
Fig 3.2: Overall plant reliability with different Capacities (for 20 -year operation

Reliability analysis for various subsystems of solar-PV plant

  Solar PV plant can be divided into various subsystems and for the reliability assessment of subsystem, linear failure rate equations are modelled in chapter 3. Based on the failure rates of the individual components, subsystem's reliability analyzed and shown below figure. In 1st year of operation, mostly breakdowns are observed at central inverters and string inverters and their reliability is predicted for 1 year of operation as 70.3% and 94.1%.

  With present failure rate, it can be concluded that central inverter's reliability tends towards zero in 10 years of operation and String inverters are able to operate with less reliability till 25 years. So, in this way all the subsystem's reliability has been predicted and analyzed for further considerations in solar PV power plant operations.
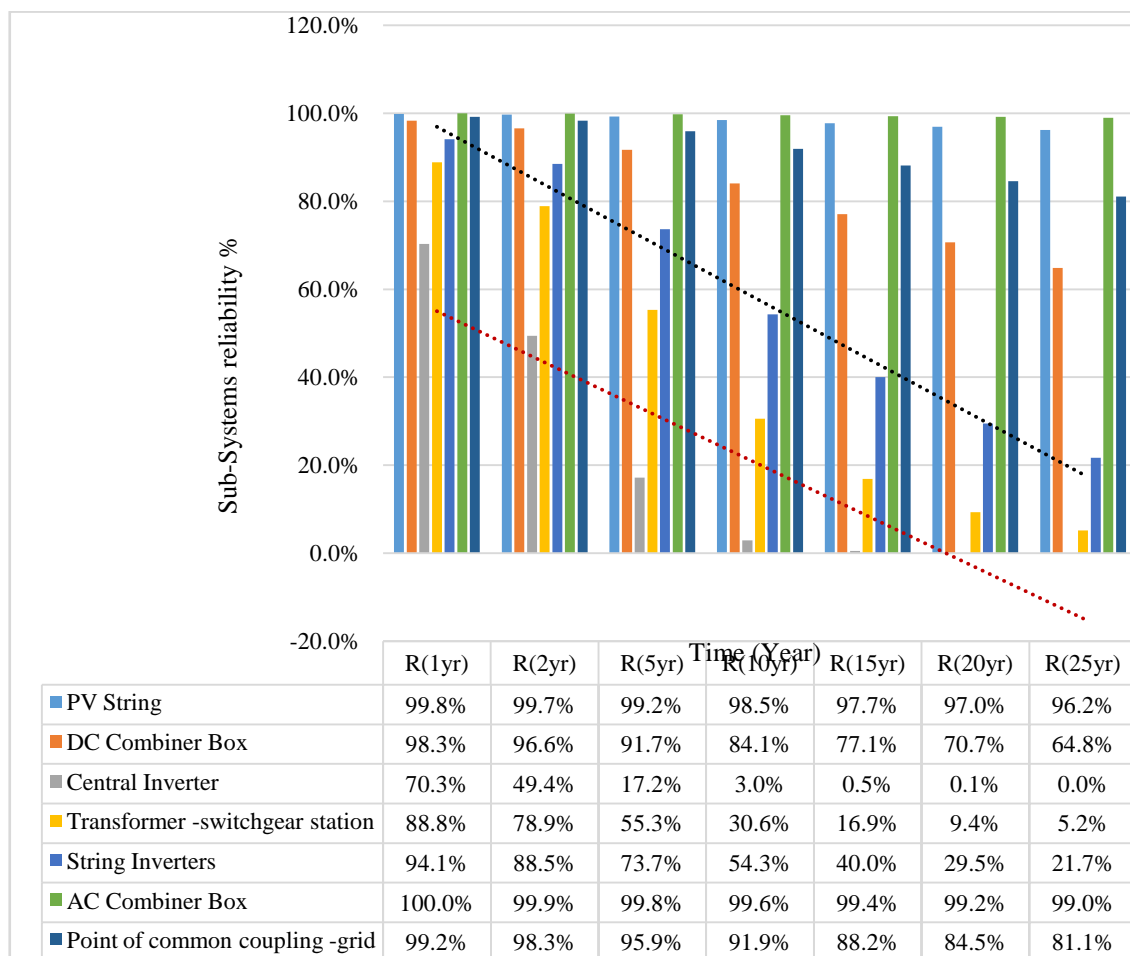
	R(1yr)	R(2yr)	R(5yr)	R(10yr)	R(15yr)	R(20yr)	R(25yr)
■ PV String	99.8%	99.7%	99.2%	98.5%	97.7%	97.0%	96.2%
■ DC Combiner Box	98.3%	96.6%	91.7%	84.1%	77.1%	70.7%	64.8%
■ Central Inverter	70.3%	49.4%	17.2%	3.0%	0.5%	0.1%	0.0%
■ Transformer -switchgear station	88.8%	78.9%	55.3%	30.6%	16.9%	9.4%	5.2%
■ String Inverters	94.1%	88.5%	73.7%	54.3%	40.0%	29.5%	21.7%
■ AC Combiner Box	100.0%	99.9%	99.8%	99.6%	99.4%	99.2%	99.0%
■ Point of common coupling -grid	99.2%	98.3%	95.9%	91.9%	88.2%	84.5%	81.1%

Figure 3.3 Subsystems reliability Analysis of solar PV plant.

Impact of Operational failure on various Solar Plants

      As the PV power capacity of solar Plant increases, the reliability of the solar power plant increases as per design and data output suggested of this analysis. From figure 4.8, considering subsystem reliability modelling and conclusion of FTA, Overall plant reliability has been predicted for all solar PV plant. Small capacity solar PV plant has lower reliability index and analyzed as 60.6% at 1st year end and it was 95.1% in the 1st month of operation like bathtub Hazard rate curve. For bigger capacity solar PV plant, reliability is predicted as 100% for 1st year of operation because of multiple parallel circuit to supply the generated power to grid which means that failure of the subsystem in larger capacity plant didn't impact its reliability so significantly as compared with small capacity solar PV plant up to 2 MW.
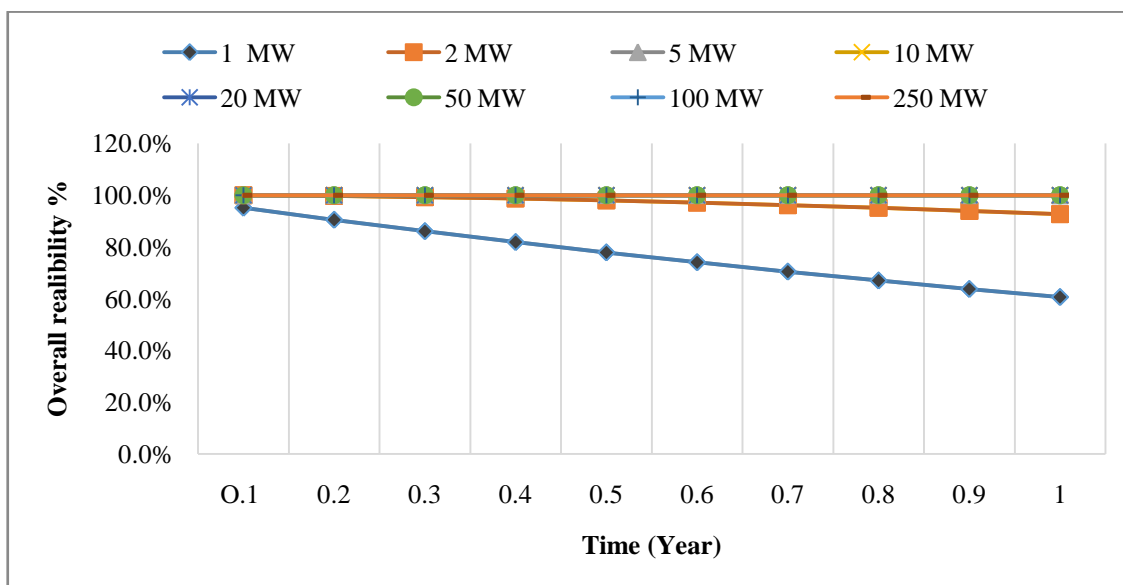
Fig 3.4: Overall reliability Analysis of solar PV plant for 1 year of operation

Similarly for 20 years of operation of solar PV plant, reliability prediction was carried out and shown in figure 4.9. With this analysis, it can be analyzed that plant having capacity more the 100MW are more reliable as compared with lower capacity PV plant. Since parallel connected system reliability is always high as compared with single circuit connected capacity hence same can be seen in this analysis.
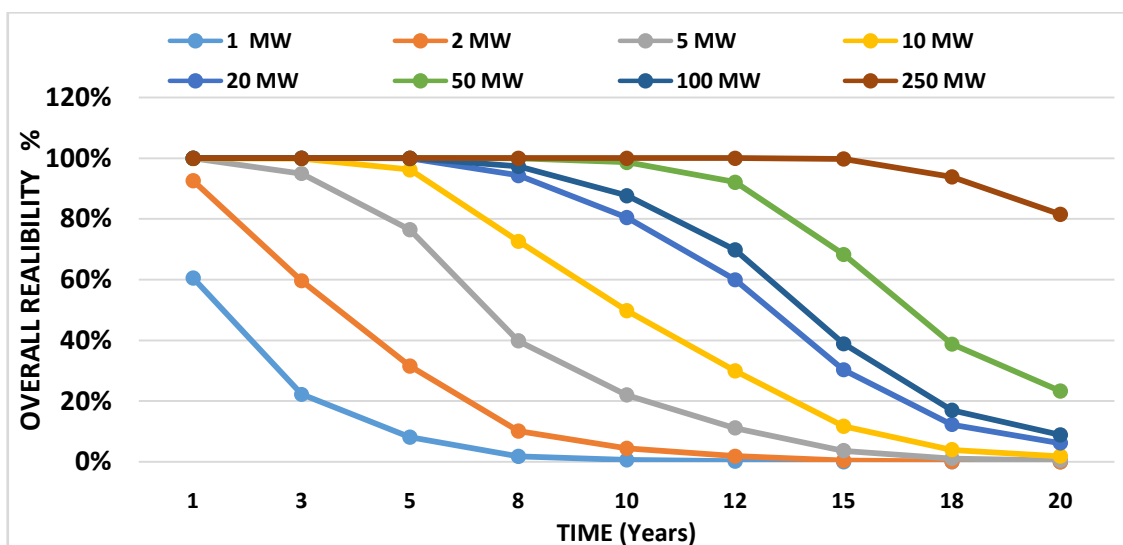

Fig 3.5: Overall reliability Analysis of solar PV plant for 20 years of operation

The expected lifetime of all the sub-systems were analyzed and predicted based on the failure rates. And with the definition of MTTR, it has been calculated. DC combiner box has longer life of 50.99 years as compared with another subsystem. After the DC combiner box, AC combiner box and PV strings have similar MTTF of 39.77 years and 38.45 years respectively. Lowest lifetime or MTTF has been predicted for Inverters and the overall plant will generate zero, if inverter has failed just after 3.67 years of operation.

Table 3.4: The mean time to failure (expected lifetime) for various subsystems of solar-PV Plant (year).

Items	MTTF (Years)
PV String	38.45
DC Combiner Box	50.99
CI	3.67
Transformer -switchgear station	10.93
SI	21.18
AC Combiner Box	39.77
Point of common coupling -grid	35.45

Overall Plant (System)	3.67

Reliability of subsystem and overall solar-PV Plant

  The probability that a solar plant will successfully carry out its intended function under conditions and for a specific period without encountering any failures is defined as reliability in the reliability context. As a result, Figure 4.10 shows the reliability of each subsystem as well as the overall reliability of the solar-PV plant. The MTTF of each subsystem was determined and listed in Table 4.4 based on Figure 4.10. According to some studies, the PV inverter (INV) is merely one of the BOS sub-assemblies. However, the current research's primary focus is largely restricted to reliability estimates for PV modules, inverters, strings, IDTs, and power transformers. Therefore, to make data analysis and calculation easier, the BOS subsystem is divided into various subsystems in this study.

  The PV string subsystem has a 0.9080 and 0.7505 reliability rating after 10, and 30 years, respectively. The MTTF of PV modules and CI subsystems, when calculated using the MTTF equation, is 38.45 and 3.67 years, respectively. The inverter's complexity or the fact that it comprises electronic components, which are strongly impacted by a variety of stress conditions, are the primary causes of the CI subsystem's lower MTTF. Therefore, compared to the expected average lifetime of the solar-PV Plant, which is in the range of 20–25 years, the lifetime of the CI in the solar PV plants is very less.
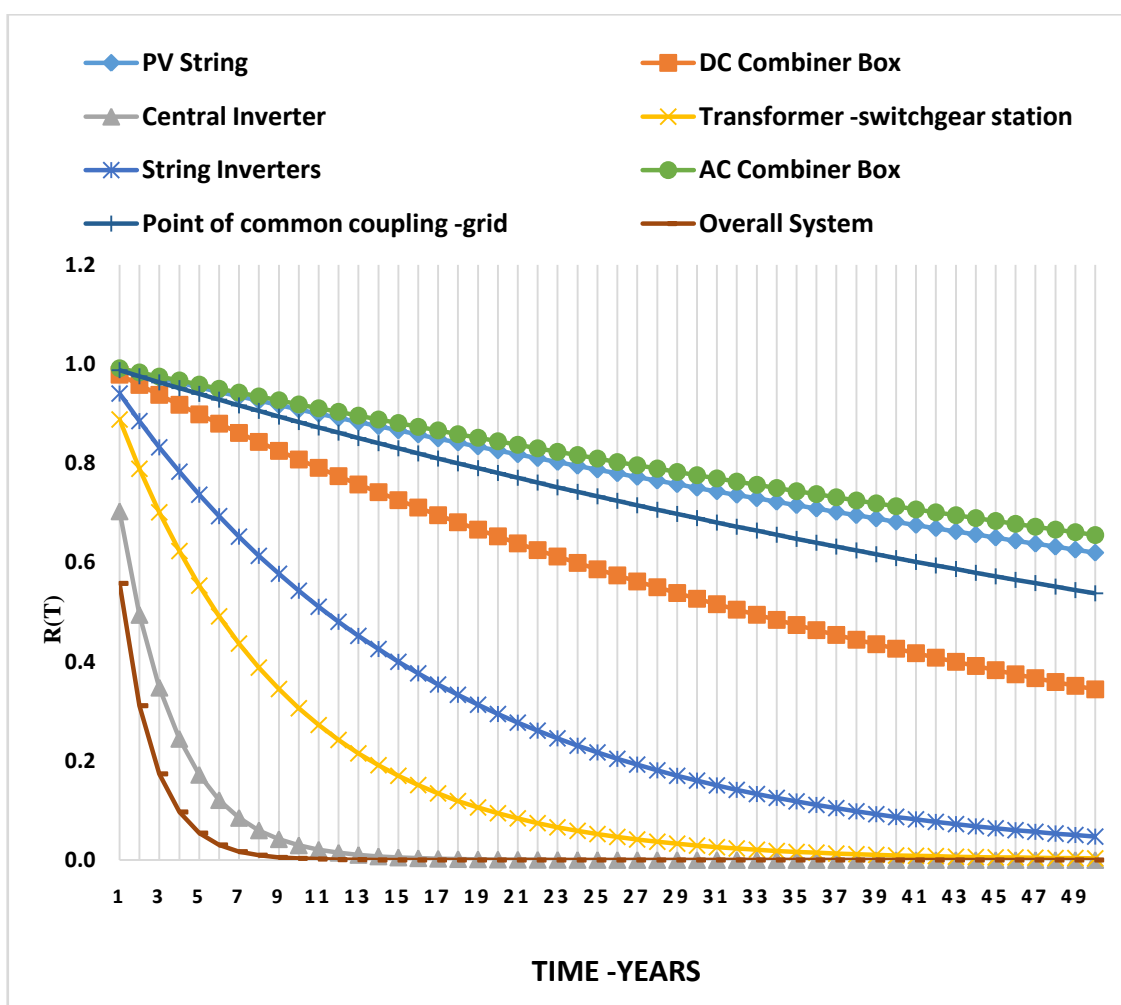

Figure 3.6: Reliability of subsystem and overall solar-PV Plant.

IV. Summary and Conclusion

  Solar photovoltaic power plants are reliable and can run faultlessly for longer duration if proper preventive maintenance has been carried out in timely manner. To ensure their continued operation and maintenance, faults should be forecast and analyzed because, like any system, they could also fail. The approach for assessing the reliability of different components in sizable PV power plants has been described in this research study. In the result and discussion section, Table 4.4 shows the ranking of the most important elements of the solar PV plant. Inverter, Strings protection system and PV modules are predicted as more

critical components of the solar Plant. Without inverter opreation DC Power can't be converted into AC power and hence can't be injected to grid. PV modules act as generator hence if Solar irradiation is available, but modules are not functioning properly than in that case also power won't be generated as required.

The component that fails in solar plant most frequently must be able to be immediately replaced or fixed just after the failure is observed into the system. If the rectification and repair work is delayed of any reasons, then MTTR will increase and hence reliability of solar PV plant decreased. The solar PV plants may operate with a high availability rate if maintenance has been performed as per the PM Annual Plan, however this is not the best option to perform corrective maintenance all the time after breakdown of any components.

For cost optimization, maintenance procedures can be made more effective. It is important to note that although the focus of this research study was on irreparable components, the suggested method can also take repair time into account to calculate the plant's economic losses which directly impact the Return on investment. Future research will also concentrate on the proper sorts of maintenance for the LSSPVPP component parts.

For LSSPVPP, a detailed reliability analysis was carried out for 8 different capacity solar PV plants considering different configurations of series and parallel blocks to form large scale solar plant. Combined data from literature and actual data from PV plants that have been operating for the past 10 years was considered in the reliability analysis.

FTA was utilized used to conduct the reliability study based on the subsystems and individual subsystem components of the central and string inverter schemes. In contrast to earlier research, this one has considered the transformer's reliability as well as the point of connection. MTTR and MTBF on the energy yield permitted an evaluation of the significance of the various failure modes using updated and more accurate data to simulate the impact of failures. It is shown why it is crucial to think of the transformer as a potential site of failure.

It can be analyzed that EL is mostly caused by the high MTTR and disastrous yield impact of failure. It has been demonstrated that lowering the MTTR for the inverters and transformers, the main sources of EL is an efficient strategy to increase EA. Implementing predictive repairs based on thorough condition monitoring would be one approach to do that.

In this research study create a comprehensive and micro-level framework for failure data analysis and fault tree analysis (FTA) based on which reliability model is developed. The Fault Tree (FT) for the DC side of a solar photovoltaic (PV) plant is constructed using knowledge from literature. Different component/fault failure rates and repair rates were used to develop the system reliability model. The failure rates are estimated and used in system reliability modeling to lower uncertainty caused by extreme values and increase the model's accuracy.

According to the FTA's data the top event, "No output or degraded output at Top Event," has a reliability/probability of 31.24% and 77.65% for a 5 MW and 20 MW Solar PV plant respectively for 20 years of operations. It means that when there will be more parallel operation within the solar plant than the reliability of the solar plant increases.

The reliability of the various subsystems as previously defined was also estimated, and it was discovered that compared to inverters and transformers, PV Strings, ACCB, DCCB, and switchyard have lower failure probabilities.

Overall Solar PV plant reliability is low for lower capacity PV system because of less parallel operation in the plant & reliability can be predicted much high for bigger capacity solar plant where significant parallel paths are made for power injection. The individual subsystem reliability is high as compared with overall plant reliability because any critical component failure may lead power output zero at point of common coupling. Hence the solar PV plant failure probability is much higher than its subsystems.

Implications and Future Scope

Regarding future study, the performance of the reliability model can be enhanced by considering information gathered from the field and fusing it with expert opinions. By adding a field failure data analysis approach and employing fuzzy logic to analyze expert opinions, a produced data analysis framework can be improved. Even in the absence of sufficient or enough data, the enhanced technique should be able to create an accurate model. To address the identified critical flaws, which sharply limit output power and result in a considerable financial loss, automatic fault detection and diagnosis systems can be built. As a result, a PV system economic analysis can be done.

A list of components rated by relative importance and suggests some potential solutions to deal with the problems brought on by the huge number of components in PV systems to glean relevant information from this reliability analysis. Using automatic monitoring and diagnostic systems to record reduced power output from modest defaults, which might result, if not caught, in potential sources of substantial economic loss, is the only likely approach to identify problems happening in PV modules and string safeguards. The output of energy

conversion can be substantially enhanced by routine inspection and the political replacement of preventive string protections (if existent) and inverters. Furthermore, automatic monitoring of inverters is simple.

Finally, automatic switches that trip when a circuit breaker malfunction can be added to circuit breakers. Table 4.4 also provides a rough estimate of the amount of effort required to move on with preventive maintenance or monitoring. The problems associated with using many components, especially in extremely large PV power systems, will be significantly reduced by improvements in monitoring and diagnostic technology. To uncover ways to increase the efficiency of actual PV power plants, further study on the topic will need to loosen the assumptions made by, for example, taking repairable failures or component deterioration into account and evaluating associated energy and cost losses.

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