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ESREF 2010

Tutorial on

"RELIABILITY ISSUE OF PHOTOVOLTAIC DEVICES AND SYSTEMS"

Part II - PV Devices and Systems

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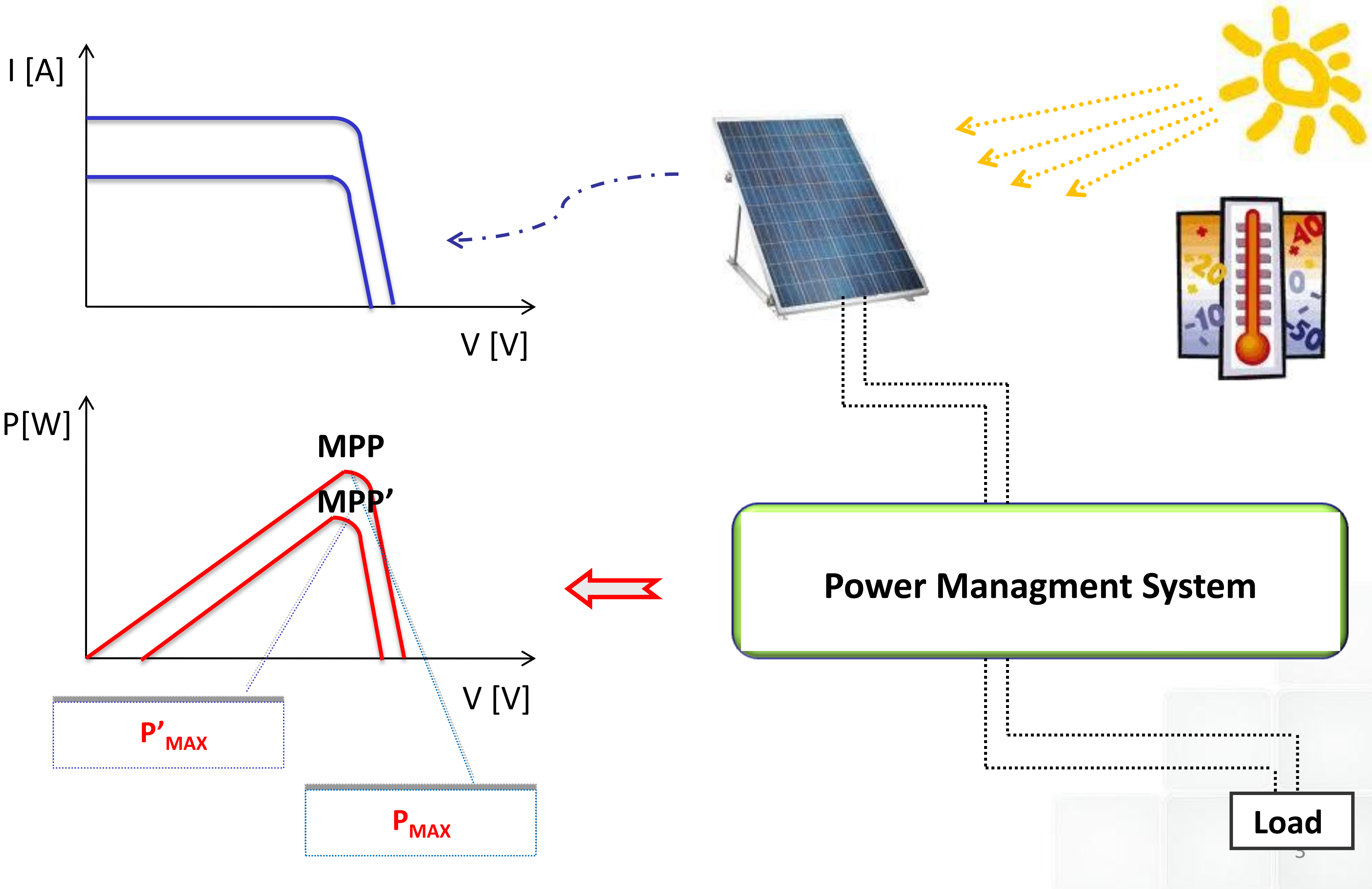
SUMMARY

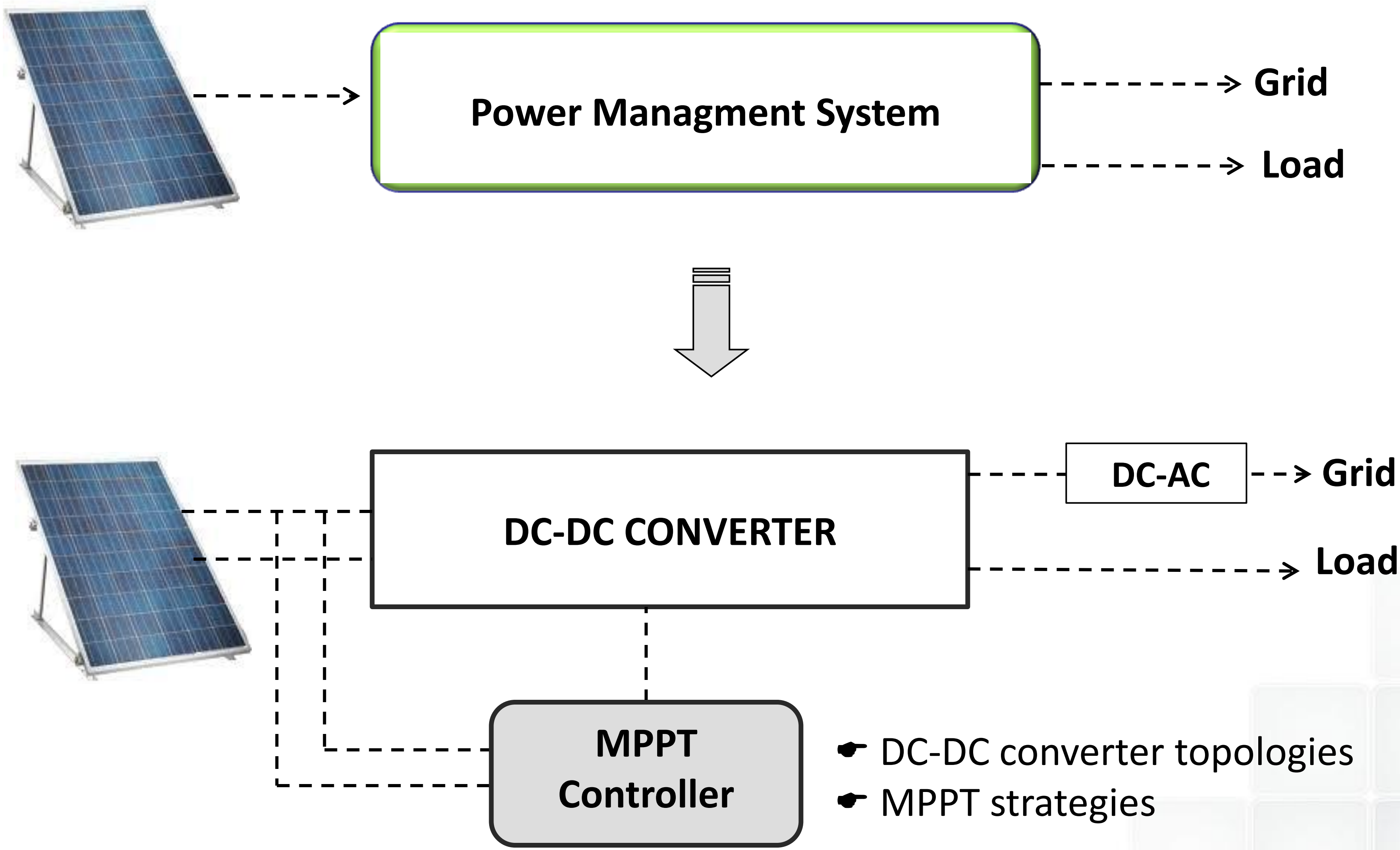
Part II: Reliability of PV devices and systems

- PHOTOVOLTAIC POWER MANAGEMENT SYSTEM
- DC-AC CONVERTER ARCHITECTURES
- DC-DC CONVERTER TOPOLOGIES
- RELIABILITY THEORY
- RELIABILITY MODEL
- DC-DC CONVERTER RELIABILITY EVALUATION

PHOTOVOLTAIC SYSTEM



PV POWER MANAGMENT



- DC-DC converter topologies
- MPPT strategies

BUS ARCHITECTURE

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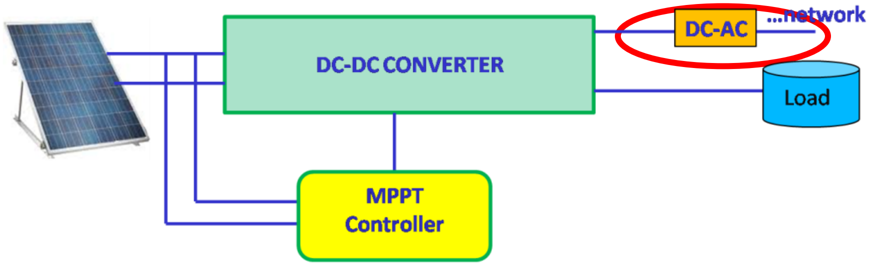
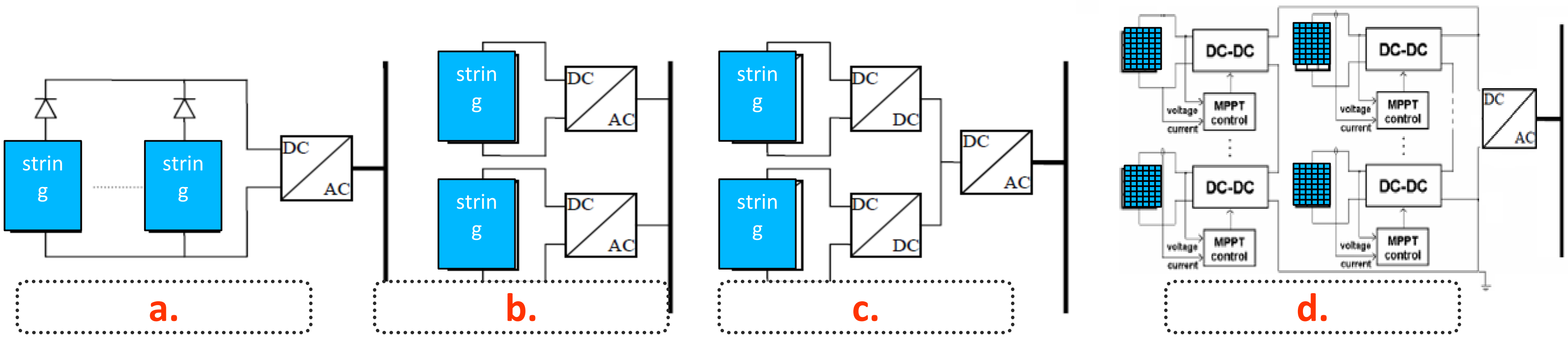


PV systems performance depends on the grid interface



a. CENTRALIZED INVERTER - PV FIELD MPPT

Only for uniform irradiation and stable temperature

b. STRING INVERTER - STRING MPPT

Energetic efficiency increase

c. MULTI-STRING INVERTER - MPPT on group of strings

A DC-DC converter for each string

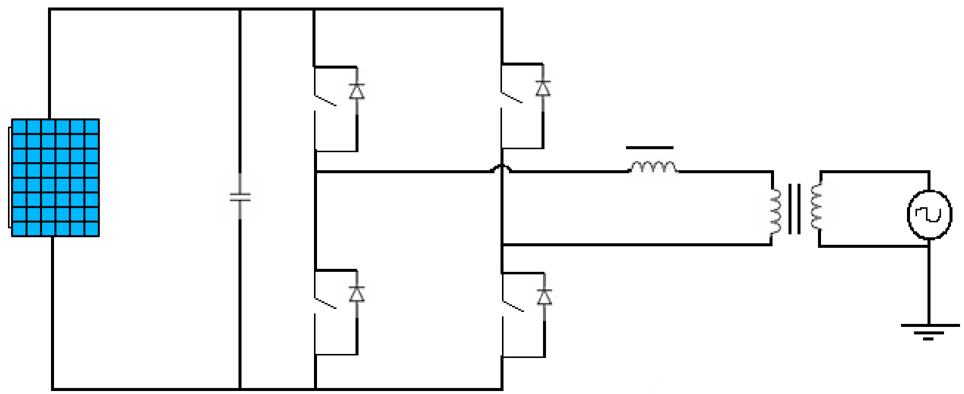
d. Distributed MPPT - Module MPPT

Module energetic efficiency increase

DC-AC CONVERTER

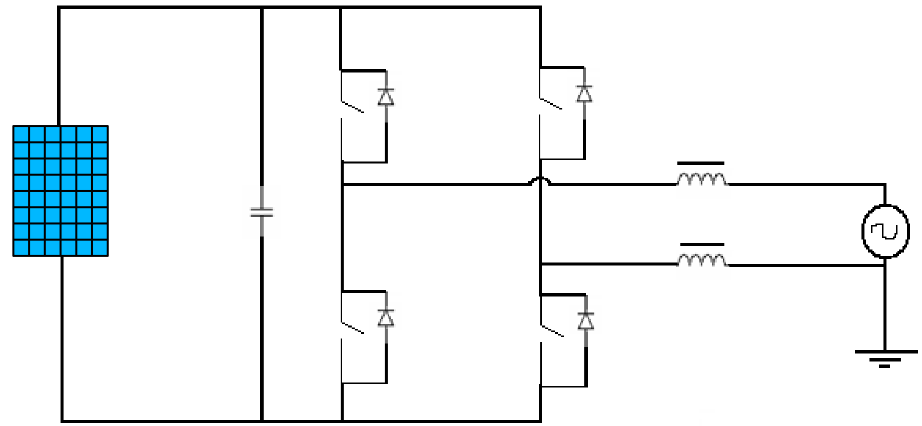
Different types of inverters are used:

- Variable frequency inverter
- Self-commutating fixed frequency inverter
- Line-commutated fixed-frequency inverter



Inverters are classified on the basis of:

- presence/absence of the transforme
- location of the power decoupling capacitors
- number of stages



DC-DC CONVERTER

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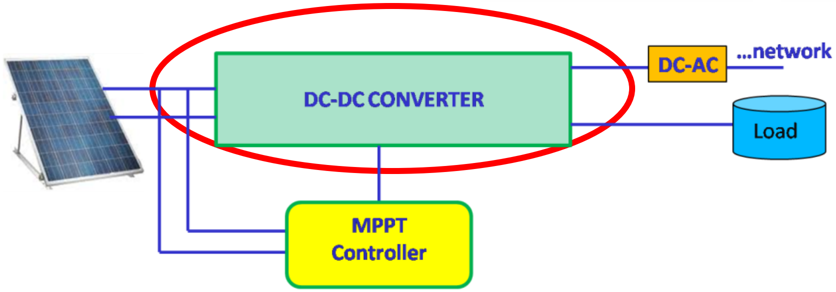
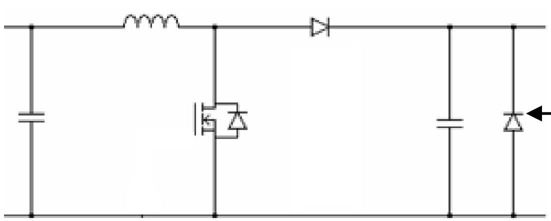


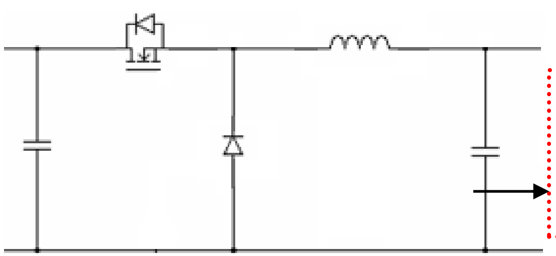
A DC-DC converter is used to manage the module output power to obtain voltages and currents suitable for network interface or for supplying the load.

DC-DC CONVERTER TOPOLOGIES



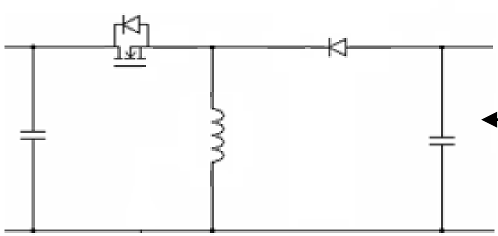
$$V_{out} = \frac{V_{in}}{(1-D)}$$

boost



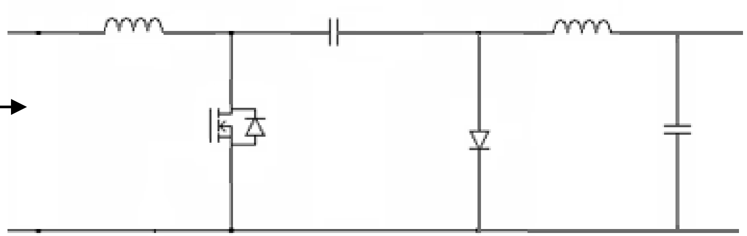
$$V_{out} = D * V_{in}$$

buck



buck-boost

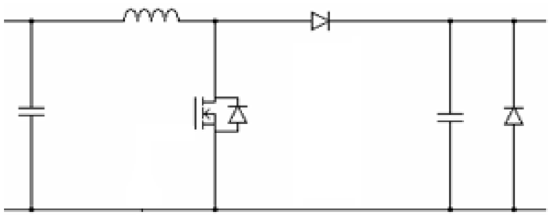
$$Vout = -\frac{D*Vin}{1-D}$$



CUK

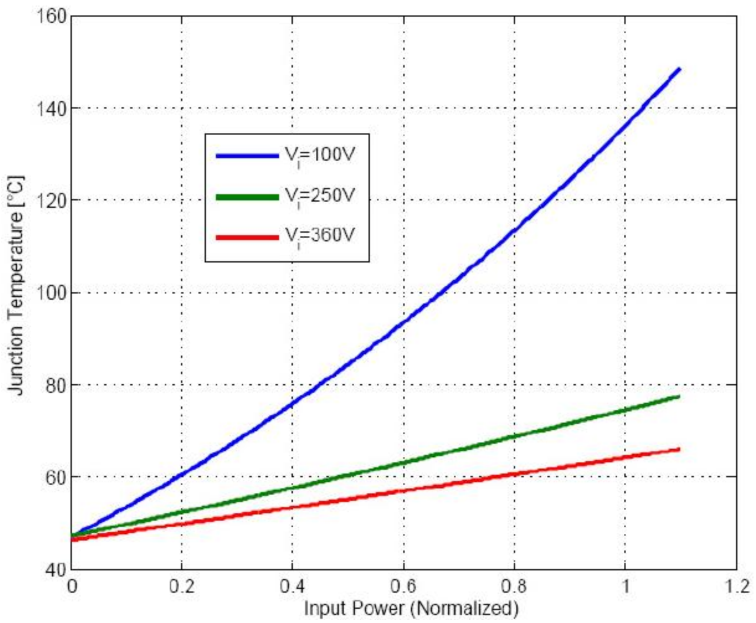
DC-DC CONVERTER

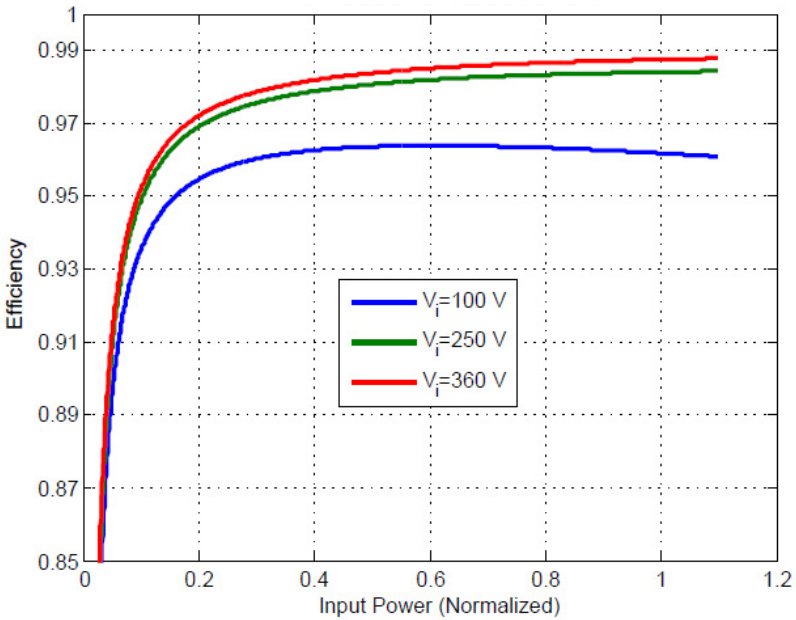
BOOST converts a DC voltage in a higher one



$$V_{out} = \frac{V_{in}}{(1 - D)}$$

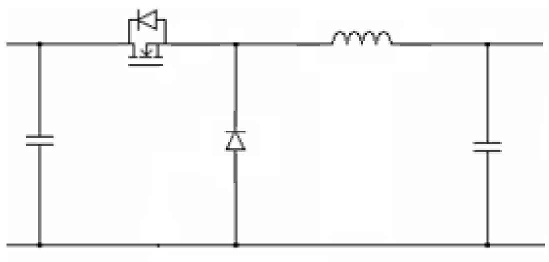
- ➔ **higher input voltage**
- ➔ **lower currents**
- ➔ **lower losses**
- ➔ **higher efficiency**
- ➔ **lower MOSFET junction temperature**





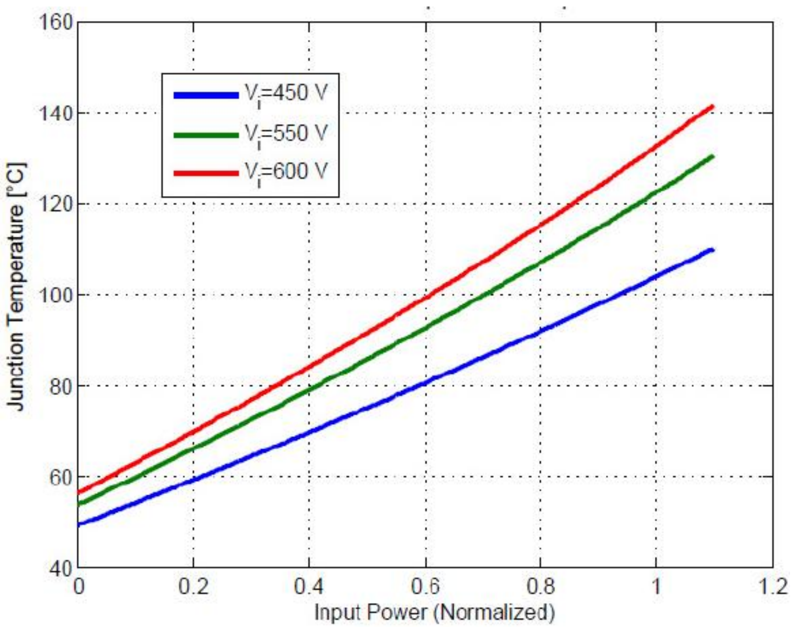
DC-DC CONVERTER

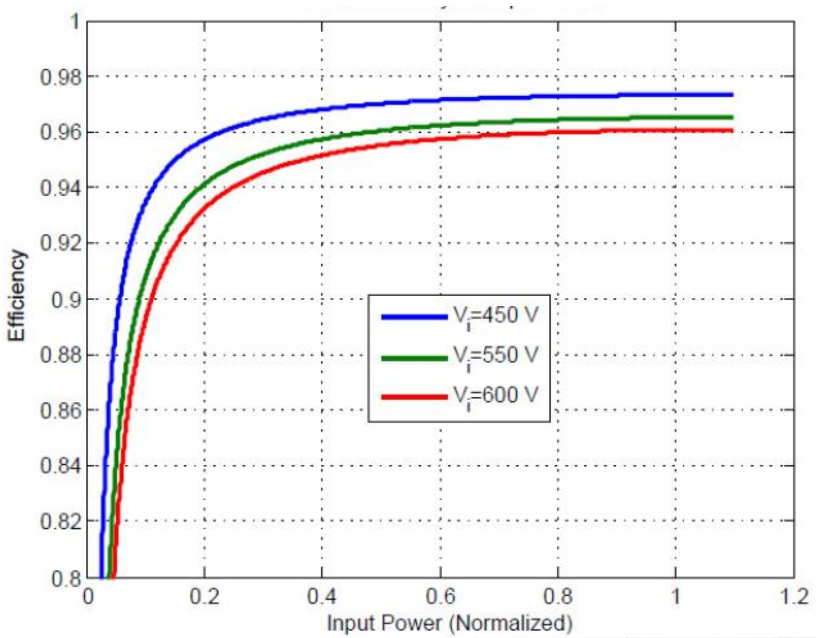
BUCK converts a DC voltage in a lower one



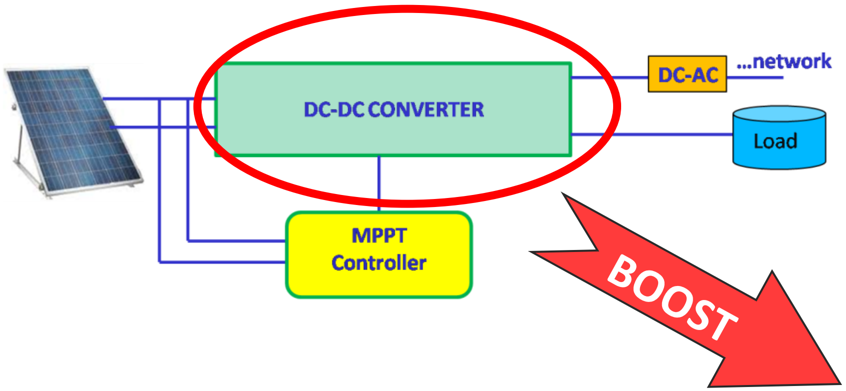
$$V_{out} = D * V_{in}$$

- **higher input voltage**
- **higher currents**
- **higher losses**
- **lower efficiency**
- **higher junction temperature**

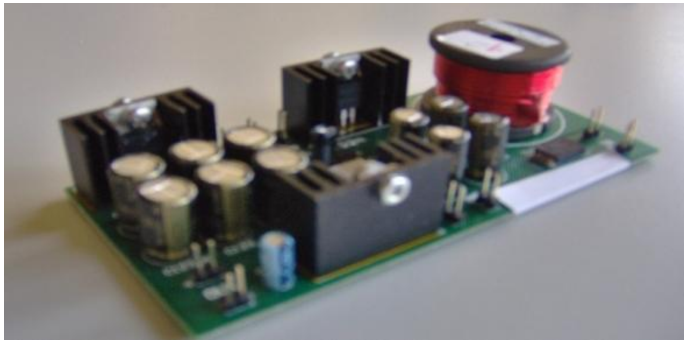


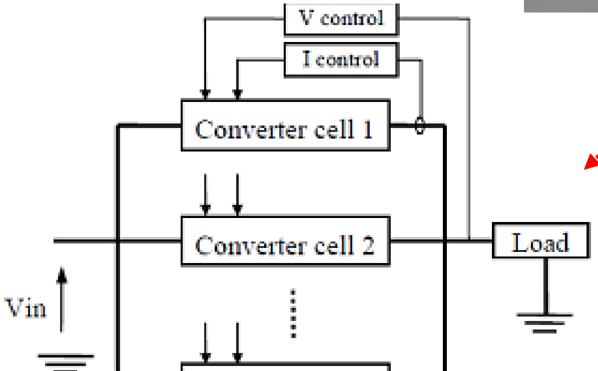


DC-DC CONVERTER

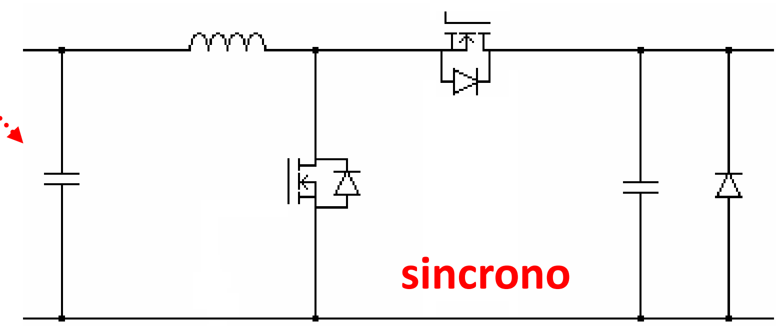


The best topology is a trade off between performance, number of devices and cost. Using a DC-DC converter for each module the energetic efficiency of the whole system increases.



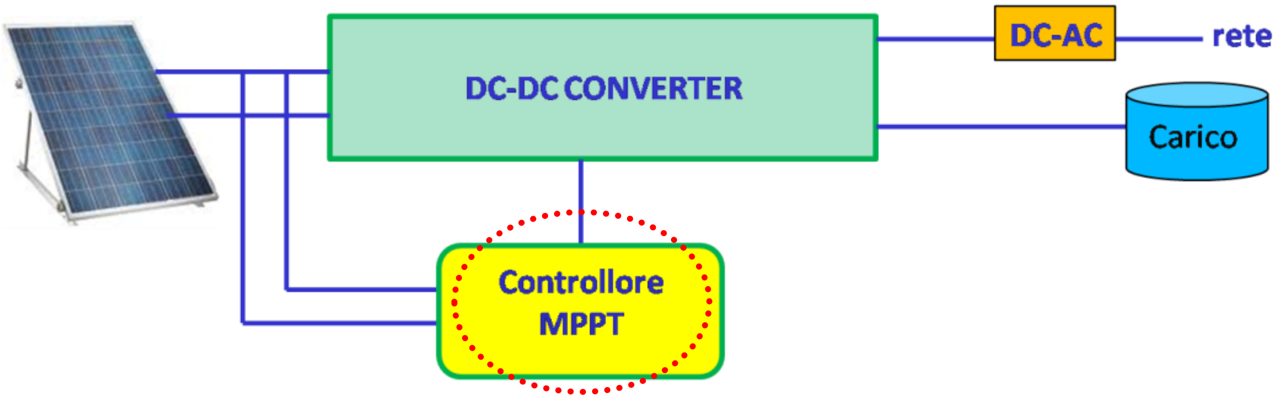


interleaved



sincrono

MPPT CONTROL

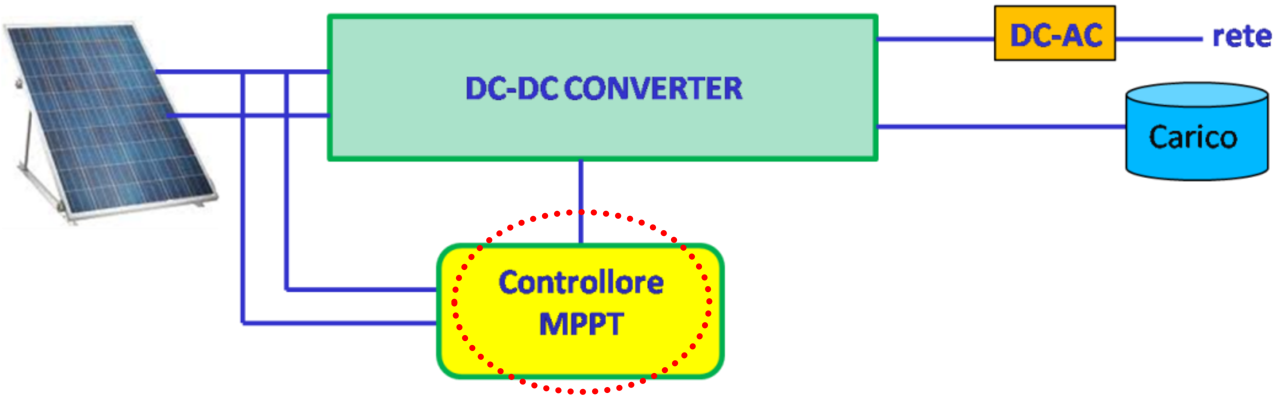


The MPPT controller is able to maximize the panel output power during day working also in mismatch condition. Many different strategies are available for MPPT. Analog and digital techniques can be implemented.

Control Techniques

- Analog/Digital
- Voltage Mode/Peak Current Mode/Average Current Mode
- Fuzzy logic and neural networks

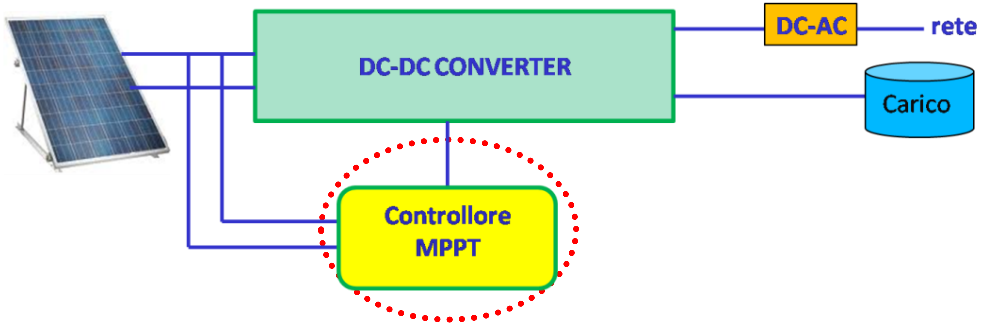
MPPT CONTROL



Strategies

- Hill climbing
- Perturb and Observe
- Incremental conductance
- Fractional Open Circuit Voltage
- Fractional Short Circuit Current

MPPT CONTROL



Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions.

Other control technique by fuzzy logic and neural networks could improve the MPPT performance sensing variations of:

- **irradiance level**
- **temperature**
- **PV module short circuit current**
- **PV module open circuit voltage**

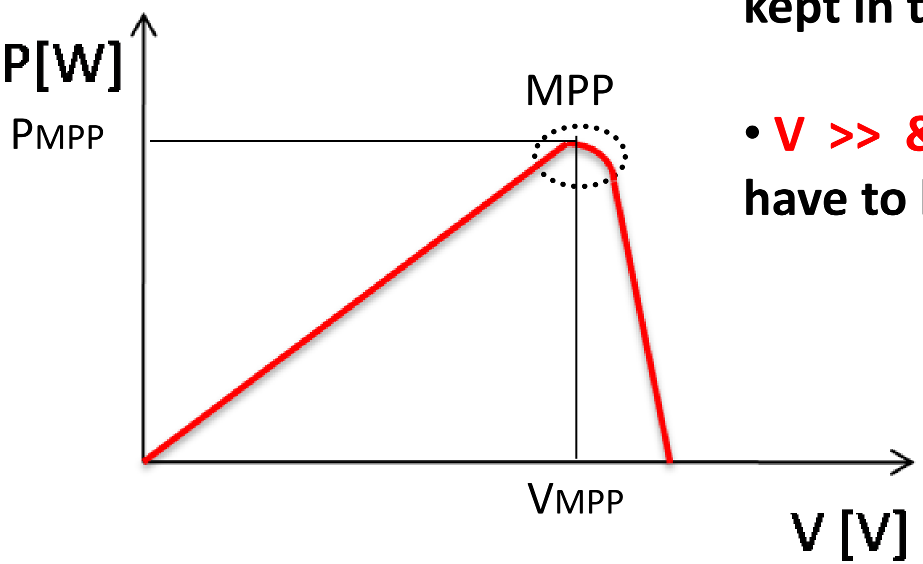
The performances are different for:

- **reliability**
- **responce time**
- **cost**
- **complexity**

MPPT CONTROL

Between all the MPPT strategies much focus is placed on perturb and observe (P&O) methods.

To track the MPP is needed to modify the duty ratio of converter switching devices perturbing the PV array current and voltage.



- **V >> & P >> -> the duty perturbation have to be kept in the same direction**

- **V >> & P << -> the duty perturbation direction have to be reversed**

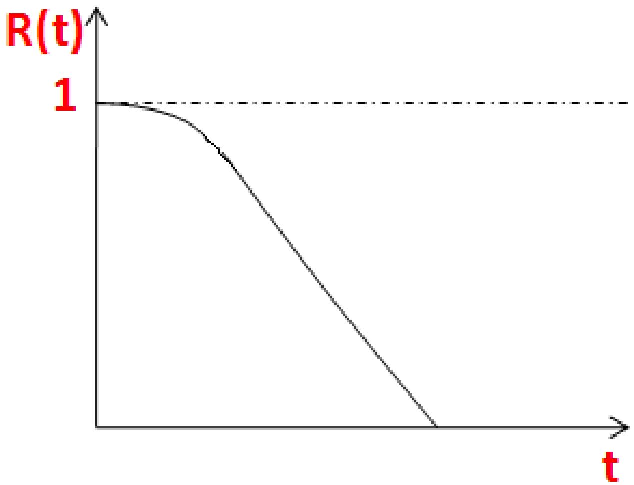
RELIABILITY THEORY

RELIABILITY [R(t)] is
the PROBABILITY than an item will perform a required function without failure under stated conditions for a stated period of time

$$R(t) \equiv \Pr\{T > t\}$$

R = reliability; Pr = probability
T = random variable = lifetime of the unit
t = mission time

R is a number in the range $0 \le R \le 1$



- $R(0) = 1$ — At the beginning the probability of device proper functioning is high
- $R(t)$ — decreases with t
- $R(t) \rightarrow 0$ — for high mission time the probability of device propser functioning is low

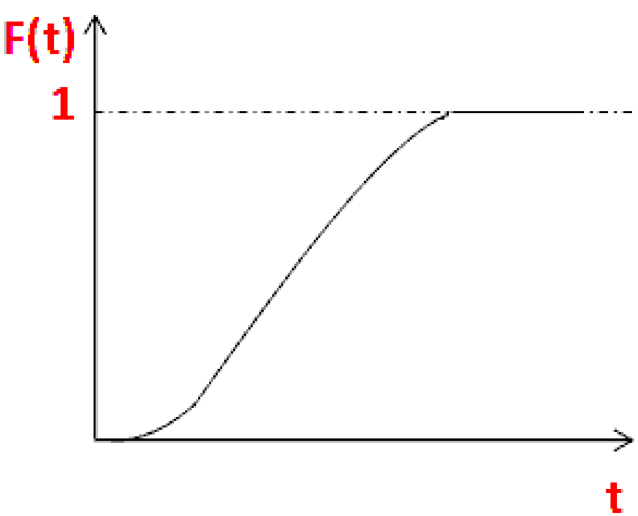
UNRELIABILITY

UNRELIABILITY [F(t)] is
the PROBABILITY than an item fails before of a period of time t

$$F(t) \equiv \Pr\{T \le t\}$$

F = unreliability; Pr = probability
T = random variable = lifetime of the unit; t = mission time

F is a number in the range 0 ≤ F ≤ 1

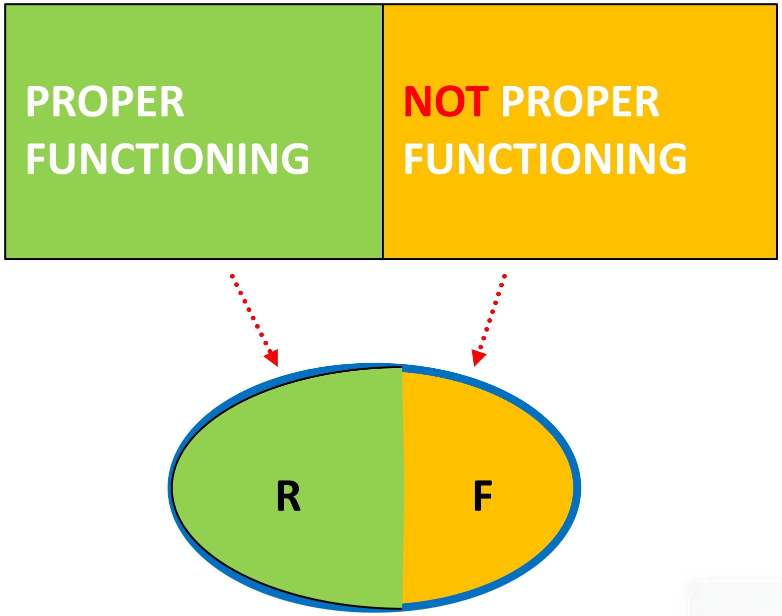


- F(0) = 0 — at the beginning the probability of device not proper functioning is low
- F(t) — increases with t
- F(t) → 1 — for high mission time the probability of device not proper functioning is high

RELIABILITY/UNRELIABILITY

Components working condition can be characterized by two events:

- **proper functioning**
- **not proper functioning**



Proper and not proper functioning cover the whole space of elementary outcomes and they are two incompatible events, so:

$$\boxed{R(t) + F(t) = 1}$$

Then knowing **R**, it is possible to calculate **F** $\rightarrow$ $\boxed{F(t) = 1 - R(t)}$

UNRELIABILITY

UNRELIABILITY [F(t)] is defined as the probability distribution function of the random variable T

$$F(t) = \int_0^t f(\tau)\, d\tau$$

F = unreliability = probability distribution function
T = random variable = device lifetime of the device
f = probability density function

$$f(t) = \frac{dF(t)}{dt}$$

So "f(t)*dt" is the probability that the device lifetime T is in the range (t, t+ dt)

$$f(t) * dt = dF(t)$$

FAILURE RATE FUNCTION

The failure rate or hazard function represents the FREQUENCY with which a component or a system fails

Since $\Pr\{t < T \leq t + \Delta t\} = F(t+\Delta t) - F(t)$ and

$$\Pr\{t < T \leq t + \Delta t \setminus T > t\} = \frac{\Pr\{t < T \leq t + \Delta t\}}{\Pr\{T > t\}} = \frac{F(t+\Delta t) - F(t)}{R(t)}$$

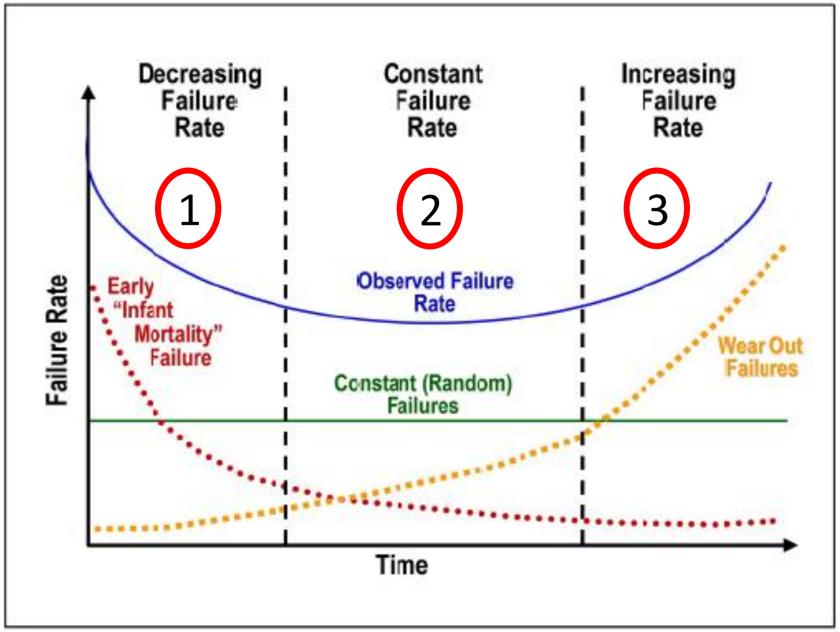
The **failure rate h(t)** is defined as:

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr\{t < T \leq t + \Delta t \setminus T > t\}}{\Delta t} = \frac{1}{R(t)} \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t} = \frac{f(t)}{R(t)}$$

f(t) and R(t) are positive functions, then:

$$h(t) \geq 0$$

BATHTUB CURVE



- Failure rate varies as a function of time
- The failure rate is expressed in FIT (Failure In Time - failure per billion of hours)

Infant Mortality Failures — 1 → high mortality age and decreasing failure rate trend. Defective products are identified and discarded

Random Failures — 2 → low mortality age and constant failure rate

Wear out Failures — 3 → high mortality age and decreasing failure rate trend. Wear out of products

RELIABILITY MODEL

Components reliability can be represented by different mathematical models:

- Exponential model
- Weibull model
- Lognormal model

EXPONENTIAL MODEL

Studies on electronic devices reliability demonstrate that a suitable model is the exponential one.

This model is characterized by the constant failure rate λ

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

$$F(t) = 1 - R(t) = 1 - e^{-\lambda \cdot t}$$

The exponential distribution is memoryless, in fact the following expression demostrates that the probability to have a device lifetime longer than ($t+t_1$) dipends only on t_1 and it doesn't depend on t.

$$\Pr\{T > t + t_1 \backslash T > t\} = \frac{\Pr\{T > t + t_1\}}{\Pr\{T > t\}} = \frac{R(t+t_1)}{R(t)} = \frac{e^{-\lambda(t+t_1)}}{e^{-\lambda t}} = e^{-\lambda t_1}$$

In case of electronic components this property means that they only break for accidental causes and not for wear.

MTTF - MEAN TIME TO FAILURE

The Mean Time To Failure (MTTF) is the expected or average time to failure

$$MTTF = \int_0^{\infty} R(t)\,dt = \int_0^{\infty} e^{-\lambda \cdot t} \cdot dt = \frac{1}{\lambda}$$

MTTF is a reliability index used for non-reparable devices or systems.

MTBF - MEAN TIME BETWEEN FAILURE

MTBF is a measure of how reliable a product is.
It is usually given in units of hours.
High MTBF values characterize high reliability products.

$$\boxed{MTBF = MTTF + MTTR}$$

where MTTR is the Mean Time to Repair

If a system is characterized by a very high MTTF or it is quickly reparable, the MTBF expression becomes:

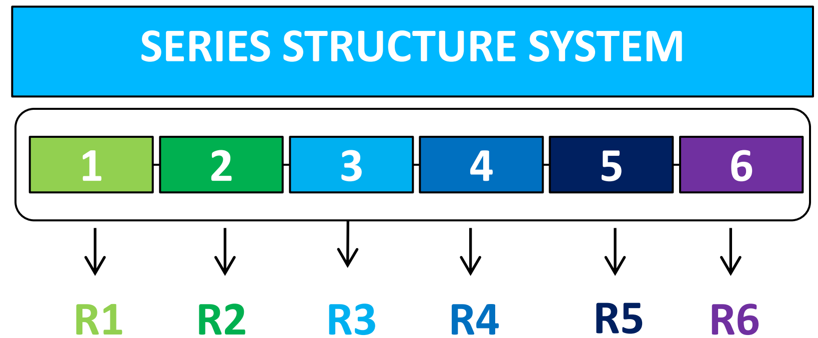
$$\boxed{MTBF = MTTF}$$

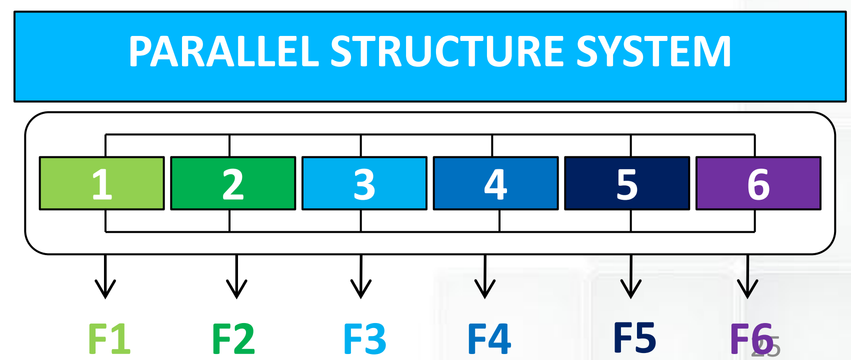
SYSTEM RELIABILITY

A system comprises different components that interact for a proper functioning. For system reliability estimation it is necessary to consider the reliability of each component and how they are connected.

Components can be connected:

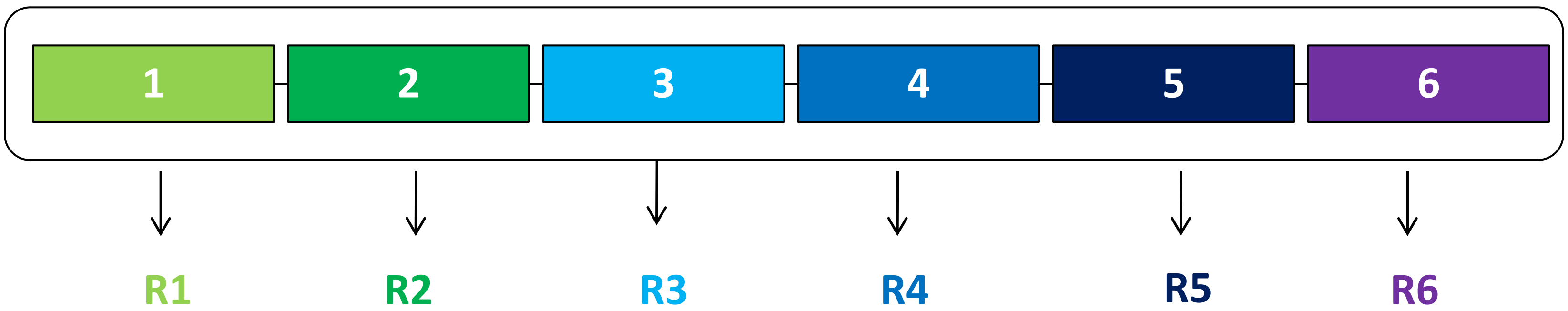
- in series
- in parallel
- in series-parallel combination





SERIES STRUCTURE SYSTEM

A series structure system functions only when all of its parts are correctly functioning.



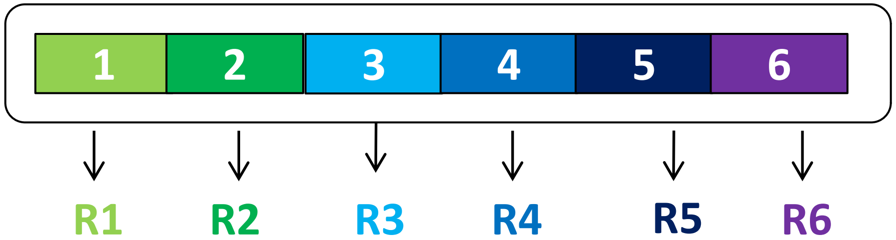
In a series structure the system proper functioning depends on the proper functiong of each part:

$$S = A_1 \cap A_2 \cap A_3 \ldots \cap A_N$$

where:
Ai = "proper functioning event" of the ith part of a system
S = the system proper functioning event

SERIES STRUCTURE SYSTEM

Under the hypothesis of stochastical independence of the event A_i the reliability (R_s) of a series system is:



$$R_s = \Pr\{S\} = \prod_{i=1}^{N} \Pr\{A_i\} = \prod_{i=1}^{N} R_i$$

The failure rate equals the sum of the failure rates of the components:

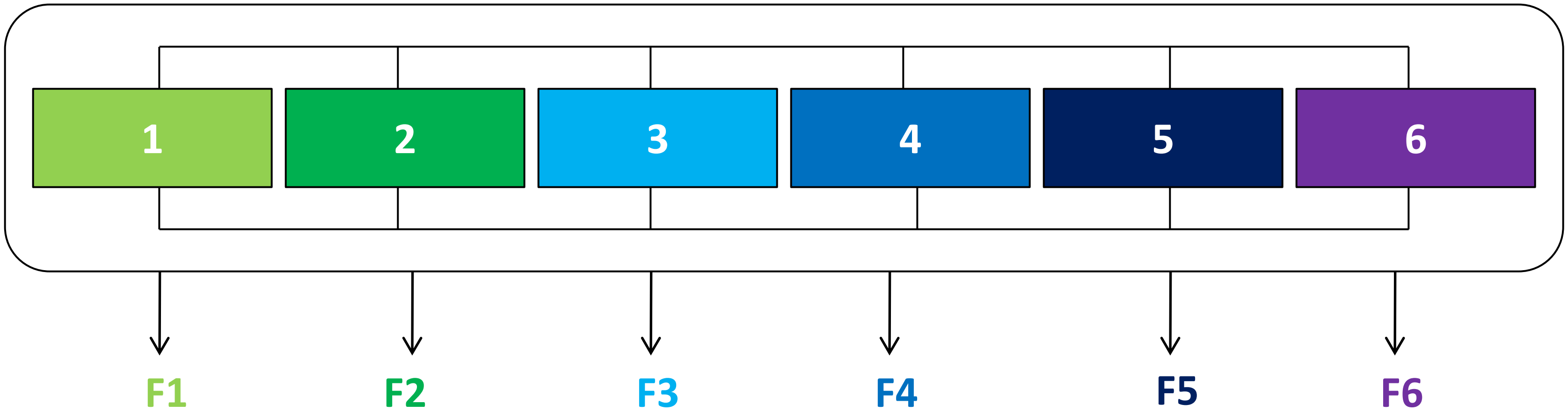
$$\lambda_s(t) = \sum_{i=1}^{N} \lambda_i(t)$$

The reliability of a series structure system is smaller than the reliability of each element:

$$R_s = \Pr\{S\} \le \min\left[\Pr\{A_i\}, \ldots, \Pr\{A_N\}\right]$$

PARALLEL STRUCTURE SYSTEM

A parallel structure system fails only when everyone of its parts fails

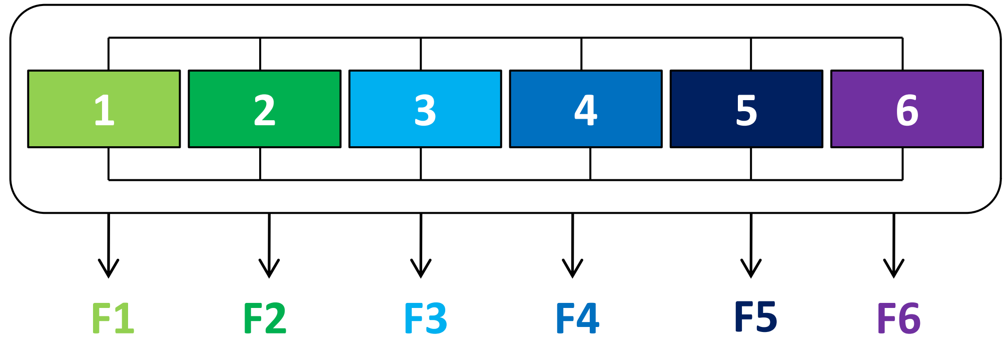


If $\overline{A_i}$ is the "not proper functioning event" of the i-th part of a system, the system function not correctly events is: $\overline{S}$

$$\overline{S} = \overline{A_1} \cap \overline{A_2} \cap \overline{A_3} \ldots \cap \overline{A_N}$$

PARALLEL STRUCTURE SYSTEM

Under the hypothesis of stochastical independence of the event A_i the unreliability of a parallel system (F_p) is:



$$F_p = \Pr\{\bar{S}\} = \prod_{i=1}^{N} \Pr\{\bar{A}_i\} = \prod_{i=1}^{N} F_i$$

The reliability of a parallel structure system is:

$$R_p = \Pr\{S\} = 1 - \prod_{i=1}^{N} F_i$$

RELIABILITY PREDICTION MODELS

Two types of analyses are usually available within a reliability prediction model

PART COUNT ANALYSIS PCA

Used at the design beginning phase when details on devices working conditions are not known. Information about the parts types and quantities, part quality levels and the environment where the equipment is presumed to work.

PART STRESS ANALYSIS PSA

Applicable only when the design is completed and a detailed part list devices/components is available. The failure rate is predicted considering temperature and electrical stress in the real working conditions.

RELIABILITY PREDICTION MODELS

Reliability Prediction Models are used to evaluate the failure rate of a system. Generally the following are used:

- **MIL-HDBK-217F**
- **TELCORDIA SR-332**
- **217 PLUS**
- **FIDES**

RELIABILITY PREDICTION MODELS

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MIL-HDBK-217F

217PLUS

- Telecommunication industry
- Military applications (converters, inverters, aircraft, ecc.)

TELCORDIA SR-332

- Electronic parts (magnetic devices)

FIDES

- Electrical/Electronic
- Electromechanical components (avionics control)

MIL-HDBK-217F

The “Reliability Prediction of Electronic Equipment” was published by the United States Navy in 1965. It had became a de facto standard also if the United States Department of Defence stopped to update it in 1995 with the latest version MIL-HDBK-217F notice 2.

It includes models for a broad range of part types and supports five environments used in the telecom industry and in military applications

Disadvantage: it doesn’t take into account some factors as burning data, lab testing data, field test data, designer experience or wear-out phenomena.

PART COUNT ANALYSIS
PCA

PART STRESS ANALYSIS
PSA

Both of these analyses are possible

PART COUNT ANALYSIS
PCA

The equipment failure rate is:

$$\lambda_{equip} = \sum_{i=1}^{N} N_i (\lambda_g \pi_Q)_i$$

where:

where:	λ_{equip}	is the total equipment failure rate
	λ_g	is the generic failure rate for the i-th generic part
	π_Q	is quality factor for the i-th generic part
	N_i	is the quantity of the i-th generic part
	N	is the number of different generic part categories in the equipment

MIL-HDBK-217F

PART STRESS ANALYSIS
PSA

The failure rate of every part of the system is evaluated with the following equation:

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$

where:

λ_p	is the part failure rate
λ_b	is the base failure rate for the device in standard condition
π_T	is temperature factor
π_A	is the application factor
π_Q	is the quality factor
π_E	is the environment factor

It is possible to calculate the SYSTEM failure rate summing all the components failure rates.

217Plus

The “Reliability Information Analysis Center (RIAC) Handbook 217Plus model” was developed by the United States Department of Defence in 2006 as an official successor of the MIL-HDBK-217 methodology. The failure rate of every part of the system is evaluated with the following equation:

$$\boxed{\lambda_p = \lambda_o \pi_o + \lambda_e \pi_e + \lambda_c \pi_c + \lambda_i + \lambda_{sj} \pi_{sj}}$$

where:

λ_p	is the part predicted failure rate
λ_o	is the failure rate from operational stresses
π_o	is the product of failure rates multipliers for operational stresses
λ_e	is the failure from environmental stresses
π_e	is the product of failure rates multipliers for environmental stresses
λ_c	is the failure from power or temperature cycling stresses
π_c	is the product of failure rates multipliers for cycling stresses
λ_i	is the failure from induced stress such as ESD
λ_{sj}	is the failure from solder joint stresses
π_{sj}	is the product of failure rates multipliers for solder joint stresses

This model considers a different base failure rate for each generic class of failure mechanism.

217Plus

The system failure rate is obtained by the following expression:

$$\lambda_{sys} = \lambda_{equipment}(\Pi_P + \Pi_D + \Pi_M + \Pi_S + \Pi_I + \Pi_N + \Pi_W) + \lambda_{software}$$

where:

λ_{sys}	is the predicted failure rate of the entire system
$\lambda_{equipment}$	is the failure rate from operational stresses
π_P	is the part process factor
π_D	is the design process factor
π_M	is the manufacturing process factor
π_S	is the system management process factor
π_I	is the induced process factor
π_N	is the no-defect process factor
π_W	is the wear out process factor
$\lambda_{software}$	is the software failure rate prediction

TELCORDIA

The "Reliability Prediction Procedure for Electronic Equipment SR-332" was developed by AT&T Bell Labs in 1997. It modified the MIL-HDBK-217F Prediction Model to better represent the equipment of the telecommunication industry including burn-in, field and laboratory test data.

This Prediction Model assumes a serial model for electronic parts and addresses failure rates at the infant mortality stage and at the steady-state stage with three different methods.

TELCORDIA METHOD I	TELCORDIA METHOD II	TELCORDIA METHOD III

TELCORDIA

TELCORDIA METHOD I

Method I is similar to MIL-HDBK-217. It considers for each part the generic failure rate, the quality factor π_Q, electrical stress factor π_S and temperature stress factor π_T.

TELCORDIA METHOD II

Method II is obtained combining Method I predictions with data from laboratory tests performed in accordance with specific SR-332 criteria.

TELCORDIA METHOD III

Method III is a statistical prediction of failure rate based on field tracking data collected in accordance with specific SR-332 criteria. The predicted failure rate is a weighted average of the generic steady-state failure rate and the field failure rate.

FIDES

The reliability methodology “FIDES Guide 2004” has been developed by FIDES Group, a consortium of French companies as Thales, Airbus France, MBDA, GIAT Industries. This prediction methodology provides models for electrical, electronic and electromechanical components and it considers factors as electrical, mechanical and thermal overstresses.

FIDES is based on the physics of failures supported by the analysis of test data, field returns and existing modeling which makes it somewhat different from traditional prediction methods which are exclusively based on the statistical analysis of historical failure data collected in the field, in-house or from manufacturers.

FIDES

Methodology steps

Component reliability prediction guide:
Calculation of component failure rates based on component characteristics and application related data (e.g. thermal and electrical stress)

Reliability process control and audit guide:
Evaluates the manufacturing quality of the component and effects of all process during the whole life cycle from the specification and design phase up to maintenance and support activities

$$\boxed{\lambda_p = \lambda_{physical} \Pi_{part\_manufacturing} \Pi_{process}}$$

where:

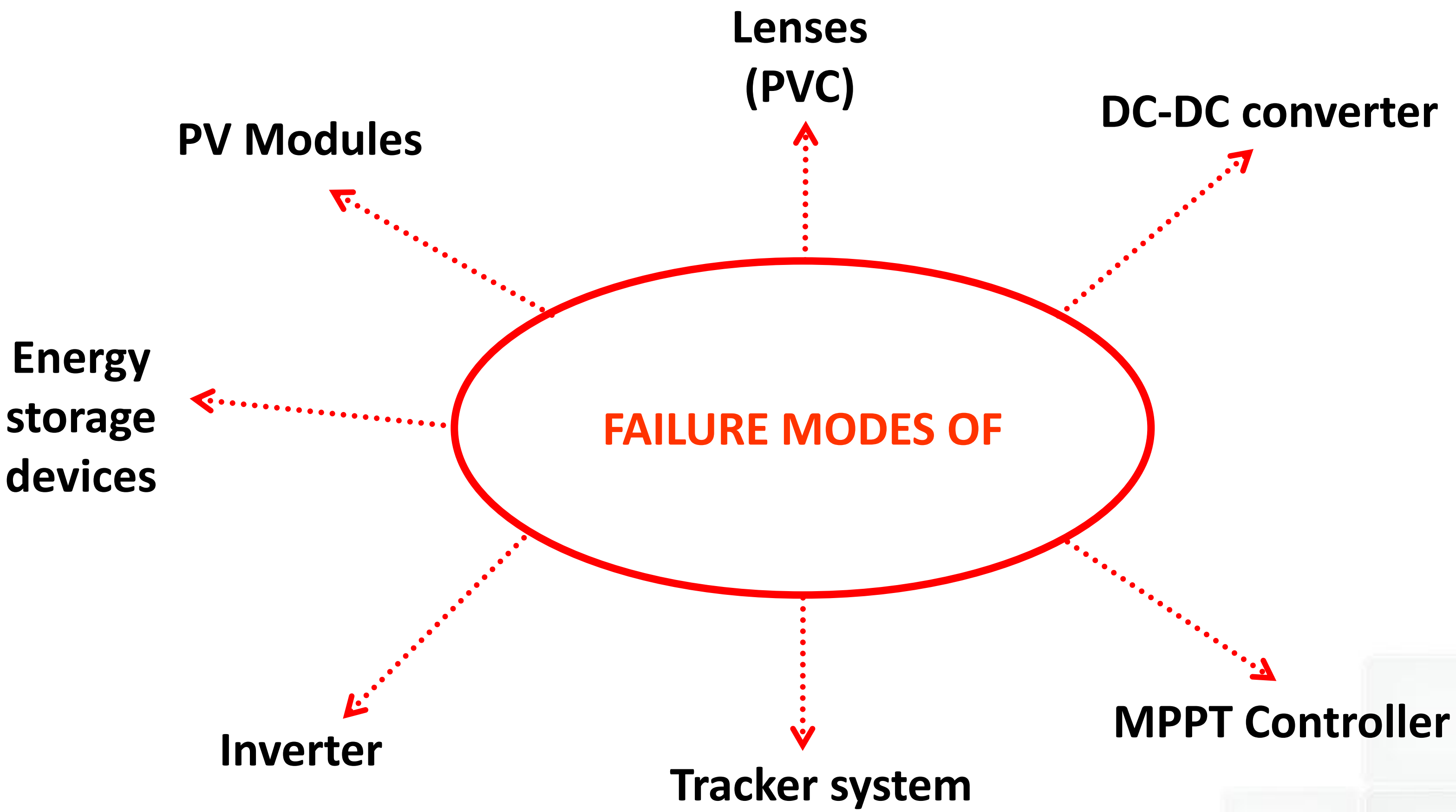
$\lambda_{physical}$ is subdivided in various contributions. Usually there is a base failure rate λ_b multiplied with acceleration factors indicating the sensitivity to operational and environmental condition of use

$\pi_{part\text{-}manufacturing}$ represents the component quality by taking into account the manufacturer quality assurance, the component quality assurance and even the experience that the user has with the specific manufacturerr

$\Pi_{process}$ represents the quality and technical control of reliability relevant aspects during the product life cycle

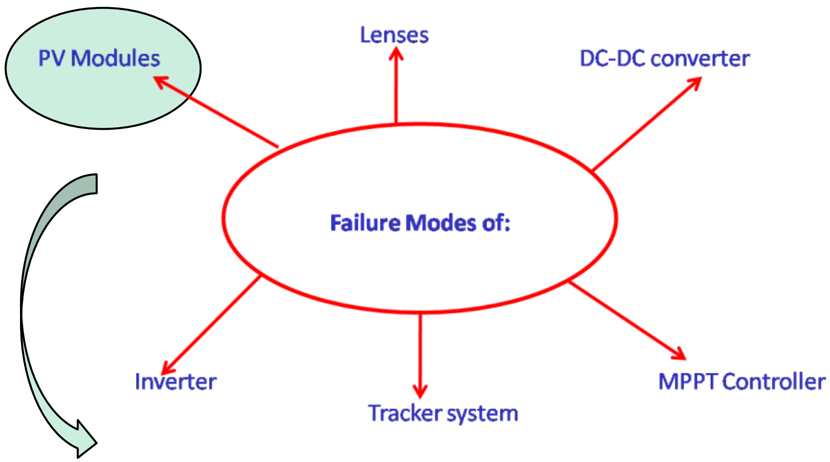
PV System Reliability Evaluation

PV System Reliability Evaluation



PV MODULES

Development of a reliable PV module requires an understanding of potential failure mechanisms:



The most reliable component of a PV system

- Broken cells
- Corrosion
- Delamination and/or loss of elastomeric properties
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures

We cannot wait for 25 or 30 years to see what failure mechanisms a module might suffer! Therefore we try to develop stress tests that accelerate the same failure mechanisms to estimate degradation rate and lifetime.

ACCELERATED TEST ON PV MODULE

Thermal cycling

Damp heat exposure & humidity freeze

UV test

Mechanical load

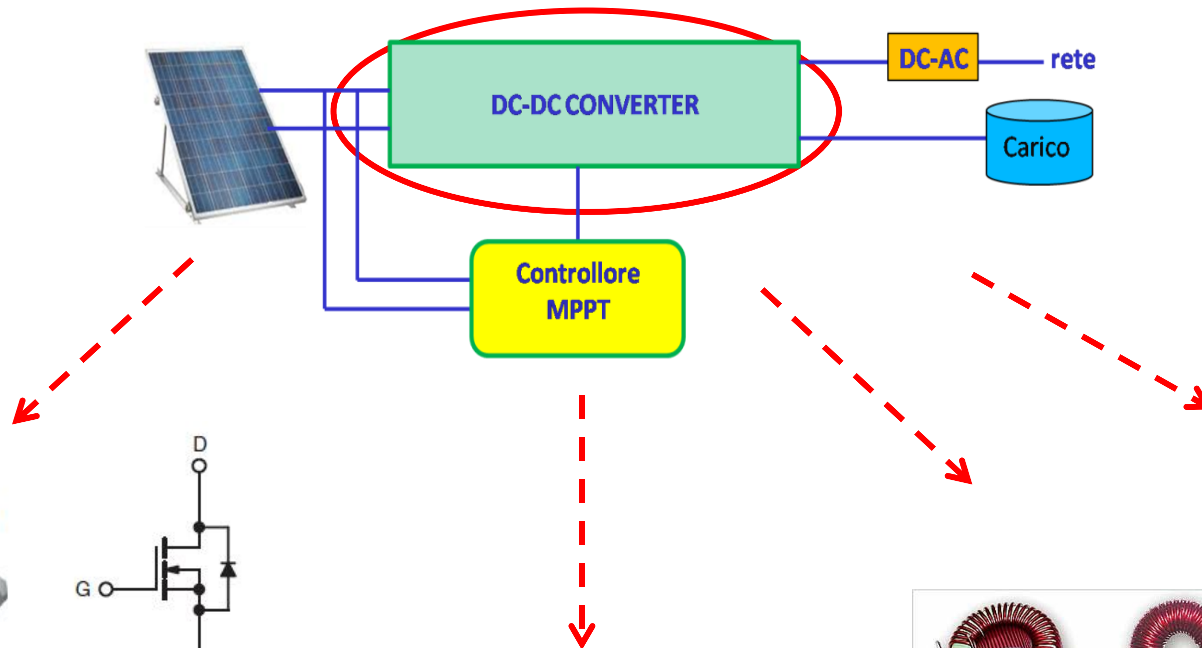
Dry and wet insulating resistance

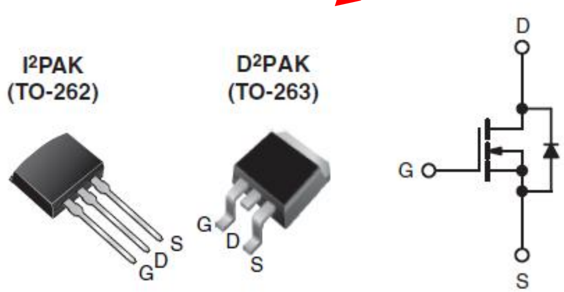
Hail test

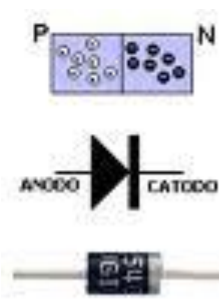
Hot spots

DC-DC CONVERTER RELIABILITY

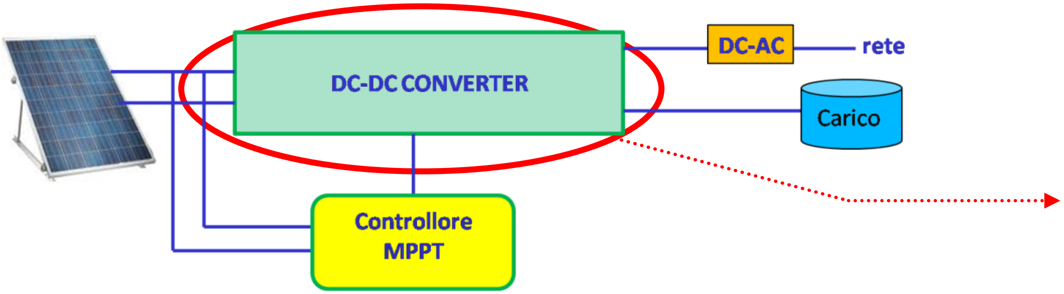
To evaluate the reliability of a PV DC-DC converter it is necessary to calculate the reliability of its each component: MOSFETs, diodes, inductors, capacitors.

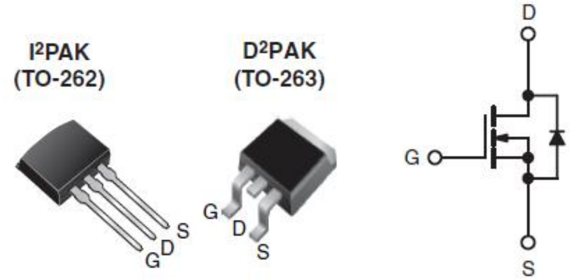






MIL-HDBK-217F: MOSFET





INTRINSIC FAILURES

Failure mechanisms due to chip or die, such as defects in the substrate, insulation films or metallization

EXTRINSIC FAILURES

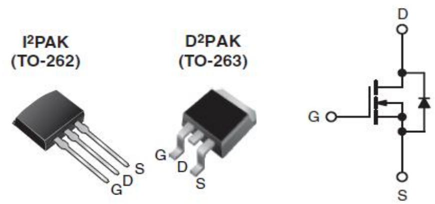
Unproper interconnection and packaging of chips may lead to device failure, for instance the stress at solder connections due to a mismatch of thermal properties of the different materials

ELECTRICAL STRESS FAILURES

Excessive electrical stresses and electrostatic discharge may cause the device to fail

MIL-HDBK-217F: MOSFET

ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE



The MOSFET failure rate is evaluated with the equation:

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$

The MOSFET Temperature factor π_T is evaluated with the next expression and it depends on MOSFET junction temperature T_j.

6.4 TRANSISTORS, LOW FREQUENCY, SI FET

SPECIFICATION
MIL-S-19500

DESCRIPTION
N-Channel and P-Channel Si FET (Frequency ≤ 400 MHz)

$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$ Failures/10^6 Hours

λ_b

Base Failure Rate - λ_b

Transistor Type	λ_b
MOSFET	.012
JFET	.0045

π_T

Temperature Factor - π_T

T_J (°C)	π_T	T_J (°C)	π_T
25	1.0	105	3.9
30	1.1	110	4.2
35	1.2	115	4.5
40	1.4	120	4.8
45	1.5	125	5.1
50	1.6	130	5.4
55	1.8	135	5.7
60	2.0	140	6.0
65	2.1	145	6.4
70	2.3	150	6.7
75	2.5	155	7.1
80	2.7	160	7.5
85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$$\pi_T = \exp\left(-1925\left(\frac{1}{T_J + 273} - \frac{1}{298}\right)\right)$$

T_J = Junction Temperature (°C)

Application Factor - π_A

Application (P_r, Rated Output Power)	π_A
Linear Amplification (P_r < 2W)	1.5
Small Signal Switching	.70
Power FETs (Non-linear, $P_r \geq$ 2W)	
$2 \leq P_r <$ 5W	2.0
$5 \leq P_r <$ 50W	4.0
$50 \leq P_r <$ 250W	8.0
$P_r \geq$ 250W	10

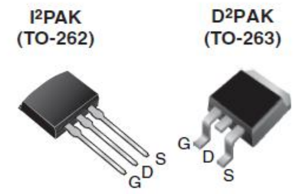
Environment Factor - π_E

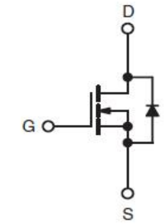
Environment	π_E
G_B	1.0
G_F	6.0
G_M	9.0
N_S	9.0
N_U	19

MIL-HDBK-217F: MOSFET

ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

6.4 TRANSISTORS, LOW FREQUENCY, SI FET





SPECIFICATION
MIL-S-19500

DESCRIPTION
N-Channel and P-Channel Si FET (Frequency ≤ 400 MHz)

$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$ Failures/10^6 Hours

Base Failure Rate - λ_b

Transistor Type	λ_b
MOSFET	.012
JFET	.0045

Temperature Factor - π_T

T_J (°C)	π_T	T_J (°C)	π_T
25	1.0	105	3.9
30	1.1	110	4.2
35	1.2	115	4.5
40	1.4	120	4.8
45	1.5	125	5.1
50	1.6	130	5.4
55	1.8	135	5.7
60	2.0	140	6.0
65	2.1	145	6.4
70	2.3	150	6.7
75	2.5	155	7.1
80	2.7	160	7.5
85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$$\pi_T = \exp\left(-1925\left(\frac{1}{T_J + 273} - \frac{1}{298}\right)\right)$$

T_J = Junction Temperature (°C)

Application Factor - π_A

Application (P_r, Rated Output Power)	π_A
Linear Amplification (P_r < 2W)	1.5
Small Signal Switching	.70
Power FETs (Non-linear, $P_r \geq$ 2W)	
$2 \leq P_r <$ 5W	2.0
$5 \leq P_r <$ 50W	4.0
$50 \leq P_r <$ 250W	8.0
$P_r \geq$ 250W	10

π_A

Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	9.0
N_S	9.0
N_U	19

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$

The Application factor π_A depends on the rated power of the MOSFET

MIL-HDBK-217F: MOSFET

85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$$\pi_T = \exp\left(-1925\left(\frac{1}{T_J + 273} - \frac{1}{298}\right)\right)$$

T_J = Junction Temperature (°C)

Quality Factor - π_Q

Quality	π_Q
JANTXV	.70
JANTX	1.0
JAN	2.4
Lower	5.5
Plastic	8.0

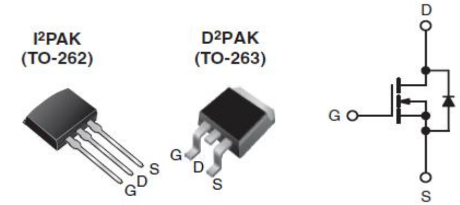
π_Q

The Qualification factor depends on devices type. In PV converters design commercial "plastic" components are used, so the π_Q = 8

Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	9.0
N_S	9.0
N_U	19
A_{IC}	13
A_{IF}	29
A_{UC}	20
A_{UF}	43
A_{RW}	24
S_F	.50
M_F	14
M_L	32
C_L	320

π_E

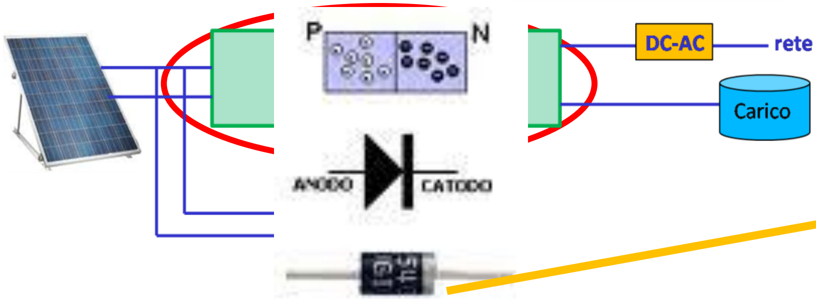


$$\boxed{\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E}$$

The environment considered is GB "Ground Benign so the Environment factor π_E is 1.

Some environment value are:
G_F=Ground Fixed
G_M=Ground Mobile
N_S=Naval, Sheltered
A_{IC}=Airborne, Inhabited, Cargo
S_F=Space, Flight
M_F=Missile, Launch

MIL-HDBK-217F: DIODE



$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi$$

The base failure rate λb depends on the diode type and application. In PV systems Schottky diodes are used so λb value is 0.003.

λb

The Temperature factor depens on the specific application considered. In our case diodes are used in switching converters, so we have to use the equation *

π_T

π_T

6.1 DIODES, LOW FREQUENCY

SPECIFICATION
MIL-S-19500

DESCRIPTION
Low Frequency Diodes: General Purpose Analog, Switching, Fast Recovery, Power Rectifier, Transient Suppressor, Current Regulator, Voltage Regulator, Voltage Reference

$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$ Failures/10^6 Hours

Base Failure Rate - λ_b

Diode Type/Application	λ_b
General Purpose Analog	.0038
Switching	.0010
Power Rectifier, Fast Recovery	.069
Power Rectifier/Schottky Power Diode	.0030
Power Rectifier with High Voltage Stacks	.0050/ Junction
Transient Suppressor/Varistor	.0013
Current Regulator	.0034
Voltage Regulator and Voltage Reference (Avalanche and Zener)	.0020

Temperature Factor - π_T
(General Purpose Analog, Switching, Fast Recovery, Power Rectifier, Transient Suppressor)

T_J (°C)	π_T	T_J (°C)	π_T
25	1.0	105	9.0
30	1.2	110	10
35	1.4	115	11
40	1.6	120	12
45	1.9	125	14
50	2.2	130	15
55	2.6	135	16
60	3.0	140	18
65	3.4	145	20
70	3.9	150	21
75	4.4	155	23
80	5.0	160	25
85	5.7	165	28
90	6.4	170	30
95	7.2	175	32
100	8.0		

$$\pi_T = \exp\left(-3091\left(\frac{1}{T_J + 273} - \frac{1}{298}\right)\right)$$

T_J = Junction Temperature (°C)

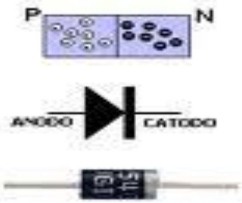
Temperature Factor - π_T
(Voltage Regulator, Voltage Reference, and Current Regulator)

T_J (°C)	π_T	T_J (°C)	π_T
25	1.0	105	3.9
30	1.1	110	4.2
35	1.2	115	4.5
40	1.4	120	4.8
45	1.5	125	5.1
50	1.6	130	5.4
55	1.8	135	5.7
60	2.0	140	6.0
65	2.1	145	6.4
70	2.3	150	6.7
75	2.5	155	7.1
80	2.7	160	7.5
85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$$\pi_T = \exp\left(-1925\left(\frac{1}{T_J + 273} - \frac{1}{298}\right)\right)$$

T_J = Junction Temperature (°C)

MIL-HDBK-217F: DIODE



$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$$

The Electrical Stress factor depends on the voltage stress ratio $\boxed{\pi_S}$

$$Vs = \frac{Vdc + Vac - peak}{Vrated}$$

Electrical Stress Factor - π_S

Stress	π_S
Transient Suppressor, Voltage Regulator, Voltage Reference, Current Regulator	1.0
All Others:	
$V_S \le .30$	0.054
$.3 < V_S \le .40$	0.11
$.4 < V_S \le .50$	0.19
$.5 < V_S \le .60$	0.29
$.6 < V_S \le .70$	0.42
$.7 < V_S \le .80$	0.58
$.8 < V_S \le .90$	0.77
$.9 < V_S \le 1.00$	1.0

For All Except Transient Suppressor, Voltage Regulator, Voltage Reference, or Current Regulator

$\pi_S = .054 \qquad (V_S \le .3)$

$\pi_S = V_S^{2.43} \qquad (.3 < V_S \le 1)$

V_S = Voltage Stress Ratio = $\frac{\text{Voltage Applied}}{\text{Voltage Rated}}$

Voltage is Diode Reverse Voltage

Quality Factor - π_Q

Quality	π_Q
JANTXV	0.7
JANTX	1.0
JAN	2.4
Lower	5.5
Plastic	8.0

Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	9.0
N_S	9.0
N_U	19
A_{IC}	13
A_{IF}	29
A_{UC}	20
A_{UF}	43
A_{RW}	24
S_F	.50
M_F	14
M_L	32
C_L	320

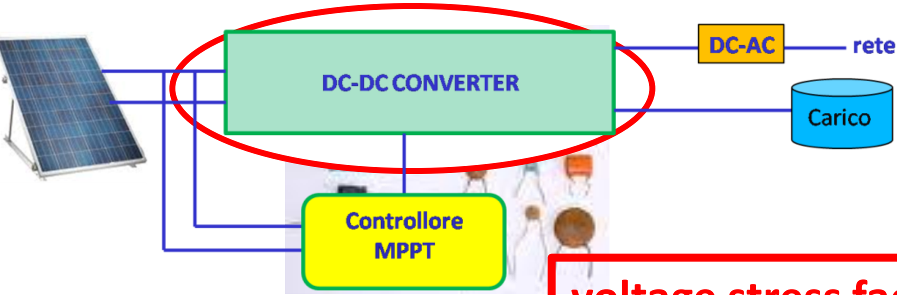
The Contact Construction factor depends on the contacts type. For metallurgically bonded contacts π_C value is 1 $\Big\}\ \pi_C$

Contact Construction Factor - π_C

Contact Construction	π_C
Metallurgically Bonded	1.0
Non-Metallurgically Bonded and Spring Loaded Contacts	2.0

π_Q and π_E are the same as MOSFET ones

MIL-HDBK-217F: CAPACITOR



voltage stress factor

The Capacitor failure rate is evaluated with the equation:

$$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E$$

λ_b Depends on the type of capacitor:
0.00051-> for metalized plastic cap
0.00012-> for aluminum cap

Series resistance factor

Quality factor

Environment factor

π_T

Temperature Factor - π_T

T(°C)	Column 1	Column 2
20	.91	.79
30	1.1	1.3
40	1.3	1.9
50	1.6	2.9
60	1.8	4.2
70	2.2	6.0
80	2.5	8.4
90	2.8	11
100	3.2	15
110	3.7	21
120	4.1	27
130	4.6	35
140	5.1	44
150	5.6	56

$$\pi_T = \exp\left(\frac{-Ea}{8.617 \times 10^{-5}}\left(\frac{1}{T+273} - \frac{1}{298}\right)\right)$$

Column 1: Ea = .15

Column 2: Ea = .35

T = Capacitor Ambient Temperature

NOTE: 1. π_T values shown should only be used up to the temperature rating of the device.

2. For devices with ratings higher than 150°C, use the equation to determine π_T (for applications above 150°C).

Capacitance Factor - π_C

Capacitance, C(μF)	Column 1	Column 2
.000001	.29	.04
.00001	.35	.07
.0001	.44	.12
.001	.54	.20
.01	.66	.35
.05	.76	.50
.1	.81	.59
.5	.94	.85
1	1.0	1.0
3	1.1	1.3
8	1.2	1.6
18	1.3	1.9
40	1.4	2.3
200	1.6	3.4
1000	1.9	4.9
3000	2.1	6.3
10000	2.3	8.3
30000	2.5	11
60000	2.7	13
120000	2.9	15

Column 1: $\pi_C = C^{.09}$

Column 2: $\pi_C = C^{.23}$

π_C

MIL-HDBK-217F: INDUCTOR

Magnetic devices are more reliable than other components. Main inductor failure mode are:

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E$$

Fail of copper winding insulation

Short between turns

High current generation

Power dissipation and hot spots increase

MIL-HDBK-217F: INDUCTOR

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E$$

Hot Spot temperature can be estimated as follows:

$$T_{HS} = T_A + 1.1\,(\Delta T)$$

where:

T_{HS} = Hot Spot Temperature (°C)
T_A = Inductive Device Ambient Operating Temperature (°C)
ΔT = Average Temperature Rise Above Ambient (°C)

ΔT can either be determined by the appropriate "Temperature Rise" Test Method paragraph in the device base specification (e.g., paragraph 4.8.12 for MIL-T-27E), or by approximation using one of the procedures described below.

SPECIFICATION	STYLE	DESCRIPTION
MIL-C-15305	-	Fixed and Variable, RF
MIL-C-83446	-	Fixed and Variable, RF, Chip
MIL-C-39010	-	Molded, RF, Est. Rel.

$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E$ Failures/10^6 Hours

λ_b

Base Failure Rate - λ_b

Inductor Type	λ_b F/10^6 hrs.
Fixed Inductor or Choke	.000030
Variable Inductor	.000050

π_T

Temperature Factor - π_T

T_{HS}(°C)	π_T
20	.93
30	1.1
40	1.2
50	1.4
60	1.6
70	1.8
80	1.9
90	2.2
100	2.4
110	2.6
120	2.8
130	3.1
140	3.3
150	3.5
160	3.8
170	4.1
180	4.3
190	4.6

$$\pi_T = \exp\left(\frac{-.11}{8.617 \times 10^{-5}}\left(\frac{1}{T_{HS}+273} - \frac{1}{298}\right)\right)$$

T_{HS} = Hot Spot Temperature (°C),
See Section 11.3

π_Q

Quality Factor - π_Q

Quality	π_Q
S	.03
R	.10
P	.30
M	1.0
MIL-SPEC	1.0
Lower	3.0

Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	12
N_S	5.0
N_U	16
A_{IC}	6.0
A_{IF}	8.0
A_{UC}	7.0
A_{UF}	9.0
A_{RW}	24
S_F	.50
M_F	13
M_L	34
C_L	610

π_E

DC-DC RELIABILITY QUALITATIVE EVALUATION

MTBFs discussed in the next must be considered only as reference values for comparison among the different DC-DC converters topologies designs using MATLAB©.

They are ONLY QUALITATIVE evaluations (no quantitative).

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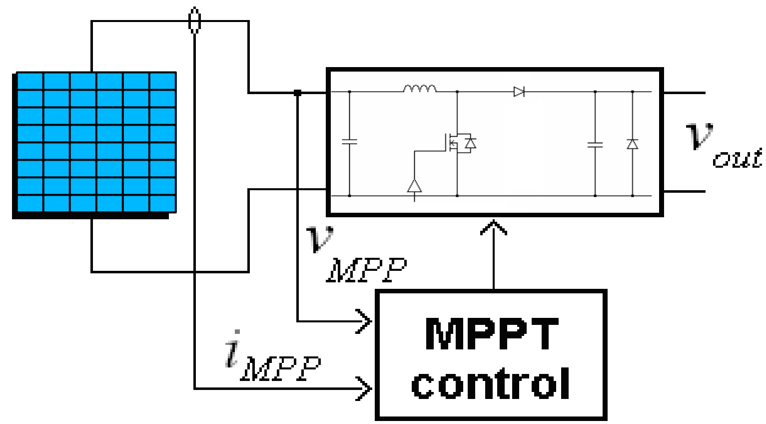
DC-DC RELIABILITY QUALITATIVE EVALUATION

BOOST

$$V_{out} = \frac{V_{in}}{(1-D)}$$



$$MTBF_{boost} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Inductor} + \lambda_{InCap} + \lambda_{OutCap}}$$

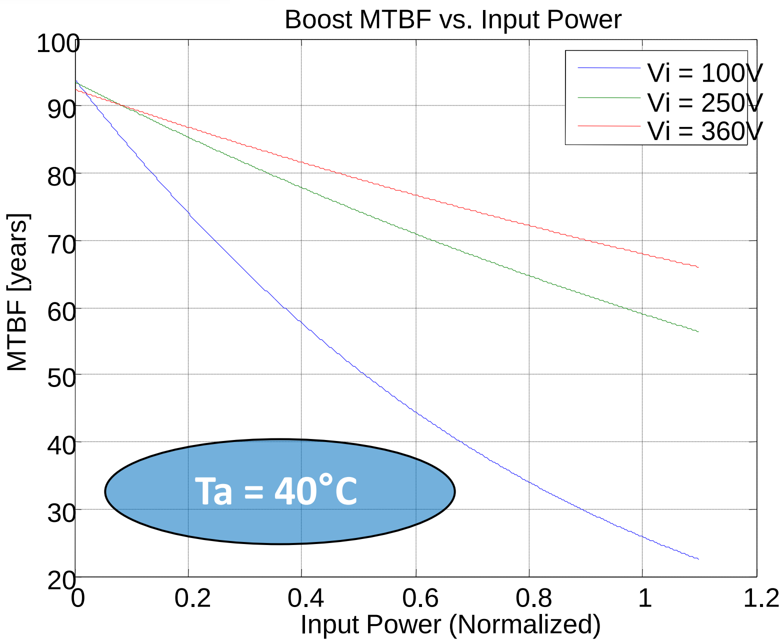
In the next, a study results on converters reliability trends are presented. The influence of temperature and input voltages on MTBF is analyzed.

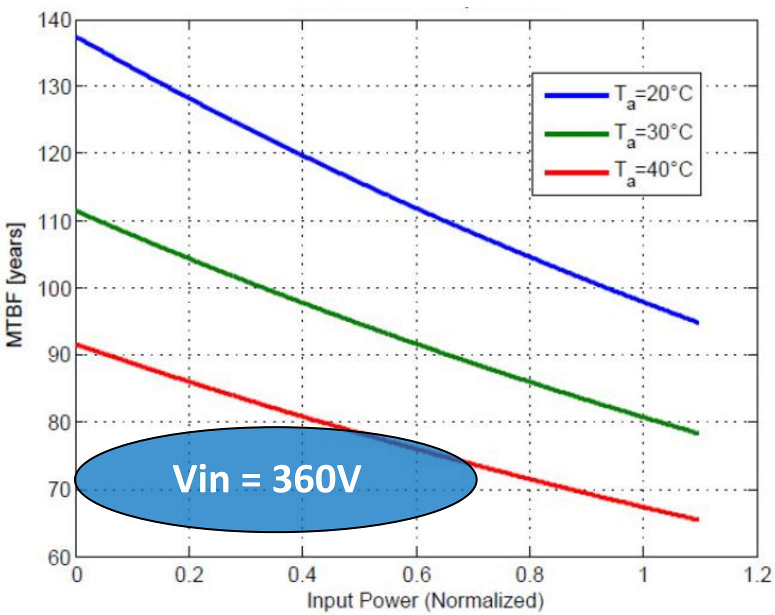
BOOST RELIABILITY QUALITATIVE EVALUATION

BOOST

Since a film capacitor has a lower failure rate compared with an electrolytic one, MOSFET becomes the largest failure rate component for converter design.

Higher input voltage-> lower currents-> lower losses -> lower FET junction temperature ->
lower FET stress -> higher converter reliability



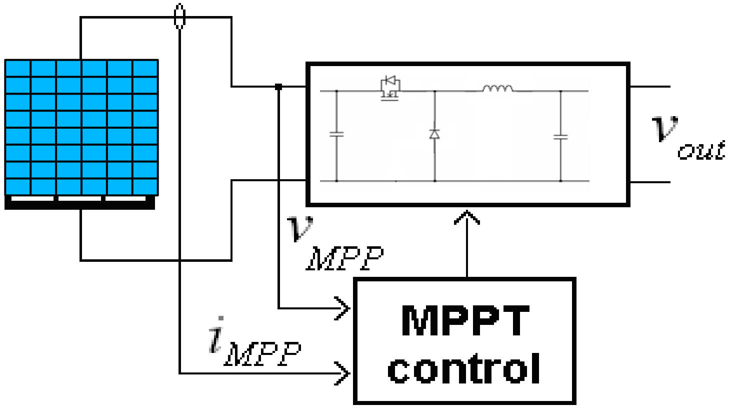


MTBF and the reliability are strongly dependent on ambient temperature. The same converter has different MTBF values if it works at different temperatures.

DC-DC CONVERTER RELIABILITY

BUCK

$$V_{out} = D * V_{in}$$



$$MTBF_{buck} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Inductor} + \lambda_{InCap} + \lambda_{OutCap}}$$

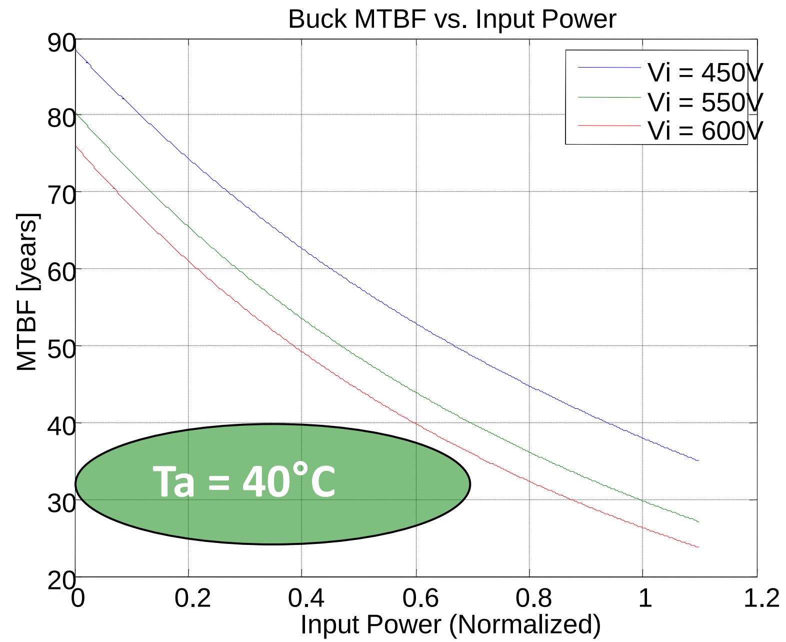
In the next results of a study on converters reliability trends are presented. The influence of temperature and input voltages on MTBF is underlined.

DC-DC CONVERTER RELIABILITY

BUCK

Since a film capacitor has a lower failure rate compared with an electrolytic one, MOSFET becomes the largest failure rate component for converter design.

Higher input voltage->higher currents-> higher losses->
higher junction temperature ->
higher FET stress -> lower converter reliability



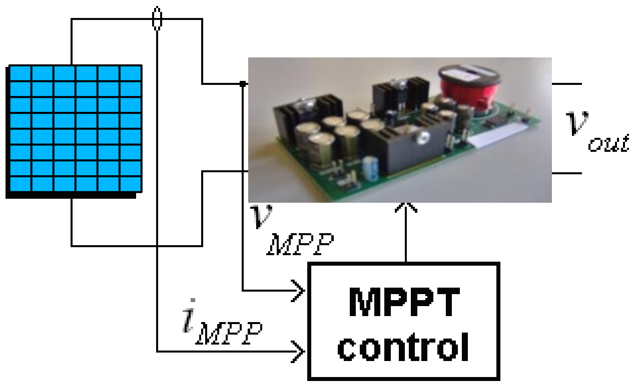
MTBF and the reliability are strongly dependent on ambient temperature.
The same converter has different MTBF values if it works at different temperatures.

DC-DC RELIABILITY QUANTITATIVE EVALUATION

Case study: MTBF calculation of a PV module converter

BOOST

COMPONENT	PART NUMBER
MOS	Fairchild FDP3682
Diode	On Semiconductor MBRP3010NTU
Inductor	Coilcraft PCV-2-184-10
Input Capacitor	Panasonic EEUFM1H121L
Output Capacitor	Panasonic EEUFM1H221



After the device choice it is possible to calculate the MTBF of the converter:

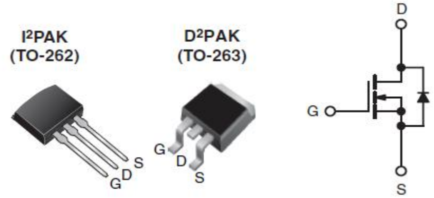
$$MTBF_{boost} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Inductor} + \lambda_{InCap} + \lambda_{OutCap}}$$

DC-DC RELIABILITY QUANTITATIVE EVALUATION

BOOST

MIL-HDBK-217F: MOSFET

$$\lambda_{MOS} = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$



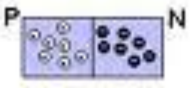
λ_b = 0.012
π_T = 8.6959 for T_j=175°C
π_A= 2
π_Q = 8 for “Plastic” components
π_E = 1 for Ground Benign

λ_{MOS} = 0.012*8.6959 * 2 *8 *1= 1.6696 Failures/10^6 Hours

BOOST

MIL-HDBK-217F: DIODE

$$\lambda_{Diode} = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$$



λ_b = 0.003 for Schottky diodes
π_T = 21.4378 for Tj =150°C
π_C = 1 for "Metallurgically bonded contacts"
π_Q = 8 for "Plastic" components
π_E = 1 for Ground Benign

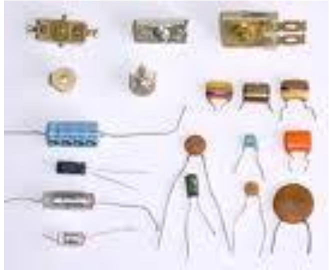
π_S = 0.1079 for $Vs = \frac{Voltage\,Applied}{Voltage\,Rated} = \frac{40V}{100V} = 0.4 \rightarrow \pi_s = 0.4^{2.43} = 0.1079$

λ_{Diode} = 0.003*2.4378 * 1 *8 *1*0.1079= 0.0555 Failures/10^6 Hours

BOOST

MIL-HDBK-217F: CAPACITOR

$$\lambda_{Cap} = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E$$



$\lambda_b = 0.00012$ for Aluminium Electrolytic Capacitor
$\pi_T = 1$ for T=25°C
$\pi_{Cin} = 3$ for Cin*=120µF
$\pi_{Cout} = 3.7954$ for Cout*=330µF
$\pi_V = 1$
$\pi_{SR} = 1$
$\pi_Q = 10$ for Commercial device
$\pi_E = 1$ for Ground Benign

λ_{InCap} = 0.00012*1*3*1*1*10*1= 0.0036 Failures/10^6 Hours
λ_{OutCap} = 0.00012*1*3.7954*1*1*10*1= 0.0046 Failures/10^6 Hours

* The capacitor failure rate is calculated considering the equivalent capacitance of capacitor systems

DC-DC RELIABILITY QUANTITATIVE EVALUATION

BOOST

MIL-HDBK-217F: INDUCTOR

$$\lambda_{Inductor} = \lambda_b \pi_T \pi_Q \pi_E$$

λ_b = 0.0003
π_Q = 3 for "lower"
π_E = 1 for Ground Benign

π_T = 0.75 obtained by

$$\pi_T = \exp\left(\frac{-0.11}{8.617\times10^{-5}}\left(\frac{1}{T_{HS}+273}-\frac{1}{298}\right)\right)$$

where $T_{HS} = T_A + 1.1\Delta t = 88.8$

T_A = 25°C

ΔT Approximation (Non-space Environments)

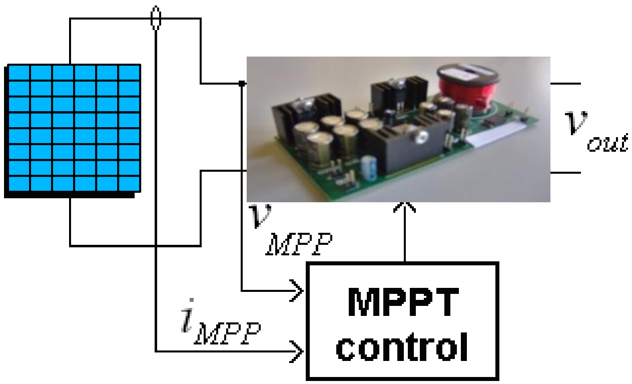
Information Known	ΔT Approximation
1. MIL-C-39010 Slash Sheet Number MIL-C-39010/1C-3C, 5C, 7C, 9A, 10A, 13, 14	ΔT = 15°C
MIL-C-39010/4C, 6C, 8A, 11, 12	ΔT = 35°C
2. Power Loss Case Radiating Surface Area	$\Delta T = 125\ W_L/A$
3. Power Loss Transformer Weight	$\Delta T = 11.5\ W_L/(Wt.)^{.6766}$
4. Input Power Transformer Weight (Assumes 80% Efficiency)	$\Delta T = 2.1\ W_I/(Wt.)^{.6766}$

W_L = Power Loss (W)
A = Radiating Surface Area of Case (in²). See below for MIL-T-27 Case Areas
Wt. = Transformer Weight (lbs.)
W_I = Input Power (W)

NOTE: Methods are listed in preferred order (i.e., most to least accurate). MIL-C-39010 are micro-miniature devices with surface areas less than 1 in². Equations 2-4 are applicable to devices with surface areas from 3 in² to 150 in². Do not include the mounting surface when determining radiating surface area.

λInductor = 0.0003*0.75*3*1= 0.000675 Failures/10⁶ Hours

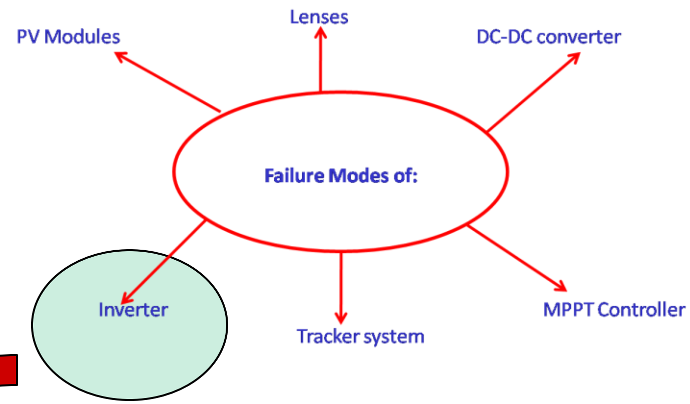
DC-DC RELIABILITY **QUANTITATIVE** EVALUATION



In conclusion the MTBF value of the PV module boost considered is:

$$MTBF_{boost} = \frac{1}{\lambda_{MOS} + \lambda_{Diode} + \lambda_{Inductor} + \lambda_{InCap} + \lambda_{OutCap}} = 0.5767 * 10^{6}\, Hours$$

DC-AC RELIABILITY



One of the most vulnerable component of a PV system

Potential failure mechanisms:

- **No intentional operation in islanding mode**
  - **Fault conditions**
  - **Maintenance purposes**
- **Inefficient MPPT function**
- **Inadequate protection:**
  - **load transient**
  - **commutation notching**
  - **capacitor switching**
  - **system faults**
- **Overheating**
- **Lightning strikes**

The investment in a new inverter is required 3-4 times over the life of a PV system

The inverter reliability can be evaluated calculating the failure rate of its each component by MIL-HDBK-217F.

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Thanks for your attention