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An FMEA analysis for photovoltaic systems: assessing different system configurations to support reliability studies

Introduction to PRA analysis for PV systems

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Structure of the presentation

- Use of probabilistic risk analysis for electric grid operation & planning and to assess the impact of renewable energy system interconnections.
- PV system model: components and qualitative FMEA analysis.
- The PRA approach for PV systems.
- First steps in PRA modeling: IE, ES and ET.
- What results could we expect?
- Enhancing PV performance with a probabilistic approach.
- FT-based reliability analysis.
- Conclusions.

Probabilistic risk analysis in grid operation and system integration

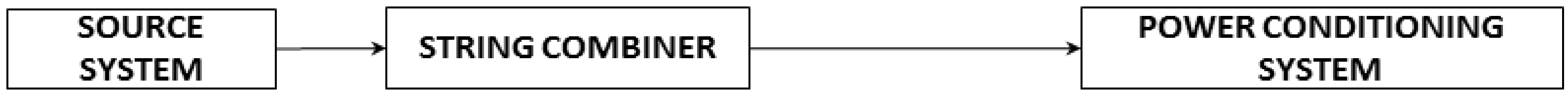
Electric utilities and grid operators face major issues from an accelerated evolution of grids towards an extensive integration of variable renewable energy sources and smart grid configurations, while also aiming at minimum costs of operation. Probabilistic risk assessment can be a proper method for real business cases in utility operational and planning activities, to manage risk for optimal technical and financial decision.

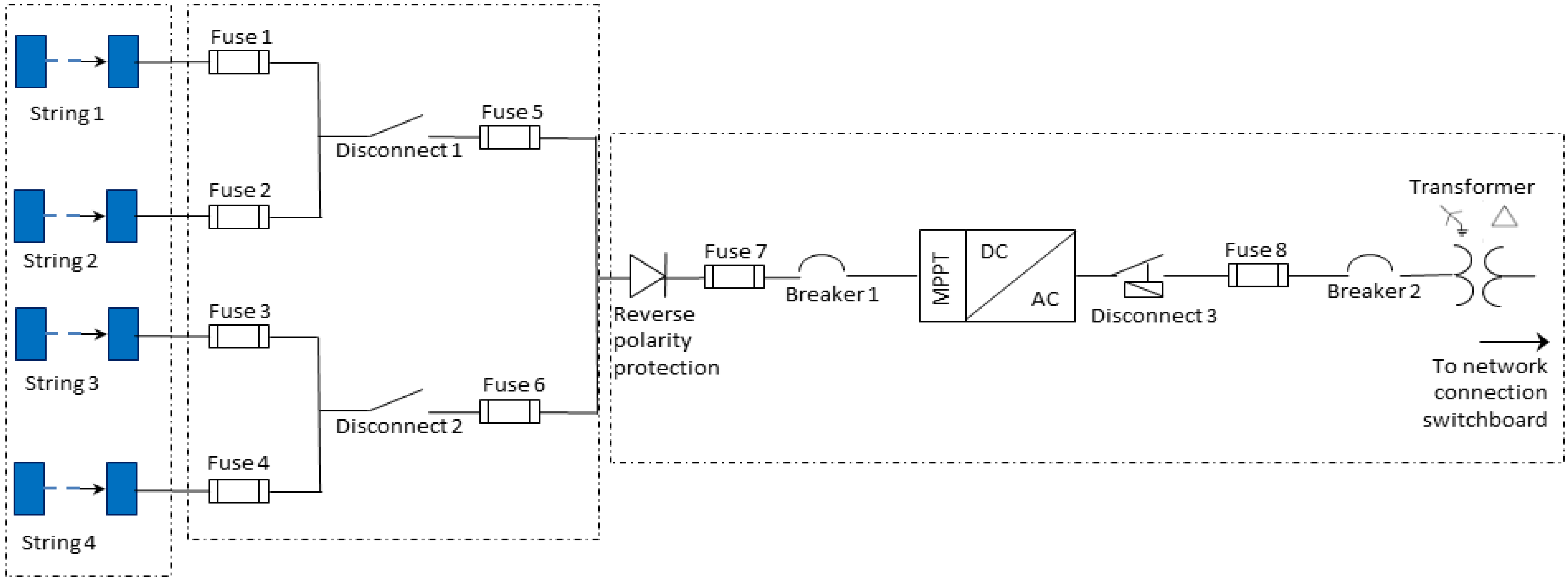
The risks of interconnecting a large number of utility-level renewable energy plants must be evaluated for dispatching purposes, due to the variability of the solar energy source.

The Long Island Solar Farm (37 MWp) on BNL campus

The PV system model

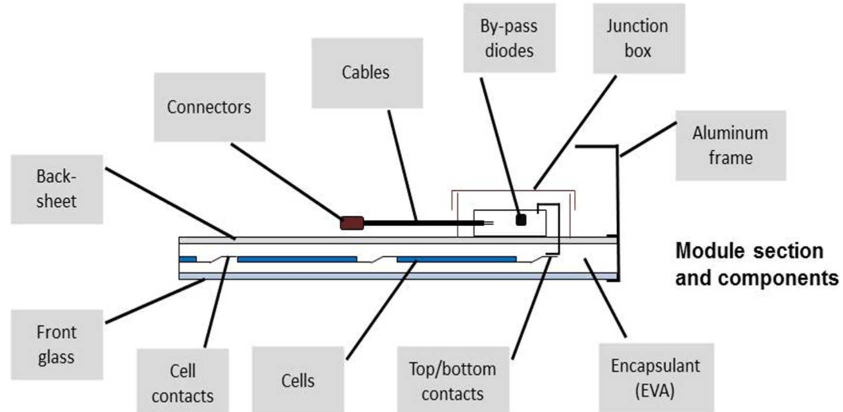
PV systems are complex systems of systems.





Source system components

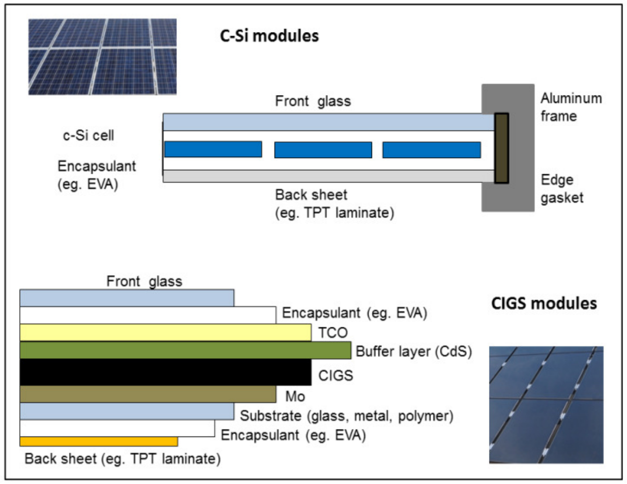
	Subsystem	Component	Subcomponent
Source System	PV module	Aluminum frame	
		Junction box	Junction box case
			Junction box sealing
			Contacts
			Bypass diodes (6)
		Cables	Wiring
			Insulation
			Connectors
		Front glass	
		Back-sheet	
		Encapsulant	
		Module edge sealing	
		Cells	Cells contacts
			Cells material
		Contacts	
	Rack	Rack structure	Module brackets
		Grounding system	
		Lightning protection	
	Cable tray (DC)	Cables	Wiring
			Insulation
			Connectors
		Metal supports	



Section of a crystalline silicon PV module

LISF rack structures

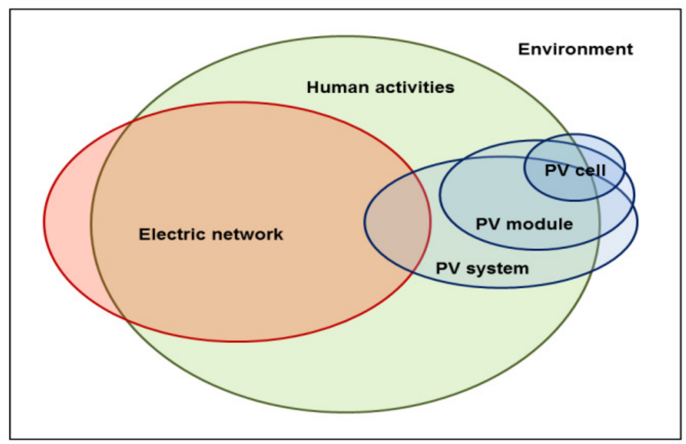
Different configurations and components



PV systems can use different types of modules and inverters. Components and configurations can be different.

They can lead to different FMEA results.

Additional specific effects are directly connected to the environmental conditions of the installation.



Failure Mode - PV Module
Front glass breakage
Delamination
Encapsulant (EVA) browning/discoloration
Back-sheet damage
Loss of circuit/open circuit in module
Short circuit in module
Cell overheat/hot spot
Cracks/ruptures on cells
Increased cell series resistance
Shunt effects in the cell
Degradation of Isc
Degradation of Voc
Light-induced cell degradation
Damages to cell/busbar contacts
Thermal damage to encapsulant
Thermal damage to contacts
Removal/loss of modules
Shading and seasonal effects
Soiling
Moisture entrance in junction box
Bypass diode failure
Arcing and overheating of junction box
Cracks/ruptures on cables
Pulling out of cables
Contacts corrosion
Connectors/cables overheat
Short circuit in cables
Open circuit in cables
Arcing at connectors

FMEA for PV modules

The FMEA analysis identified 77 failure modes for the different components of the considered PV system. Among them, 29 are for the PV modules.

The analysis has been done with reference to crystalline silicon PV. Thin-film modules could highlight different failure modes.

Some causes for modules: mechanical damages, thermal damages, delamination, corrosion, UV exposure, extreme weather conditions, high voltage stress, shading, animals.

Main effects for modules: energy output, electric safety, overheating, arcing, fire.

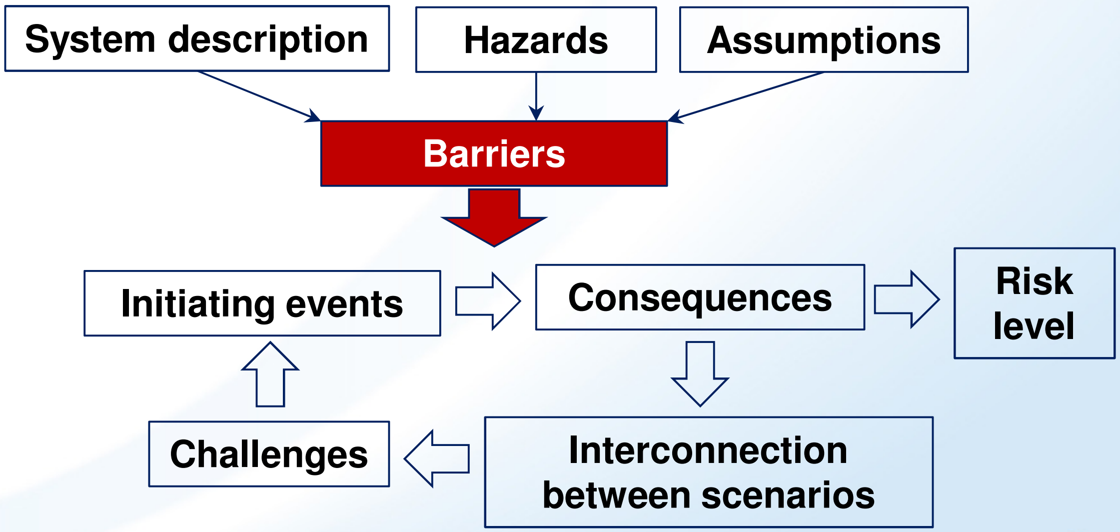
No ranking has been performed in the FMEA analysis (low credibility, high subjectivity).

FMEA for fuses

Failure Mode - Fuse	Potential Effects	Potential Causes
Opens intermittently	No energy output when opened	Loose or faulty electrical contacts
Opens spuriously	No energy output when opened	Loose or faulty electrical contacts, construction defects
High resistance	Increased heating and degradation of fuse and case holder.	Corrosion, oxidation, contaminated electrical contacts
Opens early	No energy output	Bad system configuration, human erroneous action, construction defect
Opens late	Excessive increase of current in the system, overheating, safety, arcs, fire	Bad system configuration, human erroneous action, construction defect
Fails to open	Excessive increase of current in the system, overheating, safety, arcs, fire	Bad system configuration, human erroneous action, construction defect

Probabilistic risk analysis

- Modeling: Challenges → Barriers → End states → Scenarios
- The PSA approach groups various tasks: design modeling (DM), system analysis, identification of events (E) and initiating events (IE), event sequence analysis conducted on the basis of fault trees (FTS) and event trees (ETS), and finally the evaluation of the consequences (CSQ) and the quantification of risk.
- The PRA defines a σ-algebra, leading to the definition of a norm (measure), which is called "risk".



Assumptions for system analysis

- The PV system is considered to normally operate at full power, with breakers/disconnects normally closed.
- Disconnect 1, 2 and breaker 1 sense the DC side. Disconnect 3 and breaker 2 sense the AC side.
- Disconnects open when I=0 in the system.
- Breakers open and act as protections to break the circuit.
- The reaction of the inverter triggers to open disconnect 3 on the AC side.
- No back-up batteries are considered in the system. Breakers/disconnects are supposed to work mechanically, and not DC-activated.
- Fire and structural damage are both an IE and an ES.
- Fire in the ES is always associated to and ES of electric safety, due to the issues of module power production that cannot be shut down under sunlight.
- Explosion in the ES is always associated to and ES of environmental contamination, due to the transformer oil coolant.
- Transformer is oil cooled, oil-to-air configuration with convective ventilation.
- Transformer reacts on cooling temperature, level and pressure.
- After an accident event the system can only be restored manually by the operator.

List of initiating events (IE) for PRA

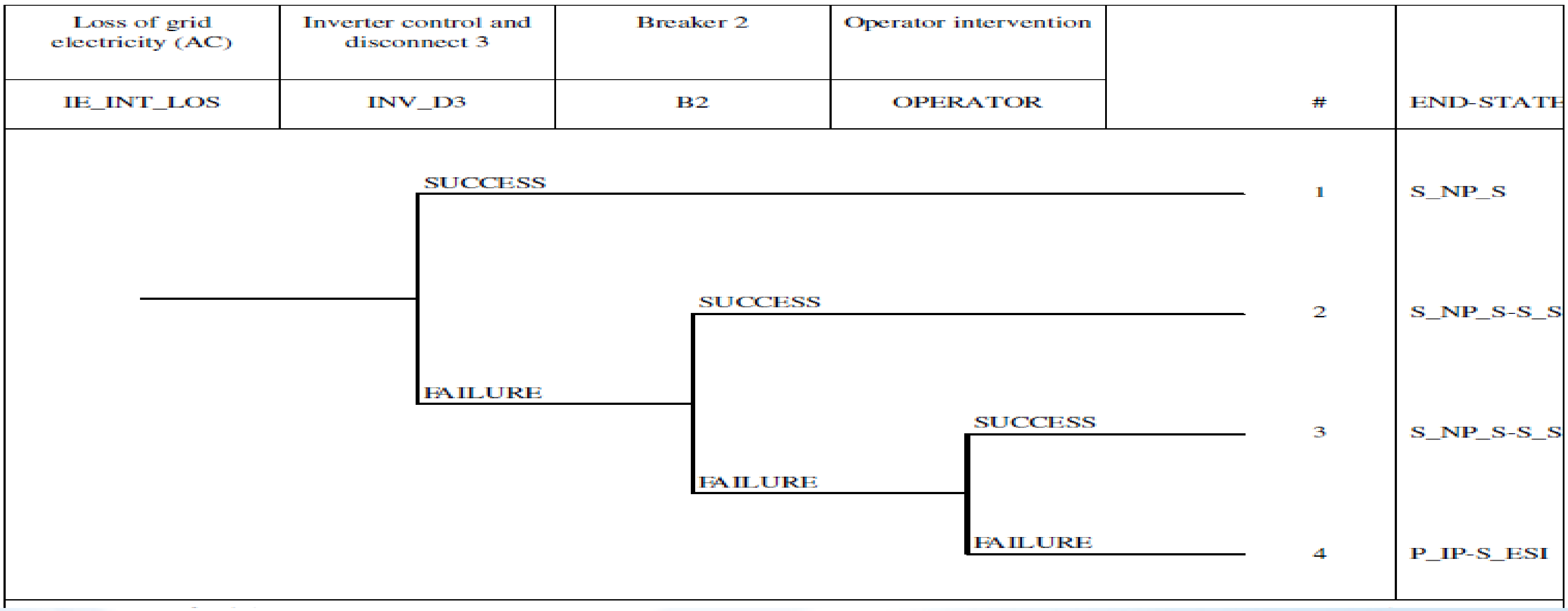
Internal IE	
Loss of grid electricity (AC)	IE_INT_LOSSGRD
Grid electricity transient fluctuations (voltage and frequency)	IE_INT_GRDFLCT
Overvoltage	IE_INT_OVERVLT
Loss of electrical connection of module strings (DC)	IE_INT_LOSSDC
Structural damage to rack	IE_INT_DMGRACK
Leakage (of transformer coolant)	IE_INT_LEAKOIL
Internal fire	IE_INT_FIRE
External IE	
Flood	IE_EXT_FLOOD
Earthquake	IE_EXT_ERTQUAKE
Extreme wind load	IE_EXT_EXRMWIND
Extreme snow load	IE_EXT_EXRMSNOW
Sand storm	IE_EXT_SNDSTRM
Animals (mainly cables, module junction box, ventilation holes)	IE_EXT_ANIMAL
Lightning	IE_EXT_LIGHTN
Sabotage (terrorism)	IE_EXT_SABOTG
Adversary action (vandalism)	IE_EXT_ADVACT
Airplane crash	IE_EXT_AIRCRSH
Explosion (considered for transformer, inverter)	IE_EXT_EXPLSN
External fire	IE_EXT_FIRE
Mechanical shock (including module cleaning actions, ground- works affecting cables, structural damages to all electric components)	IE_EXT_MECHSHCK
High humidity	IE_EXT_HUMID
High chemical air contamination	IE_EXT_CHEM
Soil/dust/pollen	IE_EXT_DUST
Shadows on modules (from surrounding constructions, trees)	IE_EXT_SHADOW

End states (ES)

Production-oriented ES		
Normal operation	P_NO	Complete success
No power	P_NP_F	Failure
Reduced power to grid	P_RP	Partial failure
Improper power to grid (for voltage, current, frequency level)	P_IP	Failure
Safety-oriented ES		
No power	S_NP_S	System safely shut-down, success
Overheating	S_OH	Failure
Overcurrent	S_OC	Failure
Fire	S_FIR	Failure
Arcs (overvoltage)	S_ARC	Failure
Explosion	S_EXP	Failure
Structural damages	S_SD	Failure
Reverse current flow	S_RCF	Failure
Corrosion	S_COR	Failure
Electric safety issues	S_ESI	Failure
Environmental contamination (loss of transformer cooling medium)	S_ENC	Failure

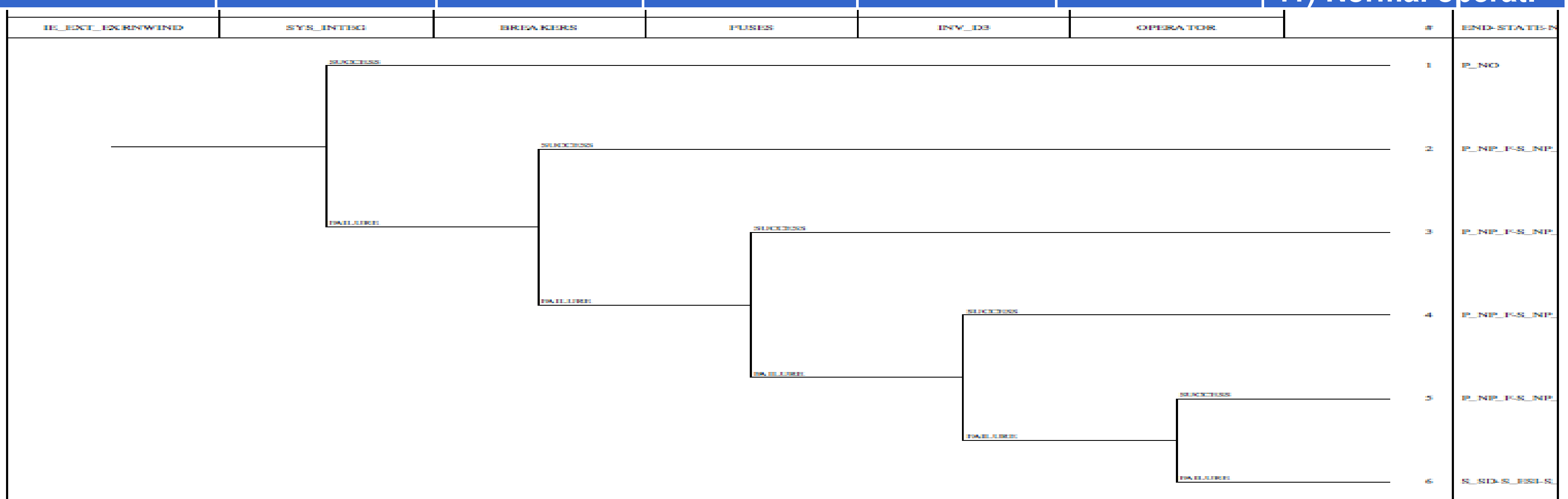
ET for loss of grid electricity

IE	FE1	FE2	FE3	ES
Loss of grid electricity (AC)	Inverter control and disconnect 3	Breaker 2 (AC)	Operator intervention	1) Electric safety issues 2) No power (success) 3) Improper power to grid 4) Structural damage



ET for extreme wind load

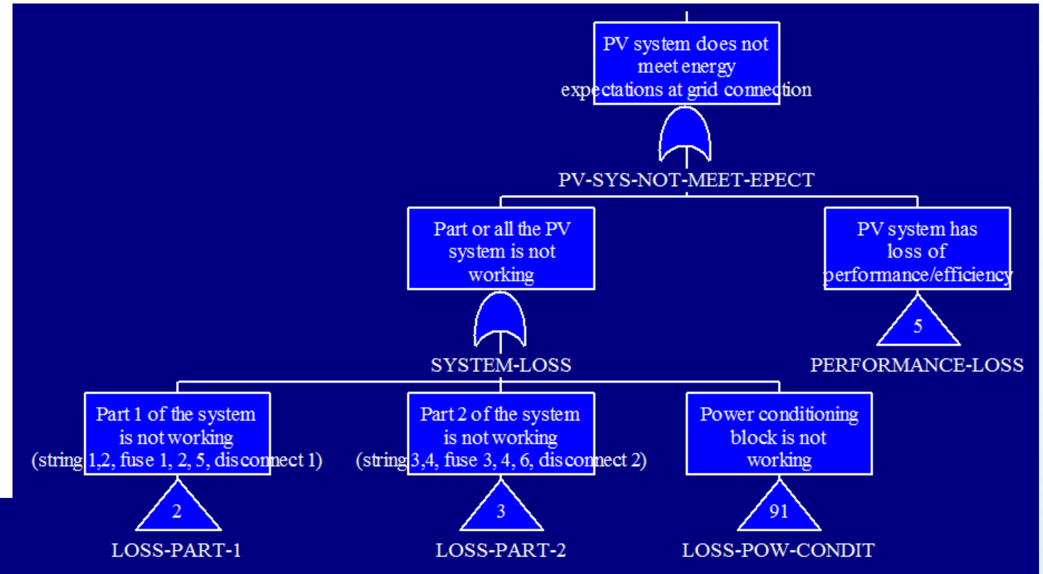
IE	FE1	FE2	FE3	FE4	FE5	ES
Extreme wind load	System integrity	Breakers (AC and DC)	Fuses (in case of short circuit)	Inverter control and disconnect 3	Operator intervention	1) Overcurrent 2) Fire 3) Overheating 4) Arcs 5) No power (F, S)) 6) Reduced power 7) Structural damage 8) Elt. safety issues 9) Explosion 10) Env. Contamin. 11) Normal operat.

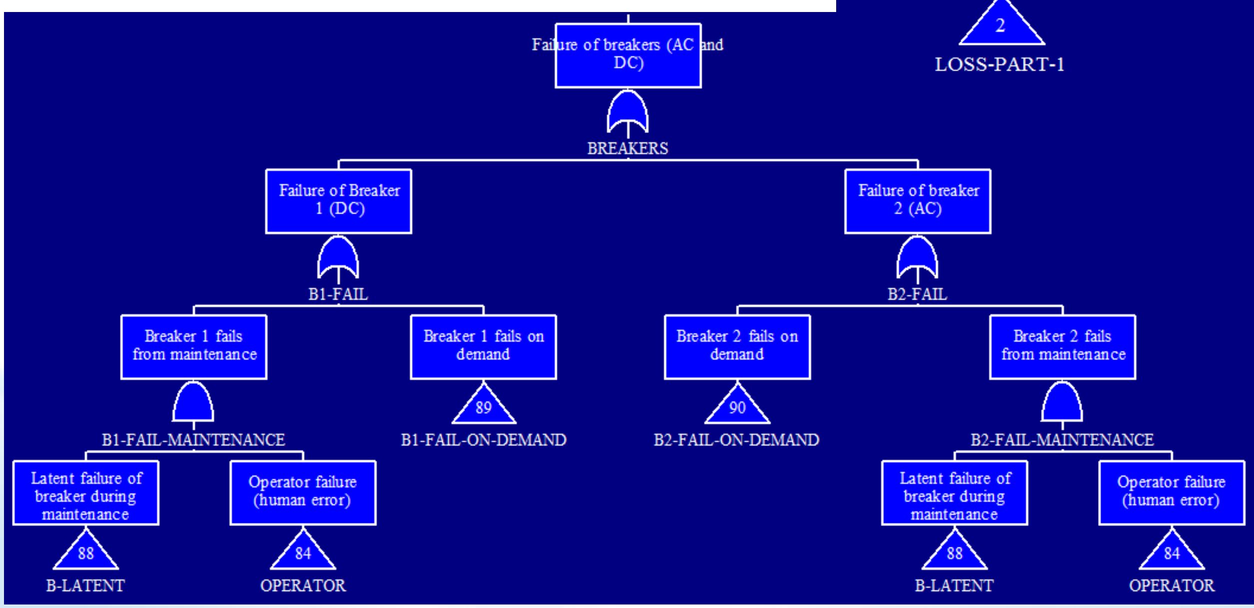


PV system and breakers failure FT

The PV system is supposed not to meet the expected energy production for loss of performance/efficiency (impairment), or for partial or total failure (outage).

Breaker failures are on demand or latent.





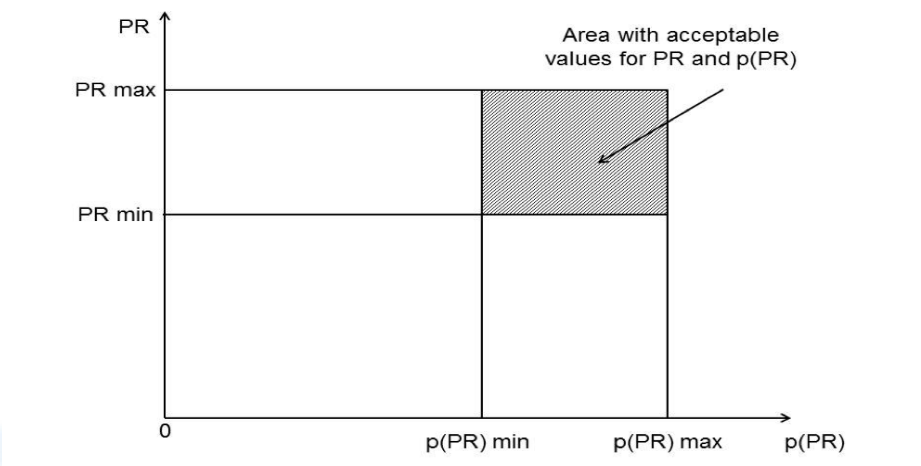
What results can we expect?

- Results will be likely expressed in relative form (ranking), due to the incomplete data for PV specific components.
- Weak points in the contribution of renewable energy systems to grid electricity will be highlighted, considering technical and environmental aspects.
- Results will support in taking financial decisions on system configuration and operation.
- A sensitivity analysis will be performed to assess elements of major impact on the model.
- Major expected uncertainties could arise from data quality and modeling assumptions.

Extend PV performance with a probabilistic approach

$$PR_{PROB} = PR * p(PR)$$

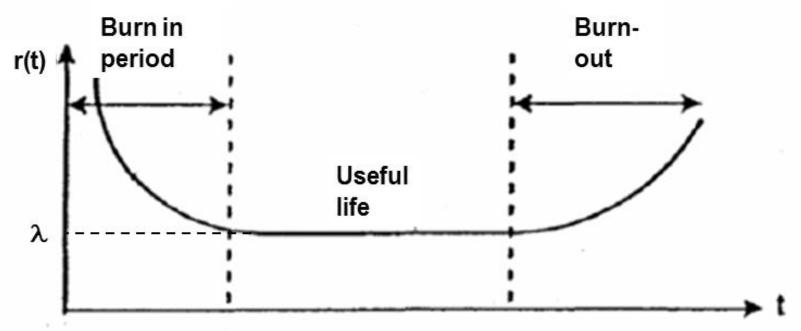
The probabilistic performance ratio (PR_{PROB}) allows taking into account both performance (performance ratio (PR) as defined in IEC 61724) and probability connected to the intrinsic reliability of PV systems, as well as the risks from other external accidental or voluntary events and the variability of solar irradiance. It provides probabilistic information on the chance that the system is working properly under the conditions specified by a defined scenario.



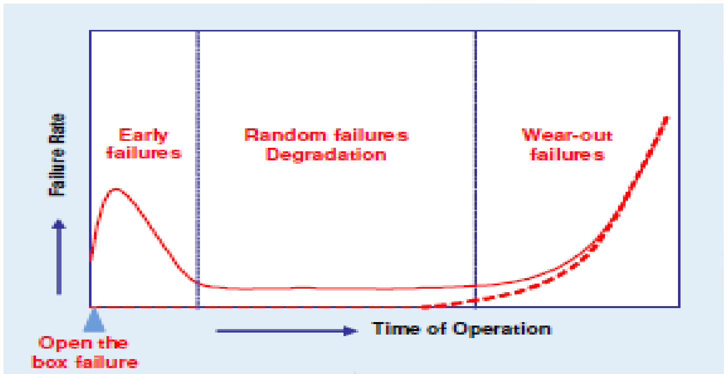
Reliability of PV devices

Reliability R(t) is the probability of survival at age t.

The failure rate r(t) (or hazard function, know as the bathtub curve) is the probability of death per unit time at age t for the element in the population.



Typical bathtub curve



"PV Module Reliability Issues Including Testing and Certification" U. Jahn, 27th EUPVSEC, Frankfurt Germany, 24 September 2012.

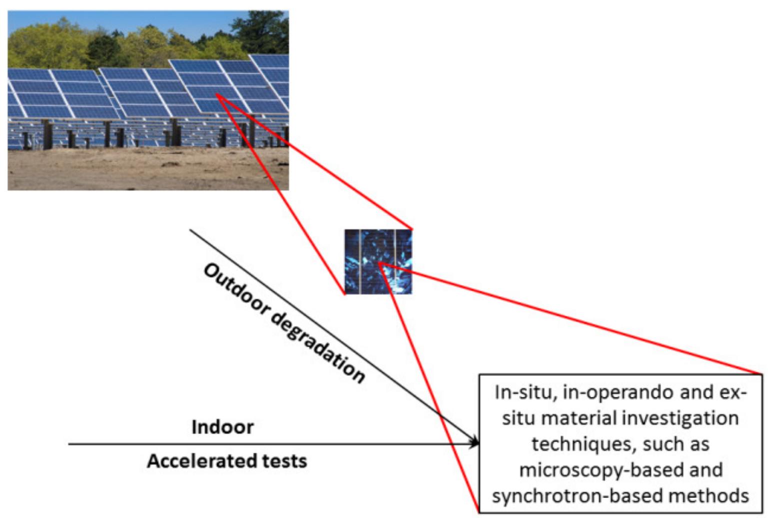
PV devices can present variations to the typical bathtub function.

However, many failure mechanisms still require detailed explanations.

A way to PV reliability investigations

Field information, along with indoor tests ruled by the international standards IEC 61215, 61646 and 61730 are insufficient to explain the details of failure and degradation mechanisms and dynamics.

This missing information makes it difficult both the identification of variables and the achievement of a detailed model design.



Complex systems should be studied following, where possible, an holistic approach.

The use of enhanced material analysis investigations could help solving some of the issues still open in PV reliability analysis.

A vision to support the PV industry

Relying on the proper reliability information, approaching PV systems with an holistic view, and deeply understanding the system dynamics are the basis on which to build a detailed PRA system model.

If PV modules could be modeled in details at sub-component level, down to material interactions, dominant pathways to system failure would be identified along with risks in specific operational scenarios.

This would become a powerful support to the PV industry to identifying the threshold of acceptability for their product, possibly along with PRA studies of the cell/module production lines.

Conclusions

- PRA has been presented as a tool to support RIDM in grid management and to rank risks in the operation of PV systems.
- Though having high credibility in its results, PRA requires appropriate knowledge of the method and the system to model.
- PV systems are complex systems of systems, to be approached in a holistic way.
- PV devices are highly influenced by physical and chemical material interactions, many of which are still not comprehensively understood.
- An interdisciplinary approach is proposed to support the PV industry.
- PRA could find in PV, but also in other renewable energies, a possible field of innovative application.

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