STUDY ON RELIABILITY AND AVAILABILITY OF LARGE SCALE GRID CONNECTED PHOTOVOLTAIC POWER PLANTS

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ABSTRACT

The availability analysis of the large scale commercial PV power plant is important for planning and long-term operation, because the analysis helps predict system behavior over time and devise appropriately timed maintenance plans. It is a important factor for the operator to be able to assess system availability under long-term operations in order to optimize decisions in design, engineering, procurement, construction, and service that result in solar farm economic improvement. There are limited studies already on the availability of PV power system in Thailand. Study on reliability and availability of large scale grid connected photovoltaic power plants concentrate on the various large scale commercial PV power plants, climate and environment in Thailand, and longtime study period. The 6 large scale commercial PV power plants that constructed with the similar configuration with AC power output ranging from 3.3 to 7.6 MWp are selected as the PV power plant samples that are plant A, B, C, D, E, and F. These PV power plant are located in central region of Thailand that is a good representative for the large scale commercial PV power station, climate, and environment in Thailand (Tropical climate). Failure evaluation result is separated in 3 parts that are PV power plant component (Internal), grid (External) and total failures analysis. Only 5 PV power plant component failures cover about 90 % of the internal equivalent PV power plant downtime that are low insulation, humidity, cable, inverter IGBT explode, and un plan shutdown. The high underground water level, humidity, high inverter temperature, unplanned operation and maintenance are the major root causes of these failures. Improving water draining system, keeping dry of cable ducts and manhole, improving inverter cooling and

humidity control system, and well-designed operation and maintenance program are the solutions of these failures. Only 3 grid failures cover all external equivalent PV power plant downtime that are under voltage, residual over voltage, and over voltage failure. Local geology, climate, grid condition, load during day time, etc. are the significant root causes of these failures but the corrective action of these failures are beyond the solar farm operator responsibility. The internal failures analysis dominates 46.17 % of the total failure while the external failures influence 53.83 % of the total failure. The average availability during 2011 to 2015 of the 6 large scale commercial PV power of plant A, B, C, D, E and F are 99.70 %, 99.79 %, 99.80 %, 99.64 %, 99.33 %, and 99.24 % respectively. The result clearly indicates that under voltage and inverter Bender failure have the highest effect to availability with grid failure. Nevertheless, the availability trend of the 6 large scale commercial PV power plants are increasing from the initial value to reach the maximum value in 2015 except in plant A and B that a little bit fluctuation. Availability mathematical model is developed by using Least Squares Method with order 2 polynomial equation and the availability data of the 6 large scale commercial PV power plants during 2011 to 2015 are used as input data. The developed mathematical model with R^2 95.95% is APP = -0.0086 X^2 + 0.086X + 99.68, X=Number of year. The simulation result by using the mathematical model is comparing with the actual availability. From the comparing result, the error is in -2.10 to 2.03 % range that is in the passable range.

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CHARPTER I

INTRODUCTION

Rationale for the study and statement of the problem

Energy crisis, green energy promotion, and environmental preservation trend have been driven the alternative energy to rapidly growth in every part of the world for a few decades. Photovoltaic (PV) and Balances of the System (BOS) performance are quickly improved and the production rate is increasing to reach the economy of scale. From these reasons, PV and BOS price sharply reduces and has highly competitive than the past decade. Those are attractive for the investor to invest in the solar farm business.

In 2016, the Grid-connected PV system are installed in Thailand about 2482.03 MW [1] and the target installed capacity are 6,000 MW in 2036 according to the alternative energy development plan AEDP 2015-2036 [2] that was assigned from the government to the Minister of Energy to be developed and established the plan. According to the plan, Feed-in tariff program, and the dropping solar cell and BOS price stimulate the investor interesting to apply for the power purchasing agreement (PPA) of ground mounted PV system in the MW scale or solar farm which providing the best investment return.

PV power plant yield and Performance ratio (PR) are the most interested solar power station parameters from the investor. These parameters will effect to Internal Rate of Return (IRR), Net Present Value (NPV), and Payback Period (PB) that indicating the project possibility in commercial. Based on the good performance PV power plant, all feasibility study of solar farm project always has the attractive result. However, the success power generation rate for the commercial target depends on many uncontrollable and controllable factors such as the solar radiation, climate, grid condition, etc. for uncontrollable factors and PV power plant design, installation, process, operation, and maintenance for controllable factors. In practical, some information is neglected because lack of information, study, knowledge, and knowhow for the large scale solar farm. Reliability and availability are the vital engineering tools that focuses on costs of failure caused by system downtime, cost of spares, repair equipment, personnel, and cost of warranty claims. Normally, these tools are used in feasibility study of PV power plant project to estimate the high accurate life time revenue and costs of the project. For reliability and availability estimation, all main solar farm component such as PV panel, cable, connector, sub-array box, array box, combiner, combiner box, inverter, transformer, MV switchgear, protection relay, and other components are included in estimation. Generally, most of the critical PV power plant component usually have the failed safe function to extend Mean Time to Failure (MTTF) because the complex equipment and systems are not free from the defects and failures that result from the manufacturing, design, installation, and operation. However, it still cannot guarantee the operation duration without failure. By the way, availability includes the affect from the power grid stable and quality and the operator often uses it for benchmark with other solar farm. Moreover, operator can use it to prepare the spare part and the maintenance plan as well.

In order to be accurate calculating of the economic analysis and the long-term operation maintenance planning, it has to include the PV power plant availability and the benchmark result with other solar farm that the simulation result is reasonable or not? Nevertheless, the availability study of PV power plant is not yet public and proof as same as other the business such as the data center that a lot of data and design are including the system availability. The reliability meaning can demonstrate in two aspects. For the qualitative point of view, reliability is defined as the item ability to remain functional at a specified moment or interval of time. For the quantitative aspect, reliability is defined as the probability that no operational interruptions are occurring under stated conditions for a specified period of time. From the experience, it shows that only probability is a reliability measure of the item [3].

The objective of this study is investigating and analyzing the reliability and availability of the commercial large-scale PV power plant in Thailand that include all solar farm component with statistic record such as system availability, estimate unsupplied energy, incident number, number of interruption hours, grid quality, force outage. Moreover, the suitable reliability and availability formula are created for the grid tie photovoltaic power plant in Thailand with the referent figure that can be used as the reference in the future.

Objectives of the study

1. To analyze the failure root cause and corrective action for improve the availability of the large-scale commercial PV power plants in Thailand.

2. To analyze an availability of the large-scale commercial PV power plants in Thailand.

3. To develop the availability mathematical model for the large scale PV system.

Expected outputs of the study

1. Understand the availability of PV power plant in Thailand.

2. Understand the failure root causes that effect to the availability and the solution for these problems.

3. Create the availability formula for the large-scale PV power plant

Expected outcomes

1. To have the guideline for developing and improving of PV power systems.

2. To obtain useful information for further considering and selecting PV power plant component.

Limitation of the study

In this research, only 6 large-scale solar farm with installed capacity from 3.3 MW_p to 7.6 MW_p that located in Thailand are evaluated for 4 years.

CHARPTER II

LITERATURE REVIEWS

PV power plant

The large-scale PV system that designed for supplying the merchant power into the electricity grid is known as PV power plant, PV power station, solar park, solar farms, and solar ranches that are differentiated from most building-mounted and other decentralised solar power applications because they supply power at Medium Voltage (MV) or High voltage of utility distribution or transmission system, rather than to Low voltage (LV) distribution system for a local user or users. The generic expression utility-scale solar is sometimes used to describe this type of project. Generally, the nameplate capacity of a PV power plant is rated in megawatt-peak (MW_p or MW_{DC}) and refers to the PV array DC power output. However, AC output (MW, MW_{AC}, or MVA) is used in many countries. Most PV power station are developed at a scale of at least 1 MW_p. The first 1 MW_p solar farm was built by Arco Solar at Lugo near Hesperia, California at the end of 1982 [4], followed in 1984 by a 5.2 MWp installation in Carrizo Plain [5]. Both have since been decommissioned. The first multi-megawatt plant in Europe was the 4.2 MW community-owned project at Hemau, Germany that commissioned in 2003 [6]. The next stage followed the 2004 revisions [7] to the feed-in tariffs in Germany when a substantial volume of solar parks were constructed. The first solar farm to be completed under this programme was the Leipziger Land solar park developed by Geosol. that commissioned in 2004 [8]. After that, many countries launch the subsidies or incentive programs that result in the wide spread of PV power plant in every region of the world. As of 2016, Yanchi solar PV power plant in Yanchi, Ningxia Hui Autonomous Region, China [9, 10] that demonstrated in Figure 1 is the world's largest operating PV power plant that has installed capacities of 1,000 MW. In addition, the projects up to 2,000 MW are planned. Most of the existing large-scale PV power plant are owned and operated by independent power producers, but the involvement of community- and utility-owned projects is increasing. In present day, more than 90% have been supported at least in part by regulatory incentives such as adder, feed-in tariffs or tax credits, but as levelized costs have dropped remarkably in the last decade and grid parity has been reached in many markets, it is possible that the external incentives cease to exist in the near future.

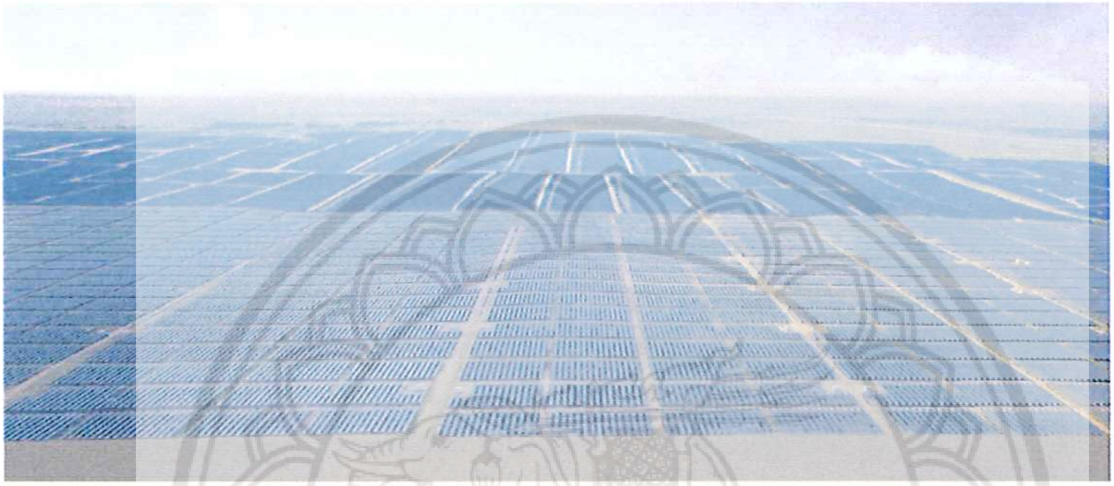


Figure 1 Yanchi solar PV power plant with 1,000 MW installed capacity in Yanchi, Ningxia Hui Autonomous Region, China [9, 10]

Reliability and Availability of PV power plant

An important issue in grid tie PV systems as their operations rely on business plans that are developed over periods of time at least 25 years, manufacturers in the PV industry are commonly offering warranties based on reliability and availability. System reliability and availability estimates are required to facilitate cost trade off studies. Estimates of reliability are necessary in developing maintenance cost projections over the system lifetime. Availability estimates provide an input annual energy generation projections. Based on BS 4778, reliability is defined as the ability of an item to perform a required function under stated conditions for a stated period of time and failure is defined as the termination of the ability of an item to perform a required function. Moreover, Observed Meantime to Failure (MTBF) is an important parameter that BS 4778 is defined as a stated period in the life of an item, the mean value of the length of time between consecutive failure computed as the ratio of the cumulative observed time to the number of failures under state condition Repairable system reliability can also be characterized by the meantime between failures (MTBF), but only under the particular condition of constant failure rate [11]. Availability is defined as the probability that an item will operate satisfactorily at a given point in time when used in an actual or realistic operating and support environment. It includes logistics time, ready time, and waiting or administrative downtime, and both preventive and corrective maintenance downtime [12]. Field data, failure times and repair times, are needed to collect and analyze. The study about reliability and availability is available in many aspects. Over the past years, the study has produced a good development in many ways.

Performance analysis and reliability of grid-connected PV system in IEA country

Ulrike, J., & Wolfgang, N. [13] presented the operational performance results of grid connection PV systems, as collected and elaborated for the Photovoltaic Power System Program of the International Energy Agency (IEA). Performance ratio (PR) obtained from 334 PV installation in 14 difference countries are compared and discussed. A working group is collecting and analyzing the operation data of photovoltaic plant in various system techniques. The objective of this joint project is to provide the technical information on the operational performance, reliability and sizing of PV system and their subsystem. To investigate the trends of system availabilities, 17 Italian system were analyzed The 17 systems with capacity of kWp to MWp and were installed between 1983 and 2002. The result shown that the Performance ratio and system availability are linear correlation, a low performance is correlated with low availability (high failure rate), The system that obtained the low PR value due to frequently the failure rate of components (inverter, DC components). In general high system availability guarantees high yield and The system that installed before 1995, the average annual availability is 94, 6% to 95.9% for the new installations.

Reliability and Availability of PVsystem in Springerville, Arizona, U.S.A.

The case study of a fielded grid-connected PV power plant in Springerville, Arizona, USA that showed Figure 2 by Elmer, C., Michael, D., Jeff, M., Michael M., & Michael, Q.[14] present that crystalline silicon PV modules is comprising approximately 80% of PV generating system's capacity. The case study using three basic activities associated with a reliability and availability program are Failure Modes and Effects Analysis (FMEA) that demonstrated in Figure 3, System Reliability/Availability Model, and Accelerated Tests. Overview of Reliability Program for PV systems. FMEA is a technique for systematically identifying, analyzing and documenting the possible failure modes on system performance or safety. System Reliability/Availability Model allows quantification of system reliability and availability using multiple data inputs, such as field data, test data, and accelerated life test data. The expected number of failures as predicted by model for each component for 5, 10, and 20 years are shown in Table 1. For the first five years, the inverter repair rate was 0.96 per inverter per years. For PV modules, the replacement rate was approximately 5 in 10,000 modules per year. Inverters are the most unreliable component in this system. Yet the availability of continuous power delivered to the grid is projected to be very high over life of this system. However, an increase in inverter reliability can still lower corrective maintenance costs over the system life.

Figure 2 Springerville PV power plant in Arizona, USA [14]

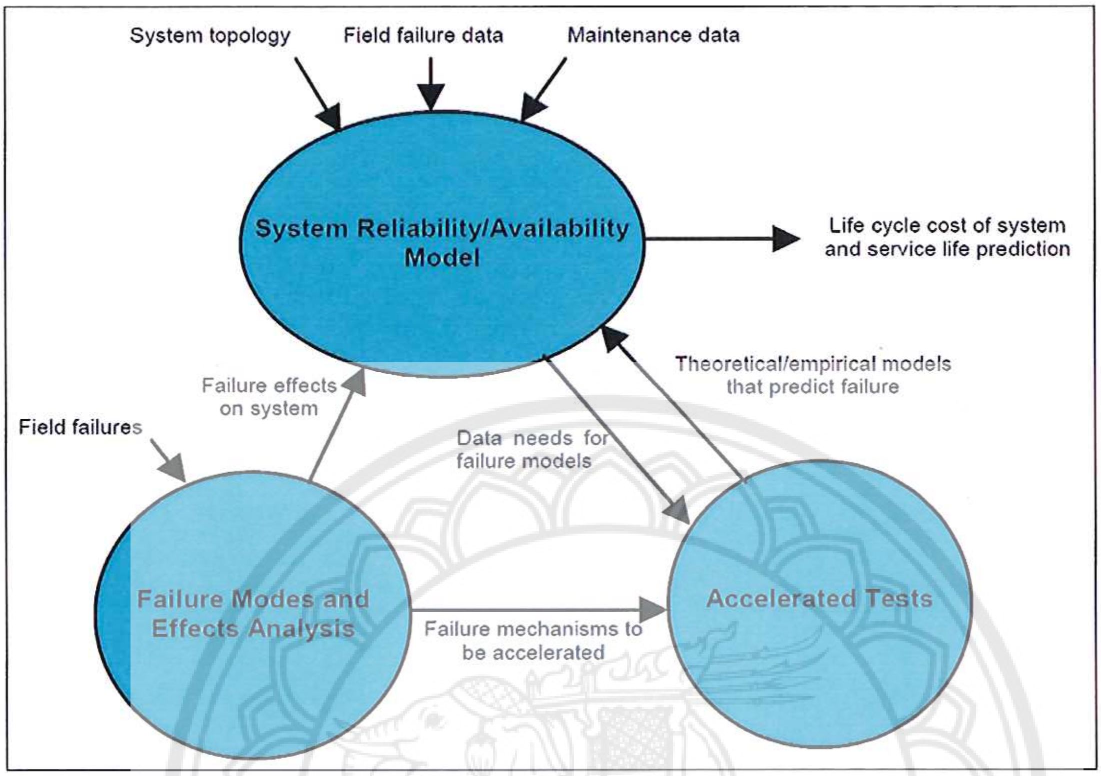


Figure 3 Overview of reliability program for PV systems [14]

Table 1 The expected number of failures as predicted by model for each component for 5, 10, and 20 years

Component	Actual Number of Failures 5 yr Cum	Expected Number of Failures 5 yr Cum	Expected Number of Failures 10 yr Cum	Expected number of Failures 20 yr Cum
PV 150 Inverter (26 cSi arrayes)	125	132	231	429
PV Module	29	26	31	38
AC Disconnect	22	17	23	31
Lightning	16	10	20	41
208/480 Transformer	4	3	3	3
Row Box	34	25	35	50
Marshalling Box	2	4	7	11
480 OVAC/34.5 KV Xformer	5	4	5	9

The PV system Reliability: An operator's Perspective

Anastasios, G. [15] presented the reports that come from the operator at the site by using the log sheet in the database to record all incidents. This record consists of the relevant information such as product failure, repair time, production impact and cost of services, which cover the 600 PV systems in continents. The system sizing from a few kWp to 70 MWp that construction from 2005 with more than 1500 inverters from 16 venders and more than 2.2 million PV modules from 35 manufacturing. The 43% of a ticket from an inverter, % from AC subsystem, 12% from the external, 9% other, 6% support structure, 6% from DC subsystem and the rest from Planned outage, modules, weather station and meter. With the observe the result so call 80/20 rule: 20% of the tickets are a response 80% loss of the energy and 5% of tickets make up 50% loss. The Inverter is the most equipment that failure; the 28% came from the software and the rest from control board, Ac contactor, Fan, Matrix IGBT, Power Supply, DC contactor, Surge arrestor, GFI component, Capacitor, Internal fuse. Internal relay and DC input fuse. The PV module is quite reliable as only 2%of ticket and only 1% for energy loss compare with 43% of ticket and 36% energy loss from the inverter. The root cause came from the incorrect handing, mounting and from the manufacturing process such as burn tab connectors, edge film discoloration, white spots, overheating diode, etc. The accurate and systematic monitoring system will help the operator to feed back the accurate data.

Reliability of various sizes of PV systems

The another case study done by Gabriele, Z., Christophe, M., & Jens, M. [16] presented a method for assessing the reliability of the large -scale grid-connected photovoltaic system. Fault tree and probability analysis are used to compute the reliability equation, and the development model is applied on military-standard data an on data taken from scientific literature. The analysis assumed that cabled do not introduce failure mode and that system design and installation are flawless, this way granting the possibility to focus only on electrical/electronic component's failures. It is also assumed that the SPDs never fail in the short circuit mode, and the measuring equipment is not opening the circuit in case of failure.

PV systems, with nominal power ranging from 100 kW to 2500 kW are designed in order to evaluate their overall reliability. To compute the total number of components needed for each system, the PV module and inverter with the characteristics shown in the Table 2. The reliability of PV systems over a period of time of 20 years, with an average of 8.5 h operations a day was analyzed. The failure rate units are hence failures/hour. In this study, system failure is intended not only as a complete shut-down, but even as a small loss due to a single cell in a single module being damaged. This consists in a very strong constraint, since a small power loss due to a single module cannot even be spotted in a large-scale PV system. As far as the inverters are concerned, using the failure rate in the Table 3, 23 inverters out of 24 would have a fault over the 20 year period.

Table 2 Number of components for each PV system

Power (kWp)	**100**	**200**	**500**	**1000**	**1500**	**2000**	**2500**
PV modules	437	874	2166	4351	6517	8702	10868
String Protection	23	46	114	229	343	458	572
DC switch	3	6	15	27	42	57	72
Inverter	1	2	5	9	14	19	24
AC circuit breaker	1	2	5	9	14	19	24
Grid protection	1	1	1	1	1	1	1
AC switch	1	1	1	1	1	1	1
Differential circuit breaker	1	1	1	1	1	1	1
Connector (couple)	874	1748	4332	8702	13034	17404	21736

Table 3 Component adopted failure rates

Component	Failure Rate (10^{-6} failures/hour)
PV modules	0.0152
String Protector (Diode)	0.313
DC switch	0.2
Inverter	40.29
AC circuit breaker	5.712
Grid protector	5.712
AC switch	0.034
Differential circuit breaker	5.712
Connector (couple)	0.00024

The energy loss caused by one inverter would be easily traceable, but for a 2.5 MW PV system, two weeks of lost production per each inverter would entail a loss of more than 4% of overall system production.

Impact of inverter configuration on PV system reliability and energy production

Aleksander Pregelj, Mirosiav Begovic, & Ajeet Rohatgi [17] presented the impact of inverter configuration on PV system reliability and energy production. The loss of potential revenue due to PV system failure should be taken into consideration when the system's life-cycle cost predictions are calculated, they demonstrated a procedure for quantifying the effect of inverter failure (as most dominant) on total life time of PV system energy production, and investigate the suitability of several inverter configurations base on criteria of total life time energy production and life cycle costs. The overall PV system performance penalty due to the inverter failures depends on several factors such as reliability characteristics of the inverter, inverter configurations and repair time. They are using the Mont Carlo analysis, a performance adjusting coefficient that accounts for determining the optimal inverter configurations. Consider the three following inverter confabulations, 1) single inverter system 2) System with N identical small inverters (N times a smaller rated power) each connected to a portion of the system (string) corresponding to its capacity.

Performance and Availability of 202 PV systems in Taiwan

H. S. Huang, J.C. Jao, K. L. Yen, & C. T. Tsai [18] concluded in their study that 60% of systems failed by inverters. Only 12% of systems failures caused by modules and over 20% caused by BOS. This information indicates that inverter is the most vital components of solar system. The data were collected for 3 years on 202 PV systems found out that performance ratios (PR) ranged from 0.6-0.9 as seen in the Figure 4

The performance ratio that presented in Figure 5 were calculated from:

Performance ratio $$PR = \frac{Y_f}{Y_r}$$

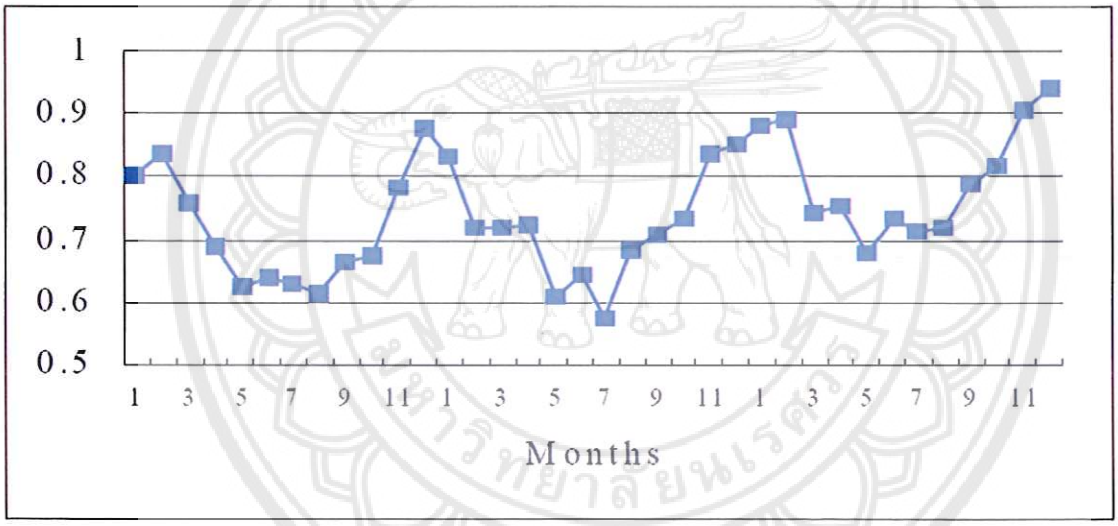


Figure 4 The variation of PR values for PV systems in Taiwan [18]

where Y_f is Final System yield (hours/day) and Y_r is Reference yield (hours/day)

Final System Yield $$Y_f = E_{pv} / P_o$$,

where E_{pv} is Energy delivered to the load (kWh) and P_o is Nominal power of PV array at standard test conditions (STC) (kWp)

Reference Yield $$Y_r = H_i / G_{stc}$$

where H_{iv} is Actual in-plane irradiation (kWh/m^2) and G_{stc} is Reference in-plane irradiation at standard test conditions = 1kW/m^2

Average availability summarized from the study was 95.7% calculated from the following equation :

$$Availability = \frac{m}{m+r} = \frac{m}{T}$$

The distribution of PV system availabilities in Taiwan is illustrated in Figure 6. Where m is mean time to failure (MTTF), r is mean time to repair (MTTR), and T is mean time between failure (MTBF = m+r). Definitions of system availability indices is presented in Figure 7.

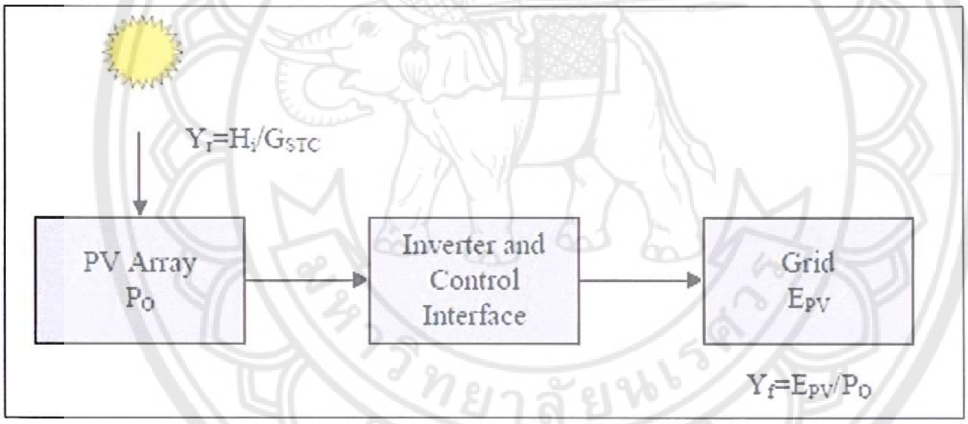


Figure 5 Definitions of PV system performance indices

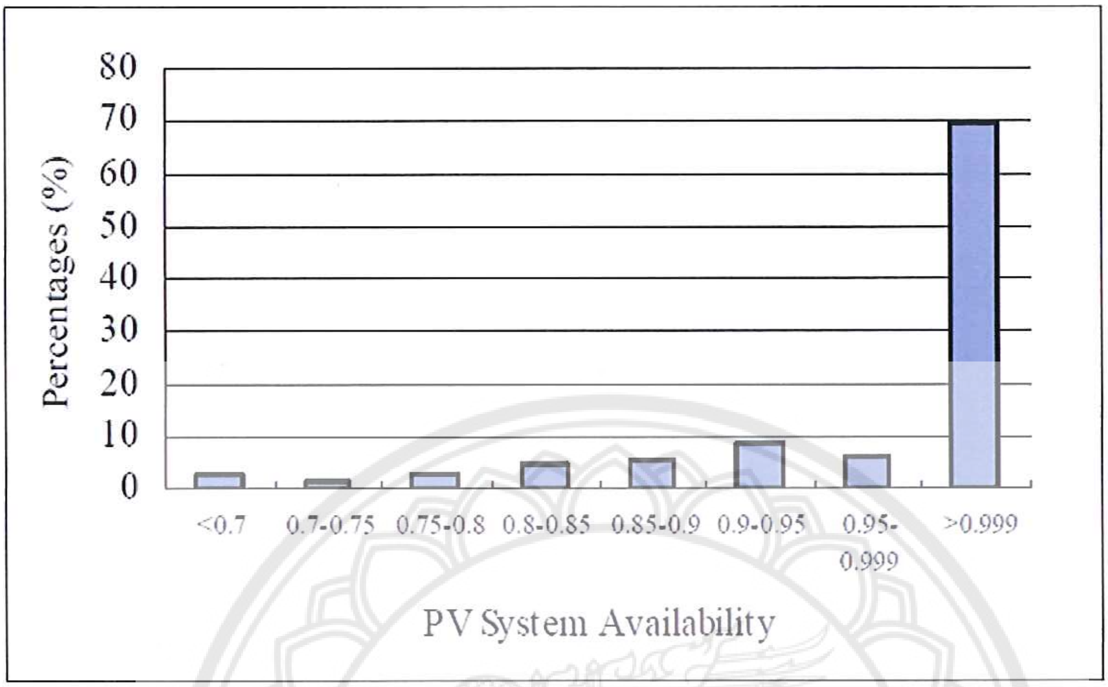


Figure 6 The distribution of PV system availabilities in Taiwan

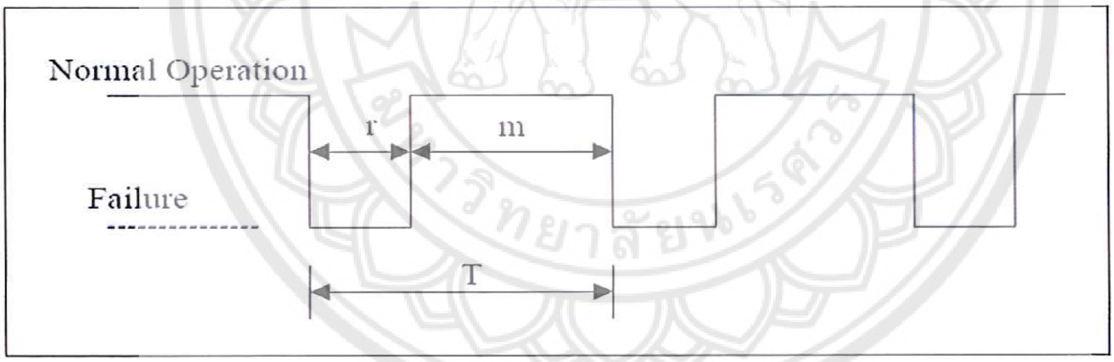


Figure 7 Definitions of system availability indices

Availability analysis of a solar power system with graceful degradation

Duane, L. H., & Francwe, A. [19] presented the availability analysis of the solar power system with graceful degradation. The reliability model is calculated by using the Reliability Block Diagram (RBDs). The power system generation by micro inverter and the system comprised of three component, Photovoltaic PV module micro inverter and load center but the result will calculate to base on the inverter and connector only. There are five systems to consider in terms of system reliability each system contains a difference a number of units, system A consists of 23 units; system B consists of 58 units; system C consists of 176 units; system D consists of 678 units, and system E consists of 5,719 units; the system calculated the system availability and capacity over 20 years, which is a typical service life of such a system. The analysis was performed to calculate a parameter in two scenarios-with and without maintenance and the operating, ambient temperature selected was 25 degree C and 6.5 operating hour per day. The repair scenarios were run to access the expected number of failure considering 99.5%,99% and 98% requires capacities. The expected number of failures (ENS) and meantime between failures (MTBF) result is presented in Table 4.

Table 4 Repairable calculation result, 99.5% required capacity

SYSTEM	99.50%		
	Availability	MTBF	ENF
A	1.00	43,964	3.97
B	1.00	17,582	9.97
C	0.9998	5,802	30.23
D	0.9999	5,685	30.47
E	0.9999	5,346	32.35

Reliability of PV systems focusing on causes

John, H. W. [20] from BP Solar International Inc. presented in his study that reliability of PV systems is best described by defining types of failures. There are 3 distinct types of failures. The first type is the total loss of power caused by the problem with inverters and other BOS components. Second type is the slow decaying of output power extended over a period of time mostly caused by the module degradation and other critical components. The third type is failure to meet the required expectation of the system owner. It was found by data collecting that the inverters are the main effects to reliability related to its failure described in Table 5. It can be concluded from the related literatures that reliability and availability plays vital roles in rating the commercial success of PV Power systems. The most critical components that are the main cause of failure in turn effect the reliability and availability the most is inverter.

Table 5 Causes of Maintenance Events by Category

Category	# of events	Cost	Notes
Inverter	37%	59%	25% from 1 lightning storm
DAS	7%	14%	90% from 1 lightning storm
AC Disconnect	21%	12%	50% due to dirt accumulation
Module/J Box	12%	3%	60% due to failed blocking diodes
PV Array	15%	6%	45% from 1 lightning storm
System	8%	6%	All utility meters

Reliability: A new approach in design of inverters for PV system

Freddy, C. H., & Calleja [21] presented the reliability: A new approach in design of inverters for PV system. The paper presented the meantime between failures (MTBF) can be calculated by using the outline in the MIL-HDBK217 which listed failure rates for the electronic devices, but the calculation for the assembly circuit must be multiplied by the factor such as the thermal stress (electrical, thermal, etc.) on the devices. These factors depend on the maximum current and voltage in the component, and the actual calculations were using the RELEX program which had all databases for electronic components and can calculate the stress factor for the maximum current, voltage and power dissipation for each component. The result shown that for the temperature above 60-70C, some topologies could have MTBFs lower than 40,000 hours (about 5 years). That will be the critical point for system that installed in hot weather areas. From the analysis, the switching transistors were the weakest, and the complexity of the circuit is not related to the reliability, but it will become importance for other functions such as efficiency. The stress factor is the highest contribution to the failure rate. The thermal design must take to be account. The overrating the transistors might be help increases the reliability.

Field Reliability Analysis Methods for Photovoltaic Inverters

Fife, J. M., Scharf, M., Hummel, S. G., & Morris, R. W. [22] present the measuring and reporting methods for PV inverters by using a sample population of 30 kW commercial-class inverters as an example calculation. Normally, equipment typically goes through three phases during its fielded lifetime: infant mortality, random failure, and wear out. The infant mortality phase is dominated by failures related to out-of-the-box quality and manufacturing defects, and manifests very early in the equipment life. The failure rate typically decreases after a break-in period. In the random failure phase, failures occur due to random events such as lightning strikes. These failures are typically infrequent and occur at the same rate regardless of inverter age. The final wear-out phase is characterized by an increasing failure rate due to wear-out of specific components. Figure 8 shows a schematic representation of these phases, which are commonly described together as the bathtub curve. Reliability, inverter downtime, and availability are the important indicators in this study. For the example calculation, the sample data set is a population of 373 PV Powered 30kW commercial inverters. In this case, the parameter being considered is warranty downtime, which is defined as unplanned inverter downtime due to inverter defects of any type.

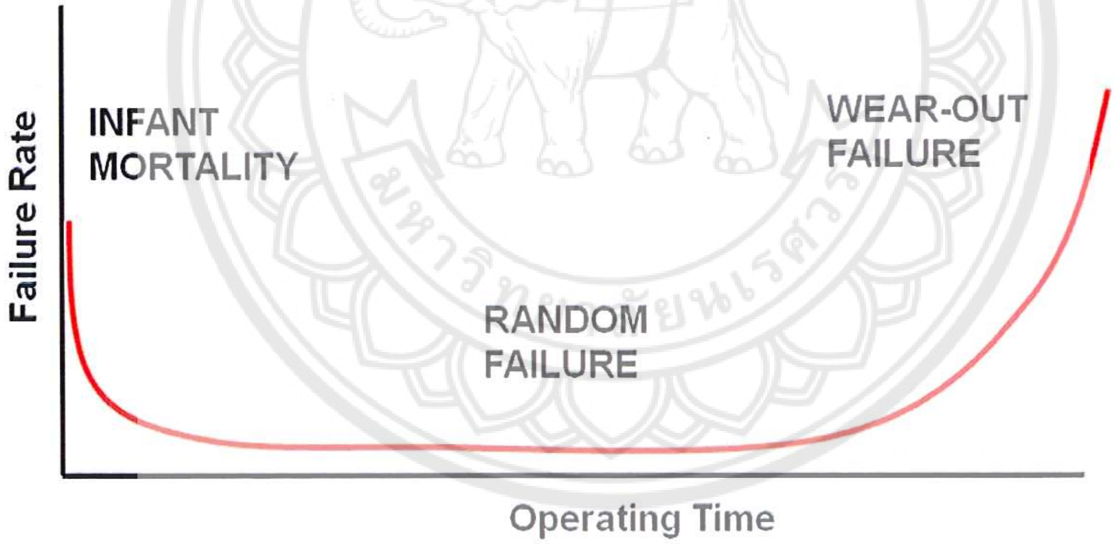


Figure 8 Classic bathtub curve

Table 6 Distribution of warranty downtime hours for a sample population of 30kW inverters

Downtime Duration	% of Downtime
< 6 hours	0.6%
6-24 hours	0.6%
> 24 hours	99.4%

Distribution of warranty downtime hours for a sample population of 30kW inverters is showed in Table 6. It is useful to plot downtime as a function of time after inverter commissioning. However, the commissioning is not available for all inverters in the sample population, the downtime will be plotted versus shipment date that demonstrated in Figure 9. Warranty downtime for a sample availability of the sample inverter population can be calculated versus time using the availability factor (AF) metric. Field hours and availability factor (AF) for a sample population of 30kW inverters is illustrated in Figure 10.

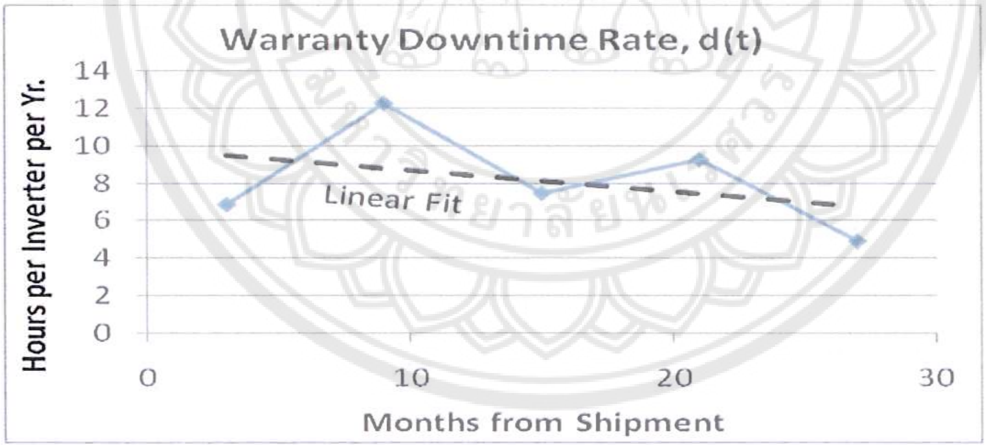


Figure 9 Warranty downtime for a sample population of 30kW inverters

From the trend toward larger PV power plants and exponential industry growth, reliability is now being viewed with importance equal to electrical conversion efficiency. For that reason, the indicators used to describe inverter reliability are being carefully scrutinized, with focus on the ones that reflect true PV plant operating cost and LCOE such as failure rate and availability.

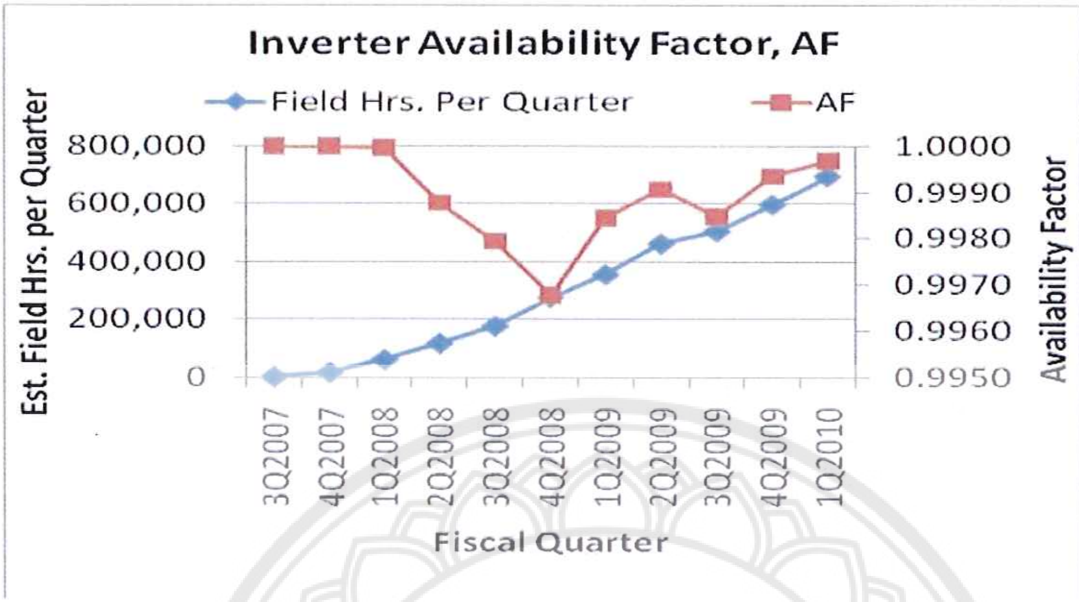


Figure 10 Field hours and availability factor (AF) for a sample population of 30 kW inverters

Reliability of PV modules and balance of system components

Neelkant, G. D. [23] presented the reliability of PV module and balance of system component. The paper reviews performance of PV modules and BOS components and discusses the role of encapsulants, adhesional strength, impurities, metallization, solder bond, integrity and breakage, corrosion backing layer, junction boxes, and high-voltage bias, testing in relation to their effect on module and inverter reliability. It is suggested that the concepts of physics of reliability of electronic packages will be useful to understand, address and resolve the new problem in PV module and inverter reliability. The test was deployed in hot and humid and hot and dry climates in the US and around globe. c-SiP V modules, the most reliable component in PV system with a rate of failure of one c-Si module per 4,200 modules-year of operation. The failure rate below 0.1 % per year. The reliability of the BOS component, the failure due to the corrosion of junction box, connection and inverter has been observed. Meantime Between Failure (MTBF) of proximately 50 years has been predicted by a theoretical analysis of an inverter not exposed to excessive temperature. However, from the field experience of the old system has shown that the inverter is the most vulnerable component in PV systems and lost 15 % of the PV plant but for the new, installation has the failure record improvement with an MTBF of 10 years, the reliability of the inverter has improved significantly over the last several years.

System Availability Analysis for a Multi-megawatt Photovoltaic Power Plant

Fife, J. M., & Morris, R. W. [24] presents an analytical method for time-dependent modeling of subsystem availability in any geographic location. It can be applied to subsystems such as solar panels, tracking devices, and power inverters. The results for each subsystem can then be combined in a system-level reliability and performance analysis of the complete photovoltaic power plant. This methodology can be useful to help assess a PV plant's financial viability, obtain more realistic estimates of expected downtime, plan preventative maintenance schedules, and budget for spares. The subject PV plant reliability analysis consists of three phases: Time-Dependent Stress (Thermal) Simulation of Each Subsystem that to obtain and understand the environmental stress at a target geographic location, Time-Dependent Probabilistic Reliability Simulation that involves calculating subsystem reliability while taking into account the component stresses by using life-stress relationships to accomplish. this, and System-Level Analysis that classical methods of system-level reliability analysis are may be used to estimate the overall performance of the system taking into account downtime due to failures and other causes of subsystem unavailability. The first two phases dealing with subsystems, such as modules, trackers, junction boxes and inverters, are shown schematically in Figure 11. This example deals with temperature stress, salt, hail, and ice. As an example of this analysis process, a hypothetical solar power inverter with active cooling control will be used. The inverter power profile is based on a fixed mount installation. The geographic location is assumed to be Needles, California. Three failure modes of the inverter are modeled. The failure modes are associated with components 1, 10, and 12. For each failure mode, an Arrhenius-Weibull life-stress model is assumed. The model parameters for each of these are given in Table 7. From the simulation result, example calculation of cumulative failure rates for three inverter failure modes and the overall inverter subsystem and average downtime per year due to inverter failures is presented in Figure 12. Availability is then calculated as a function of time based on the downtime and shown in Figure 13. The method applied above in the inverter example may also be applied to any geographic location where stress (temperature) data is available. By performing the same analysis for two other geographic locations, a comparison of relative inverter availability may be made. As an example, take a 10 MW peak PV power plant with 5 MW average output and 3500 hours of generating time per year.

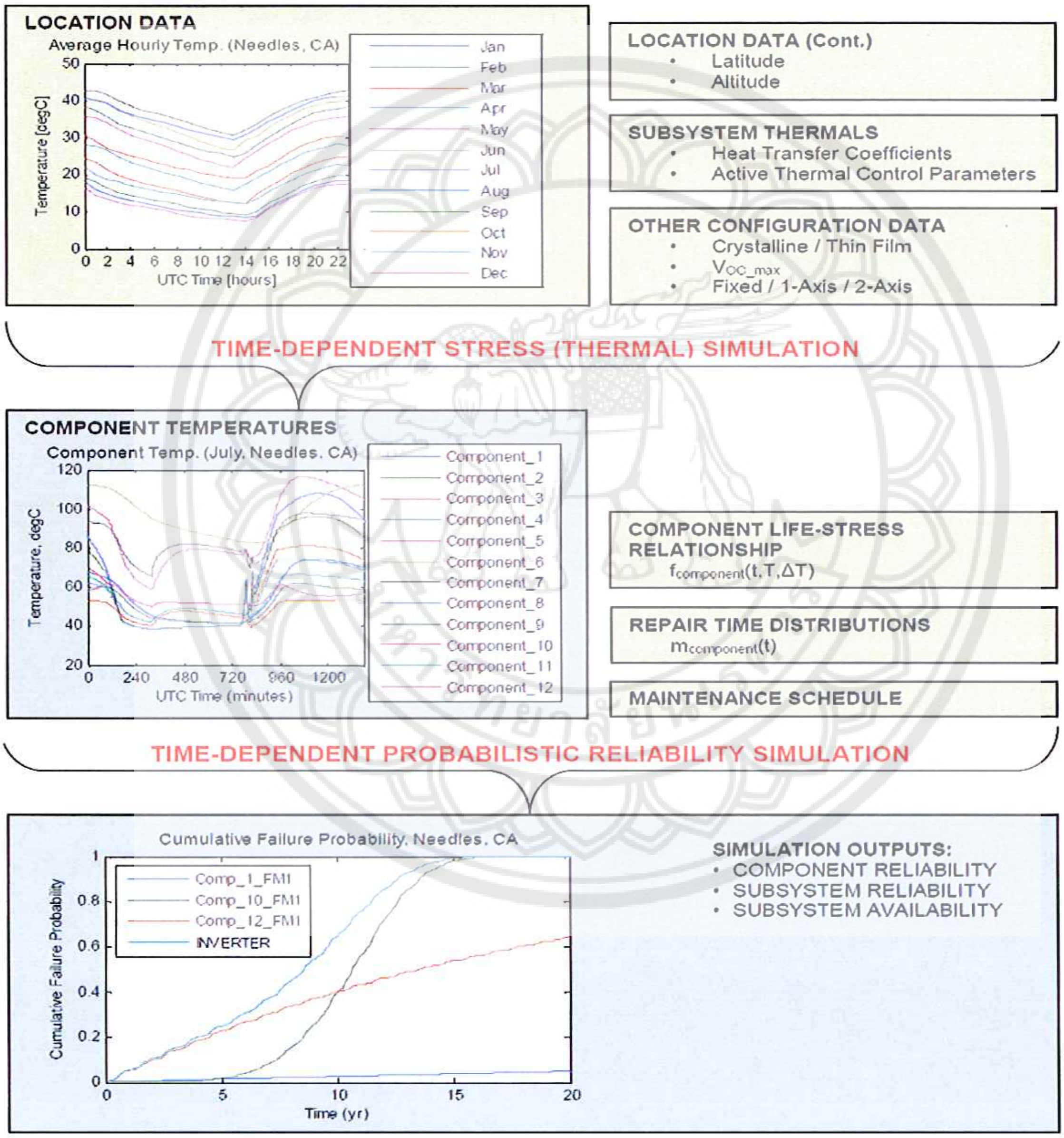


Figure 11 Two phases of subsystem (inverter) reliability analysis for a limited case considering only temperature stresses. Blue boxes represent simulation outputs

Table 7 Arrhenius-Weibull life-stress parameters for the inverter reliability example

Failure mode	β	α(T_0) (hr)	T_0 (degC)	Ae (eV)
Comp_1_FM1	1	1.0e6	100	1.0
Comp_10_FM1	5	1.0e5	40	0.3
Comp_12_FM1	1	2.0e5	48	1.0

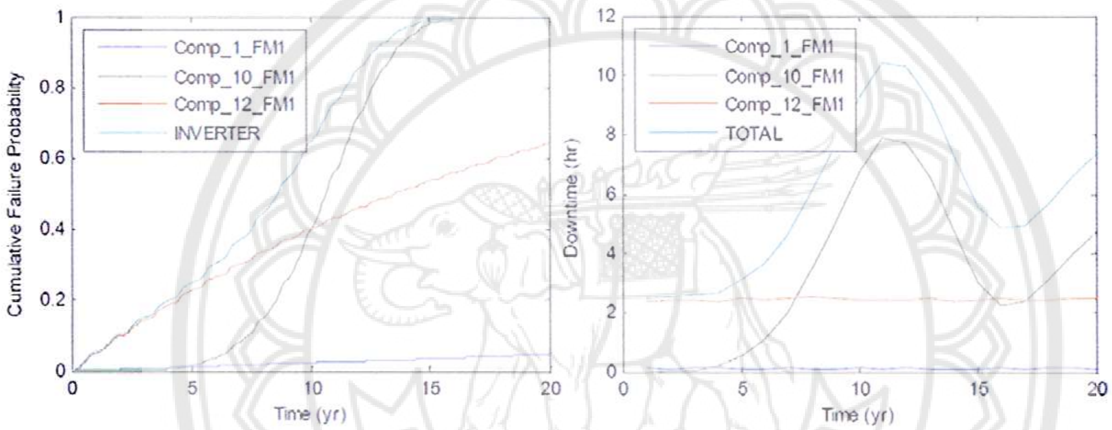


Figure 12 Example calculation of cumulative failure rates for three inverter failure modes and the overall inverter subsystem and average downtime per year due to inverter failures

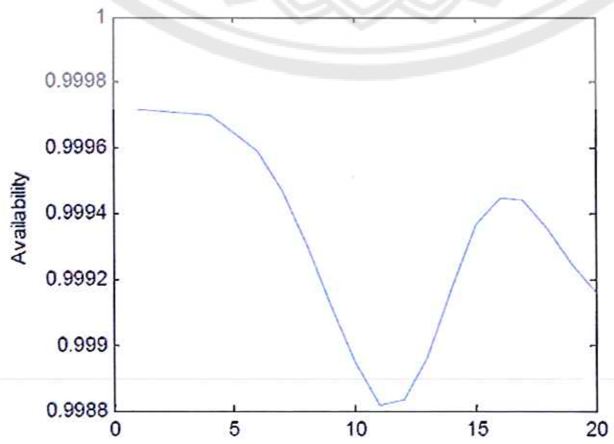


Figure 13 Availability of the example inverter based on downtime due to failure

Assuming the inverter is the dominant failure mode, the annual energy loss is estimated as the product of the inverter unavailability, average power output, and the number of generating hours per year. Multiplying the energy loss by an average cost of electricity of $0.05 per kWh yields the annual cost of downtime due to inverter failures. These values are also shown in Table 8.

Table 8 Average predicted inverter availability and resulting MWh lost annually for a hypothetical 10MW PV power plant

Location	Avg. Avail.	MWh Lost Annually	$ Lost Annually
Needles, California	0.9933	117	$6,000
San Jose, California	0.9956	77	$4,000
Bozeman, Montana	0.9971	51	$3,000

Reliability Study of Grid Connected PV system

IEA Task 7 Reliability [25] Study of Grid-Connected PV system, Field experience and recommended Design Practice. The study has been looking at the failure statistics over the time from resident PV programs in Germany, and Japan showed the typical learning curve of decreasing the failure rate the inverter still proved to be the weakness component. The PV module had the failure rate down to 0.01% per year, cell and glass damage from hot spot, degradation and wrong data from manufacturing. The inverter shows the trouble-free operation for 10 years, critical are novel electronic components, e.g. inverter special grid interface or ac/dc RCDs This need some field experience. A theoretical analysis shows that inverter should have a Meantime Between Failure (MTBF) about 50 Years, as long as they are not exposed to excessive temperature but the actual experience is quite difference. The inverters were the most vulnerable component in the PV system. Main reason for low yield came from the inverter failure, overrate the power of modules, partial shedding, of the array, soiling and faulty connections on the dc side. The good design and installation practice will help to reduce the failure, junction boxes, string sizing. String fuses; this will result in the more reliable system. The minimum level of maintenance is recommended as well, to inspect the arrays one a year, to clean arrays regularly, perform a monthly check of electrical production.

Economical Design of Utility-Scale Photovoltaic Power Plants with Optimum Availability

Moradi-Shahrbabak, Z., Tabesh, A., & Yousefi, G. R., [26] presents an algorithm for the economical design of a utility-scale photovoltaic (PV) power plant via compromising between the cost of energy and the availability of the plant. The algorithm inputs are the plant peak power and the price of inverters with respect to their power ratings. The outputs are the optimum inverter ratings and the interconnection topology of PV panels that displayed in Figure 14. This paper introduces the effective levelized cost of energy (LCOE) (ELCOE) index as the core of the proposed design algorithm. ELCOE is an improved index based on the conventional LCOE that includes the availability of a power plant in economical assessments. To investigate the advantages of the introduced ELCOE compared with the conventional LCOE, these two criteria are compared for 100-kW PV power plants using the four aforementioned basic topologies. The investigation results are summarized in Table 9. Comparing the total price of the inverters shows that the excess costs of inverters in modular, string, and multistring topologies are 300%, 70%, and 15% higher than that of the centralized topology, respectively. Given the price of commercially available PV inverters at present, the case studies result in this paper is showed in Figure 15 that, for 0.1–100-MW PV power plants, the economical ratings of inverters range from 8 to 100 kW. The recently installed PV power plants confirm the feasibility of the calculations based on the suggested algorithm.

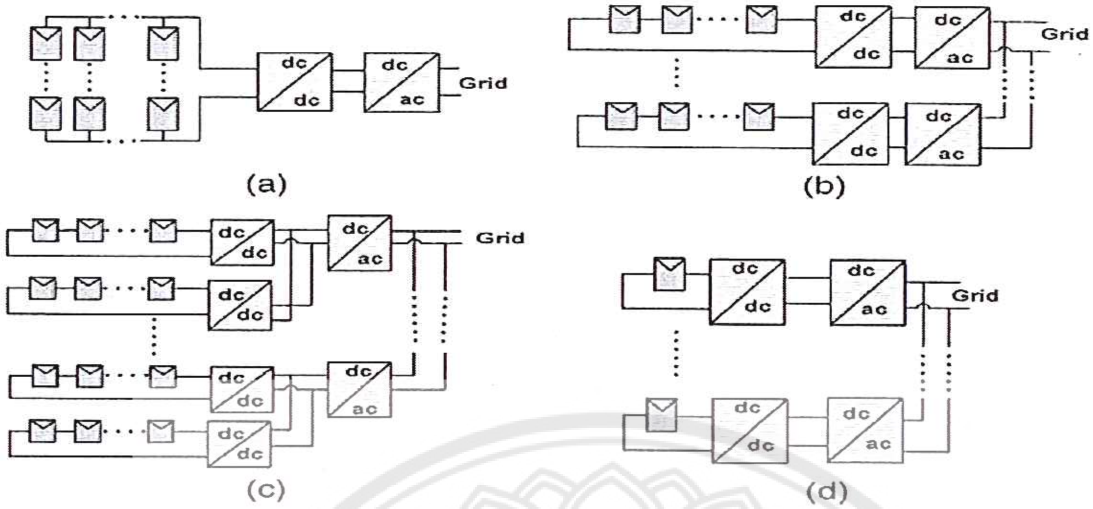


Figure 14 Basic topologies for PV energy systems: (a) Centralized, (b) string, (c) multistring, and (d) ac modular

Table 9 Availability analysis of a 100 kW PV power plant

	Centralized	Multi-String	String	Modular
1- INVERTER:				
Size [Kw]	100	10	3.34	0.7
Numbers	1	10	30	1.43
Unit Price [$]	43.5k	5k	2.44k	1.2k
Total Price [$]	43.5k	50k	73.17k	171.6k
2- PV PLANT:				
Total Cost [$]	595k	603k	688k	834k
Efficiency [%]	80	82	81.6	83
3- AVILABILITY	ANALYSIS:			
NSEE [MWh/yr]	147	1.28	0.39	0.07
LCOE [$/kWh]	0.190	0.210	0.225	0.282
ELCOE [$/kWh]	0.241	0.219	0.231	0.278

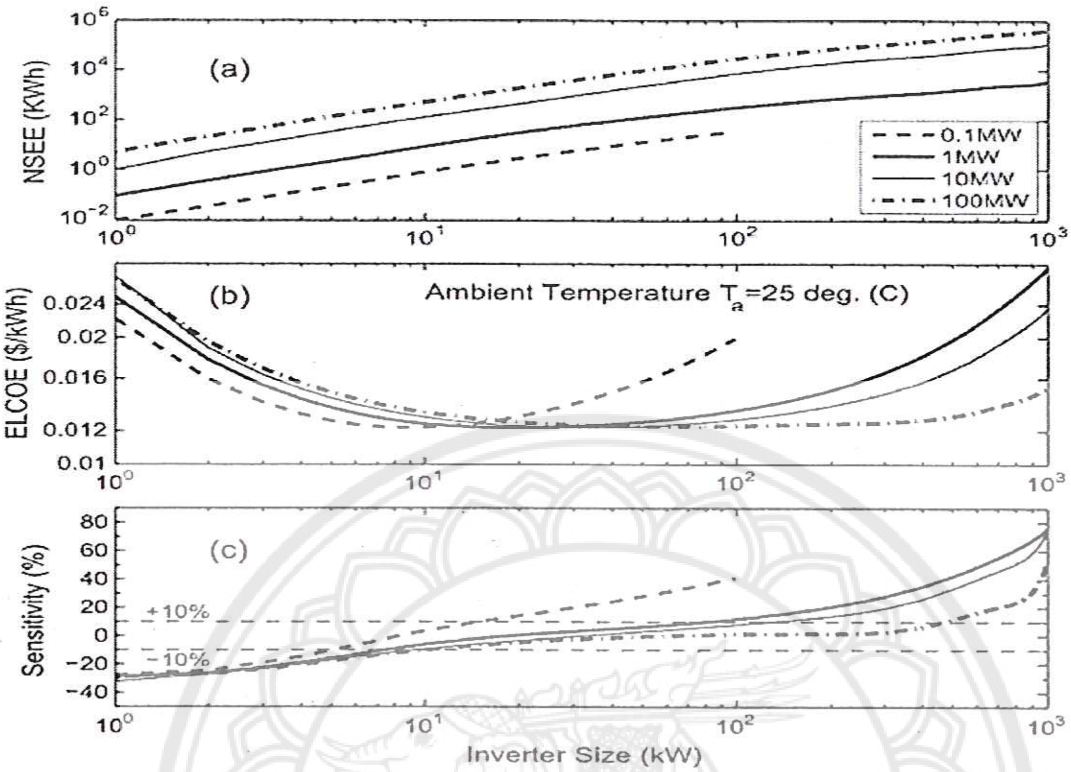


Figure 15 (a) NSEE for megawatt-scale PV plants. (b) ELCOE versus the inverter size. (c) Sensitivity of ELCOEi with respect to the inverter size

Comparative study of difference PV module configuration reliability

W.M. Rohouma, I.M. Molokhia, & A.H. Esuri [27] presented comparative study of difference PV module configuration reliability, the paper emphasizes the existing manufacture module and illustrates the reliability analysis of difference system configuration. AC bus level connection using module integrated inverter and DC bus level connection by using the analytical approach. The failure rate of the inverter and other components are assumed to be constant, and the MTTF (meantime time to failure) is the average useful life = $1/\lambda$. The reliability formula will be quantified by multiplying the reliability of each component in the system. Rsys=Rarray X Rbattery X Rcharger X Rinverter. The studies are focused on central inverter system, string inverter system and module integrated inverter system. The central inverter consists of PV modules in series and parallel charger controller, battery bank and DC to AC inverter. String inverter configuration will be more practical to divide the system into k parallel subsystem, and inter connects the subsystem on AC side. The module integrated or AC module is a solar module combine with module mounted inverter. The bi-directional inverter will be connected to the battery and performed the grid then the AC module inverter will convert the energy supply to load and charge the battery, during the night the battery will energize the load. From the case study calculation, the result shown that the MTTF of the central inverter system =3.0 years, string inverter system = 5.5 years and module integrated the MTTF =13.3 years.

Reliability Assessment for Components of Large Scale Photovoltaic Systems

Ahadi, A., Ghadimi, N., & Mirabbasi, D. [28] study an analytical approach to evaluate the reliability of large-scale, grid-connected PV systems. The fault tree method with an exponential probability distribution function is used to analyze the components of large-scale PV systems that their electrical structure is presented in Figure 16 and number of components per each PV system is showed in Table 10. The system is considered in the various sequential and parallel fault combinations in order to find all realistic ways in which the top or undesired events can occur that the fault tree for the PV system is illustrated in Figure 17 and component failure rates is displayed in Table 11. For the total system reliability calculation and the simulation that use Fussele Vesely method, there are 7 PV system sizes that are 100, 200, 500, 1,000, 1,500, 2,000 and 2,500 kW and 11 PV system components that are PV module, string protection, DC switch, inverter, AC circuit breaker, grid protection, AC switch, differential circuit breaker, connector, battery system, and charge controller are the input dataset. The result of the calculation and simulation is presented in Figure 18 and the ranking of the most critical components appears in Table 12. This approach can be used to ensure secure operation of the system by its flexibility in monitoring system applications.

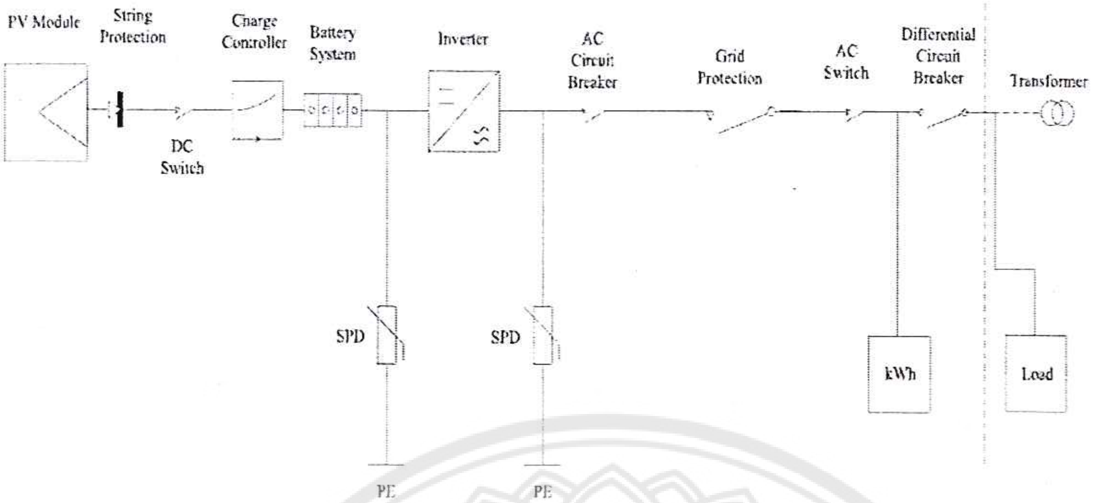


Figure 16 Electrical structure of the large scale PV system

Table 10 Number of components per each PV system

Power (kW)	100	200	500	1000	1500	2000	2500
PV modules	437	874	2116	4351	6517	8702	10,868
String protection	23	46	114	229	343	458	572
DC switch	3	6	15	27	42	57	72
Inverter	1	2	5	9	14	19	24
AC circuit breaker	1	2	5	9	14	19	24
Grid protection	1	1	1	1	1	1	1
AC switch	1	1	1	1	1	1	1
Differential circuit breaker	1	1	1	1	1	1	1
Connector (couple)	874	1748	4332	8702	13.034	17.404	21.736
Battery system	16	30	76	150	224	298	372
Charge controller	1	1	1	1	1	1	1

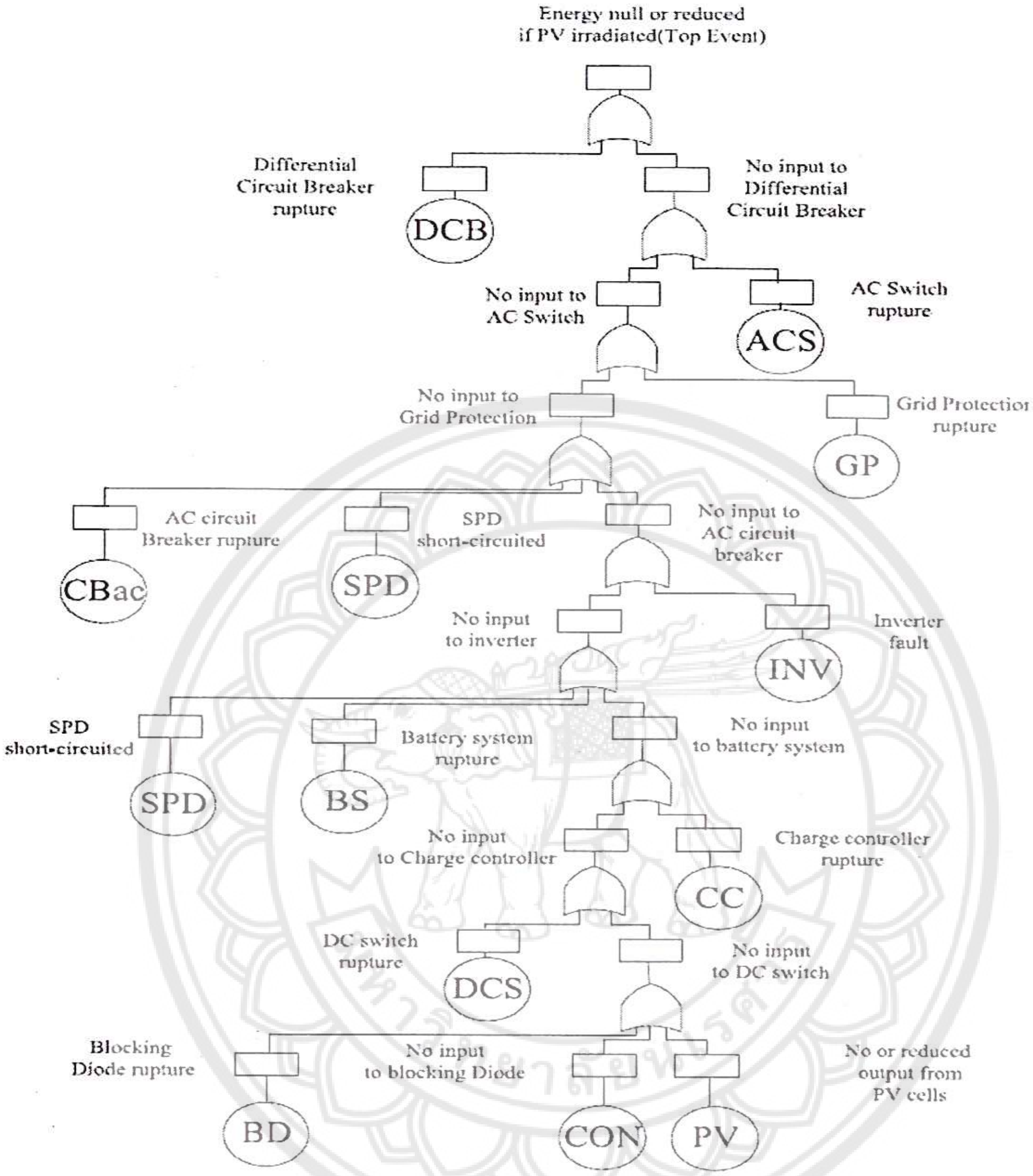


Figure 17 Fault tree for the PV system

Table 11 Component failure rates

Component	Failure rate (10^{-6} failures h^{-1})	Reference	
PV modules	0.0152	[18]	
String protection	0.313	[35]	Sect. 6-2
DC switch	0.2	[35]	Sect. 22-1
Inverter	40.29	[21]	
AC circuit breaker	5.712	[35]	Sect. 14-5
Grid protection	5.712	[35]	Sect. 14-5
AC switch	0.034	[35]	Sect. 14-1
Differential circuit breaker	5.712	[35]	Sect. 14-5
Connector (couple)	0.00024	[35]	Sect. 17-1
Battery system	12.89	[36]	
Charge controller	6.44	[36]	

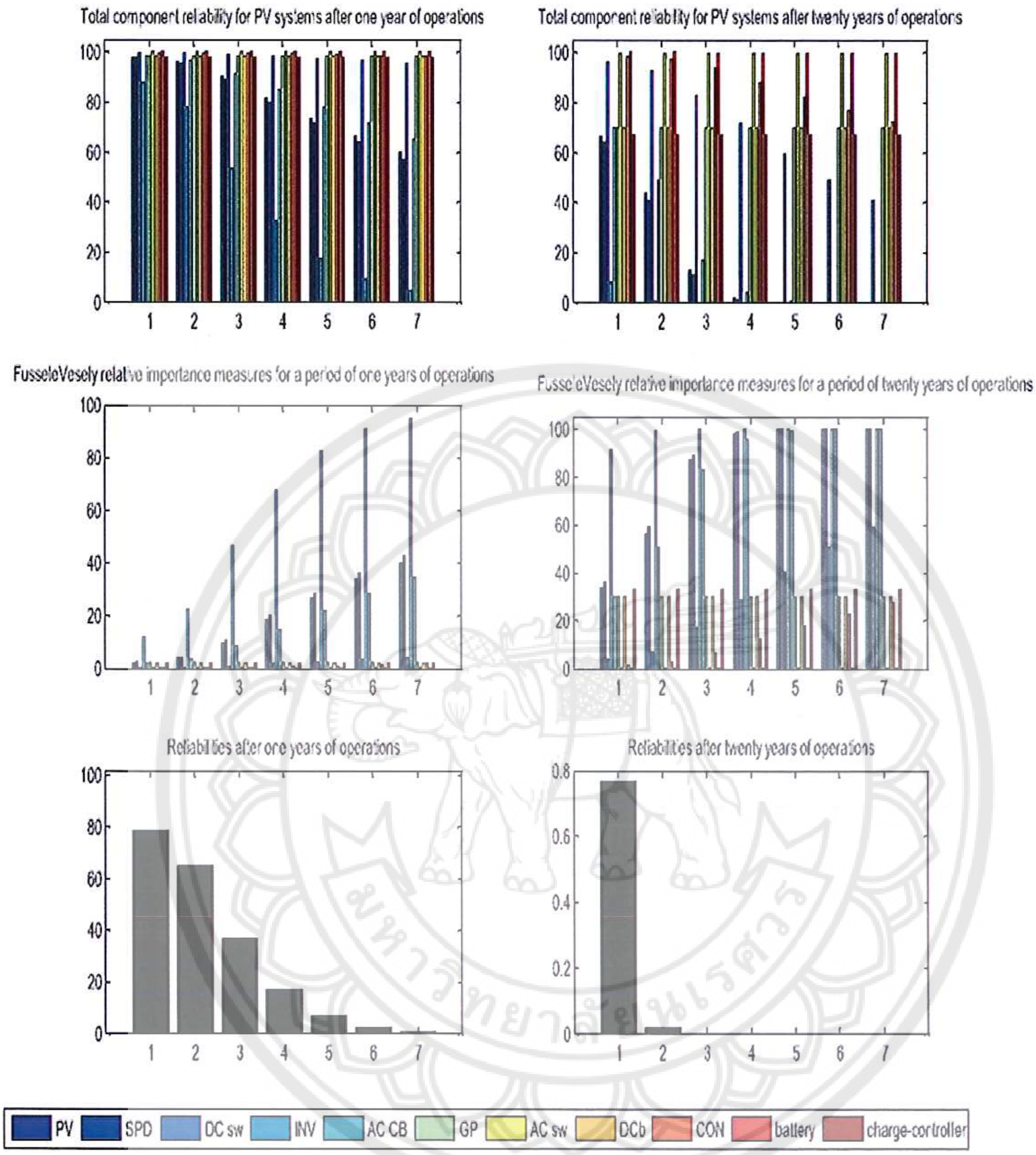


Figure 18 The all results of reliability for seven PV systems

Table 12 Critical component priorities

Priority	Component
1	Inverter
2	String protection
3	PV modules
4	AC circuit breaker
5	DC switch
6	Charge controller
7	Grid protection
8	Differential circuit breaker
9	Connector (couple)
10	AC switch
11	Battery system

Long term reliability evaluation of PV module

Izumi, T., Sanekazu, I., Kenji, N., Kiyoshi, T., Kengo, M., & Hiroshi, K. [29] presented the long-term reliability evaluation of PV module, the long-term reliability of the Photovoltaic (PV) modules is importance for the reliability of the photovoltaic generating system. Especially, the milky white phenomena and the series resistance increasing of crystalline silicon PV module influenced the output of PV module. The two kinds of the PV modules' degradation are observed. The milky white phenomena are the gap caused between the PV cell and the EVA of the glass side. The phenomena decrease the short circuit current by decreasing the light which reached the PV cell and causes the decrease in efficiency. The series resistance increasing in PV module by the growth of the micro crack will decrease the efficiency of the module due to a decrease of Fill Factor (FF). The method of test is the dump heat test, the thermal cycling test, the thermal chock test, Fluctuating irradiation and the humidity test under the irradiation. The accelerated test will be executed with the module sort-circuited.

A design tool to study the impact of mission-profile on the reliability of SiC-based PV-inverter devices

Sintamarean, N.C., Wang, H., Blaabjerg, F., & Rimmen, P.de P. [30] introduces a reliability-oriented design tool for a new generation of grid connected PV-inverters that its proposed reliability oriented design structure is presented in Figure 19. The proposed design tool consists of a real field mission profile model (for one year operation in USA-Arizona), a PV-panel model, a grid connected PV-inverter model, an electro-thermal model and the lifetime model of the power semiconductor devices. The PV-system design ratings for simulation model is displayed in Table 13.

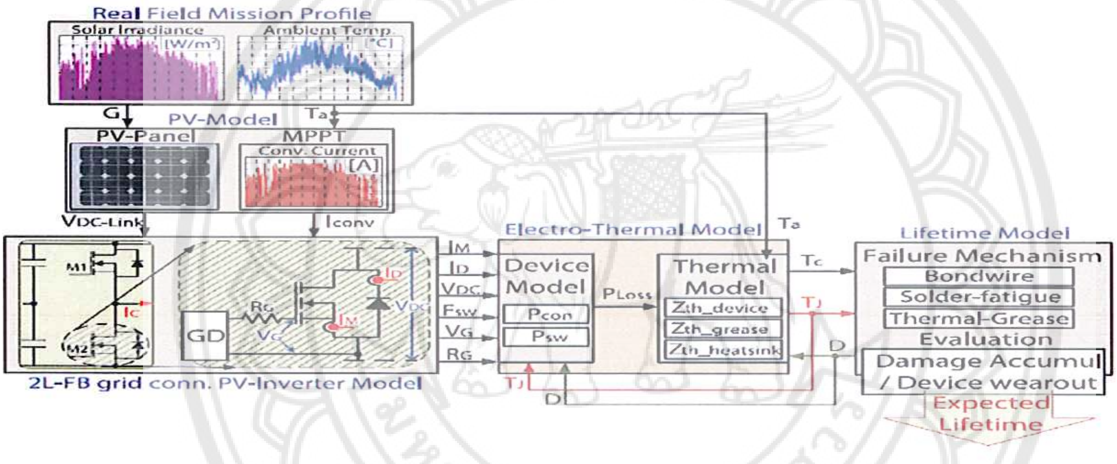
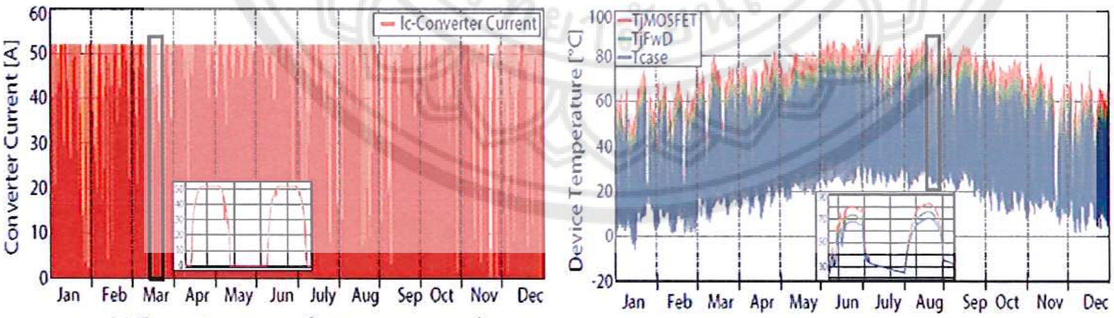


Figure 19 **Proposed reliability oriented design structure for the new generation of grid connected PV-inverters**

The simulation model able to consider one year real field operation conditions (solar irradiance and ambient temperature) is developed. Thus, one year estimation of the converter devices thermal loading distribution that illustrated in Figure 20 is achieved and is further used as an input to a lifetime model. The proposed reliability oriented design tool is used to study the impact of MP and device degradation (aging) in the PV-inverter lifetime. In addition, proposed electro-thermal model structure for device junction and case temperature estimation is the key model in device degradation that showed in Figure 21. The obtained results that available in Table 14 indicate that the MP of the field where the PV-inverter is operating has an important impact in the converter lifetime expectation, and it should be considered in the design stage to better optimize the converter design margin. In order to improve the accuracy of the lifetime estimation, it is crucial to consider also the device degradation feedback (in the simulation model) which has an impact of 30% in the precision of the lifetime estimation.

Table 13 PV-system design ratings

3L-FB VSI PV-inverter specifications			S = 25 kVA
Rated power			V_N = 230 V (RmS) (325 V
Conv. Output phase voltage			peak)
Max. DC-link Voltage			I_{max} = 37 A (RMS) (52 A peak)
Switching frequency			$V_{DC\text{-}max}$ = 1000 V
			f_{sw} = 50 kHz
Thermal impedance values		R_{th} = 0.13 (K/W)	r = 570 (s)
Heatsink		R_{th} = 0.0059 (K/W)	r = 1.3 (s)
Thermal grease			
LCL-filter	L_c = 4e − 4H	L_g = 1.5e − 4H	C_r = 0.4 μ F
parameters			
Parameters			
Device			CREE MOSFET module (CCS050M 12CM2)
characteristics			
Device types			
PV-Panel characteristics-connection			
PV-panel type		ET black module (ET-M660250BB)	
Conn. type		Series = 24	Parallel = 3



(a) Converter current for one year operation

(b) Thermal loading estimation for one year operation

Figure 20 The realistic PV-inverter loading current (a) and thermal loading estimation (b) of the inverter devices (MOSFET, Diode) for one year operation in USA-Arizona

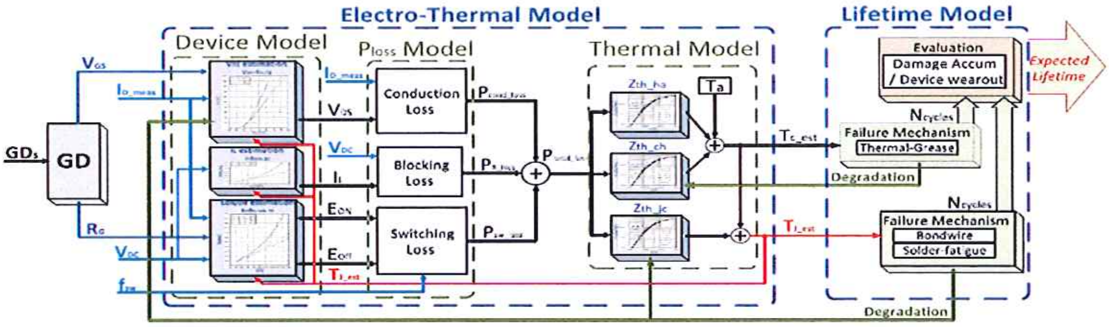


Figure 21 Proposed electro-thermal model structure for device junction and case temperature estimation

Table 14 MP and device-aging impact in lifetime

MP	Lifetime		Degradation impact in lifetime
	Without degradation	With degradation	
USA-Arizona	5.5 (years)	4.2 (years)	30%

Critical components test and reliability issues for Photovoltaic Inverter

Catelani, M., Ciani, L., & Reatti, A. [31] evaluate the behavior of the critical components of a photovoltaic inverter. Normally, the trend of the MTBF (MeanTime Between Failure) vs temperature that presented in Figure 22 is linearly decreased when the temperature increased that confirming the important role in reliability. So, the thermal analysis of the inverter is presented and a series of thermal tests were carried out in order to individuate the most critical components. A 500 kW PV inverter has been subjected to several tests of thermal stress, in a special thermal chamber, to evaluate its operating range in temperature simulating the ventilation conditions of a shelter. From the testes, the first components subject to failure are the DC link capacitors as depicted in Figure 23. To improve the reliability of inverter, derating and redundancy techniques are used and the result of these techniques is showed in Table 15. The example 750 kW power plants with 2 scenarios that are operating 3 of 4 x 250 kW inverter and 14 of 18 x 55 kW inverter are considering for the optimum redundant configuration. It found that MTBF values of the first scenario is 188.395 while the second scenario is 58.912. The scope of such analysis is to optimize the inverter design and therefore its efficiency taking into account the real operative condition that are present when the equipment is installed on the field. Finally, by means of the data obtained with this study correlated with some reliability optimization rules, such as derating and redundancy, it is also possible to improve the maintenance policy of the PV inverter hence its availability and that of the whole PV plant.

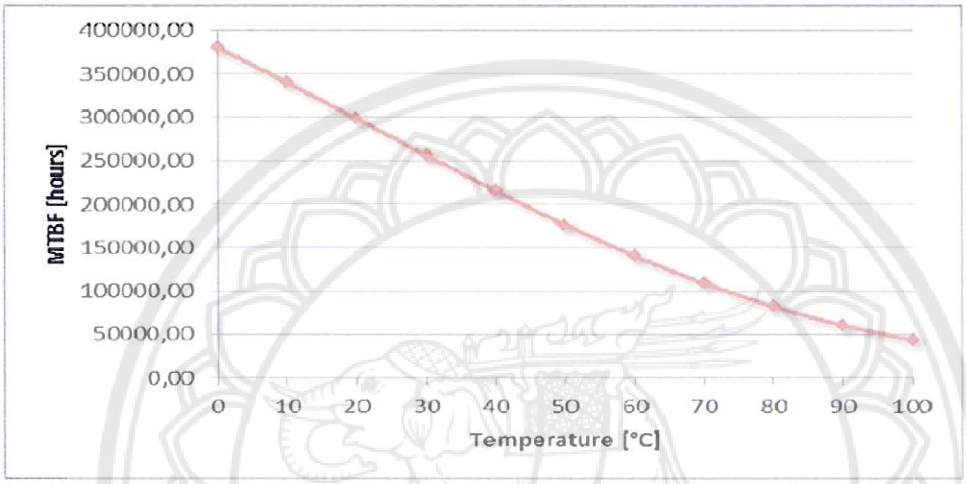


Figure 22 MTBF (Mean Time Between Failure) vs temperature

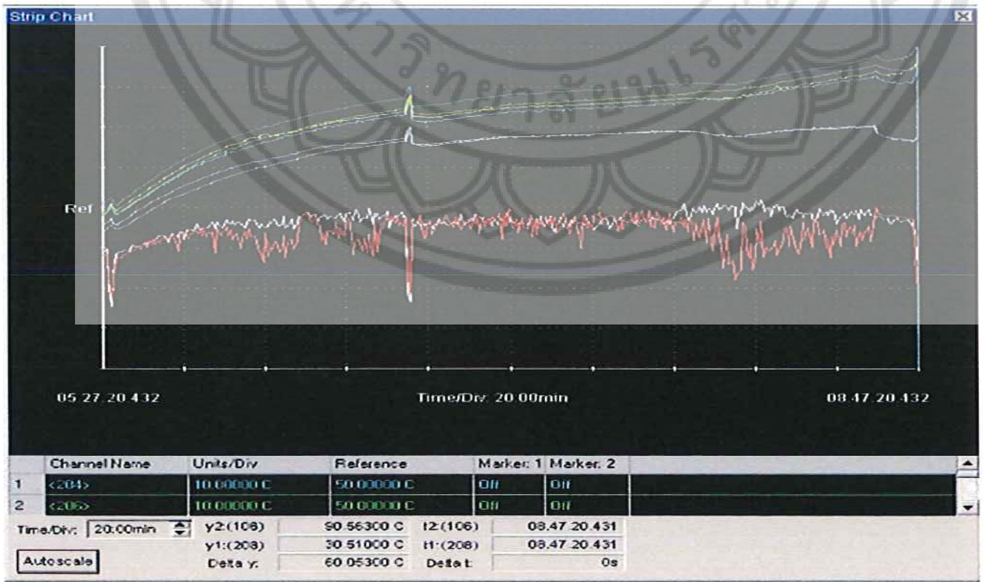


Figure 23 DC link capacitor voltage and chamber temperature trends during destructive test session

Table 15 Duty cycle vs MTBF

Duty Cycle	Operating hours	MTBF [h]
40%	9	320.370
50%	12	256.520
60%	15	213.891
75%	18	171.212

Photovoltaic Inverter: Thermal Characterization to Identify Critical Components

Catelani1, M., Ciani1, L., & Simoni, E. [32] study the critical components of a photovoltaic inverter from the thermal point of view. Generally, the trend of the MTBF (Mean Time Between Failure) vs temperature is linearly decreased when the temperature is increased while the MTBF versus the system electrical stress is decreased in parabolic curve when the system electrical stress is increased. Normally, the system electrical stress is increasing in the same way with temperature that confirming the important role in reliability. The MTBF vs temperature and system electrical stress is presented in Figure 24. From this reason, the thermal analysis of the inverter is presented and a series of thermal tests were carried out in order to individuate the most critical components. It found that the most critical components are the DC capacitors and the insulated-gate bipolar transistors (IGBT).

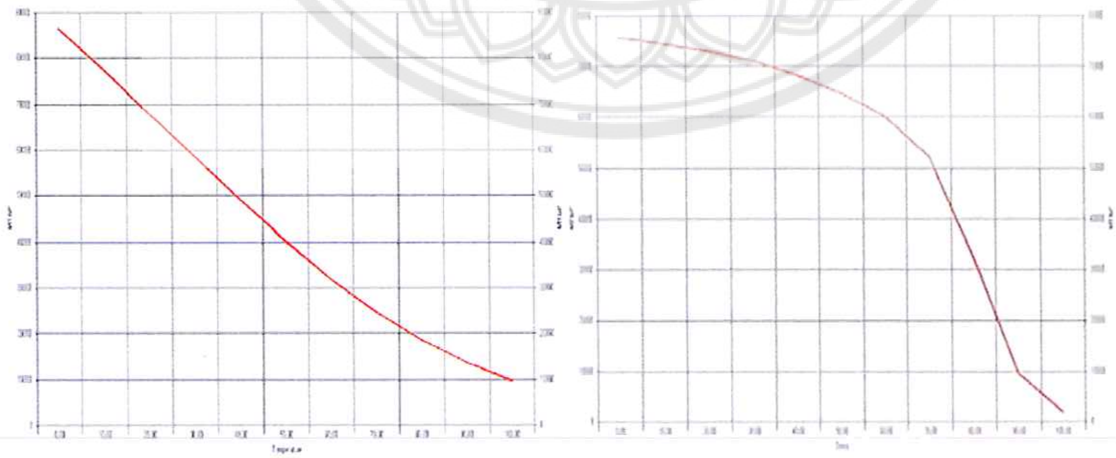


Figure 24 The MTBF vs temperature and system electrical stress

From this point, the measurement set up that showed in Figure 25 is made and the PV inverter under test is powered and functioning during the test. A first thermal test phase was carried out with an internal temperature of the chamber of 50°C. The inverter under test is at the maximum operative temperature with maximum output power in order to put in evidence the behavior of the critical components. From the test, the temperature of IGBTs and DC capacitors are displayed in Figure 26. From the Figure, IGBT temperature is quite stable that no problems are present in the IGBT functioning while DC capacitors is constantly increasing without a stabilization due to an anomalous behaviors of such devices that represents the typical case of an uncorrected functioning of the inverter with the presence of a thermal escape. Moreover, it could leads to a rupture of the device. To solve this problem, the cooling system are designed and installed.

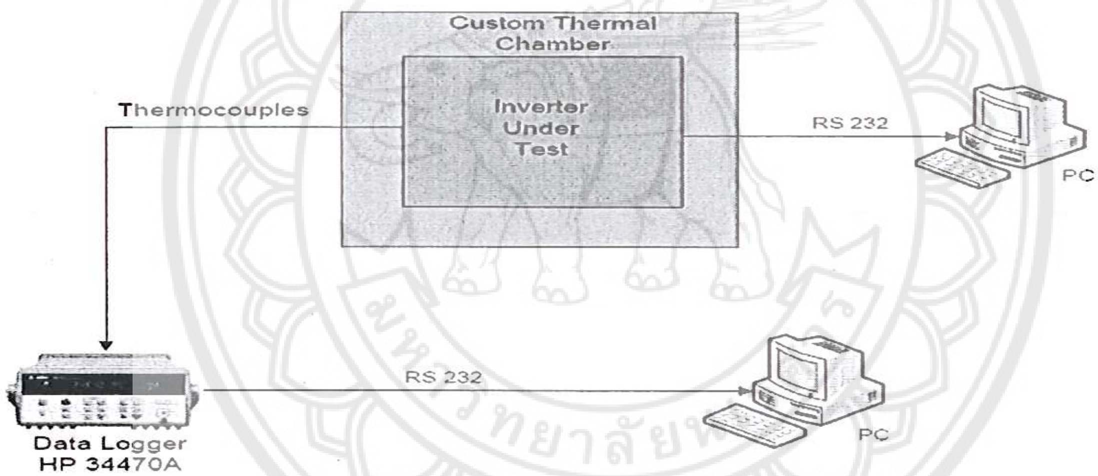


Figure 25 Measurement set-up [32]

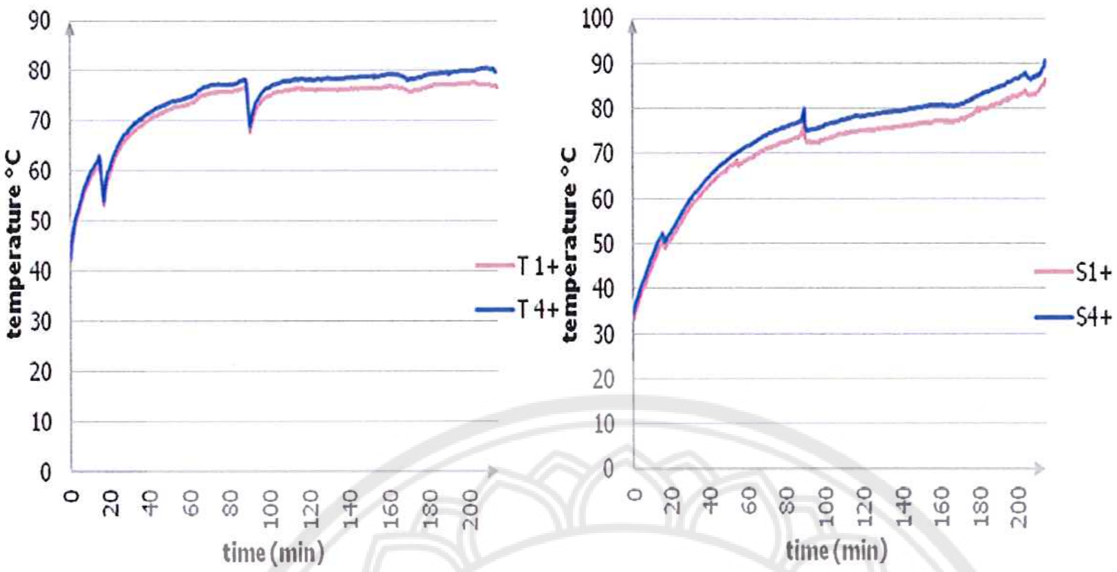


Figure 26 The temperature of IGBTs and DC capacitors

After that, the inverter is tested again and the temperature of DC capacitors is illustrated in Figure 27 that stabilized below 70 °C. The result of this study is possible to optimize the inverter design and therefore its energy yield taking into account the real operative condition presents when it is installed on the field. In this way, it will be also practicable to optimize the design of the diagnostic system of the PV inverter. Finally, by means of the data obtained with this study it is also possible to improve the maintenance policy of the PV inverter hence its availability and that of the whole PV plant.

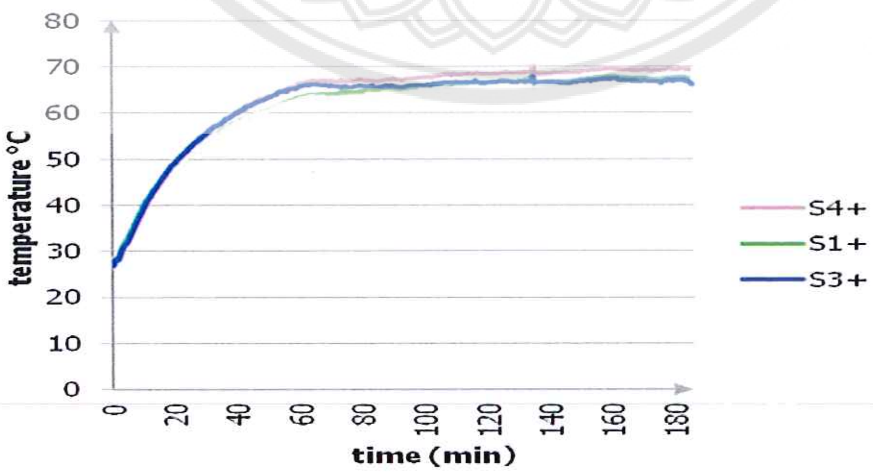


Figure 27 Capacitors temperature vs time after installed cooling system

Assessment of PV system Monitoring Requirement by Consideration of Failure Mode Probability

Pearsall1, N. M., & Atanasiu, B. [33] considers the failure modes that must be addressed by the monitoring, using results from a consultation process within the PV community based on a modified Failure Modes Effects Analysis (FMEA). The first task was to define the failure or loss modes that would be included. An initial list was considered, where delegates discussed the most important modes on the basis of their experience. For most operational problems, the main effect is a reduction in the energy output of the system. The cause of that reduction could be related to a single component or be at the system level. Thus the "failure" modes identified within the FMEA relate mainly to the causes of reduction. Table 16 provides a summary of the 31 modes that were included in the FMEA consultation. They are divided into three sections, A, B and C, relating respectively to module, system and environmental effects. The second task is estimating Risk Priority Number (RPN). The occurrence and severity indices for the different modes are represented in the FMEA and to indicate, where possible, the information sources used to determine these. In most cases, the index was derived from a combination of actual field experience and expert opinion based on career experience. The two indices were then combined to give the RPN prior to detection. Finally, the RPN were averaged for each failure mode and normalized to provide a measure of the modes with the highest risk of substantial energy losses. The results are presented in Figure 28 and Table 17. Where a variation in either index with system type was indicated, this variation was preserved by calculating an average RPN for each suggested variation. The maximum and minimum values for each mode shown in Figure 28 show the extent of the variation in that mode. Where the two columns are the same height, no variations were suggested by the experts. In Table 17, the conditions under which higher RPN values are obtained for each mode are described. If we consider, the maximum RPN values for all modes, the analysis yields ten modes with RPNs above the average of 0.24. We will consider those ten modes in more detail. Table 18 summarizes the monitoring requirements to address these modes, remembering that the identification of losses is influenced by the frequency of measurement and the frequency with which the measurement data are analyzed. The updated European PV System

Monitoring Guidelines will be issued at the end of 2009 for general use by all those with an interest in monitoring systems.

Table 16 Summary of failure/loss modes included in the FMEA

Mode Ref.	Mode	Explanatory comments and consultation remarks
A01	Module failure	Faults that lead to short circuit or open circuit failure of the module. Some of the other modes (particularly A04 and A05X can be the cause of this fault. The occurrence probability increases with the number of modules in the system, although the severity at system level decreases.
A02	High level of module performance degradation	Degradation levels above those expected from manufacturer guarantees. The occurrence probability increases with the number of modules in the system. This would tend to occur for groups of modules rather than single modules where the cause in packaging, environment or manufacturing faults.
A03	Broken or cracked cells; broken or cracked module glass	The occurrence probability increases with the number of modules in the system. Broken glass may not lead electrical losses at least in the first instance, whereas broken cells are more problematic, so future analyses should separate these two modes.
A04	Module junction box damage or fault	No comments.
A05	Hot spot damage to module	No comments.
A06	High module operating temperature	Where this is due to mounting/ventilation issue.
A07	Bypass diode failure	No comments.
A08	String failure	No comments.
B01	Inverter failure	Faults that lead to complete shutdown of the inverter. Some of the other modes (particularly B09) can be the cause of this fault. The occurrence probability increases with the number of inverters in the system, although the severity at system level decreases.
B02	Low inverter efficiency	Values that are substantially below the predicted value for the system design
B03	Low MPP tracking efficiency	No comments.
B04	Faulty circuit breakers or switches	Faulty or blown fuses should be explicitly included in this mode
B05	Damaged or faulty cabling	No comments.
B06	Earthing or insulation faluts	It was suggested that these are two separate faults, with earthing issues being considered at installation and insulation faults occurring during operation
B07	Array/inverter mismatch, incorrect sizing	Resulting in lewer yield and efficiency than predicted
B08	Accidental switch off of inverter	Prolonged disconnection but no technical faults

Table 16 (cont.)

Mode Ref.	Mode	Explanatory comments and consultation remarks
B09	Overtheating of inverter	May be the cause of an inverter failure (B01)
B10	Fluctuation of grid specifications	Very dependent on local grid and load conditions
B11	Corrosion of contacts, connections	No comments
B12	Battery failure	No comments
B13	Poor charge controller performance	May lead to battery failure (B12) if not addressed
B14	Overtheating of battery	May lead to battery failure (B12) if not addressed
B15	Overconsumption (stand alone system)	System load levels substantially above design values. It was noted that this mode could be the cause of B12 (battery failure)
B16	Damage from electrical arcing	The severity is very dependent on the location of the arcing damage, the system configuration and the potential for further damage from any fire risk.
C01	Array shading	Additional to that accounted for in the system design. During operation, the most likely increase in shading will come from the growth of vegetation
C02	Accumulation of dirt/snow/ice (requiring intervention)	No comments
C03	Lightning strikes, lightning induced damage	No comments
C04	Component damage due to extreme weather conditions	No comments
C05	Component damage due to animals, insects etc.	No comments
C06	Component damage due to vandalism	Deliberate damage to any part of the system
C07	Theft of components	Leading to reduction in output. The severity is directly dependent on the nature of the theft and ranges from a few percentage points to loss of the whole system. Small systems in unmanned locations are more vulnerable to theft.

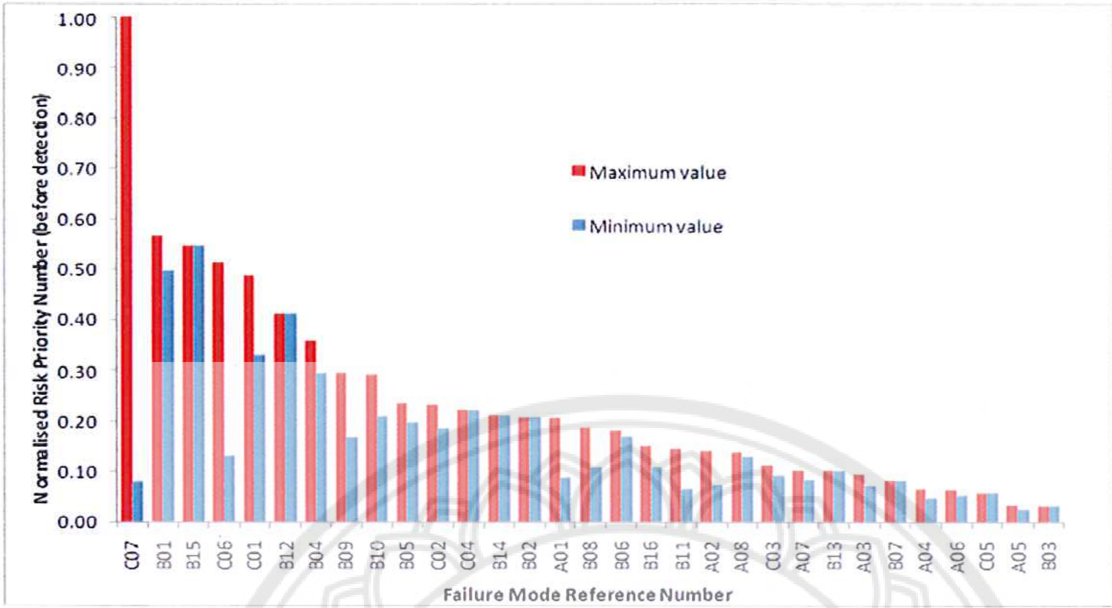


Figure 28 Normalised average RPN values for the 31 failure modes presented in descending order of maximum value. The two columns represent the maximum and minimum values obtained for that mode

Table 17 Categorization of variations in RPN provided by the respondents to the consultation. The variations result in a change in one or both of the occurrence or severity index assigned and thus the resulting RPN value

Mode Ref. No.	Mode	Higher RPN values assigned for:
A01	Module failure	Large system (>1MW) due to number of modules, concentrator systems due to thermal stress
A02	High level of module performance degratation	Thin film compound technology (although noted that this is packaging dependent), hot and humid climates
A03	Broken or cracked cells; boken or cracked module glass	Large systems (>1MW) due to number of modules, systems prone to vandalism
A04	Module junction box damage of fault	Small and island systems due to the low number of strings
A05	Hot spot damage to module	Slight increase for open circuit failure mode
A06	High module operating temperature	BIPV systems due to the low number of strings
A07	Bypass diode failure	Small and island systems
A08	String failure	Small systems due to the low number of strings

Table 17 (cont.)

Mode Ref. No.	Mode	Higher RPN values assigned for:
B01	Inverter failure	Small increase in severity for small and island systtems due to low number of inverters in system
B04	Faulty circuit breakers or switches	Small and island systems
B05	Damaged or faulty cabling	Small and island systems
B06	Earthing or insulation faults	Locations with high humidity
B08	Accidental switch off of inverter	Small and island systems
B09	Overheating of inverter	Small residential systems, island systems
B10	Fluctuation of grid specifications	Locations with weak electrical grids
B11	Corrosion of contacts, connections	Island systems
B16	Damage from electrical arcing	Residential systems
C01	Array shading	Residential systems, rural locations
C02	Accumulation of dirt/snow/ice (requiring intervention)	Humid environment, concentrator systems
C03	Lightning strikes, lightning induced damage	Locations with high frequency of strikes
C06	Component damage due tto vandalism	Urban systems, façade systems
C07	Theft of components	Remote systems, unmanned systems

Table 18 Summary of monitoring requirements for 10 modes with the highest derived RPN

Mode Ref.	Mode Name	Measurements required to identify	Description of analysis	Frequency aspects	Other modes addressed by the same monitoring action
C07	Theft of components	System output visual inspection (manual or CCTV)	Problem indicated by reduced or zero output. Identification as theft needs further checks including visual inspection	For high risk location, regular visual checks may be advisable. Frequency of output data analysis	CCTV or other visual checks also address C06 and to a lesser extent C04 and C05
B01	Inverter failure	System output	Periodic check of system output-identification of cause of failure will require additional measurements and analyses	Frequency depends on the load variation and climate since the battery index will vary with season. This fault is also characterized by repeated non availability of power	B08 (inverter switch off)

Table 18 (cont.)

Mode Ref.	Mode Name	Measurements required to identify	Description of analysis	Frequency aspects	Other modes addressed by the same monitoring action
B15	Overconsumption (stand alone system)	Battery index availability to load total system loads	Comparison of seasonal variation of battery index with expectation. Check with calculation of total system loads.	Frequency depends on the load variation and climate since the battery index will vary with season. This fault is also characterized by repeated non availability of power	Persistently low battery indice may be a precursor to B12 (battery failure) or indicate poor countroller performance (B13)
C06	Component damage due to vandalism	System output Visual inspection manual or CCTV	Problem indicated by reduced or zero output. Identification as vandalism needs further checks incluing visual inspection	For high risk locations, regular visual checks may be advisable. Frequency of output analysis likely to be dictated by other actions.	CCTV or other visual checks also address C07 and to a lesser extent C04 and C05
C01	Array shading	System output In-plane irradiance	Problem indicated by output variation not matching that of irradiance and by variation of effect with time and season. Can be confirmed by visual inspection	Need to observe variation across the day - data intervals of not less than 10 minute averages recommended in most cases. Daily data need to be stored to allow sequential investigation.	A06 (partially). B03, B07, C02 B08 and all other modes that rely on system output measurement at longer intervals. B09 and B10 if resolution allows inverter shutdowns to be observed
B12	Battery failure	System output Availability to load Battery capcity, battery voltage	Usually identified by a major reduction in system availability. May be characterized by capacity and voltage measurements.	Analysis of battery index may allow prevention of failure. Otherwise, analysis would be undertaken once fault is observed.	Related to B13 and B15 in terms of cause of the failure

Table 18 (cont.)

Mode Ref.	Mode Name	Measurements required to identify	Description of analysis	Frequency aspects	Other modes addressed by the same monitoring action
B04	Faulty circuit	System output over time	Fault identified by reduced or zero output. If available, string comparisons will help to identify problem. Further investigation need to establish failure mode.	Frequency of analysis of system outputs dependent on the loss levels to be identified higher frequency for large systems.	All modes identified by sustained reduced output over a variety of operatings conditions (A08, B05, B06, B11, B16, C03-C07)
B09	Overheating inverter	Inverter operating period, inverter output, ambient or inverter temperature	Problem indicated by reduced output from inverter when temperature is high. Cause can be inferred from daily plots of variables and further analysis	Similar data intervals to C01 and B10 with specific checks carried out during periods of hot weather	See response to C01
B10	Fluctuation of grid specification	Inverter output, irradiance, grid voltage and frequency (possible)	Problem indicated by output variation not matching that of irradiance and by periods of very low inverter output. Can be confirmed by inverter records of grid specifications if available	Similar data intervals to C01 and B09, with specific checks carried out during periods of hot weather.	See response to C01
B05	Damaged or faulty cabling	System output over time	Fault identified by reduced or zero output. If available, string comparisons will help to identify problem. Further investigation need to establish failure mode.	Frequency of analysis of system outputs dependent on the loss levels to be identified. Higher frequency for large systems.	All modes identified by sustained reduced output over a variety of operating conditions (A08, B04, B06, B04, B11, B16, C03-C07)

Diagnostic architecture: A procedure based on the analysis of the failure causes applied to photovoltaic plants

Cristaldi, L., Faifer, M., Lazzaroni, M., Khalil, M.M.A.F., Catelani, M., & Ciani, L. [34] Analyze the failure modes and causes and diagnostic architectures for grid-connected photovoltaic system with one main inverter that presented in Figure 29. The PV power plant is possible separated into 3 main subsystems, photovoltaic modules connected in series and parallel, power conditioning subsystem that includes inverters and BOS (Balance Of System) subsystem that is composed by generator and module junction box, solar cable connectors, fuses, DC and AC wires, DC and AC switches. The failure modes of PV module can be classified in 6 modes that are encapsulation failures from discoloration and delamination, module corrosion failures from deterioration, broken interconnection and solder buses failures from thermal expansion and contraction or repeated mechanical stress, cells cracking failures from mechanical loads due to wind (pressure and vibrations) and snow (pressure), dust failures from different transmittance of light, and hot-spots failures from PV cell high temperature. The inverter failures can be classified into three major categories: manufacturing and inadequate design problems, control problems and electrical components failures. The failures of BOS components are considered the major reason behind the presence of non-producing modules in PV field. In fact, for these plants, high level of reliability is necessary in order to operate, without failures, in the time taking into consideration also the typical lifetime of these plants. To this aim the monitoring of both plant parameters and plant performances is a very important task that can be obtained, by means of a well-designed diagnostic and monitoring system. The smart monitoring of PV plants must be able to carry out the necessary performance measurements, evaluate the ageing of PV panels and early detect the possible failures previously described. Figure 30 shows a possible schematics diagram of the PV system smart performance monitoring that can be detected as reported the failure modes in the Table 19. The experimental activity has been implemented by using a sun simulator and a test chamber.

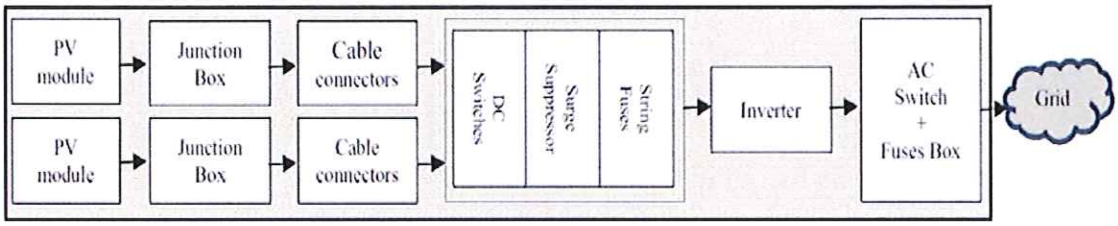


Figure 29 Simplified schematic diagram of photovoltaic plant

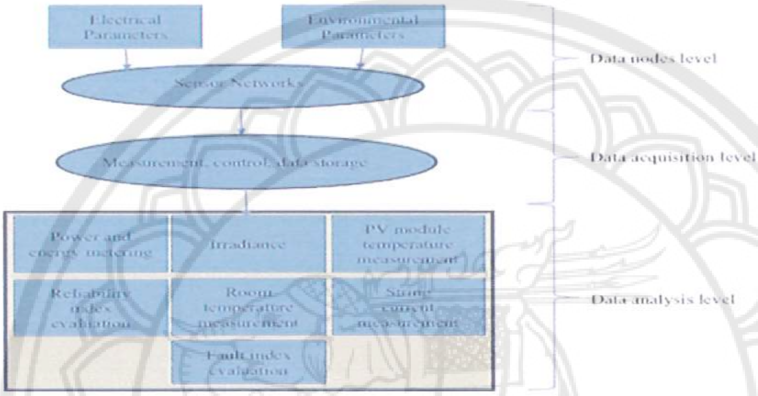


Figure 30 PV smart monitoring system

Table 19 Failure modes detection strategies

Failure mode	Detectability	Requirement
Encapsulation	MPP value of the PV panel is below the value given by the model. Out put of the other PV panels are good. We can compare the actual and model MPP	The PV panels have to be clean
Module corrosion	Model approach: a comparison between the value assigned to the value assigned to the series resistance during the characterization of the PV panel and the value estimated by means of the model	This failure mode can be detected only if the model algorithm allows to evaluate the parameter of the electrical model

Table 19 (cont.)

Failure mode	Detectability	Requirement
Cells cracking	Model approach: open circuit voltage decrease so we have to compare the value obtained by the actual characteristic with the value given by the model	*I-V* curve has to be obtained by means an electronic load
Dust	It can be detected comparing the actual and model MPP. All PV panels of the string show the same problem	An algorithm that compares all the MPPs value
PV inverter: general failure		If the plant has centralized or string inverter, the data base alarms has to be read by the monitoring system
BOS 1. Theft 2. Broken fuse 3. Broken cable	No string current	The three failure mode can be detected by means of devoted sensors

The acquired data have been obtained by a 5 W_p PV panel operating at about 25 °C. Table 19 reports the experimental data obtained by testing 10 PV panels. For each PV panel the MPP value has been obtained in two different conditions: first the PV panels have been tested when new or as good as new and carefully clean, second the same PV panels have been tested after a certain number of days during which they were exposed to the weather conditions according to a pattern reported in the last column of Table 20. This approach allows to improve complex system maintenance policies and, at the same time, to achieve a reduction of unexpected failure occurrences in the most critical components.

Table 20 Results of the measurements performed during the test period

# PV panel	MP considered for new PV (W)	MP considered for used PV (W)	Test conditions	Conditions classification (see Fig. 7)
1	0.474	0.457	Horizontal, no rain. 34 days	Increasing level 1
2	0.471	0.443	Horizontal, no rain. 34 days	
3	0.448	0.418	Horizontal, no rain. 34 days	
4	0.467	0.455	Horizontal, no rain. 34 days	
5	0.468	0.438	Horizontal, no rain. 34 days	
6	0.506	0.489	30°, rain, 24 days	
7	0.470	0.454	30°, rain, 24 days	
8	0.474	0.456	Horizontal, no rain. 21 days	
9	0.478	0.466	Horizontal, no rain. 21 days	
10	0.505	0.494	Horizontal, no rain. 21 days	

Reliability Performance Assessment in Modeling Photovoltaic Networks

Tonţ, G., & Tonţ, D.G. [35] present the reliability analysis of switched mode power converters estimating distribution parameters of different phases for PV useful-life period. The first step in analyzing the reliability is representing the system by an equivalent reliability block diagram (RBD) for the first level of detail to study the estimated reliability for typical PV system as represented in Figure31. In the reliability block diagram was taken into account the next parts of the PV system: The PV array (1), the PV array circuit combiner (2), the ground fault protector (3), the DC fuse switch (4), AC/DC invertor (5), the AC fuse switch (6), the utility switch (7), the main service pannel (8). It must to be mentioned that the AC/DC invertor (5) and the main service pannel (8) were considered separately because there were many cases when just one of them was damaged.

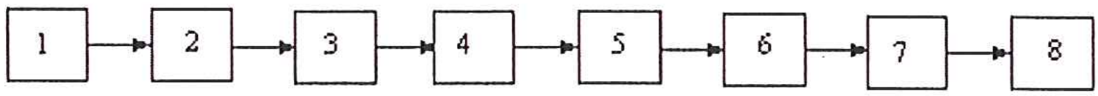


Figure 31 Reliability Block Diagram for a photovoltaic system

Table 21 The Weibull parameters values

PV system	Weibull parameters		Correlation coefficient
	β	η	
PV array	1.0783	1.0323	0.9632
PV array circuit combiner	1.0642	1.0215	0.9752
Ground fault protector	1.0564	1.0367	0.9748
DC fuse swith	1.0647	1.0204	0.9468
AC/DC invertor	1.0539	1.0194	0.9735
AC fuse switch	1.0745	1.0245	0.9784
Utility switch	1.0578	1.0576	0.9687
Main service pannel	1.0739	1.0781	0.9877

If the resulting system level failures are used to extract Weibull distribution parameters, assuming that all failures are caused to only one failure mode, significant errors may be introduced. For the analyzed PV system it was calculated the empiric reliabilities which was compared with the reliabilities obtained using the analytical method. The parameter values and the correlation coefficients for each case are presented in Table 21. The values of Weinbull parameters correspond the high values of the correlation coefficient. The analytical curve based on the parameters values were determined using the regression analysis and plotted in the Figure 32. From the Figure, the total reliability highly decreases after approximately 15.5 years of working of the PV system. From the analyzing, the initial failures are generally the result of manufacturing errors that are not caught in inspection prior to burn-in or placing in service. Failures resulting from time/stress dependent errors may occur in this period. Random failures and wear out failures are generally a factor of design. Wear out of mechanical parts also begins the moment the product is put into service. Photovoltaic (PV) energy system is assumed to work without interruptions over its entire life. In PV systems, the inverter is responsible for the majority of failures, and most inverter failures are blamed on the aluminum electrolytic capacitors typically used in the dc bus.

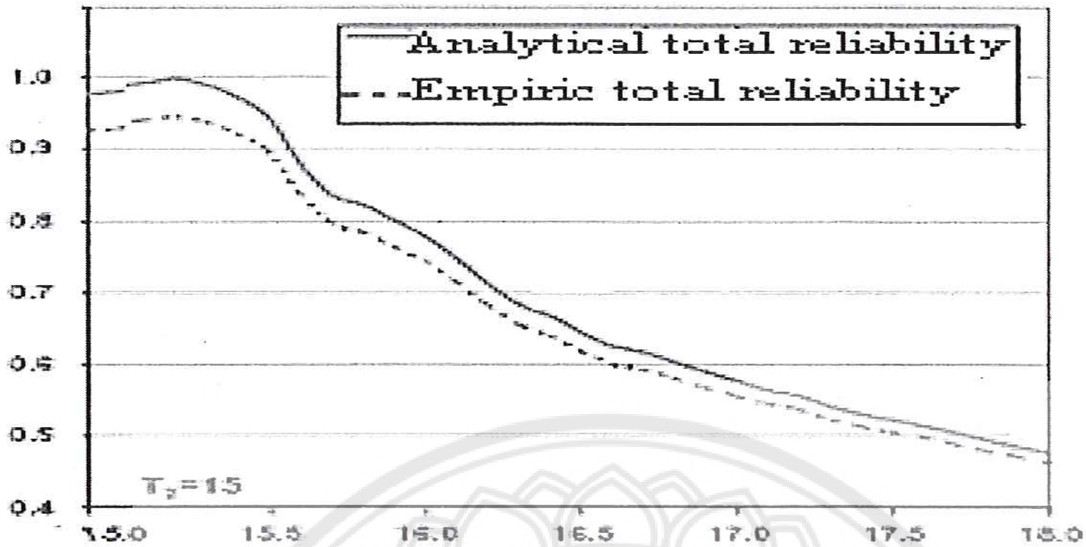


Figure 32 The total reliability of the PV system: 1- empiric total reliability; 2 – analytical total reliability [35]

Information-based reliability weighting for failure mode prioritization in photovoltaic (PV) module design

Francis, R., & Colli, A. [36] present the prioritization of PV failure modes extending Colli using a Shannon information-weighted reliability approach is demonstrated. We call this information-weight the surprise index that developed for used within FMEA worksheets. The surprise index approach facilitates the prioritization of failure modes by weighting the consequence of their failures by the information in the failure generation model. In our case study, we modify FMEA data to compute the SI for a research solar PV array. The FMEA severity, occurrence and detection classifications are given in Table 22. The system under consideration is presented in Figure 33, consists of PV modules, racks, cables, string combiners, and power conditioning units. The DC and AC systems on both sides of the inverter unit are considered. Table 23 shows a portion of the FMEA worksheet for the PV modules, in particular considering crystalline silicon PV technologies. This table gives the severity, likelihood, and detection ratings for each failure mode considered, while Table 24 indicates the probabilities considered and the information scores for use in computing the SI. Table25 finally indicates the comparison between the SIs and RPNs. Notice that while some rankings are similar for both the SI and the RPN, some of the rankings are quite different. This evaluation highlights a couple of aspects. First, by using fairly broad likelihood categories, differences in failure mode probabilities over several orders of magnitude may be obscured. But the failure modes that may require special attention for contingency planning may have been overlooked if relying only on the RPN.

Table 22 FMEA severity and likelihood classifications used to calculate the RPN. Note that the RPN ranges from 1 to 125 in this application

	Severity ranking criteria
Rank	Description
1	Minor failure/degradation, hardly detected, no influence on the system performance
2	Failure/degradation will be detected by plant owner/operator and/or will cause slight deterioration of parts or system performance.
3	Failure/degradation will be detected by plant owner/operator and/operator, will create dissatisfaction, and/or will cause deterioration of parts or system performance.
4	Failure/degradation will be easily detected by plant owner/operator, will create high dissatisfaction, and/or will cause extended deterioration of parts and system relevant non-functionality/loss of performance.
5	Failure/degradation will result in non-operation of the system or sever loss of performance
	Occurrence ranking criteria
1	Unlikely-failure rate per unit-hour in the order of E-7
2	Remote probability-failure rate per unit-hour in the order of E-6
3	Occasional probability - failure rate per unit-hour in the order of E-5
4	Moderate probability-failure rate per unit-hour in the order of E-6
5	High probability - failure rate per unit - hour inn the order of E-3 and E-2
	Detection ranking criteria
1	Almost certain that the problem will be detected (Chance 81-100%)
2	High probability that the problem will be detected (chance 61 - 80%)
3	Moderate probability that the problem will be detected (chance 41-60%)
4	Low probability that the problem will be detected (Chance 21-40%)
5	None/minimal probability that the problem will be detected (chance 0-20%)

The selected units may lead to reduced deliberation over contingency planning for highly unlikely, yet quite severe failures simply because of the qualitative scale selected. The objective of proper scoring is to improve the sensitivity and specificity of expert judgments by rewarding expert predictions that are both risky and correct. The surprise index may potentially aid in systematic evaluation of deep uncertainties in PV module design, as failure modes that might be overlooked using traditional PRA may be addressed using the information-based approach.

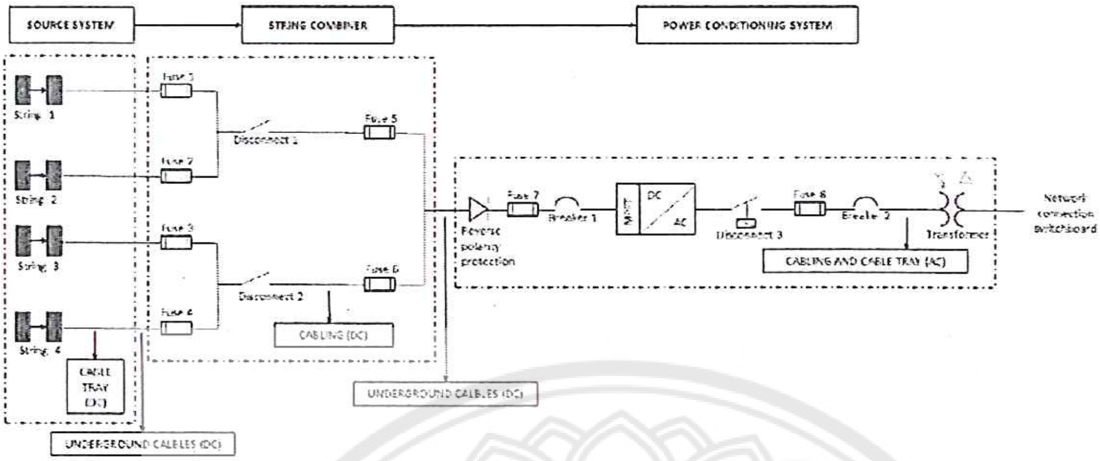


Figure 33 Simplified photovoltaic system model with the principal components of the BNL's NSERC PV array

Table 23 FMEA Worksheet excerpt for case study PV modules

Sub component	Function or process	Potential Failure Mode	Potential Effects	Potential Causes	Severity Rating	Occurrence Rating	Detection Rating
Module (active components cells and contacts)	Electric connections	Loss of electric function	No energy output, safety, fire	Shorts, arcs, open contacts	5	2	3
		Impairment of electric function	Reduced energy output, hot spot damage	High series resistance, low shunt resistance, aging, shading, soiling	4	2	4
Junction box/bypass diode	Electric connections	Open contracts	No energy output	Disconnections, improper installation, corrosion	5	1	3
		Short, arc in contacts	No energy output, safety, thermal damages, fire	Damaged insulation, aging, animals, lightning	5	1	2

Table 23 (cont.)

Sub component	Function or process	Potential Failure Mode	Potential Effects	Potential Causes	Severity Rating	Occurrence Rating	Detection Rating
		Poor contact/intermittent	Reduced energy output, no energy output thermal damage	Material defects, oxidation, aging	4	1	4
		Shorted diode (end-to-end)	Reduced energy output, loss of module power	Material defects , aging, thermal stress, mechanical stress, electrical stress, contamination ,processing anomaly	4	1	4
		Open diode	Reduced energy output, thermal damages in module, fire, safety	Very high resistance, material defects	3	1	5
		Parameter change in diode	Reduced energy output, improper intervention	Material defects, aging, continuous thermal stress	3	1	5
connectors	Electric connections	Open	No energy output	Damage, disconnection , animals, vandalism, strong wind, pulled cables	5	1	2
		Poor contact/intermittent	Reduced energy output, no energy output, thermal damage	Corrosion, improper installation, lightning damage	5	1	4

Table 23 (cont.)

Sub component	Function or process	Potential Failure Mode	Potential Effects	Potential Causes	Severity Rating	Occurrence Rating	Detection Rating
		Short	No energy output, safety, thermal damages, fire	Damages, improper installation, animals, vandalism	4	1	5
Encapsulation	Encapsulation	Loss of air tightness	Hunmidity/water/contaminant entrance, increased degradation, reduced energy output, no energy output	Bad lamination, high voltage stress, hot spots, high cell/module temperature corrosive effects in the module structure, aging, damage from frame distortion, cleaning actions, extreme wind, snow load, vandalism, animals lightning, earthquake, accidental impacts	2	2	5

Table 24 Information score for PV module failure modes

Sub-component	Function/Process	Potential Failure Mode	Considered probability	Information score
Module (active components-cells and contacts)	Electric connections	Loss of electric function	1.35E-06	14
		Impairment of electric function	1.35E-06	14
Junction box/bypass diode	Electric connections	Open contacts	4.51E-07	15
		Short, are in contacts	4.51E-07	15
		Poor contact/intermittent	4.51E07	15
		Shorted diode (end-to-end)	2.26E-07	15
		Open diode	2.26E-07	15
		Parameter change in dioded	2.26E-07	15
connectors	Electric connections	open	4.51E-07	15
		Poor contact/intermittent	4.51E-07	15
		Short	4.51E-07	15
Encapsulation	Encapsulation	Loss of air tightness	4.06E-06	12

Table 25 Comparison of surprise index and risk priority number for PV module sub components

Sub-component	Function/Process	Potential Failure Mode	Surprise Index	Risk Priority Number	SI Ranking	RPN Ranking
Module (active components-cells and contacts)	Electric connections	Loss of electric function	203	30	9	2
		Impairment of electric function	216	32	8	1
Junction box/bypass diode	Electric connections	Open contracts	219	15	7	8
		Short, are in contacts	146	10	10	11
		Poor contact/intermittent	234	16	4	6
		Shorted diode (end-to-end)	245	16	3	6
		Open diode	230	15	5	8
		Parameter change in dioded	230	15	3	8

Table 25 (cont.)

Sub-component	Function/Process	Potential Failure Mode	Surprise Index	Risk Priority Number	SI Ranking	RPN Ranking
Connectors	Electric connection	Open	146	10	10	11
		Poor contact/intermittent	292	20	1	3
		Short	292	20	1	3
Encapsulation	encapsulation	Loss of air tightness	124	20	12	3

Performance and degradation analysis for long term reliability of solar photovoltaic systems

Sharma, V., & Chandel, S.S. [37] review the performance and degradation analysis studies of solar photovoltaic modules, accelerated aging testing under laboratory and outdoor field testing conditions. The factors affecting the performance of PV module are PV cell technologies, ambient temperature, solar irradiation, tilt angle of PV module, and other factors such as dust accumulation, humidity, and air velocity.

Table 26 Degradation mechanism, corresponding stress factors and accelerated aging tests [37]

Degradation mechanism	Stress factor: High temperature	Moisture	Thermal cycling	UV	High voltage	Accelerated stress test
Broken interconnect	✓	✓			✓	Thermal cycle
Broken cell	✓				✓	
Solder bond failures	✓	✓	✓		✓	
Junction box failure	✓	✓				
Open circuits leading to arcing	✓				✓	
Corrosion	✓	✓			✓	Damp heat exposure
Delamination of encapsulant	✓	✓	✓	✓	✓	
Encapsulant loss of adhesion and elasticity	✓	✓	✓		✓	Humidity freeze
Encapsulant discoloration	✓			✓		UV test
Hot spots	✓					Hot spot test
Shunts at the scribe lines	✓	✓				
Electrochemical corrosion of TCO	✓	✓			✓	Dry and wet insulation resistance
Gound fault	✓	✓			✓	
Bypass diode failures	✓		✓			Bypass diode

The common main parameters for evaluation of PV system performance are Final yield (Y_F), Reference yield (Y_R), Performance ratio (PR), PVUSA rating, Capacity factor (CF), and System efficiency. For PV module degradation modes, various degradation modes are finally responsible for performance loss and failure that are packaging material degradation, adhesion loss, interconnect degradation, moisture intrusion, and semiconductor device degradation. A summary of the degradation mechanism and corresponding stress factors causing the degradation and accelerated aging tests to study these defects is given in Table 26. The current PV module qualification standard tests are available in IEC 61215 for crystalline PV modules and IEC 61646 for thin film PV modules. According to qualification standard tests, eight modules are picked up randomly from the same batch and subjected to18 rigorous tests in a fixed sequence. The modules of the whole batch out of which these modules are picked up will be regarded as qualified if performance degradation during any of these tests or after any sequence of tests is within the acceptable limits (< 5%). Out of the randomly selected eight modules, one module is kept as reference and is not subjected to any accelerated stress test. The second module is subjected to electrical characterization under sun simulator to determine performance at different radiation conditions, then bypass diode thermal test, and finally to hot spot endurance test to determine the ability of PV module to bear the localized heat due to partial shadowing of the cells/cracked/mismatched cells. The remaining six modules are divided into 3 groups with two modules in each group and subjected to different mechanical and environmental tests.

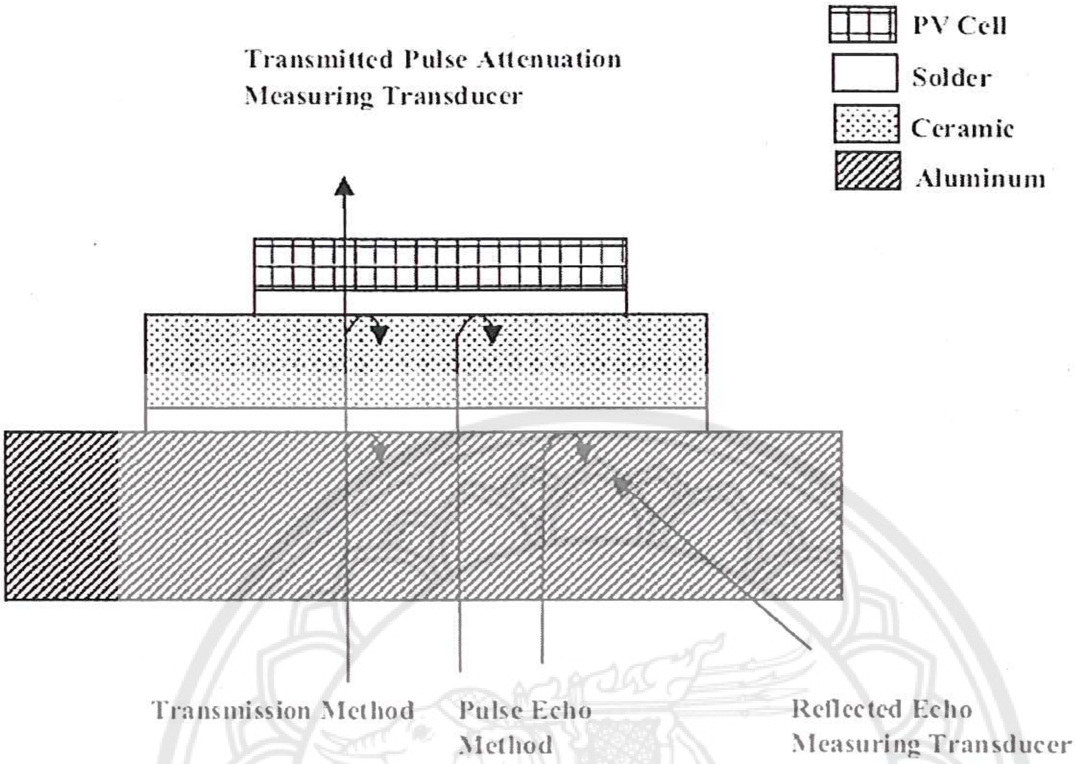


Figure 34 Ultrasonic inspection methodology [37]

The important techniques for the failure mode analysis of PV modules that available in the past few year are Electrical characterization, Visual inspection, Ultrasonic inspection that displayed in Figure 34, Infrared imaging (IR imaging), Electroluminescence imaging (EL imaging), Attenuated total reflectance infrared microscopy (ATIR), Scanning electron microscopy (SEM), and X-ray micro-tomography. Summary of failure mode analysis techniques is showed in Table 27.

Table 27 Summary of failure mode analysis techniques

Name of the technique	Type of defect identified
(a) Non destructive	
Ultrasonic imaging	Capable of locating air voids, debonding and delamination which are not visible
Infrared/thermal imaging	Hot spot generation, increase in the series resistance
Electroluminescence imaging (EL imaging)	Helpful in differentiating in the increased series resistance and reduced shunt resistance which is difficult because both of these defects lead to hotter areas in IR imaging
Computed tomography (CT) using X-rays	Studying reliability and failure analysis issues such as μ-cracks in Si cells of PV module
(b) Destructive	
Scanning electron microscopy (SEM)	Study the morphology of the defect sample
X ray tomography	Studying the chemical changes which have occurred in the area of interest

Reliability assessment of photovoltaic power systems: Review of current status and future perspectives

Zhang, P., Li, W., Li, S., Wang, Y., & Xiao, W. [38] reviews the state-of-the-art technologies for evaluating the reliability of large-scale PV systems and the effect of PV interconnection on the reliability of local distribution system. The discussions are extended to emerging research topics including time varying and ambient-condition-dependent failure rates of critical PV system components, accurate operating models of PV generators in both interconnected and islanded modes, and the reliability evaluation of active distribution networks with PV penetration and transmission level Giga-PV system. A vision for the future research is presented, with a focus on the cyber-physical perspective of the PV reliability, modeling of PV voltage control scheme for reliability assessment, reliability assessment for PV systems under extreme events and PV reliability assessment considering cybersecurity. Large-scale grid-connected PV systems are usually connected in a centralized, a string/multi-string structure, and the micro-inverter system. When compare these topology, It found that the micro-inverter system has a potential to best optimize the PV power generation under partial shading conditions. At the same time, micro-inverter system may also improve reliability by reducing converter temperature and eliminating electrolytic capacitors. For reliability evaluation of critical components in PV system, it found that the PV modules can also fail or degrade in their long-term lifecycle from many causes. Dust accumulation and PV connection topology are the important aspect associated with PV module reliability. Many studies present that total cross-tied (TCT) and bridge-linked (BL) configurations increase the operational lifetime of the PV arrays by 30%. The reliability of PV inverter depends on the performance of each component in PV inverter. A study indicate that failures often occur in switching stage and temperature is the most likely cause of failure. The electrolytic capacitor is the most dominant component for inverter failure while IGBT and MOSFET is the runner-up. Moreover, PV industry representatives at the DOE workshop agreed that the most urgent problem affecting inverter reliability is the quality of the dc-bus capacitors. The reliability of various structures of inverters such as single-stage, integrated topology, two-stage configuration, three-stage configuration AC-bus level, and DC-bus level are studied and the results show that higher system reliability can be achieved by using module-integrated inverters. Reliability evaluation methods of PV system that commonly used are Markov process method, Monte-Carlo simulation, State Enumeration, Reliability Block Diagram, and Fault Tree Analysis. For reliability indices for PV system, the traditional reliability indices such as mean time between failures (MTBFs), mean time to repairs (MTTRs), loss of load probability (LOLP), and loss of load hours (LOLHs) have been used in many studies. The loss of power probability (LPP) index which considered the extreme values of data as functions of certain recurrence intervals and The Yearly Expected Energy Production (YEEP) index that obtained based on a multi-state system model by considering both component failures and PV power outputs is introduced in a few papers. Future perspectives on PV reliability assessment is available in 4 topics that are Cyber-physical system perspective on reliability assessment of PV system, Modeling voltage control scheme in reliability assessment, PV reliability assessment under extreme weather conditions, and PV reliability assessment considering cyber vulnerability, attack and security. Reliability evaluation of power grids with PV systems are focused in 2 group that are active distribution network including PV microgrids and reliability for future Giga-PV system connected to power transmission grid.

From these literature review, they present that the availability and reliability study of large scale PV power plant is mainly focusing on the PV module, BOS and the inverter which play the vital role of the availability and reliability of the PV power plant. When analyze the inverter failure components, it is obviously pointing out that electrolytic capacitor, IGBT, and MOSFET are the most common inverter failure components. Therefore, it is possible to conclude that the availability and reliability of inverter are dominated by these components. The failure cause of these components is mainly from extreme environment, temperature, thermal and mechanical stress that is the critical factor for the inverter life cycle. However, all of these factor tests are executed in Japan, China, Europe or United States but the present growth PV market are available in every part of Asia. The reliability cannot demonstrate for the financial result. The higher equipment installed is the lower reliability. For the root cause analysis that will affect the reliability are come from the design, operation, PV, inverter, BOS and the construction which is needed to categorize and grouping to demonstrate the effect to the power production and the availability.

The availability is the most important factor for the PV power plant revenue estimation that used in the financial model, return of investment and planning for spare part, preventive maintenance and corrective action. These actions are required for power plant. This study concentrates on the reliability and availability of the individual selected PV Power plant. The analyzing method and mathematic model for the reliability and availability are developed and tested with the collected data from the selected solar farm. The simulation result is compared with the result of the selected power plants.

CHAPTER III

RESEARCH METHODOLOGY

In this research, the availability of the 6 commercial large scale Photovoltaic (PV) power plants in Thailand are evaluated for understanding the failure root cause and corrective action for improving the availability. In addition, the availability mathematical model for the large scale PV system is developed for forecasting the future availability of these solar farms and it is possible to use this mathematical model for estimating the availability of other commercial large scale PV power plant in Thailand. Moreover, the result of this study is possible used as the information to improve the preventative maintenance schedules, and budget for spares that result in reducing the maintenance cost projections over the system lifetime. All of commercial large scale PV power plant are located in the central region of Thailand. However, these PV power station are scattering located in many provinces. The system architecture of the 6 commercial large scale PV power plants is presented in Figure 35. From the Figure, 6 major component of solar farm are PV modules that convert solar energy to DC electricity, array box that collect DC electric current from PV strings and deliver to inverter with various important protection features, inverter that invert DC electricity to AC electricity with power quality and protection that complying with grid code, transformer that step up low voltage electricity from inverter to medium or high voltage electricity for injecting to utility grid at selling point, and selling point that the electricity from the solar power station are injecting to utility grid by passing selling meter. The PV power plant single line diagram for the medium voltage part, low voltage part, and array box are displayed in Figure 36, 37, and 38 respectively.

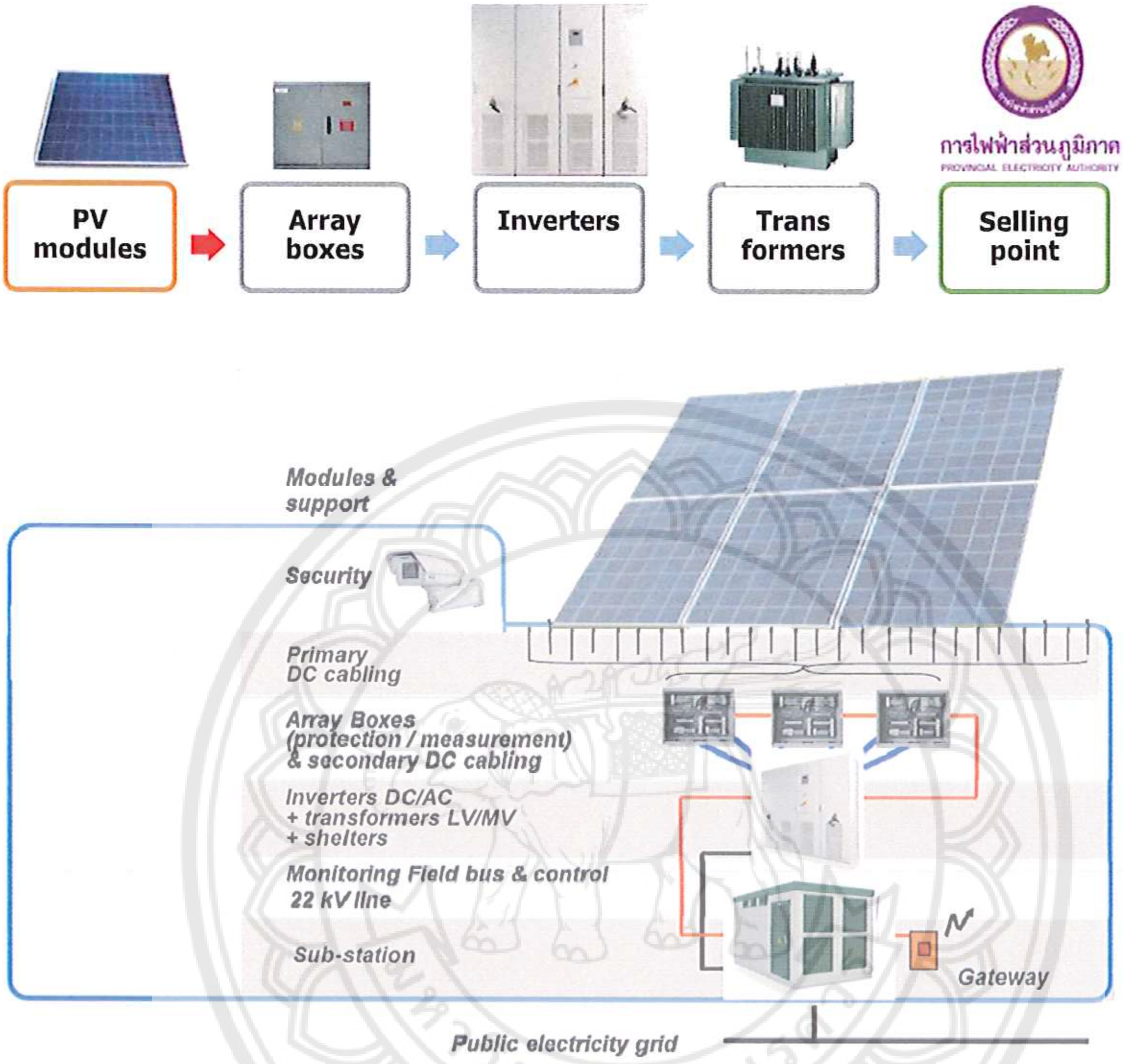


Figure 35 Commercial large scale PV power plant system architecture (source from Schneider Electric)

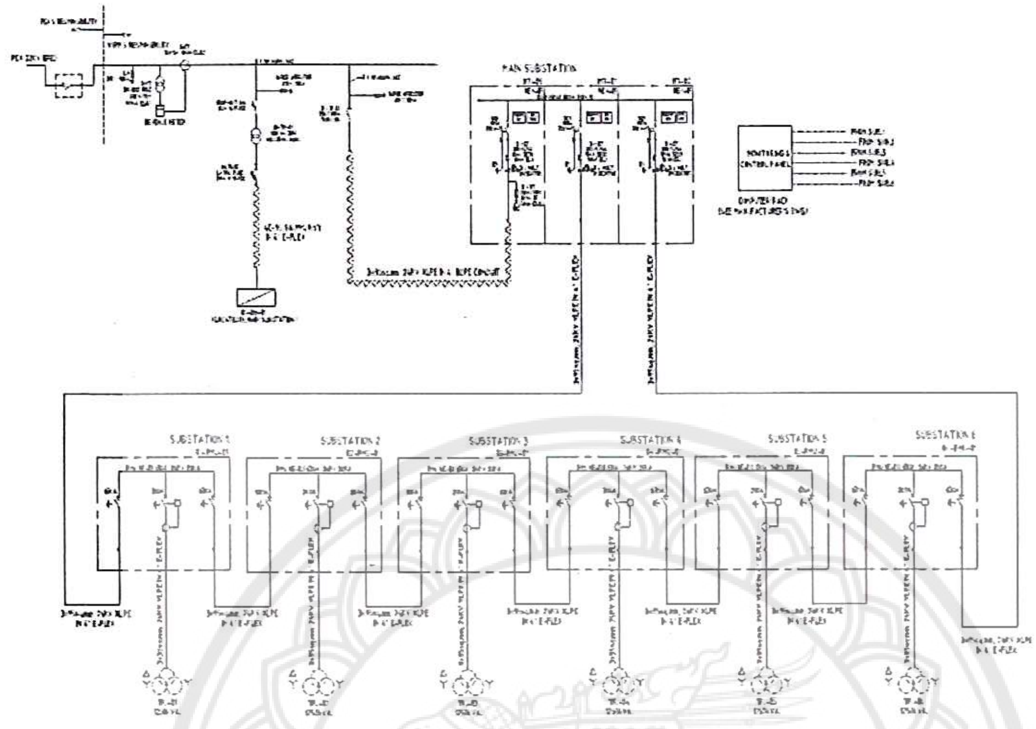


Figure 36 The PV power plant single line diagram for the medium voltage part

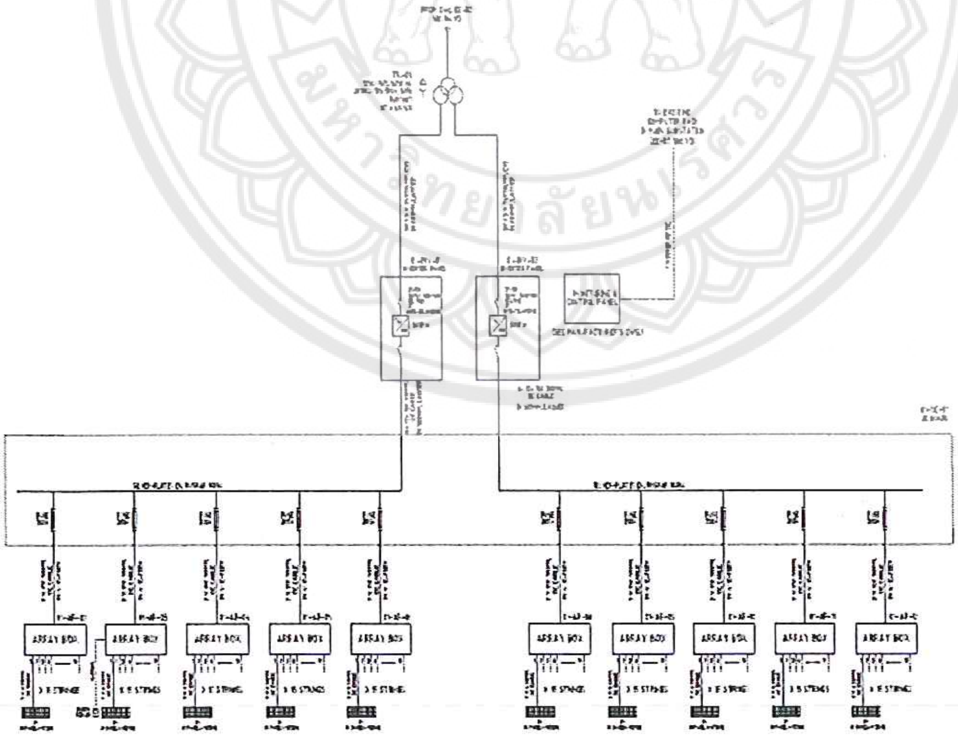


Figure 37 The PV power plant single line diagram for the low voltage part

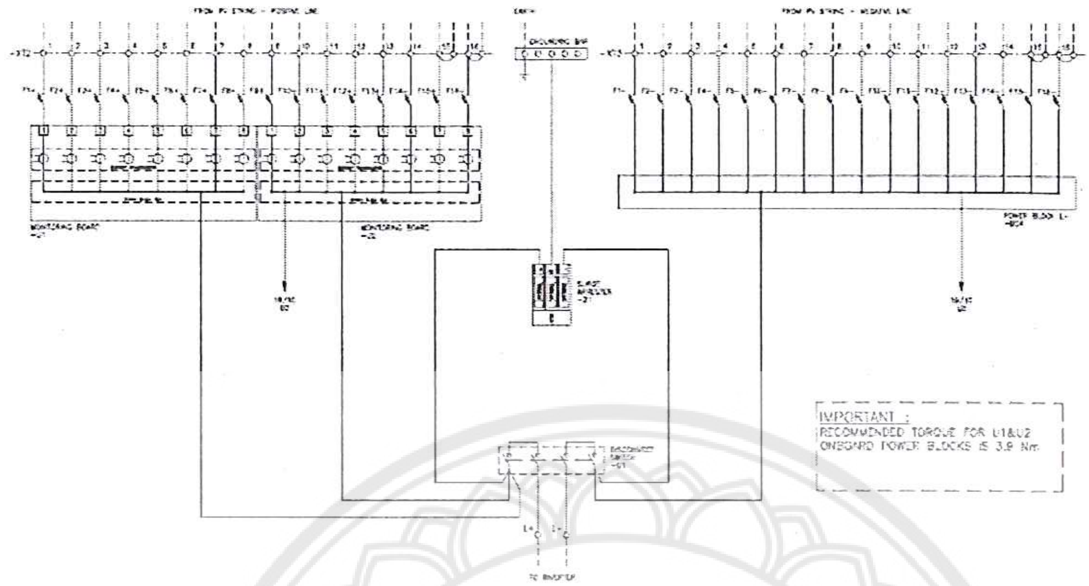


Figure 38 The PV power plant single line diagram for array box (source from Schneider Electric)

All of commercial large scale PV power plant is constructed by based on these single line diagram. The operation data of the 6 commercial solar farms had been measured and recorded during 2012-2015. The availability is analyzed and evaluated by using the recorded data and the performance evaluation result of these solar power stations as the referent data. Moreover, the root causes of availability are categorized for designing the preventive maintenance. The dissertation methodology is separated to 4 steps (Figure 39) as following;

1. Literature reviewing
2. PV power plant samples and data measuring
3. Efficiency and performance evaluation
4. Availability and reliability evaluation

Literature reviewing

The literature reviewing in this research is displayed in the chapter II. The most of the literature that reviewed is concentrating in the availability and reliability of large scale PV power plant. Moreover, the availability, reliability, failure mode, and failure cause of the component in utility scale PV power station are also mentioned in the literature. The information from the literature reviewing is used as the idea to analyze and evaluate the availability of the 6 commercial large scale PV power plants in this research. The result of this research is possible used to predict the future availability of these PV power stations and other solar farms in Thailand that is the most significant factor for the PV power station revenue estimation that used in the financial model, return of investment and planning for spare part, preventive maintenance and corrective action. PV Power plant revenue estimation that used in the financial model, return of investment and planning for spare part, preventive maintenance and corrective action.

PV power plant samples and data measuring

1. PV power plant samples

An objective of this dissertation is to analyze the availability of the 6 commercial large scale PV power plants. Therefore, the selecting of the commercial solar farm samples have to focus on the location of the PV power station that should be in the same region to limit the effect of other factor such as whether condition, geography, utility grid condition, and other factors. From this point, the 6 commercial large scale PV power plants with the centralized inverter concept that are located in central region of Thailand are selected as the PV power plant samples.

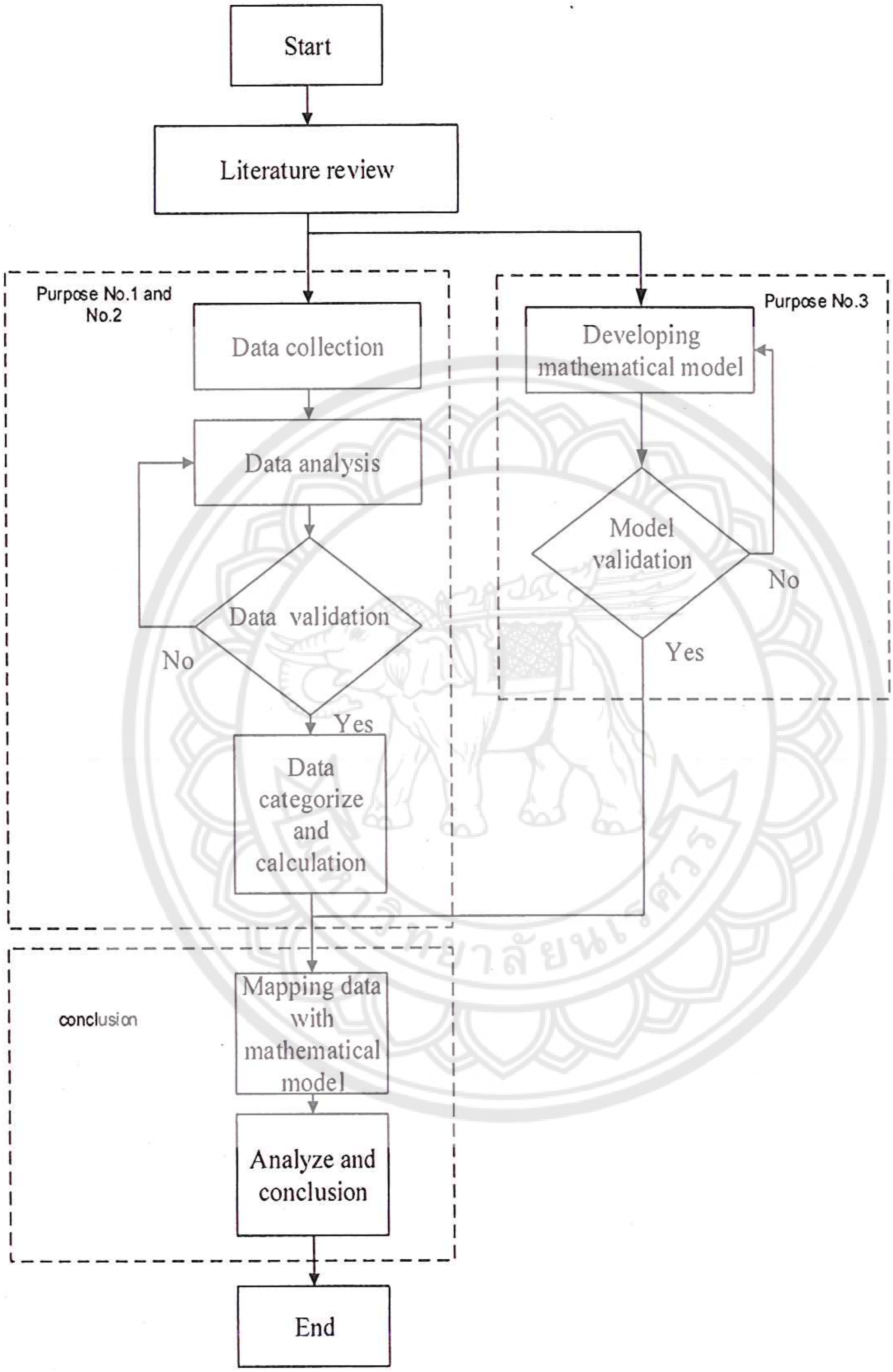


Figure 39 The dissertation methodology

The name and location of the 6 commercial large scale PV power plants are demonstrated in Table 28. The position of the 6 commercial large scale PV power plants are showed in Figure 40.

Table 28 The name and location of the 6 commercial large scale PV power plant

No.	Name	Location	PV power plant picture
1	Plant A	Phetchabun province	
2	Plant B	Phetchabun province	
3	Plant C	Phetchabun province	
4	Plant D	Chai Nat province	

Table 28 (cont.)

No.	Name	Location	PV power plant picture
5	Plant E	Nakhon Sawan province	
6	Plant F	Nakhon Sawan province	

From the Figure, the position of these solar farms are in 3 provinces of central region that are Phetchabun, Nakhon Sawan, and Chai Nat. These provinces are connecting together. Phetchabun locates locates on the east of Nakhon Sawan while Chai Nat locates locates on the south of Nakhon Sawan. Because of these PV power plant are located in central region and the distant between these solar power stations is not over 140 km., the whether condition and geography is really similar. Therefore, the effect from these factors are limited. The specification of the 6 commercial large scale PV power plants are illustrated in Table 29. From the Table, the DC and AC output of the 4 commercial large scale PV power plant that are C, D, E, and F are equal while the 2 commercial large scale PV power plant that are A and B are lower than other solar farms. It is possible that the effect of the different total power output from the PV array and inverter is available but it is limited and not significant. The inverters of the 6 solar farms that is the most critical component and dominating the availability of the PV power station are the same model that eliminated the effect from inverter.

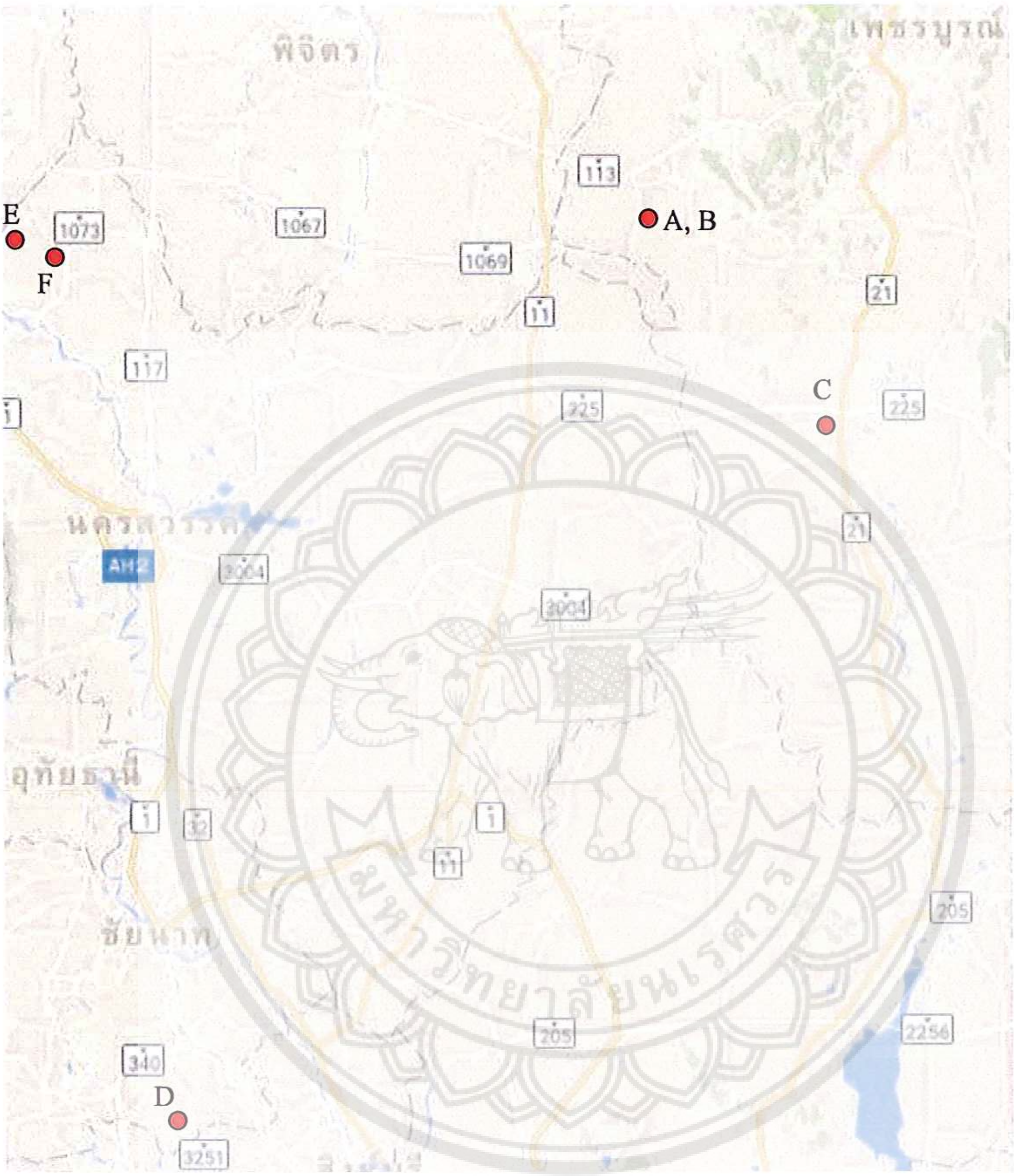


Figure 40 The satellite photography of six PV power plants and distant between them

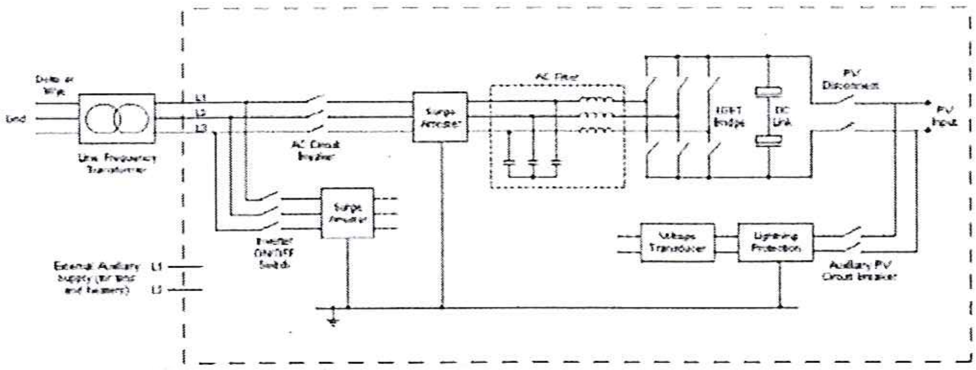


Figure 41 The inverter circuit topology

Table 29 The specification of the 6 commercial large scale PV power plant

PV power plant features	A	B	C	D	E	F
PV power plant topology	Central inverter	Central inverter	Central inverter	Central inverter	Central inverter	Central inverter
DC/AC Output power (MW_p/MW)	3.3/3.0	5.3/4.5	7.6/6.5	7.6/6.5	7.6/6.5	7.6/6.5
PV module technology	CIS	mc-Si	mc-Si	mc-Si	mc-Si	mc-Si
Inverter type	Central inverter	Central inverter	Central inverter	Central inverter	Central inverter	Central inverter
Inverter power/ Total number (kW/inverter), DC link voltage around 860 Vdc	500/6	500/9	500/13	500/13	500/13	500/13
Inverter output system and voltage	3 Ø 400 VAC	3 Ø 400 VAC	3 Ø 400 VAC	3 Ø 400 VAC	3 Ø 400 VAC	3 Ø 400 VAC
Combiner box	30	63	91	91	91	91
Transformer size/ number (kVA/transformer)	1,250/3	1,250/4 630/1	1,250/6 630/1	1,250/6 630/1	1,250/6 630/1	1,250/6 630/1

2. Data measuring

For analyzing and evaluating the availability of the 6 large-scale commercial PV power plant to identify the root cause and design the corrective action for improvement, the vital operating parameters of these PV power station such as solar irradiance, ambient temperature, PV module temperature, PV array voltage, PV array current, inverter output voltage, inverter output current, inverter output power, inverter output reactive power, inverter status, point of common coupling (PCC) voltage, PCC current, PCC power, PCC reactive power, grid status, and PV power plant component status are measured and recorded with 1 minute interval time or faster by the solar power station monitoring system. The solar power station monitoring architecture is presented in Figure 42. The grid status, it includes the normal grid operation and failure such as under/over voltage, under /over frequency, line fault, plan and unplanned shutdown, etc. and PV power plant component status includes normal component operation and component failure such as disconnect from grid, active power reduction, switchgear open circuit, Ring Main Unit (RMU) that feet to the inverter substation open circuit (for loop topology), the transformer switchgear open circuit, inverter fault, inverter degradation due to high temperature, the total current of array box fault, switch disconnector/circuit breaker open circuit at the array box, and the array channel current fault, etc. The list of sensors and instrument that used for measuring the significant parameters in the 6 large-scale commercial PV power plant are available in Table 30.

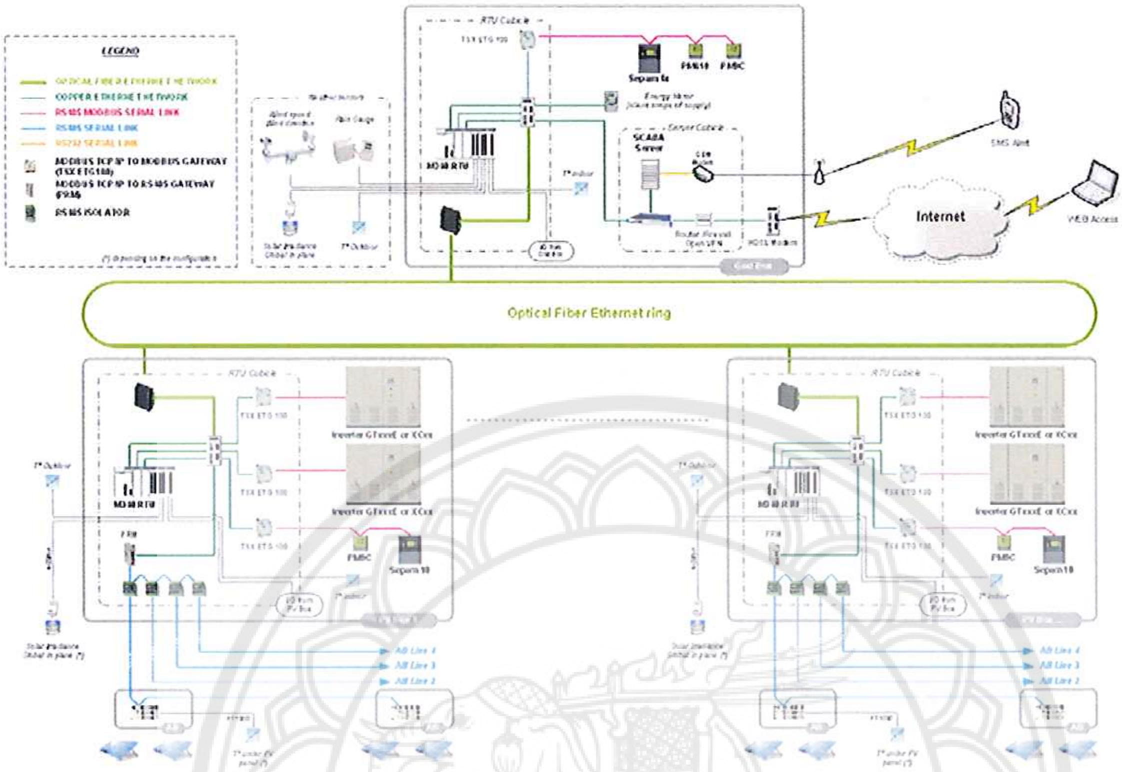


Figure 42 The solar power station monitoring architecture
(source from Schneider Electric)

For solar irradiance, ambient temperature, and PV module temperature, their measured data are converted to digital signal and transfer to the server of the PV power plant monitoring system by RS 485 or fiber optic cable. PV array voltage, PV array current, inverter output voltage, inverter output current, inverter output power, inverter output reactive power, and inverter status are measured by the embedded sensors in the inverters while PCC voltage, PCC current, PCC power, and PCC reactive power are measured by power meter. The grid status is measured by protective relay and PV power plant component status is signaling to RS 485 converter by itself. These measured data are transferred to the server of the solar farm monitoring system by RS 485 of inverters, power meter, protective relay, and RS 485 converter. All measure data are recorded in the server of the PV power station monitoring system. For the failure data, they are analyzed and validated that possible classify in 3 failure groups that are internal impact, external impact and no impact to the PV power plant power production. These impact will be used for the final calculation of the PV power station availability and the mathematic model comparing.

Table 30 The list of sensors and instrument that used for measuring the significant parameters in both PV power plant

Parameters	Sensors and instrument					
	A	B	C	D	E	F
Solar irradiance	CMP 11 pyranor meter					
Ambient temperature	RTD pt-100					
PV module temperature	RTD pt-100					
PV array voltage and current	Sensors in an Array box					
Inverter output voltage, current, power, and reactive power	Embedded sensors in an Inverter					
Inverter status	Embedded sensors in an Inverter					
PCC voltage, current, power, and reactive power	Power meter					
Grid status	Protective relay					
PV power plant component status	Component signal output					

The flow chart of the process for data collection and evaluation is displayed in Figure 43 and the data categorize and analysis procedure is illustrated in Figure 44. The problem causes are possible from internal and external factor that the external factor is mainly influenced by grid or utility failures such as under/over voltage, under/over frequency, line fault, plan and unplanned shutdown, etc. while internal factor is importantly dominated by PV power plant component and equipment such as PV module, DC combiner box, inverter, transformer, switchgear, RMU, cable, structure, control system, accessories plan, unscheduled shutdown etc. The fault can be categorized by the root cause of the failure that demonstrated in Figure 45. The data collection and categorize will base on the assumption that the 20% of cases are responses to 80% loss of the energy and 5 % of cases make up 50% loss that will make more the accurate the action plan for the preventive and corrective action plan to improve the availability.

To analyze the reliability and availability of the large-scale commercial PV power plant in Thailand, the unsupplied energy will calculate to determine for the actual plant availability, it will calculate base on an alarm list that impact in the energy not supply which was recorded by the monitoring system, the formula is theoretical energy minus the energy supply to utility. From the result of energy not supply will lead to calculate for reliability and availability for the individual plant (6 PV power plant).

Efficiency and performance evaluation

The analysis and evaluation processes are based on IEC 61724 standard and EU Guidelines, 4.3 [39]. These processes are used to evaluate the efficiency and performance of the 6 large-scale commercial PV power plant in this dissertation. The important parameters for analysis is presented follow this:

$$Y_r = H_I/G_{ref} \quad (1)$$

$$Y_A = E_A/P_0 \quad (2)$$

$$Y_f = E_{use,PV,day}/P_0 \quad (3)$$

$$PR = Y_f/Y_r \quad (4)$$

$$L_C = Y_r - Y_A \quad (5)$$

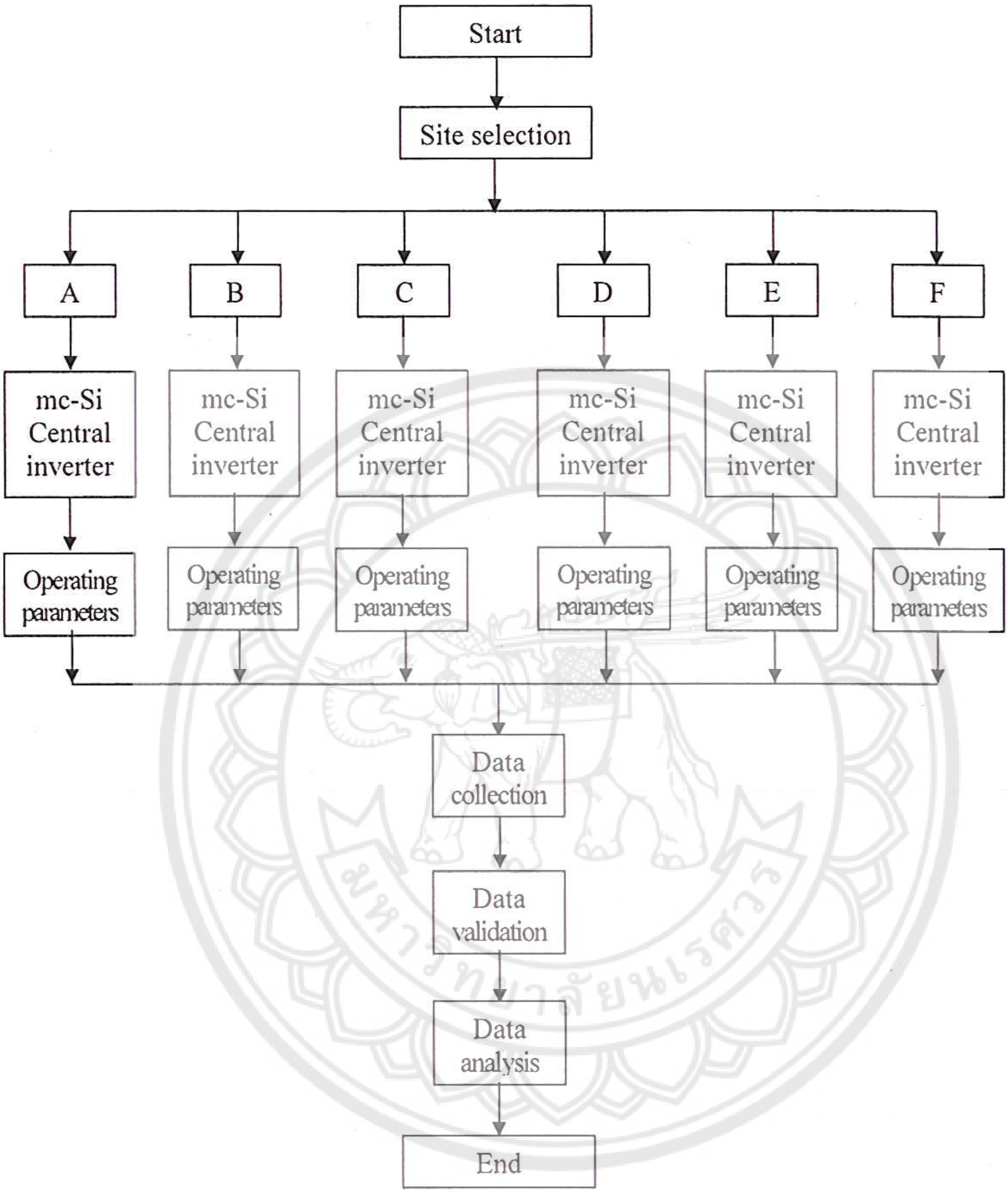


Figure 43 The flow chart of the process for data collection and evaluation

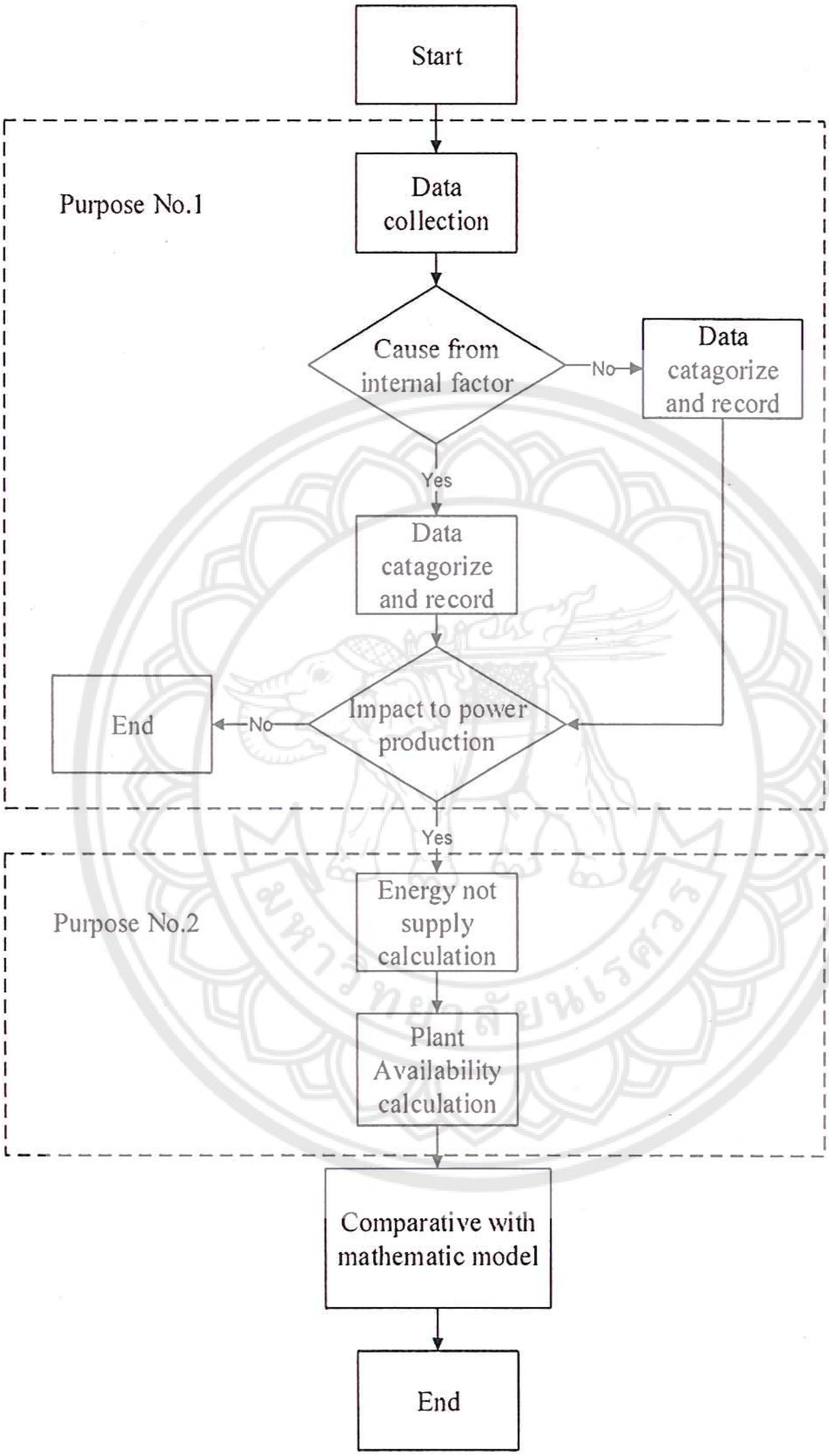


Figure 44 The data categorize and analysis procedure

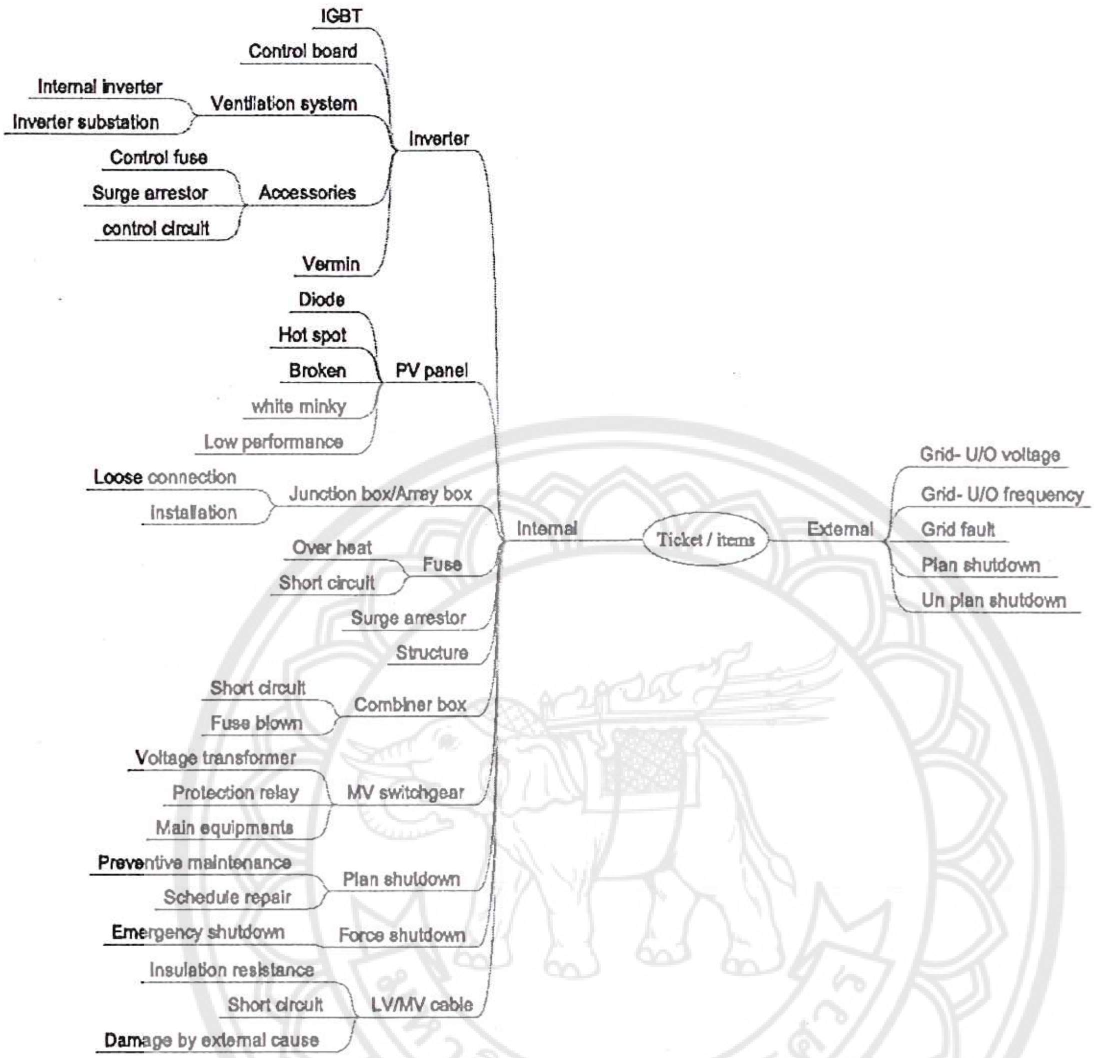


Figure 45 The fault can be categorized by the root cause of the failure

$$L_S = Y_A - Y_f \quad (6)$$

$$L_T = L_C + L_S \text{ or } Y_r - Y_f \quad (7)$$

Y_r = Reference yield (h/d)

H_I = Global irradiation in the plane of the array (kWh/m^2)

G_{ref} = STC reference in plane irradiance (W/m^2)

Y_A = Array yield (h/d)

E_A = Annual mean yields (kWh)

P_0 = Nominal power (kW_p)

Y_f = Final PV system yield (h/d)

$E_{use,PV,day}$	=	Direct PV energy contribution to use (kWh)
PR	=	Performance ratio
L_C	=	Array capture losses (h/d)
L_S	=	System losses (h/d)
L_T	=	Total losses
h/d	=	Specific energy of 1 kW_p PV system that operate at rated capacity for 1 hour/day
Reference yield (Yr)	=	The solar energy theoretically available per kilowatt peak of installed PV per day.
Array yield (Y_A)	=	The number of hours per day that the array would need to operate at it nominal power P_0 to contribute the same daily array energy to the system as was monitored.
Final PV system yield (Y_f)	=	The portion of the daily energy of the entire PV plant which is delivered to the load per kilowatt peak of installed PV array.
Performance ratio (PR)	=	The overall effect of losses on the array's nominal power due to array temperature, incomplete utilization of irradiation, and system component inefficiencies or failures.
Array capture losses (L_C)	=	The losses are caused by operating cell temperatures higher than 25 °C (thermal capture losses) and by miscellaneous causes such as low irradiance, wiring, string diodes, partial shading, contamination, snow covering, non-homogenous irradiance, maximum power point tracking errors, reduction of array power caused by inverter failures or by fully charged accumulator (standalone systems), spectral losses, losses caused by glass reflections (use of pyranometers)
System losses (L_S)	=	The losses are gained from inverter conversion losses in grid-connected systems and from accumulator storage losses in stand-alone systems.
Total losses (L_T)	=	The summation of L_C and L_T that represent the overall loss in PV system.

Availability and reliability evaluation

1. Availability and reliability theory

A few standard reliability metrics are generally used for expressing and evaluating the failures number or downtime of a system. Availability definitions and standard metrics have been developed for industry-specific but grid connected inverters has no industry-specific standard that reliability metrics have been adopted. In addition, some metrics are normally used without specifying the details of their definitions. What follows is the reliability metrics that can be useful by themselves or adapted for application to PV inverters. Reliability, commonly denoted R or R(T), is ordinarily defined as the probability of success, the idea that an item is fit for a purpose with respect to time, the capacity of a designed, produced or maintained item to perform as required over time, the capacity of a population of designed, produced or maintained items to perform as required over specified time, the resistance to failure of an system over time, the durability of an system, or the probability that a system will operate properly for a specified time period under the design operating conditions without failure. Statistically, reliability can be expressed as: [11]

$$R(T) = 1 - F(T) = 1 - \int_{0}^{T} f(t)dt \tag{8}$$

R(T) = Reliability

F(T) = The probability of failure over a specified time period T

f(t) = The failure probability distribution

Clearly, for this definition of reliability to be meaningful, the time interval, (T), must be stated. In addition, failure must be clearly defined. For example, in the case of an inverter, failure may be defined simply as the inability to produce power, or it may include loss of auxiliary functions such as data transmission. With the increasing complexity of remote monitoring and control systems at the inverter level, this distinction is becoming increasingly important. For PV inverters, R(T) can be estimated for a population of N inverters that are fielded as:

$$R(T) = 1-(N_f(T)/N) \tag{9}$$

N = Population of inverters that are fielded

N_f = the total number of inverters that failed in the sample population during the time period (0,T)

Mean time to failure (MTTF) and mean time between failures (MTBF) are commonly used metrics in the PV inverter industry, but are also some of the most difficult to interpret. Strictly defined, MTTF is the expected time to failure (and replacement) of non-reparable systems such as residential PV inverters:

$$MTTF = \int_0^\infty t f(t)dt \tag{10}$$

MTTF = the expected time to failure and replacement of non-reparable systems

In the case of reparable systems such as commercial PV inverters, MTBF is used, and is defined similarly as the expected time between two successive failures (and repairs). For brevity, MTTF is used here to also represent MTBF. Several considerations should be taken into account when specifying or interpreting MTTF. Most of these arise from the fact that MTTF is typically estimated with the following equation:

$$MTTF = T_{Total} / Y \tag{11}$$

T_{Total} = The total number of inverter hours for a given population

Y = the total number of failures in that population during that time period

One important consideration specific to estimating MTTF with equation 11 is that it produces an average value for the interval from which the data is taken. Referring to the bathtub curve, failure rates are typically changing during the infant mortality and wear-out periods. Therefore, using field data from these periods to calculate MTTF will result in an average failure rate for that time period, and does not provide information about the changing failure rate, which can be very important in understanding the expected total number of failures during the lifetime of an inverter population.

The renewal function, $M_i(T)$ gives the expected number of failures of a component during the time interval (0,T). This function takes into account both the failure probability distribution, and immediate renewal of the component after repair. The renewal function is the solution to the fundamental renewal equation:

$$M_i(T) = F_i(T) + \int_0^T M_i(T-t) f_i(t)\,dt \qquad (12)$$

$M_i(T)$ = the expected number of failures of a component during the time interval (0,T)

This equation is recursive in $M_i(T)$, and, for most failure probability distribution functions, must be solved numerically. The expected number of repairs per unit time (per year for example) is the differential of $M_i(T)$:

$$m_i(t) = dM_i(t) / dt \qquad (13)$$

$m_i(t)$ = The expected number of repairs per unit time

Note, that equations 21 and 22 are specific to a single component in an inverter. To estimate the number of repairs of all component in an inverter, the component renewal functions can be summed.

A simple nonparametric failure rate can show this either cumulatively or as a rate. For a sample population of N inverters with at least T years of operation, the cumulative failure rate can be calculated from the number of failures observed. The average number of cumulative failures per inverter in the first T years of operation for a given inverter population can be estimated as,

$$CFR(T) = \frac{1}{N}\sum_{j=1}^{N} Y_j(T) \tag{14}$$

CFR(T) = The average number of cumulative failures per inverter in the first

T years of operation for a given inverter population

$Y_j(T)$ = The number of failures or repairs for the j-th inverter on the interval (0,T)

N = The total number of inverters in the sample population

To calculate the failure and/or repair rate from the cumulative failure rate, differentiate:

$$FR(T) = dCFR(t) / dt \tag{15}$$

Note that CFR(T) and FR(t) are similar to $M_i(T)$ and $m_i(t)$, respectively. The difference is that $M_i(T)$ and $m_i(t)$ are based on fi(t) and can be used to predict failure rates for any time period, while CFR(T) and FR(t) are based on field data and are limited to the time period of the data provided. However, FR(t) may still be useful for failure prediction by serving as a data set for fitting a parameterized failure rate model that can be extrapolated into the future. Another important note is that CFR(T) and $M_i(T)$ are not cumulative failure probability distributions like F(T), which, by definition, must approach unity as T goes to infinity. CFR(T) and $M_i(t)$ can be greater than unity because they reflect the number of expected failures of reparable equipment, which can be repaired more than once over a time interval.

One of the most basic ways of quantifying lost energy production is simply inverter downtime multiplied by average inverter power. Given existing field data from a population of N inverters that operated for time T, it is possible to estimate average cumulative downtime per inverter on an interval (0, T) by summing the downtimes due to individual inverter failures:

$$D(T) = \frac{1}{N}\sum_{j=1}^{N} D_j(T) \qquad (16)$$

D(T) = Average cumulative downtime per inverter on an interval (0,T)

$D_j(T)$ = The downtime due to failure and repair of the j-th inverter on the interval (0,T)

To calculate the downtime per inverter per unit time from the average cumulative downtime, simply differentiate:

$$d(t) = dD(t) / dt \qquad (17)$$

d(t) = Downtime per inverter per unit time from the average cumulative downtime

When calculating downtime, an important distinction is whether it excludes hours when energy cannot be produced such as nighttime.

Availability is considered one of the most important reliability metrics for reparable systems. It is generally defined as the ratio of (a) the total time a functional unit is capable of being used during a given interval to (b) the length of the interval, the probability that a system will operable when called upon. Likewise, unavailability is the probability that a system will not be available when called upon. There are many forms and definitions of availability, mostly differing by what is included in the downtime and total time, and whether steady state is assumed or not. One of the forms most applicable to PV inverters is operational availability (A_O)

$$A_O = \text{Uptime} / \text{Total time} = 1\text{-}(\text{Downtime} / \text{Total time}) \qquad (18)$$

A_O = Operational availability

Uptime= The time that the equipment perform its intended purpose when call upon

Downtime= The time that the equipment dose not perform its intended purpose when call upon

Total time= The total time that the equipment could be called upon to perform it intended purpose

In the definition of A_O, downtime includes both indirect and direct maintenance and repair time as well as logistics time and waiting or administrative downtime. In calculating A_O for PV inverters, two main approaches can be taken: considering only times when power production is possible (daylight hours), or considering all field time (both daytime and nighttime). IEEE Std. 762, which defines metrics for electric power generating equipment, seems to suggest availability should consider both daytime and nighttime hours by defining Availability Factor (AF) as:

$$AF = (AH / PH)\ 100 \tag{19}$$

AF = Availability Factor

AH = Available hours, which includes both service hours (producing power) and reserve shutdown hours (available to but not producing power)

PH = Period hours, which is the entire time the equipment is in the active state (but not necessarily producing power)

AH therefore may consist of both daytime and nighttime hours when a PV inverter is able to produce power. For PV inverters, AF is very simple to calculate: the downtime hours are simply added together, whether they occur during daytime or nighttime, and are divided by the total field time of the inverter, and the result is subtracted from unity. An alternate operational availability metric for PV inverters, which we will term A_{DC}, could be defined whereby Total Time is the time when conditions are sufficient to produce power, as opposed to the "period time" or "active time" described by IEEE Std. 762. Note that this approach would not include in total time any of the following:

1. Periods of darkness from approximately sundown minus 30 minutes to sunrise plus 30 minutes.

2. Cloudy or bad weather hours when there is insufficient irradiance or when weather conditions prohibit the field from generating power such as when the arrays are pointed off sun during very high winds.

3. Times when there is natural or induced damage to the PV field or to the AC grid, such as being hit by lightning.

To yield a correct formulation of availability for A_{DC}, Downtime must also only be accrued during periods when Total Time is accrued.

The availability calculation for PV power plant is based on the generating electrical energy by the installed PV system and the unsupplied electrical energy. The availability level equation in % is presented follow this:

$$\text{Availability Level} = \frac{E_U}{E_U + E_{NS}} \tag{20}$$

E_U = The supply electrical energy to utility (kWh), the energy inject by the PV system to grid that measured at the point of connection.

E_{NS} = The unsupplied energy during unavailability of the PV system (kWh)

Energy not supplied (E_{NS}) is calculated from the main equipment that detected for leading to energy losses. The states of the equipment and the power limitation by the degradation are taken into account to calculate E_{NS}. The calculation of E_{NS} is displayed as following:

$$E_{NS} = E_{Theoretical} - E_U \tag{21}$$

$E_{Theoretical}$ = The Energy that should be produced during the unavailability time (kWh)

For the theoretical energy calculating method, it is based on the energy that should be generated. The energy is calculated from the average performance ratio. Thus, the theoretical energy equation is possible express as following:

$$E_{Theoretical} = PR_{Ref} \text{ x } E_{ideal} \quad (22)$$

$$E_{ideal} = \frac{H_i}{G_{ref}} \text{ x } P_{peak} \quad (23)$$

$$PR_{Ref} = \sum_{30days} \frac{E_{TU}}{E_{Ideal}} = \frac{\sum_{30days} E_{TU}}{\sum_{30days} \frac{H_i}{G_{ref}} \text{ x } P_{peak}} \quad (24)$$

PR_{Ref} = The average performance ratio for 30 days of the PV power plant

E_{ideal} = The ideal energy that PV power plant is performing at 100% without any loss at 25°C

H_i = The solar energy measured during Δt time (Wh/m²) by a pyranometer in the PV array plain

G_{ref} = The reference irradiation (=1000 w/m²)

P_{peak} = The installed PV system capacity (kWp)

2. Method to develop the reliability and availability formula for the large Photovoltaic power plant

The analysis is follow the Practical Reliability Engineering [11]. Failure rate is a parameter that highly used in reliability performance by tracking the difference type of failure along with the failure number that is accrued by a product during its field service. Failure rate equation is displayed as following:

$$\lambda = K/T \quad (25)$$

λ = The failure rate (F)

K = The number of failure and T is the total operating time

Failure rate may be expressed in term of failure per hour but the figure is quite small. Therefore, it is commonly expressed in failure per one million hours (10^6 hour).

Mean Time Between Failure (MTBF) is the ratio of total operating time to the total number of failure.

$$MTBF = T/K \tag{26}$$

T = The total operating time

K = the number of failure

The MTBF is the reciprocal of the failure rate and can be express as:

$$MTBF = E(\tau) = \int_0^{\alpha} R(t)dt \tag{27}$$

$$MTBF = 1/\lambda \tag{28}$$

The exponential reliability distribution is a reliability performance of equipment that usually described by mathematic function as knows as reliability distribution. The reliability is the probability that the component does not fail during interval [0,t]. The exponential reliability distribution equation is expressed as the following:

$$P(a < x < b) = \int_a^b f(x)dt \tag{29}$$

When the device is only subject to failure that occur at random intervals and expect failure number is the same for equally long operating periods.(i.e. The failure rate λ is constant).

$$R(x) = 1 - f(x) \tag{30}$$

$$F(t) = \lambda e^{-\lambda t} \tag{31}$$

The probability no failure occurring before time t

$$R(t) = \int_0^t f(t)dt \tag{32}$$

$$R(t) = e^{-\lambda t} \tag{33}$$

The exponential reliability distribution is possible applied during the random failure period of the bathtub curve. The value e is the base of natural logarithm and λ is a constant that is called the chance failure rate. The value t is an arbitrary operating time for measuring the reliability. Exponential reliability distribution example is showed in Figure 46.

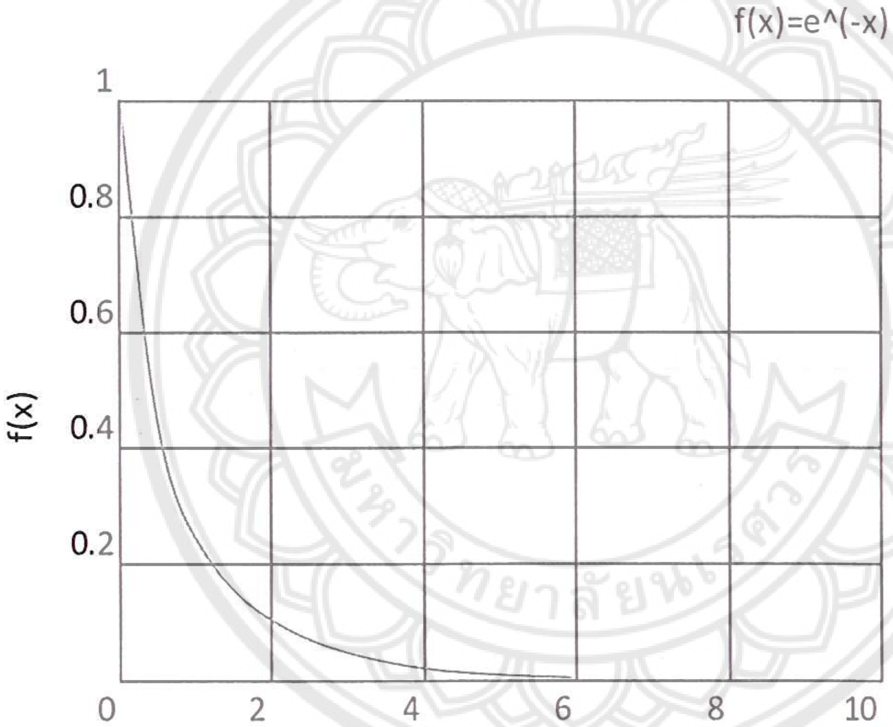


Figure 46 Exponential Reliability distribution

Unreliability is the function that adverse function of reliability. It is possible expressed in relation to reliability as following:

$$Q = 1 - R(t) \tag{34}$$

System reliability model is a serial reliability model that each component of the system has to be working for overall system success. The system reliability model structure is illustrated in Figure 47 and its mathematical model is expressed as following:

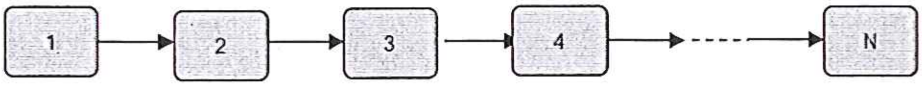


Figure 47 The system reliability model structure

$$R = R_1 \, X \, R_2 \, X \, R_3 \, X \, R_{4---} X \, R_n \tag{35}$$

$$R(t) = e^{-(\lambda t1+\lambda t2+\lambda t3+\lambda t4+--+\lambda tn)} \tag{36}$$

Inherent availability (A_i) is the probability that an item will operate satisfactorily at a given point in time when used under stated conditions in an ideal support environment. It excludes logistics time, waiting or administrative downtime, and preventive maintenance downtime. It includes corrective maintenance downtime. A_i is generally derived from analysis of an engineering design and is calculated as the mean time to failure (MTTF) divided by the mean time to failure plus the mean time to repair (MTTR). It is based on quantities under control of the designer. A_i can be express as following:

$$A_i = MTTF/(MTTF + MTTR) \tag{37}$$

MTTF = The Mean Time Between Failure

MTTR = The Mean Time To Repair

From the Inherent availability (A_i) definition, unavailability can be express as following:

$$U = \frac{MTTR}{MTBF+MTTR} \tag{38}$$

When $MTTR << MTBF$, it is possible to approximate U as following:

$$U = \frac{MTTR}{MTBF} \tag{39}$$

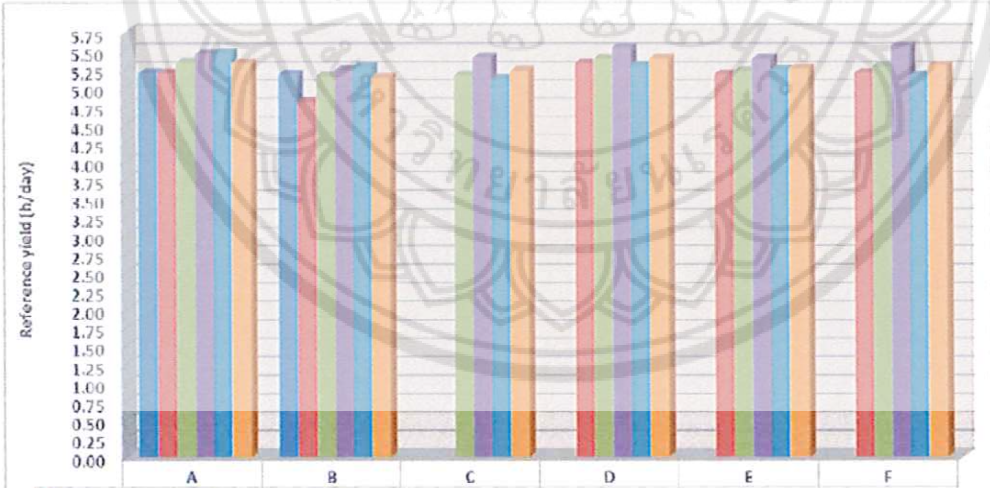
$$U = MTTR\ X\ \lambda \tag{40}$$

CHAPTER IV

RESULT AND DISCUSSION

Efficiency and performance evaluation result

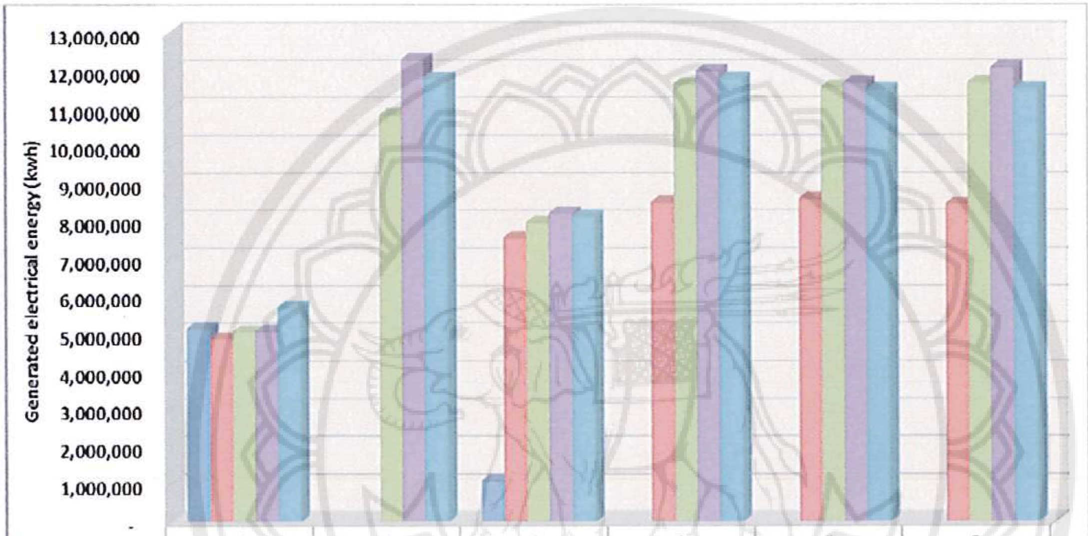
A and B solar power stations have been COD since 2011, D E, and F PV power stations have been COD since 2012, and C PV power plant has been COD since 2013. Therefore, the collected data that used in the efficiency and performance evaluation of plant A and B solar farms are in 2011 to 2015, D E, and F solar power plant are in 2012 to 2015, and C solar power station is in 2013 to 2015. The data recorded for each PV power station groups are, 5, 4, and 3 years respectively. Annual daily average solar radiation of the 6 large scale commercial PV power plants in each site during 2011 to 2015 is demonstrated in Figure 48. From the Figure, it is obviously indicating that the annual daily average solar radiation of the 6 large scale commercial solar farms is not vitally different in the same year. When compares with the annual daily.



	A	B	C	D	E	F
2011	5.21	5.18				
2012	5.20	4.87		5.34	5.19	5.20
2013	5.35	5.16	5.17	5.39	5.23	5.29
2014	5.46	5.24	5.41	5.55	5.40	5.57
2015	5.47	5.29	5.12	5.31	5.25	5.17
Average	5.34	5.14	5.24	5.40	5.27	5.31

Figure 48 Daily average solar irradiance of the 6 large scale commercial PV power plants in each site during 2011 to 2015

Average solar radiation of Thailand at 5.05 kWh/m² day that given by DEDE, all of solar radiation in each site is slightly higher than the average value except B in 2012. The generated electrical energy of the 6 large scale commercial PV power plants in each site during 2011 to 2015 is illustrated in Figure 49. In the Figure, the generated electrical energy of the 6 large scale commercial solar power station is mainly dominated by the solar radiation of the sites in each year.

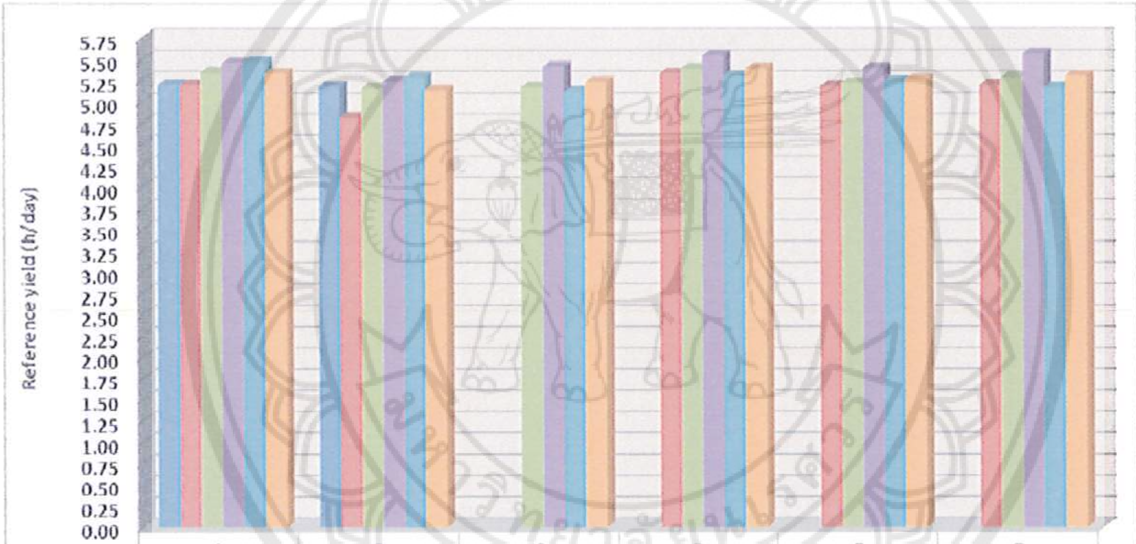


	A	B	C	D	E	F
2011	5,132,480		1,097,374			
2012	4,864,205		7,559,088	8,482,287	8,583,152	8,444,231
2013	5,039,043	10,823,042	7,944,416	11,619,524	11,534,894	11,667,987
2014	5,054,773	12,278,280	8,197,248	11,978,352	11,665,519	12,061,167
2015	5,685,458	11,773,928	8,113,116	11,773,861	11,477,573	11,503,661

Figure 49 The generated electrical energy of the 6 large scale commercial PV power plants in each site during 2011 to 2015

However, the generated electrical energy of B in 2011 is about one eighth of the normal electrical energy when compare with the generated electrical energy in other years because B generated power only in the November and December. A little bit lower generated electrical energy of D, E, and F in 2012 when compare with the generated electrical energy in other years is also the same reasons with B in 2011. These PV power plant started to generate power in the late of March 2012.

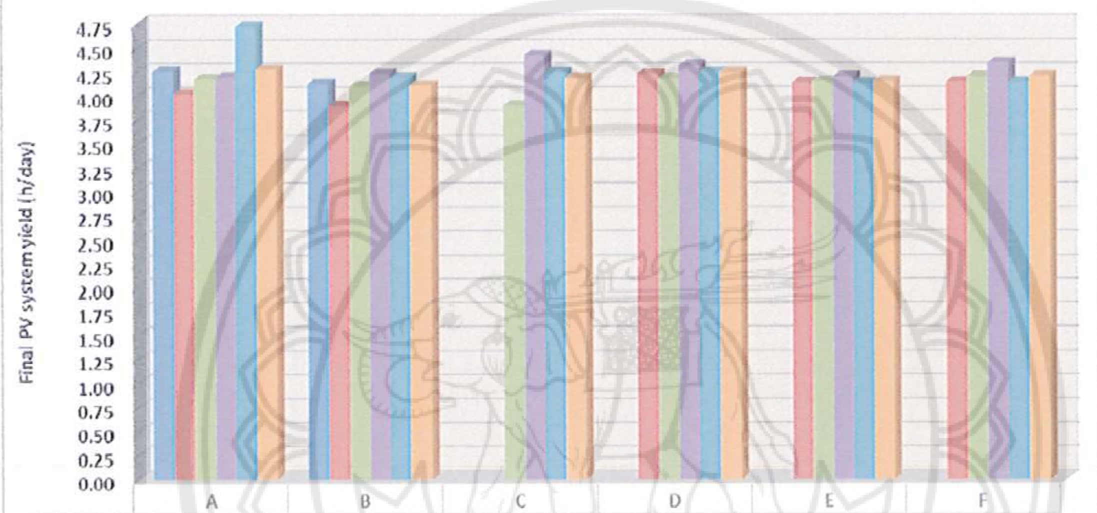
Nevertheless, the recorded data from these PV power plant monitoring systems are not complete for every important parameter that resulted in impossible to evaluate every PV power plant performance parameter. Especially, Y_A L_C and L_S cannot evaluate from the collected data. Only L_T that is the summation of L_C and L_S is possible calculated from these data. Consequently, only Y_r, Y_f, L_T, and PR are estimated in this thesis. After analyzing and evaluating the recorded data as the technical analysis processes of IEC 61724 standard and EU Guidelines, the efficiency and performance evaluation result of the 6 large scale commercial PV power plants during 2011 to 2015 such as Y_r, Y_f, L_T, and PR are demonstrated in Figure 50, 51, 52, and 53 respectively.



	A	B	C	D	E	F
2011	5.21	5.18				
2012	5.20	4.82		5.34	5.19	5.20
2013	5.35	5.16	5.17	5.39	5.23	5.29
2014	5.46	5.24	5.41	5.55	5.40	5.57
2015	5.47	5.29	5.12	5.31	5.25	5.17
Average	5.34	5.14	5.24	5.40	5.27	5.31

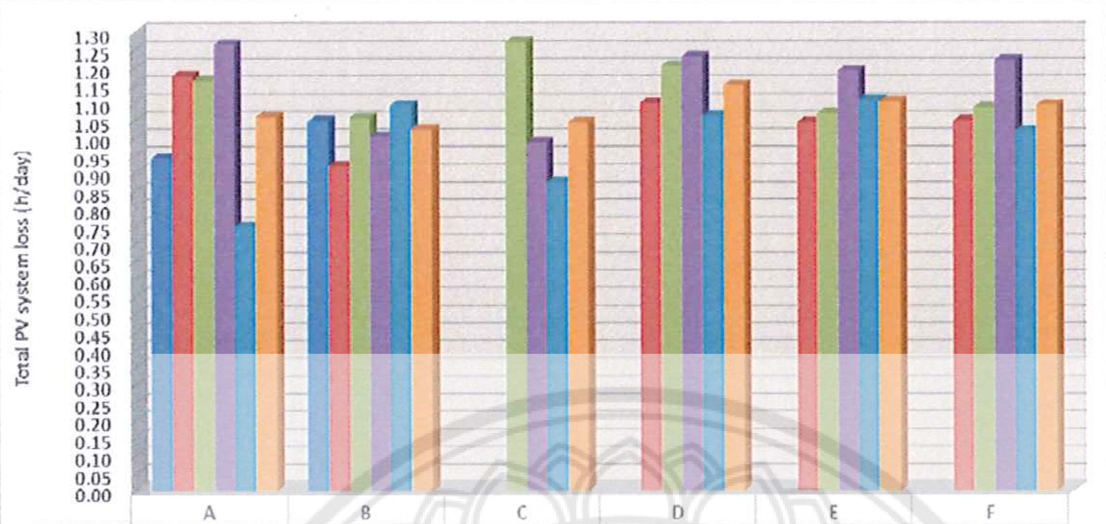
Figure 50 Y_r of the 6 large scale commercial PV power plants during 2011 to 2015

From the Figure 50, average Y_r of the 6 large scale commercial PV power plants during 2011 to 2014 are in 4.82 to 5.57 h/day range that really remarkable wild gap. However, Y_r at 4.82 h/day is occurring only 1 time for B in 2012 while Y_r other large scale commercial PV power stations and B in other years are higher than or equal 5.12 h/day. From this point, it is possible to overlook Y_r at 4.82 h/day and estimate Y_r of the 6 large scale commercial solar farm in 5.12 to 5.57 h/day range that not significantly different. From the Figure 51, average Y_f of these solar power plants in each year during 2011 to 2015 is approximately the same that are in 4.15 and 4.35 h/day range. From the Figure 52 almost of L_T in each year of the 6 large scale commercial PV power station is not importantly different except A in 2015 that is pretty lower than usual.



	A	B	C	D	E	F
2011	4.26	4.14				
2012	4.03	3.90		4.24	4.15	4.15
2013	4.18	4.11	3.90	4.19	4.16	4.21
2014	4.20	4.24	4.43	4.32	4.21	4.35
2015	4.72	4.19	4.24	4.24	4.14	4.15
Average	4.28	4.11	4.19	4.25	4.16	4.21

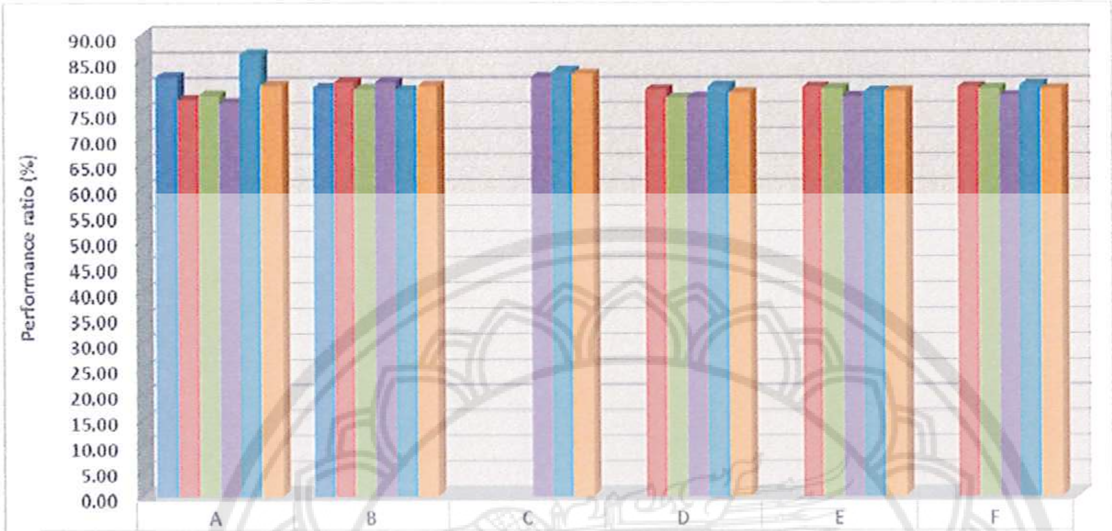
Figure 51 Y_f of the 6 large scale commercial PV power plants during 2011 to 2015



	A	B	C	D	E	F
2011	0.94	1.05				
2012	1.18	0.92		1.10	1.05	1.05
2013	1.16	1.06	1.27	1.20	1.07	1.09
2014	1.27	1.00	0.99	1.23	1.19	1.22
2015	0.75	1.09	0.88	1.06	1.11	1.02
Average	1.06	1.03	1.05	1.15	1.10	1.09

Figure 52 L_T of the 6 large scale commercial PV power plants during 2011 to 2015

Moreover, L_T of A in 2014 and C in 2013 are quite higher than usual. The cause of the higher L_T is possible from the PV system component failure in 2014 for A and the initial PV system component failure for C while lower L_T is possible from the very success solution for the PV system component failure. The highly reduced L_T of A from 1.27 in 2014 to 0.75 h/day in 2015 is the obviously evident of very success PV system component failure solution. PV module and other PV system component replacing are the most common solutions for improving L_T. Especially, A that CIS PV module with higher power than name plate in the initial period is used in this solar power plant has far higher electrical energy in the first year than the second year that the CIS PV module power reduce to the stabilize power. Therefore, L_T of the 6 large scale commercial solar power stations are in 0.88 to 1.23 h/day when not including the higher and lower L_T than usual. From the Figure 49, PR result is in the same trend with Y_f and invert trend with L_T. PR of A in 2014 and C in 2013 are pretty lower than usual while A in 2015 is really higher than usual. The higher and lower PR than usual is result from higher and lower L_T than usual. Consequently, PR of the 6 large scale commercial solar power stations are in 76.83 to 82.90% when not including the higher and lower PR than usual.



	A	B	C	D	E	F
2011	81.86	79.77				
2012	77.39	80.88		79.38	79.86	79.84
2013	78.25	79.52		77.66	79.54	79.47
2014	76.83	80.84	81.75	77.82	77.92	78.06
2015	86.29	79.31	82.90	79.98	78.88	80.23
Average	80.13	80.06	82.33	78.71	79.05	79.40

Figure 53 PR of the 6 large scale commercial PV power plants during 2011 to 2015

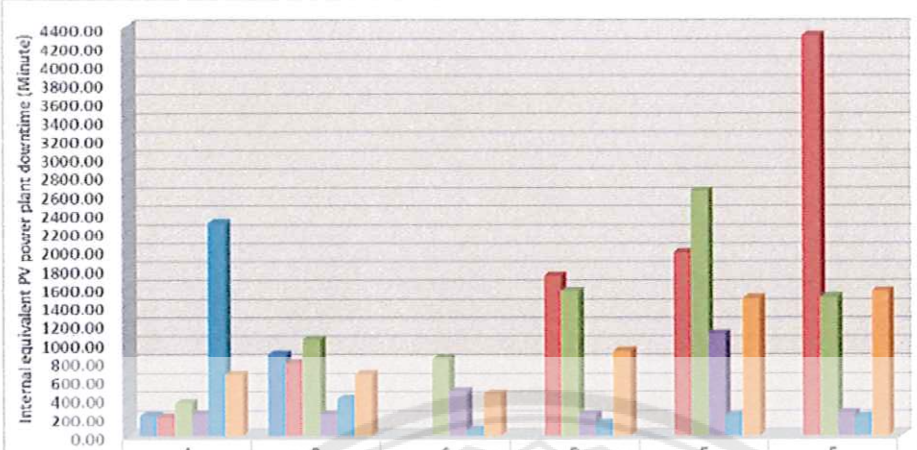
From the efficiency and performance evaluation result, it found that almost of evaluated parameters of the 6 large scale commercial solar power plants have no significant different except A and C that the evaluated parameters are far different in a few years. The far different values of evaluated parameters are from the PV system component failure in 2014 for A and the initial PV system component failure for C. In addition, the very success solution for the PV system component failure in A and C is another cause of the far different values of evaluated parameters. However, the different evaluated parameters of these PV power plant is not directly effect to the availability and reliability evaluation because they are temporary occurring. From these reasons, the reliability and availability evaluation result of the 6 large scale commercial solar power plants are mainly dominated by the PV power plan management and local grid condition because the other factors that effect to the reliability and availability of these PV power plant is almost the same.

Availability and reliability evaluation result

After evaluating the availability and reliability of the 6 large scale commercial solar power plants, the evaluated result is presented as follows:

1. **PV power plant component and grid failures analysis result**

Because of failure time of PV power plant component, and grid effect to the generated power output of the 6 large scale commercial solar power plants in different degree, the failure time of each PV power plant components and grid have to estimate in equivalent PV power plant downtime form. In this form, the failure time of each PV power plant component and grid are multiply with the factor of each PV system component to calculate the equivalent time that the PV power plant completely shut down or stop operation. From the PV power plant component and grid failures analysis during 2011 to 2015, the equivalent PV power plant downtime of the PV power plants component (Internal), grid (External), and total failures of the 6 large scale commercial solar power plants are displayed in Figure 54, 55, and 56 respectively. From Figure 54, the internal equivalent PV power plant downtime of the 6 large scale commercial solar farms are various that depend on many factors.

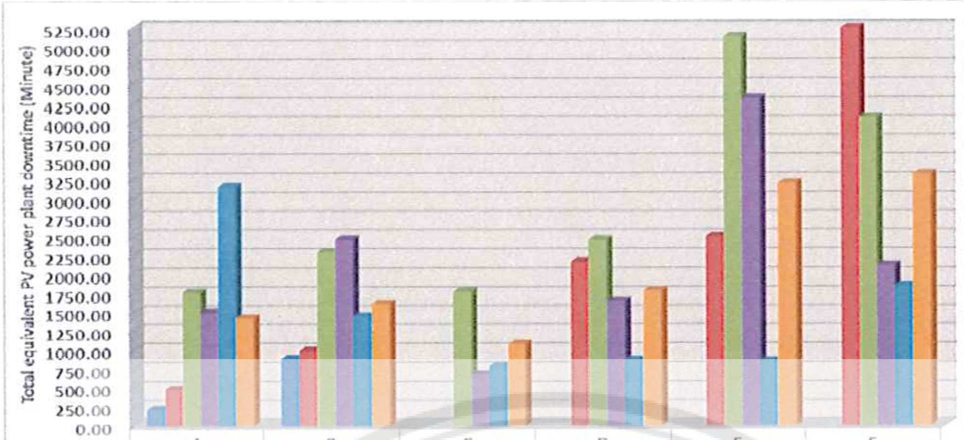


	A	B	C	D	E	F
2011	220.00	880.00				
2012	204.50	783.40		1725.69	1977.62	4308.85
2013	354.98	1039.18	824.77	1564.58	2641.54	1497.62
2014	238.20	230.93	479.92	230.00	1098.54	249.30
2015	2292.80	401.82	62.01	145.09	214.77	203.08
Average	662.10	667.07	455.57	916.34	1483.12	1564.71

Figure 54 The internal equivalent PV power plant downtime the 6 large scale commercial solar power plants during 2011 to 2015

	A	B	C	D	E	F
2011	0.00	0.00				
2012	283.00	210.00		444.00	525.00	940.00
2013	1408.00	1258.00	946.00	893.00	2487.00	2578.00
2014	1260.00	2230.00	207.00	1424.00	3227.00	1873.00
2015	861.00	1048.00	724.00	725.00	639.00	1648.00
Average	762.40	949.20	625.67	871.50	1719.50	1759.75

Figure 55 The external equivalent PV power plants downtime the 6 large scale commercial solar power plant during 2011 to 2015



	A	B	C	D	E	F
2011	220.00	880.00				
2012	487.50	993.40		2169.69	2502.62	5248.85
2013	1762.98	2297.18	1770.77	2457.58	5128.54	4075.62
2014	1498.20	2460.93	686.92	1654.00	4325.54	2122.30
2015	3153.80	1449.82	786.01	870.09	853.77	1851.08
Average	1424.50	1616.27	1081.24	1787.84	3202.62	3324.46

Figure 56 The total equivalent PV power plants downtime the 6 large scale commercial solar power plant during 2011 to 2015

Nevertheless, E and F have far higher internal equivalent PV power plant downtime than other large scale commercial PV power stations that are possible from the location and climate because these PV power plant are located in nearby area that is the lowland with high underground water level and humidity. Moreover, PV power plant components in these solar power plants are the identically same model and lot that is possible has the same defect. These factors are possible dominating to the PV power plant component failure rate of these PV power stations. D also has significantly higher internal equivalent PV power plant downtime than other large scale commercial PV power plants because it has the geography, climate, and PV power plant components like E and F. However, the PV power plant component failure rate is not seriously as F and E because D was COD after F and E about 3 to 4 months. Thus, the operator prepared the solutions to face with these problems and reduced the PV power plant component failure rate in the satisfactory level. For A, B, and C, they are located in the flat foot of the hill that underground water level and humidity are lower than D, E, and F. Moreover, PV power plant components of these solar power stations is different lot from D, E, and F that result in the lower PV power plant component failure rate. From Figure

55, the external equivalent PV power plant downtime of the 6 large scale commercial PV power plants are also diverse that depend on the local grid condition. However, E and F have far higher external equivalent PV power plant downtime than other large scale commercial solar power stations that are result from the weaker local grid condition. From Figure 56, the total equivalent PV power plant downtime of the 6 large scale commercial PV power stations are also different that depend on the internal and external equivalent PV power plant downtime. From this point, E and F have far higher total equivalent PV power plant downtime while C has the lowest total equivalent PV power plant downtime. The overall equivalent PV power plant downtime ratio of the 6 large scale commercial solar power stations during 2011 to 2015 are demonstrated in Figure 57. The Figure clearly indicates that the PV power plant availability is mostly influenced by the external equivalent PV power plant downtime with the ratio at 53.83% while the internal equivalent PV power plant downtime dominates about 46.17% of total. From the internal equivalent PV power plant downtime analysis, the percentage of the PV system equipment failures of the 6 large scale commercial PV power plants during 2011 to 2015 are showed in Figure 58. From the Figure, inverter Insulation, cable, inverter humidity, inverter IGBT, and inverter off-un plan shutdown are the main failures in the 6 large scale commercial PV power station. Inverter Insulation respond most of equivalent PV power plant downtime in D, E, and F while cable and inverter humidity play more important role in equivalent PV power plant downtime in A, B, and C.

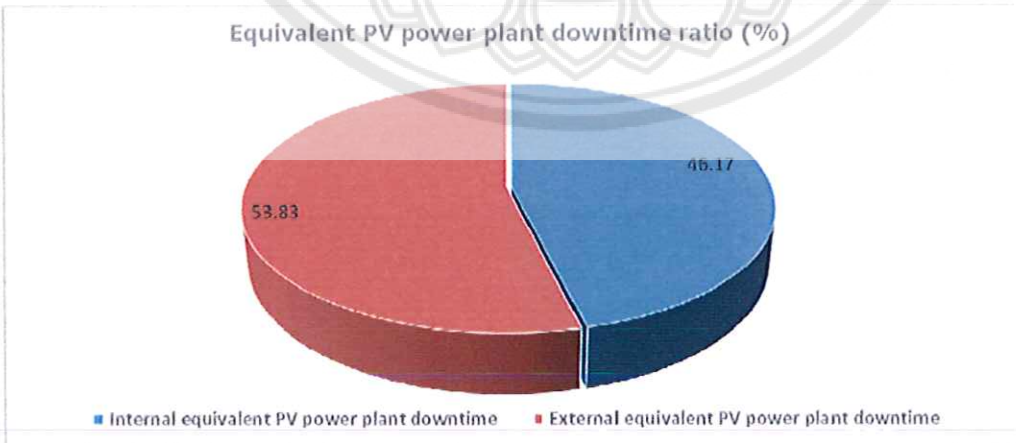
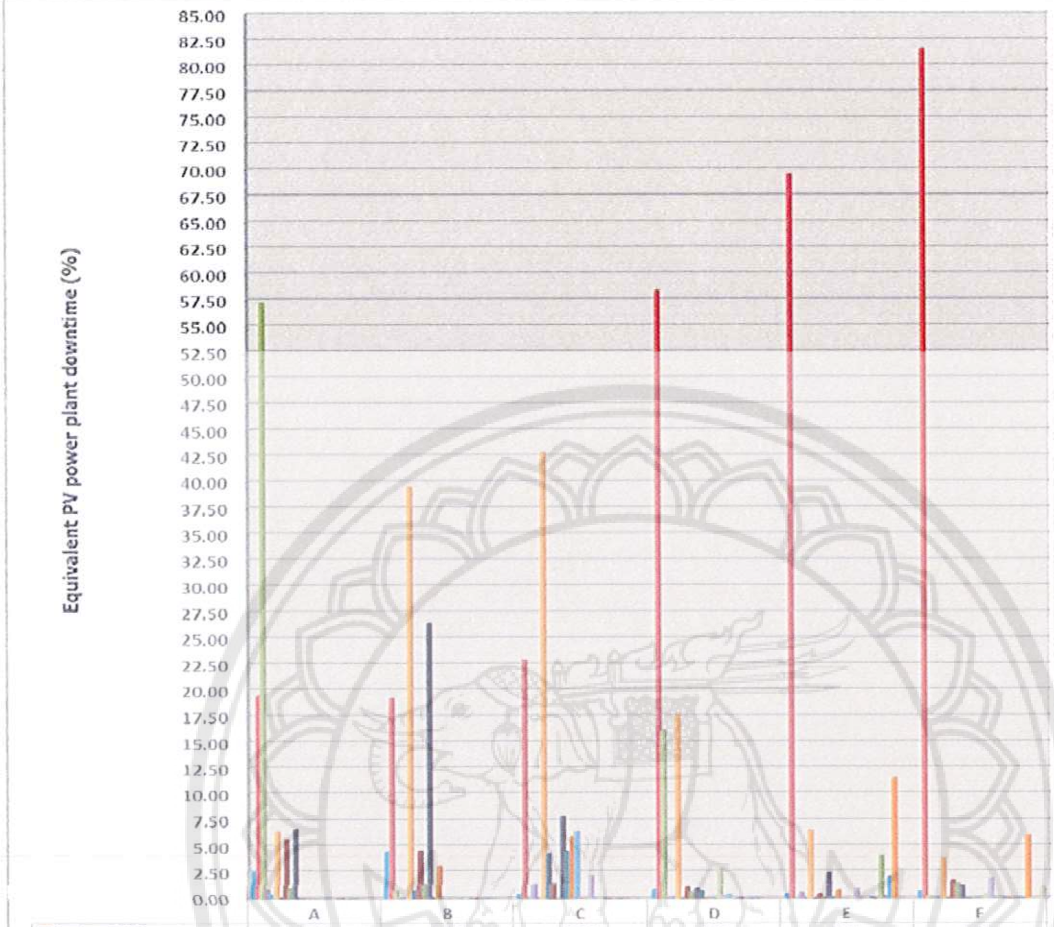


Figure 57 The overall equivalent PV power plant downtime ratio of the 6 large scale commercial solar power stations during 2011 to 2015



	A	B	C	D	E	F
Inv low VAC	2.53	4.46	0.39	0.82	0.41	0.71
Inv Insulation	19.47	19.20	22.91	58.38	69.59	81.56
Cable	57.20	0.74	0.00	16.10	0.00	0.17
Inv over VDC	0.80	0.00	1.32	0.00	0.57	0.00
Inv G4 card	0.38	0.00	0.00	0.00	0.00	0.00
Inv humidity	6.31	39.49	42.84	17.72	6.51	3.79
Inv local E-stop	0.07	0.78	4.22	0.00	0.01	0.00
Inv over temp	5.61	4.52	1.39	1.12	0.41	1.65
Inv UPS	0.97	1.34	0.00	0.72	0.16	1.38
Inv IGBT	6.65	26.38	7.83	0.96	2.38	1.22
Inv control LV	0.00	0.05	4.53	0.75	0.14	0.00
Inv main bord	0.00	3.04	5.92	0.00	0.79	0.00
Inv AC contact	0.00	0.00	6.36	0.01	0.00	0.02
Inv over VAC	0.00	0.00	0.03	0.00	0.00	0.00
Inv DC discon	0.00	0.00	0.03	2.83	0.14	0.35
Inv too cold	0.00	0.00	2.23	0.23	0.92	1.83
160 A DC fuse	0.00	0.00	0.00	0.36	0.00	0.00
Inv high f	0.00	0.00	0.00	0.00	0.03	0.00
Inv over IAC	0.00	0.00	0.00	0.00	0.12	0.00
Inv control unit	0.00	0.00	0.00	0.00	0.01	0.00
Inv drop fuse	0.00	0.00	0.00	0.00	4.05	0.00
Inv earth fault	0.00	0.00	0.00	0.00	0.21	0.00
Inv Interrupt	0.00	0.00	0.00	0.00	2.04	0.00
Inv off-unplan shutdown	0.00	0.00	0.00	0.00	11.53	6.04
Inv switch fault	0.00	0.00	0.00	0.00	0.01	0.00
Inv Com.fault	0.00	0.00	0.00	0.00	0.00	0.16
Inv LV lack fuse	0.00	0.00	0.00	0.00	0.00	1.11

Figure 58 The percentage of the PV system equipment failures of the 6 large scale commercial PV power plants during 2011 to 2015

For inverter Insulation, it is the failure from the lower than limit of the PV array insulation resistant that result from the humidity in PV array, PV module insulation failure, cable insulation failure, and other factors. The lowland with high underground water level and humidity of D, E, and F site locations are extremely stimulating the failure from inverter Insulation while the flat foot of the hill with lower underground water level and humidity of A, B, and C site locations are reducing the failure from inverter Insulation that result in higher failures from cable and inverter humidity. From these reasons, they are supporting the internal equivalent PV power plant downtime analysis result. The overview percentage of the PV system equipment failures of the 6 large scale commercial PV power plants during 2011 to 2015 are showed in Figure 59.

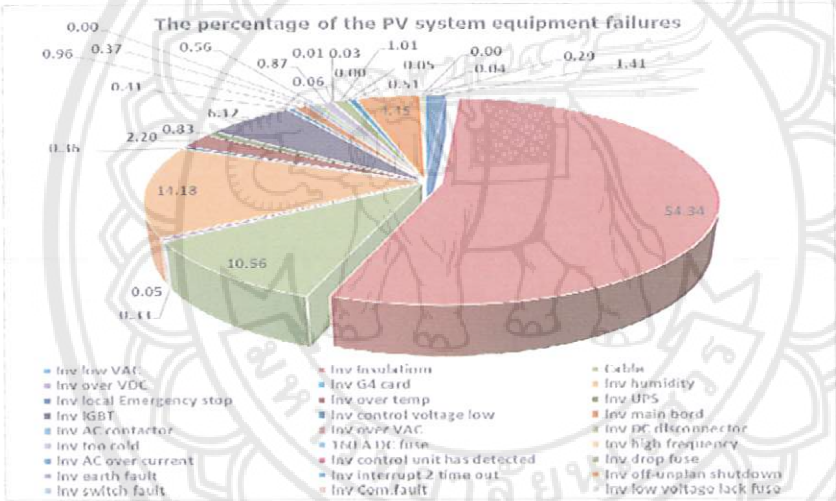
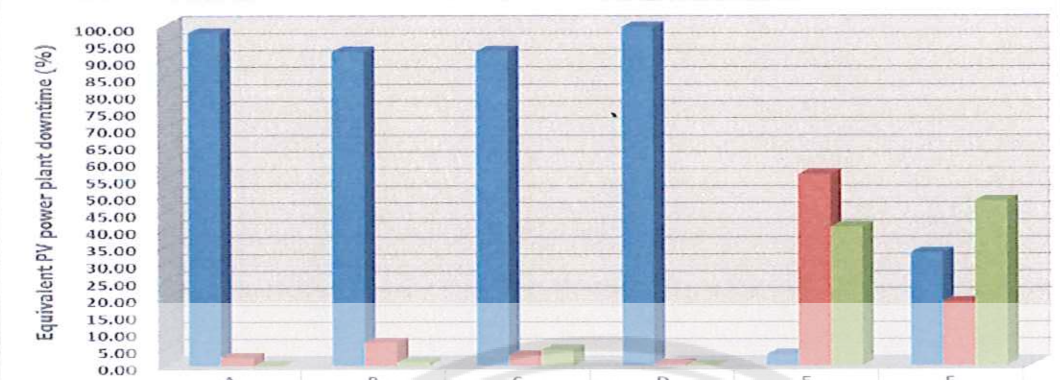


Figure 59 The overview percentage of the PV system equipment failures of the 6 large scale commercial PV power plants during 2011 to 2015

From the Figure, inverter Insulation, inverter humidity, cable, inverter IGBT, and inverter off-un plan shutdown are the top 5 PV power plant component failures that cover about 90 % of internal equivalent PV power plant downtime. From all failure, about 90 % is relating with inverter and about 35 % is directly from inverter. From this point, it is supporting many studies that inverter is the most sensitive component in PV system. From the external equivalent PV power plant downtime analysis, the percentage of the PV grid failures of the 6 large scale commercial PV power plants during 2011 to 2015 are illustrated in Figure 60.



	A	B	C	D	E	F
UV (27)	97.80	92.33	92.43	99.51	3.27	33.13
OV (59)	2.20	6.72	2.93	0.49	56.08	18.58
ROV (59N)	0.00	0.95	4.64	0.00	40.64	48.29

Figure 60 The percentage of the PV grid failures of the 6 large scale commercial PV power plants during 2011 to 2015

From the Figure, under voltage (27) residual over voltage (59N), and over voltage are the major grid failures in the 6 large scale commercial PV power station. Under voltage responds almost of equivalent PV power plant downtime in A, B, C and D while over voltage and residual over voltage play more important role in equivalent PV power plant downtime in E and F. These analysis result is implying that the grid of A, B, C and D have the sufficient load during daytime while the grid of E and F have not enough load during daytime. The overview percentage of the grid failures of the 6 large scale commercial PV power plants during 2011 to 2015 are showed in Figure 61.

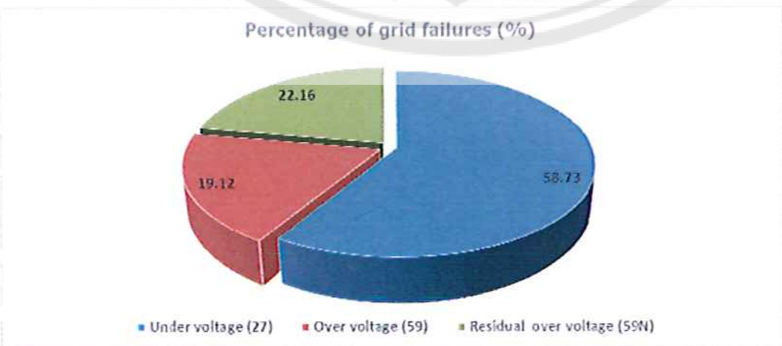


Figure 61 The overview percentage of the grid failures of the 6 large scale commercial PV power plants during 2011 to 2015

From the Figure, under voltage, residual over voltage, and over voltage are the grid failures that cover about 100 % of external equivalent PV power plant downtime. All failure is relating with the grid (Feeder) that these solar farms are connected during feeding generated power. From the total equivalent PV power plant downtime analysis, it is obviously point out that under voltage, inverter Insulation, residual over voltage, over voltage, inverter humidity, cable, inverter IGBT, and inverter off-un plan shutdown are the important failures. That cover than 95 % of total equivalent PV power plant downtime. The overview percentage of the total failures of the 6 large scale commercial PV power plants during 2011 to 2015 are presented in Figure 62.

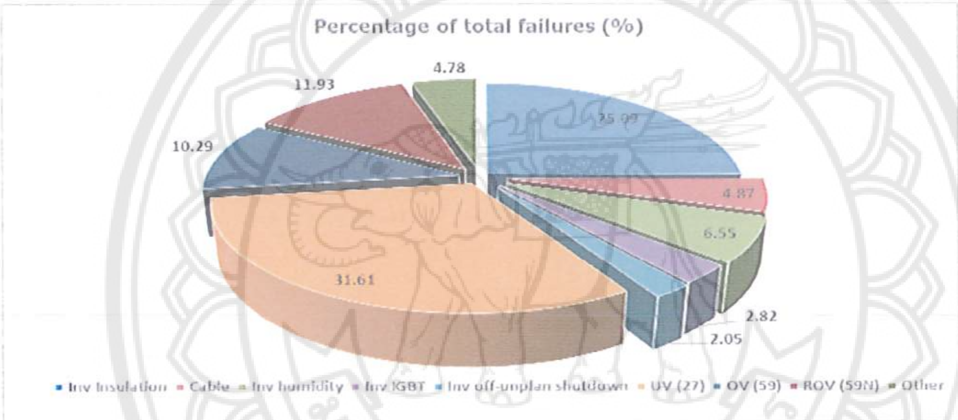


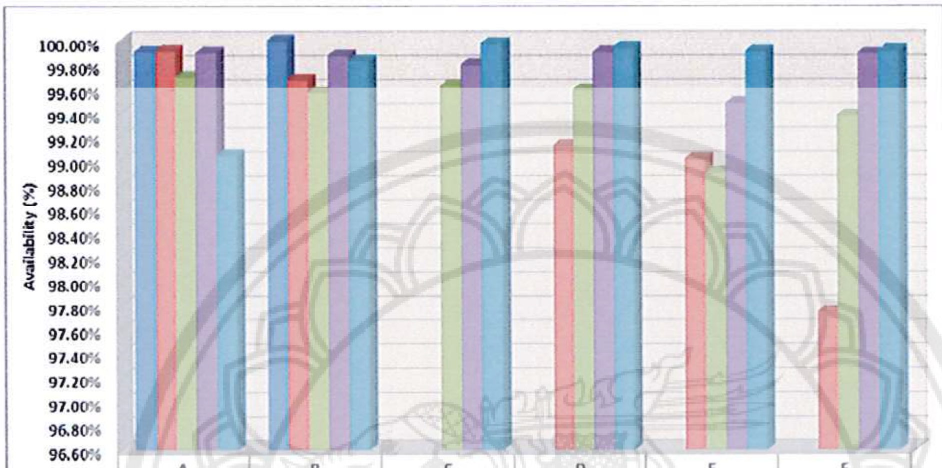
Figure 62 The overview percentage of the total failures of the 6 large scale commercial PV power plants during 2011 to 2015

For under voltage, residual over voltage, and over voltage, there are many root causes that influencing these failures such as local geology, climate, grid condition, load during daytime, etc. However, these root causes are uncontrollable and no exactly corrective action for improve the failure rate because they are located beyond the solar farm operator responsibility. For inverter Insulation, inverter humidity, and cable failures, the significant root causes of these failures are the high underground water level and humidity. In inverter Insulation failure case, the high underground water level and humidity are the root causes of the PV array insulation resistant reducing to lower than the limit that result in the inverter stopping operation. Moisture is the main cause of PV module insulation resistant reducing while the high underground water level is the major cause of the submerged cable in the flooded cable ducts and manhole for long period that result in cable insulation resistant reducing. In inverter humidity failure case, the moisture in the inverter is the failure root causes that stop inverter operation. In cable failure case, the high underground water level is the important cause for the cable insulation resistant reducing from the submerged cable in the flooded cable ducts and manhole for long period that stimulating the leakage current or short circuit until insulator break down. For inverter IGBT failure, a significant failure root cause is the high inverter temperature that result in the higher leak current and loss in IGBT, misstep switching timing, and IGBT degradation. These failures are possible leading to the inverter stopping operation, exploding, or catching fire. Unplanned operation and maintenance are the vital root causes of inverter off-un plan shutdown. For the corrective action of these failure, improving water draining system in the PV power station and keeping dry of cable ducts and manhole is a suitable solution for inverter Insulation and cable failures, improving inverter cooling and humidity control system are the appropriating corrective action for inverter humidity and IGBT failures, and well-designed operation and maintenance program is a proper solution for inverter off-un plan shutdown.

From the failure root cause and corrective action analysis, it is possible to conclude that the high underground water level, humidity, high inverter temperature, unplanned operation and maintenance are failure root causes of the large scale commercial PV power plant. The suitable corrective action for these failure root causes are improving water draining system in the PV power plant and keeping dry of cable ducts and manhole, improving inverter cooling and humidity control system, and well-designed operation and maintenance program. From the information in this section, they are completing the first objective of the dissertation that are analyzing the failure root cause and corrective action for improve the availability of the large-scale commercial PV power plants in Thailand

2. Availability evaluation result

The availability evaluation of the 6 large scale commercial PV power plants during 2011 to 2015 is based on the total operating time and the equivalent PV power plant downtime data. The total operating time is the total period that the equipment could be called upon to perform its intended purpose or the enough irradiance exists and all other system conditions are met that the system will function as intended and produce rated power. From this definition, it is possible to estimate the total time of the 6 large scale commercial PV power plants from the monitoring data of these PV power plants. From the monitoring data, the estimated total time of each day are various from 11 to 13 hours that depend on daylight. The availability evaluation result of the 6 large scale commercial PV power plants during 2011 to 2015 is displayed in Figure 63.



	A	B	C	D	E	F
2011	99.91%	100.00%				
2012	99.92%	99.68%		99.13%	99.02%	97.75%
2013	99.70%	99.57%	99.62%	99.59%	98.90%	99.38%
2014	99.90%	99.88%	99.80%	99.90%	99.48%	99.89%
2015	99.05%	99.83%	99.97%	99.94%	99.91%	99.92%

Figure 63 The availability evaluation result of the 6 large scale commercial PV power plants during 2011 to 2015

From the Figure, the availability of the 6 large scale commercial solar farm during 2011 to 2015 is not significantly different except A in 2015 at 99.05 %, E in 2013, at 98.90% and D, E, and F in 2012 at 99.13 %, 99.02 %, and 97.75 % respectively that result from the PV power plant overhaul program of A in 2015 and the initial failure of D, E, and F in 2012 and E in 2013. In addition, the availability of these PV power plants about 50 % are over 99.80% that imply to the good operation and maintenance of them. However, the average availability of D, E and F is lower than other solar farms in initial period that result from the weaker grid condition and lower load during daytime, inappropriate management with high underground water level and humidity, and unplanned operation and maintenance.

The availability evaluated result of the 6 large scale commercial PV power plants during 2011 to 2015 clearly indicates that the availability trend of A and B are a little bit fluctuation in the high level while C, D, E, and F are increasing to reach the high level in 2014 to 2015. To evaluate the higher precise availability of the 6 large scale commercial PV power plants, the life time evaluation period at 25 years is necessary for availability evaluation of the large scale commercial solar farms. This evaluated result completes a part of the second objective of this dissertation.

3. Availability mathematical model development for the large scale PV system

The availability can be evaluated from the mathematic formula that described in the method to develop the reliability and availability formula for the large Photovoltaic power plant. The analysis follows the Practical Reliability Engineering [11], and applied the quantity and impact factor into the serial system reliability and system availability formula. The result of reliability and availability is presented in Table 31 and Table 32 respectively. From the system reliability table, the system still remained the function for the first year is 54.46%, 29.66% for the second year, 16.15% for the third year, 8.80% for the fourth year, 4.79% for the fifth year, 0.23% for the tenth year, 0.01% for the fifteenth year, and 0% for the twentieth year. The reliability will less while more products installation and more in time of use. From the stem availability table. The system availability for the plant that has the spare part and well organizes for the trouble shooting is 99.80% and 99.77% when calculate with quantity and the impact factor of the equipment. 98.1% for the plant that without the spare part that cause to spend more time for the MTTR. And 97.26% when calculate with quantity and the impact factor of the equipment which is similar to the market perspective 97.5%

Table 31 The result of a system reliability by the theory formula

Product	Quantity	% impact	Failure rate/hour	Failure rate/year (with 9 hr operation)	Reliability with quantity and impact factor							
					1st year	2nd year	3rd year	4th year	5th year	10th year	15th year	20th year
PV	27,300	1%	7.84E-08	2.58E-04	96.54%	93.21%	89.99%	86.88%	83.88%	70.35%	59.01%	49.50%
Fuse-string	2,821	1%	6.70E-07	2.20E-03	96.94%	93.98%	91.11%	88.32%	85.62%	73.31%	62.77%	53.74%
Switch	91	14%	6.44E-08	212E-04	99.73%	99.45%	99.18%	98.91%	98.63%	97.29%	95.96%	94.64%
Fuse DC box	91	14%	6.70E-07	2.20E-03	97.18%	94.44%	91.77%	89.18%	86.67%	75.11%	65.10%	56.42%
Inverter	13	8%	4.00E-05	1.31E-01	87.69%	79.89%	67.42%	59.12%	51.84%	26.87%	13.93%	7.22%
RMU	6	50%	1.09E-07	3.59E-04	99.89%	99.78%	99.68%	99.57%	99.46%	98.93%	98.40%	97.87%
TR	7	14%	6.74E-07	2.21E-03	99.78%	99.56%	99.34%	99.12%	98.90%	97.81%	96.74%	95.67%
Switchgear	3	100%	1.37E-07	4.50E-04	99.87%	99.73%	99.60%	99.46%	99.33%	98.66%	98.00%	97.34%
Busbar	3	100%	3.88E-07	1.28E-03	99.62%	99.24%	98.86%	98.48%	98.11%	96.25%	94.42%	92.64%
Cable-Main	3	100%	5.61E-06	1.84E-02	94.62%	89.52%	84.71%	80.15%	75.83%	57.51%	43.61%	33.07%
Cable-ring	6	50%	5.61E-06	1.84E-02	94.62%	89.52%	84.71%	80.15%	75.83%	57.51%	43.61%	33.07%
Cable-DC box	91	1%	5.61E-06	1.84E-02	98.17%	96.38%	94.62%	92.89%	91.19%	8316%	75.83%	69.15%
Grid	1	100%	7.34E-05	2.41E-01	78.57%	61.74%	48.51%	38.12%	29.95%	8.97%	2.69%	0.80%
System reliability				4.37E-01	54.46%	29.66%	16.15%	8.80%	4.79%	0.23%	0.01%	0.00%

Table 32 The result of a system availability by the theory formula

Product	Quantity	% impact	Failure rate/year	MTTR (with spare part)	Unavailability hour	Unvialability hour per year	Unavailability hour/year with qty and impact	MTTR (withour spare part)	Unvavialability hour	Unavailability hour per year	Unavailability hour/year with qty and impact
PV	27,300	1%	6.87E-04	4	3.14E-07	0.00	0.31	168	1.32E-05	0.04	12.98
Fuse-string	2,821	1%	5.87E-03	3	2.01E-06	0.01	0.20	48	3.22E-05	0.11	3.28
Switch	91	14%	5.65E-04	8	5.16E-07	0.00	0.02	168	1.08E-05	0.04	0.46
Fuse DC box	91	14%	5.87E-03	3	2.01E-06	0.01	0.09	168	1.13E-04	0.37	4.81
Inverter	13	8%	3.50E-01	16	6.40E-04	2.10	2.10	336	1.34E-02	44.15	44.15
RMU	6	50%	9.59E-04	24	2.63E-06	0.01	0.00	720	7.88E-05	0.26	0.12
TR	7	14%	6.20E-03	24	1.62E-05	0.05	0.05	1800	1.21E-03	3.98	3.98
Switchgear	3	100%	1.20E-03	24	3.29E-06	0.01	0.03	1800	2.47E-04	0.81	2.43
Busbar	3	100%	3.40E-03	24	9.32E-06	0.03	0.09	168	6.52E-05	0.21	0.64
Cable-Main	3	100%	4.92E-02	24	1.35E-04	0.44	1.33	168	9.43E-04	3.10	9.30
Cable-ring	6	50%	4.92E-02	24	1.35E-04	0.44	0.20	168	9.43E-04	3.10	1.43
Cable-DC box	91	1%	4.92E-02	24	1.35E-04	0.44	0.38	168	9.43E-04	3.10	2.66
Grid	1	100%	6.43E-01	12	8.81E-04	2.89	2.89	16	1.17E-03	3.86	3.86
					Unavailability day/year	0.72	0.86		Unavailability day/year	7.01	10.01
					Availability day/year	364.28	364.14		Availability day/year	357.99	354.99
					availability	99.80%	99.77%		availability	98.1%	97.26%

From the availability evaluated result from the actual plant and the calculation from the theory formula. The availability mathematical model is developed by using Least Squares Method. The availability data of the 6 large scale commercial PV power plants during 2011 to 2015 and the result from availability formula are used as input data. However, the highest and lowest availability values are excluded for limited the error and fluctuation of data. The selected availability data are averaged in each year and fit with order 2 polynomial equation. The average availability data and the developed mathematical model is showed in Figure 64. From the Figure, the mathematical model is illustrated follow this:

$$A_{PP} = -0.0086X^2 + 0.086X + 99.68 \tag{48}$$

A_{PP} = Availability of large scale commercial PV power plants

X = Number of Years

The R^2 of the developed mathematical model is 95.95% that is really good and acceptable. The developed mathematical model is used to simulate the availability of the 6 large scale commercial PV power plants during their lifetime at 25 years and the result is demonstrated in Figure 65. From the Figure, the average availability of the 6 large scale commercial PV power stations are increasing to reach the maximum value at 99.90% in the fifth year and slightly decrease to the minimum value at 96.46% in the twenty fifth year.

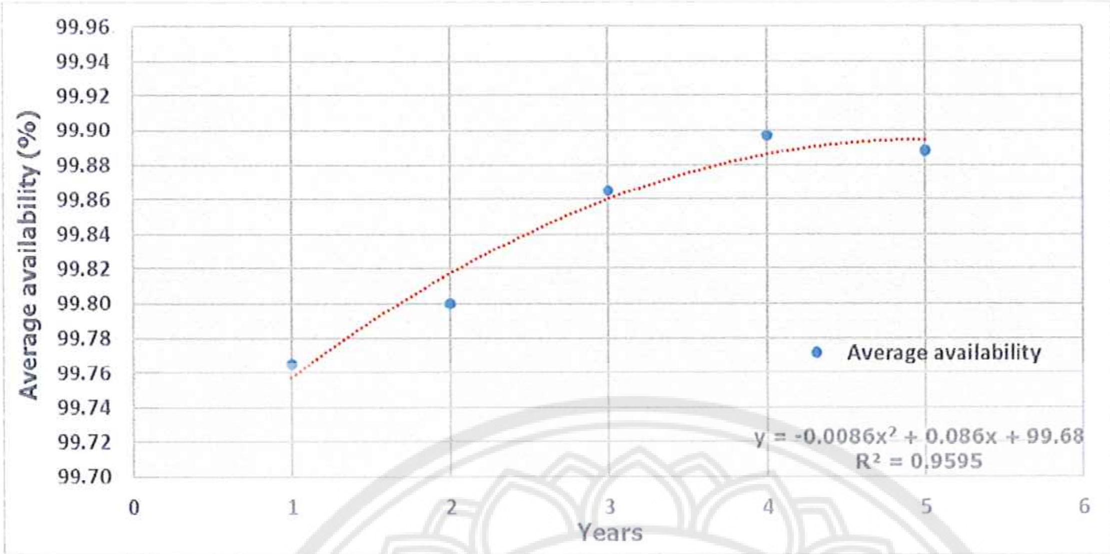


Figure 64 The average availability data and the developed mathematical model

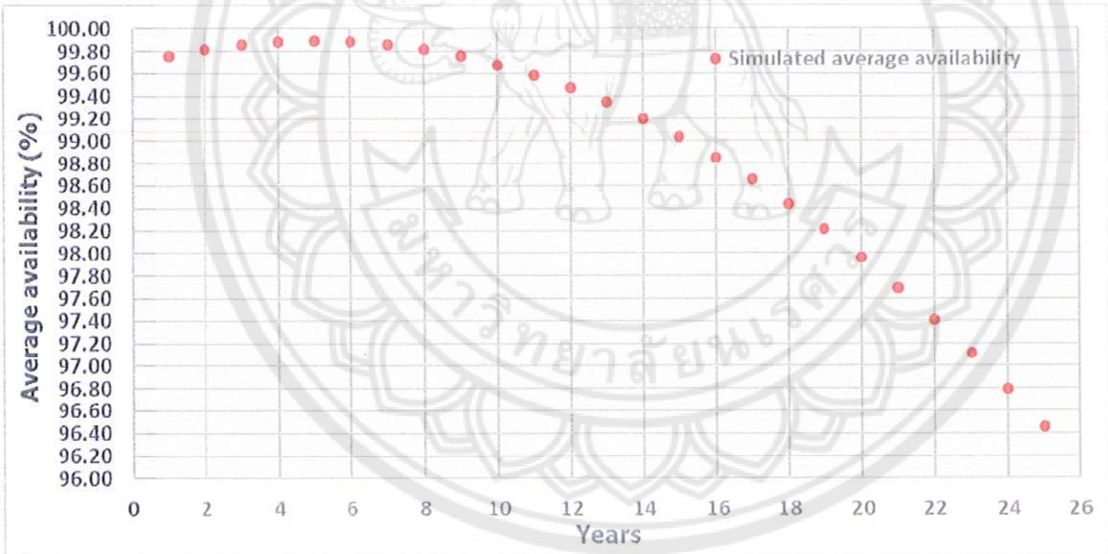


Figure 65 The simulate the availability of the 6 large scale commercial PV power plants during their lifetime at 25 years

Nevertheless, this simulation result is based on the internal and external factors is the same as the data input for developing mathematical model. The comparing result of the simulated average availability with the actual availability of the 6 large scale commercial PV power plants during 2011 to 2015 is presented in

Table 33. From the Table, the different availability between actual and simulated availability are in -2.05 to 0.23 % range that is very small and the simulation error is also in -2.10 to 2.03 % range that is in acceptable range. Thus, it is possible to infer that the developed mathematical model is really accurate and reliable. Moreover, it can be used to estimate the availability of other large scale commercial PV power plants in Thailand that have the similar configuration.

Table 33 **The comparing result of the simulated average availability with the actual availability of the 6 large scale commercial PV power plants during 2011 to 2015**

Year	Availability (%)						
	A	B	C	D	E	F	Simulation
2011	99.91	100.00					99.77
2012	99.92	99.68		99.13	99.02	97.75	99.80
2013	99.70	99.57	99.62	99.59	98.90	99.38	99.87
2014	99.90	99.88	99.80	99.90	99.48	99.89	99.90
2015	99.05	99.83	99.97	99.94	99.91	99.92	99.89
Year	Different Availability (%)						
	A	B	C	D	E	F	Average
2011	0.14	0.23					0.19
2012	0.12	-0.12		-0.67	-0.78	-2.05	-0.70
2013	-0.17	-0.30	-0.25	-0.28	-0.97	-0.49	-0.41
2014	0.00	-0.02	-0.10	0.00	-0.42	-0.01	-0.09
2015	-0.84	-0.06	0.08	0.05	0.02	0.03	-0.12
Year	Error (%)						
	A	B	C	D	E	F	Average
2011	0.14	0.23					0.19
2012	0.12	-0.12		-0.68	-0.79	-2.10	-0.71
2013	-0.17	-0.30	-0.25	-0.28	-0.98	-0.49	-0.41
2014	0.00	-0.02	-0.10	0.00	-0.42	-0.01	-0.09
2015	-0.85	-0.06	0.08	0.05	0.02	0.03	-0.12

From the accurate availability simulation result, it is supporting that the developed mathematical model is workable and reliable. To develop the higher accurate availability mathematical model of the large scale commercial PV power plant in Thailand, the lifetime availability data for 25 years and the various large scale commercial PV power plants sample that cover every part of Thailand are the essential required data in developing process. These developed availability mathematical model and the simulation result complete the third objective of this dissertation.

CHAPTER V

CONCLUSION

Nearly 3 decades, electricity generated from photovoltaic (PV) power systems is an important renewable energy source which involves zero greenhouse gas emission and no fossil fuel consumption. In Thailand, the trend of PV systems is mainly focusing in a large scale grid-connected generation systems or PV power plants in the last decades. Solar farm installation has been continuously grown in every part of Thailand. However, the growing rate is various that depend on government policy. A few years ago, the large scale commercial PV power plant economics are being intensively studied in Thailand by increasing detail. Small improvements in subsystem efficiency and reliability are closely watched both from a predictive/planning standpoint, and from an operational standpoint because small differences in these performance metrics can translate into significant differences in every economic indicator. Analyzing the availability of PV power plant is important for planning and long-term operation, because the analysis helps predict system behavior over time and devise appropriately timed maintenance plans. It is a vital factor for the operator to be able to assess system availability under long-term operations in order to optimize decisions in design, engineering, procurement, construction, and service that result in PV power plant economic improvement. There are many studies already on the availability of PV power system but almost of these study based on climate and environment in other country which is not in the tropical climate. Therefor the result of these study is not effectively used in Thailand. Study on reliability and availability of large scale grid connected photovoltaic power plants concentrate on the various large scale commercial PV power plants, climate and environment in Thailand, and longtime study period. The 6 large scale commercial PV power plants that constructed with the similar configuration with AC power output ranging from 3.3 to 7.6 MWp are selected as the PV power plant samples that are plant A, B, C, D, E, and F. These PV power plants are located in central region of Thailand that is a good representative for the large scale commercial PV power station, climate, and environment in Thailand. The conclusion of the study result in this dissertation is presenting follow this:

For efficiency and performance evaluation result, the average Y_r, Y_f, L_T, and PR, during 2011 to 2015 of plant A are 5.34 h/day, 4.28 h/day, 1.06 h/day, and 80.13 % respectively, plant B are 5.14 h/day, 4.11 h/day, 1.03 h/day, and 80.06 % respectively plant C are 5.24 h/day, 4.19 h/day, 1.05 h/day, and 82.33 % respectively plant D are 5.40 h/day, 4.25 h/day, 1.15 h/day, and 78.71 % respectively, plant E are 5.27 h/day, 4.16 h/day, 1.10 h/day, and 79.05 % respectively and plant F are 5.31 h/day, 4.21 h/day, 1.09 h/day, and 79.40 % respectively. These evaluated parameters of the 6 large scale commercial PV power plants present no significant different. From this point, the availability evaluation result of these solar farms are significantly dominated by geography, climate, operation and maintenance of the 6 large scale commercial PV power stations because the other factors that effect to the availability of these solar power plants are almost the same.

Failure evaluation result is separated in 3 parts that are PV power plant component (Internal), grid (External) and total failures analysis. The failure time of each PV power plant components and grid are estimated in equivalent PV power plant downtime form. From the internal failures analysis, only 5 PV power plant components failures cover about 90 % of the internal equivalent PV power plant downtime that are inverter Insulation failure with 54.34 % sharing, inverter humidity failure with 14.18 % sharing, cable failure with 10.56 % sharing, inverter IGBT failure with 6.12 % sharing, and inverter un plan shutdown with 4.45 % sharing. For the causes of these failures, the high underground water level, humidity, high inverter temperature, unplanned operation and maintenance are the main root causes of these failures. For the solutions of these failures, improving water draining system in the PV power station, keeping dry of cable ducts and manhole, improving inverter cooling and humidity control system, and well-designed operation and maintenance program. For the external failures analysis, under voltage failure with 58.73 % sharing, residual over voltage failure with 22.16 % sharing, and over voltage failure with 19.12 % sharing are covering 100 % of the external equivalent PV power plant downtime. For the causes of these failures, local geology, climate, grid condition, load during day time, etc. are the significant root causes of these failures. However, the corrective action of these failures are beyond the solar farm operator responsibility. For the total failure analysis, it found that the internal failures analysis dominates 46.17 % of the total failure while the external failures influence 53.83 % of the total failure. This failure analysis result completes the first objective of this dissertation

For the availability evaluation result, the average availability during 2011 to 2015 of the 6 large scale commercial PV power of plant A, plant B, plant C, plant D, plant E and plant F are 99.70 %, 99.79 %, 99.80 %, 99.64 %, 99.33 %, and 99.24 % respectively. The result clearly indicates that under voltage and inverter Insulation failure have the highest effect to availability with grid failure. Nevertheless, the availability trend of the 6 large scale commercial PV power plants are increasing from the initial value to reach the maximum value in 2015 except in plant A and plant B that a little bit fluctuation. To evaluate the higher precise availability of the large scale commercial solar farms, the life time evaluation period at 25 years is necessary for availability evaluation. This availability evaluation completes the second objective of this dissertation, In order to maintain or improve the plant shutdown by the internal failure the spare part available, professional operation, service level agreement formed the inverter manufacturing, preventive maintenance plan, corrective action, and the plant monitoring system must be well organized. The new plant green field needs to consider the product and equipment selection, properly design, monitoring system and professional construction.

From availability mathematical model development for the large scale PV system, it is developed by using Least Squares Method with order 2 polynomial equation and the availability data of the 6 large scale commercial PV power plants during 2011 to 2015 are used as input data. The developed mathematical model is $A_{PP} = -0.0086 X^2 + 0.086X + 99.68$. The R^2 of the developed mathematical model is 95.95% that is pretty good and acceptable. The developed mathematical model is used to simulate the availability of the 6 large scale commercial PV power plants during their lifetime at 25 years and the result is comparing with the actual availability. From the comparing result, the error is in -2.10 to 2.03 % range that is in the passable range. This availability mathematical model development for the large scale PV system completes the third objective of this dissertation

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