Reliability analysis of Power-electronic circuits in Grid Connected Photovoltaic system using Fiabilipy-2.7 Python package

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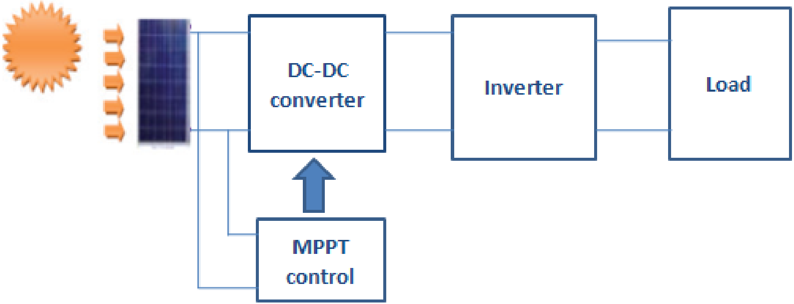
by-
Priyadarshini. K

Introduction

- The current trend in Photovoltaic (PV) systems for residential applications is towards grid-connected systems, with powers between 1 kW and 5 kW.
- In these applications, a major issue is the maintenance cost, which is directly related to reliability.
- In a typical system, the PV cells have an operational life in excess of 20 years. The power stage, however, usually has a much shorter operational life.
- The International Energy Agency reported that 98% of the failures were related to the power stage, and the average time to failure was about 5 years. Similar results were obtained in the German "1000 Roofs" program, and in the Japanese "Residential Japan" program.

Grid Connected Photovoltaic System



Block diagram of Grid connected Photovoltaic system

What is Reliability Engineering?

- Manufacturers often suffer high costs of failure under warranty. Therefore, there is need for a time-based concept of quality. Reliability is usually concerned with failures in the time domain.
- Engineering definition of reliability, *" The probability that a component or system will perform a required function without failure under stated conditions for a stated period of time"*.
- The main aim of reliability engineering is minimizing costs and generating reliable products.
- Reliability is dependent on the type and quality of the parts and materials used in the device, tension each part endures, the ambient conditions etc.
- Reliability is a key necessity in power electronics devices by which the life time, number of failures and associated cost are estimated.

Reliability Prediction

Standards based reliability prediction is a methodology based on failure rate estimates published in globally recognized standards, both military and commercial. The commonly used standards include

- **MIL-HDBK-217**
- Bellcore/Telcordia (SR-332)
- NSWC-06/LE10
- China 299B
- RDF 2000

These standards include parts count and parts stress analysis methods. The parts count method requires less information, typically part quantities, quality levels and application environment.

Reliability (Part Count method)

- The failure rate in most of electronic systems is constant and is represented by λ.
- The MIL-HDBK 217 handbook lists the failure rates for electronic devices. To predict the reliability of an electronic assembly it is necessary to first calculate the actual failure rates of the components involved. The actual failure rate is given by:

$$\lambda_{part} = \lambda_b \prod_{i=1}^{n} \pi_i$$

  where n is the number of factors of the device that take into account the stresses.
- Total failure rate is obtained by summation of failure rate each part or component given by

$$\lambda_{total} = \sum_{n=1}^{N} \lambda_{part}$$

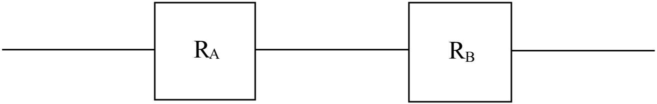
Reliability (Part count method)

- The Mean Time between Failures is calculated by

$$MTBF = {\lambda_{tot}}^{-1}$$

- The Reliability R can be calculated as:

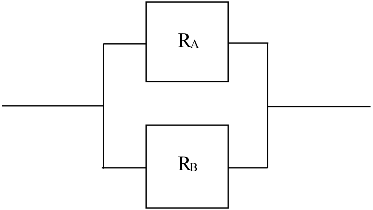
$$R(t) = e^{-\lambda_{tot} t}$$



- In a series configuration, a failure of any component results in the failure of the entire system. Therefore all the units in a series system must succeed for the system to succeed.
- In a pure series system, the system reliability is equal to the product of the reliabilities of its units.

$$R_S = R_A . R_B$$

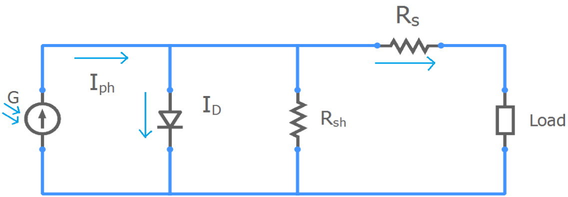
$$R_S = \prod_{i=1}^{n} R_i$$



- In a simple parallel system, at least one of the units must succeed for the system to succeed.
- Units in parallel are also referred to as redundant units.
- Redundancy is a very important aspect of system design and reliability in that adding redundancy is one of several methods of improving system reliability.

$$R_S = 1 - (1 - R_A)(1 - R_B)$$

$$R_S = 1 - \prod_{i=1}^{n}(1 - R_i)$$



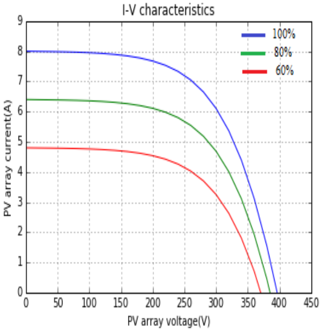
Equivalent circuit of PV module

$$V_{array} = 54.68 \log_e \left(\frac{I_{ph} - I_{array} + 0.005}{0.005} \right) - 3.74 I_{array}$$

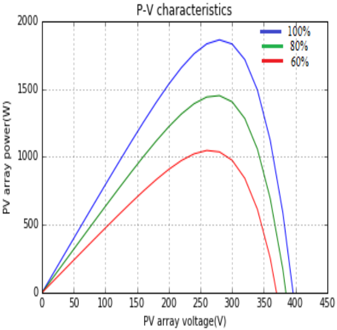
$$P_{array} = 54.68 I_{array} \, log_e \left(\frac{I_{ph} - I_{array} + 0.005}{0.005} \right) - 3.74 I_{array}^2$$

At maximum power

$$\frac{dP_{array}}{dI_{array}} = 0$$



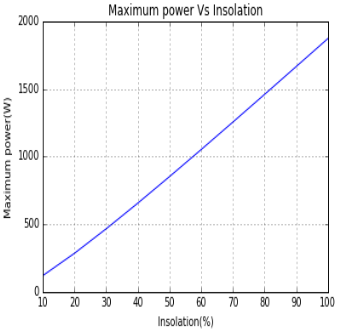
I-V characteristics of PV module



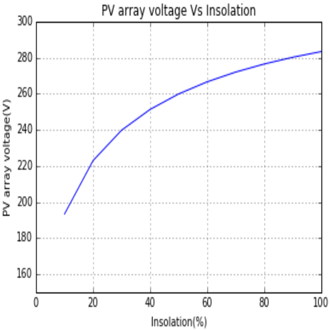
P-V characteristics of PV module

Table 1: Maximum power obtained for various levels of solar insolation

Insolation	I_{ph}(A)	I_{mpp}(A)	V_{mpp}(V)	Power(W)
100%	8	6.6078	283.32	1872.12
90%	7.2	5.9447	280.16	1665.47
80%	6.4	5.2801	276.43	1459.58
70%	5.6	4.6144	271.97	1254.96
60%	4.8	3.9477	266.55	1052.29
50%	4.0	3.2804	259.85	852.43
40%	3.2	2.6132	251.27	656.64
30%	2.4	1.9470	239.75	466.80
20%	1.6	1.2832	222.92	286.07
10%	0.8	0.6258	193.36	121.01



PV array maximum power Vs solar insolation level

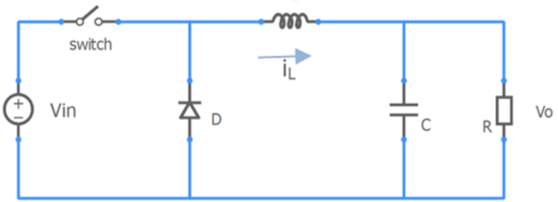


PV array voltage Vs solar insolation level

DC-DC Converters

- A DC-DC converter is an electronic circuit that converts a source of direct current from one voltage level to another.
- They are widely used in photovoltaic generating systems as an interface between the photovoltaic panel and the load, allowing the follow-up of the maximum power point tracker(MPPT).
  There are different types of DC-DC converters,
  - Buck
  - Boost
  - Buck-boost
  - Cuk
  - SEPIC

Buck converter is also known as step-down converter because the output voltage is less than the input voltage.



Circuit diagram of Buck converter

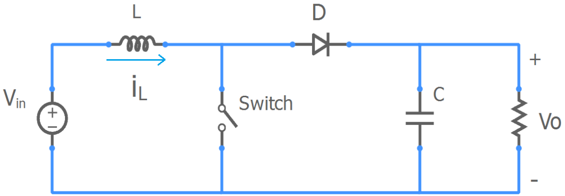
$$V_o = dV_{in}$$

$$I_o = \frac{P_o}{V_o}$$

$$\Delta I_o = \frac{(1-d)V_o}{Lf_{sw}}$$

Boost Converter

Boost converter is also called as step-up converter because the output voltage is more than the input voltage.



Circuit diagram of Boost converter

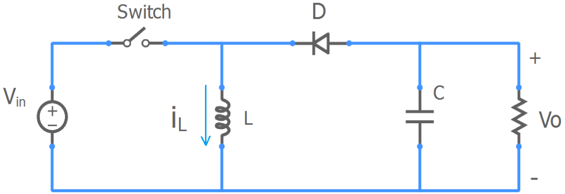
$$V_o = \frac{V_{in}}{(1-d)}$$

$$I_{in} = \frac{P_{in}}{V_{in}}$$

$$\Delta I_o = \frac{dV_{in}}{Lf_{sw}}$$

Buck-Boost Converter

The output voltage of this converter can be less than that of the source or greater than the source voltage, depending on the duty ratio of the switch. When d<0.5 it acts as step-down and step-up for d>0.5.

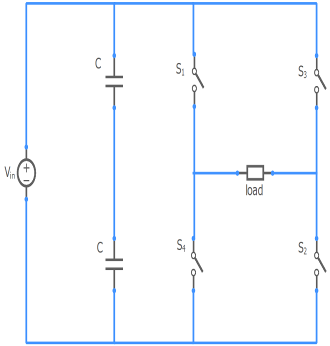


Circuit diagram of Buck-Boost converter

$$V_o = \frac{-V_{in}d}{(1-d)}$$

$$I_{in} = \frac{P_{in}}{V_{in}}$$

$$\Delta I_o = \frac{dV_{in}}{Lf_{sw}}$$



Circuit diagram of Inverter

$$V_{DC}I_{DC} = VICos\phi$$

$$I_m = \left(\frac{V_{DC}I_{DC}}{VCos\phi}\right).\sqrt{2}$$

$$I_{Drms} = \sqrt{\frac{1}{2\pi}\int_0^{\phi}\left(I_m Sin(wt-\phi)\right)^2 dwt}$$

$$I_{Drms} = \sqrt{\frac{I_m^2}{2\pi}\left[\frac{\phi}{2} - \frac{Sin2\phi}{4}\right]}$$

Components

Converter

- The components of the converter considered in this study are:
  - MOSFET - SPP04N50C3
  - Diode - DSEI12-12A
  - Capacitor - 680μF which is 450 volt rating
  - Inductor - 400mH.
- All the converters are operating in continuous mode.
- The load voltage is assumed to be constant and it is taken as 175 volts for step-down converters and 400 volts for step-up converters.

Inverter

- The components of the inverter considered in this study are:
  - MOSFET - SPP04N50C3
  - Capacitor - 1000μF which is 400 volt rating

Table 2: Failure rate and stress factors

MOSFET	$\lambda = \lambda_b \pi_T \pi_A \pi_Q \pi_E$ $\pi_T = exp\left(-1925\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right)$ $T_j = T_c + \theta_{jc} P$ $T_c = T_a + \theta_{ja} P$
Diode	$\lambda = \lambda_b \pi_E \pi_Q \pi_s \pi_T$ $\pi_T = exp\left(-1925\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right)$ $\pi_s = {V_s}^{2.43}$
Capacitor	$\lambda = \lambda_b \pi_T \pi_Q \pi_E \pi_C \pi_V$ $\pi_T = exp\left(\frac{-0.35}{8.617x10^{-5}}\left(\frac{1}{T_a+273} - \frac{1}{298}\right)\right)$ $\pi_C = C^{0.23}$ $\pi_V = (\frac{S}{0.6})^5 + 1$
Inductor	$\lambda = \lambda_b \pi_T \pi_Q \pi_E$ $\pi_T = exp\left(\frac{-0.11}{8.617x10^{-5}}\left(\frac{1}{T_{HS}+273} - \frac{1}{298}\right)\right)$

Table 3: Failure rate and MTBF of Step-down converters

Converter	**Buck**		**Buck-boost(d<0.5)**	
Insolation level	100%	10%	100%	10%
λ_M(MOSFET) Failures/10^6 *hours*	24.46	2.20	6.0706	2.1734
$\lambda_D(Diode)$ Failures/10^6 *hours*	0.0103	0.0026	0.0099	0.0027
$\lambda_C(Capacitor)$ Failures/10^6 *hours*	0.0412	0.0215	0.0412	0.0215
$\lambda_I(Inductor)$ Failures/10^6 *hours*	$3.2x10^{-5}$	$3.2x10^{-5}$	$3.2x10^{-5}$	$3.2x10^{-5}$
MTBF(hours)	40792	448917	163349	455017

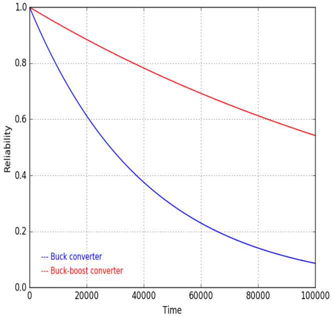
Table 4: Failure rate and MTBF of Step-up converters

Converter	Boost		Buck-boost(d>0.5)	
Insolation level	100%	10%	100%	10%
λ_M(MOSFET) Failures/10^6 *hours*	5.23	2.175	8.238	2.182
λ_D(*Diode*) Failures/10^6 *hours*	0.0104	0.0026	0.0087	0.0026
λ_C(*Capacitor*) Failures/10^6 *hours*	0.0412	0.0215	0.0412	0.0215
λ_I(*Inductor*) Failures/10^6 *hours*	$3.2x10^{-5}$	$3.2x10^{-5}$	$3.2x10^{-5}$	$3.2x10^{-5}$
MTBF(hours)	189414	454617	120647	453099

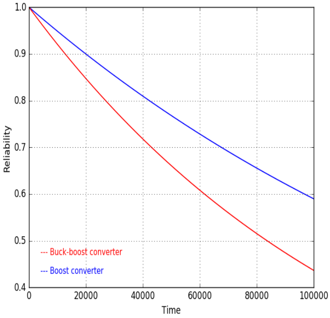
Python Package - Fiabilipy-2.7

- Author: Simon Chabot, Akim Sadaoui
  Home Page: http://fiabilipy.org
  Requires: numpy, scipy, sympy, networkx
- Fiabilipy-2.7 is a python package providing functions to learn engineering reliability.
- With this package, one can build easily some components, put them together to build a complete system and finally evaluate some metrics (reliability, maintainability, Mean-Time-To-Failure, and so on).
- Using this package each component of converter and Inverter are built, put them together to build a complete system and finally MTBF and reliability of the system is easily evaluated using the tool.

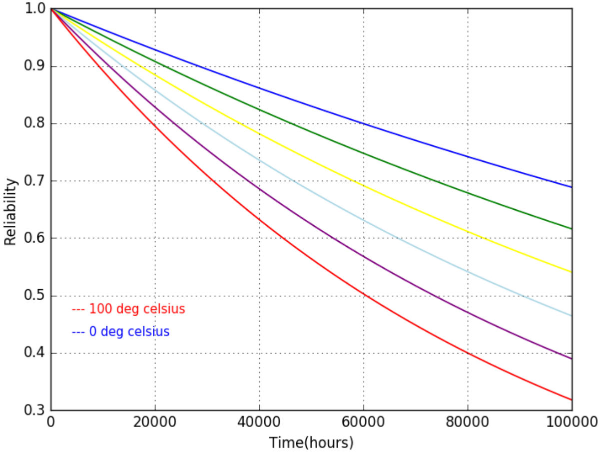
```
from fiabilipy import Component
comp = Component('a', 1e-4)
comp.mttf
comp.reliability(1000)
```



Reliability Vs Time of Step-Down converters

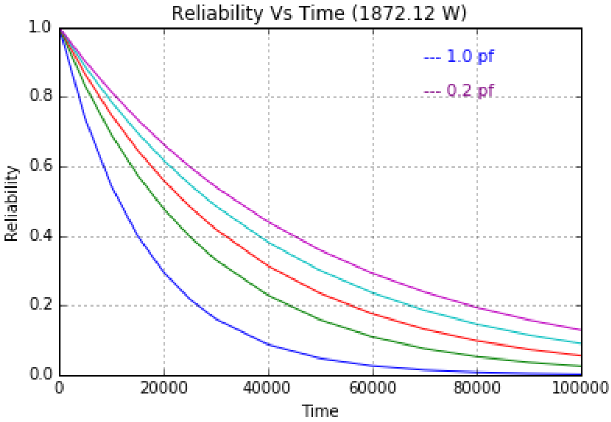


Reliability Vs Time of Step-Up converters

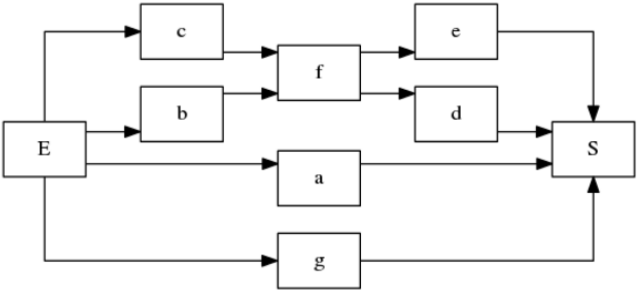


Reliability of boost converter for varying temperature

Reliability of Inverter

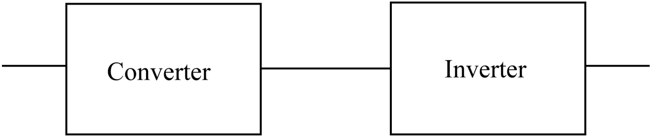


Reliability of Inverter for different power factors at 1872.12 W



A example of Complex system

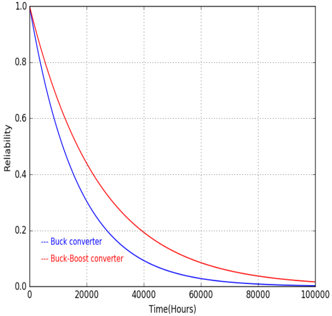
from fiabilipy import System S = System()
S['E'] = [a,b,c,g] S[a] = S[g] = S[e] = S[d] = 'S'
S[b] = S[c] = [f]
S[f] = [e,d]
S.mttf
S.reliability(t)



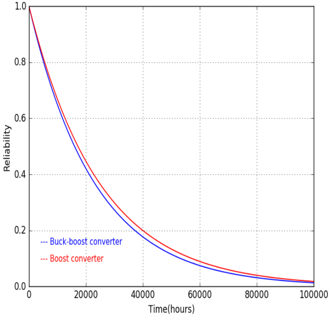
Block diagram of combined system of Converter and Inverter

$$R_S = R_C.R_I$$

Reliability of combined system



Reliability vs Time of combined system at 100% insolation and pf = 0.8



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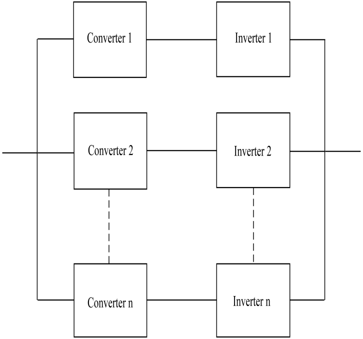
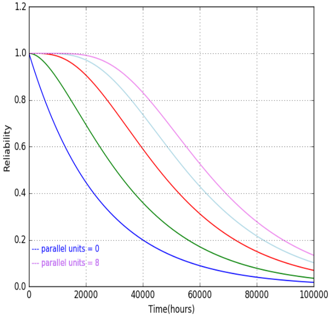
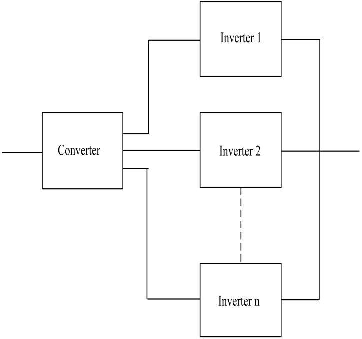


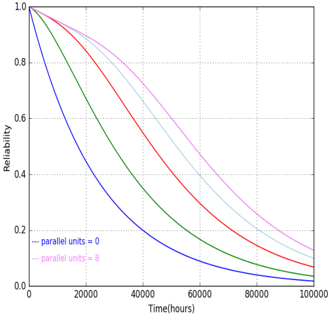
Block diagram of parallel arrangement of power stage in Grid connected photovoltaic system



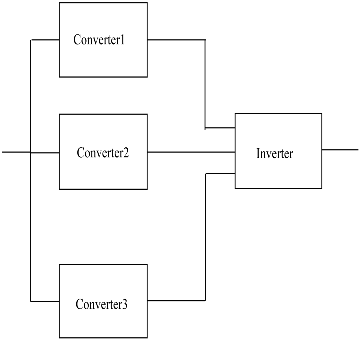
Reliability versus Time of combined parallel system at 100% insolation and pf = 0.8



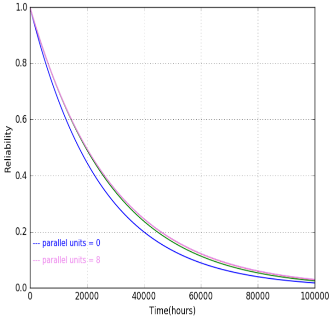
Block diagram of series-parallel arrangement of power stage in Grid connected photovoltaic system



Reliability versus Time of combined system at 100% insolation and pf = 0.8



Block diagram of series-parallel arrangement of power stage in Grid connected photovoltaic system



Reliability versus Time of combined system at 100% insolation and pf = 0.8

Advantages of Python and fiabilipy-2.7

- Python is a widely used high-level, an open source general purpose, interpreted, dynamic programming language.
- Its design philosophy emphasizes code readability, and its syntax allows programmers to express concepts in fewer lines of code than possible in languages such as C++ and Java.
- Readability: python looks more like a readable, human language then like a low-level language. This gives you the ability to program at a faster rate.
- By using fiabilipy-2.7 python package tool, analysis of reliability of complex systems became simple and easy.
- Fiabilipy enables the users to model a system trought a Markov process.

- From the analysis, switches i.e. MOSFET has highest failure rate when compared with other components in converter because losses are more due to switching. When losses are more the junction temperature increases and failure rate of the component increases..
- The comparison of reliability of three different converters is analysed. It is evident that among step-down converters Buck-boost is more reliable and among step-up converters Boost converter is more reliable.
- The comparison of reliability of Inverter for various power factors is analysed.
- The reliability of different arrangement of power stage in Grid connected photovoltaic system is analysed.
- By using fiabilipy-2.7 python package tool, analysis of reliability of complex systems became simple and easy.

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THANK YOU