OPTIMUM USE OF THE LOSS FACTORS MODEL (LFM) FOR IMPROVED PV PERFORMANCE MODELLING

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1) What is the Loss Factors Model?

The LFM is a PV performance model where the coefficients are based on the shape of measured IV curves under different irradiance and temperature conditions (either indoor or outdoor).

The relative efficiency ("Eff.measured" / "Eff.nameplate") otherwise known as the Module Performance Ratio DC (PR_{DC} or MPR) is the product of the LFM's 6 independent and normalised physically significant loss parameters.

The LFM can be used to analyse all existing PV technologies (e.g. standard and "high efficiency" c-Si; Thin Film such as CdTe, CIGS; OPV) at all sites and at all orientations (e.g. fixed tilt, tracked and CPV).

2) What the LFM can do

- Optimisation of PV manufacture by quantifying limiting losses (e.g. how much of the potential P_{MAX} is lost due to the parasitic R_{SERIES}?)
- Identify module variability, atypical behaviour and under performance.
- Generate coefficients for modelling such as P_{MAX} thermal coefficient (gamma γ $\%P_{MAX}/K$) and Low light efficiency (η 0.2kW/m²/ η 1.0kW/m²)
- Validate online measurements, characterise and quantify any degradation identifying the causes.
- Commissioning getting fast values for $P_{MAX.MEASURED}$ / $P_{MAX.NOMINAL}$
- Once coefficients are established it can be used to predict site energy yield and can check systems on line for optimized Levelized cost of Energy (LCoE) and effective risk mitigation.

3) How the LFM differs from of other models

The 1-diode (and similar models)[4] fit their coefficients (e.g. I_{SC0}, R_{SHUNT}, R_{SERIES}, I_O and Ideality Factor n) to model an entire IV curve.

It is not always possible to find a perfect fit to the whole curve simultaneously particularly when there are non-uniformities in the module, shading, degradation, non ohmic back contacts or properties such as bias dependent current.

Any "imperfections" in the curve such as current mismatch steps or rollover due to non-ohmic back contact behaviour cause the model fit to depend on how the algorithms minimise the RMS error which may be dependent on the IV point distribution or possibly weighted towards V_{MP},I_{MP} where it is most important.

Models such as the SAPM [4] need up to 29 parameters to fit the I_{SC}, I_{MP}, V_{MP} and V_{OC} (and their temperature coefficients). R_{SC} and R_{OC} are not modelled explicitly but these matter when coming to investigate degradation modes. Their parameters are not normalised and many tend to have a non-physical meaning making understanding them difficult.

The LFM has been developed to extract the maximum amount of physically significant information from just 6 normalised (and for the most part independent) parameters with two check parameters.

LFM coefficients are derived from fitting points to the IV curve such as I_{SC}, I_{MP}, V_{MP} and V_{OC} as shown in figure 1.

It then fits gradients for R_{SC} and R_{OC} and quantifies how much loss is associated with each of these 6 values rather than the measured Amps, Ohms or Voltage which are module area and design specific.

The 6 LFM Values are all "normalised losses" because they are scaled by measurements at reference conditions (e.g. $I_{SC.STC}$) meaning values are area independent and work from cm² cells through modules to strings, combiner boxes, inverters, stations and multi MWp arrays [5].

Normalised values can be used to study the reproducibility of modules. For example as the normalised V_{OC} is given by

$nV_{OC} = V_{OC.MEASURED}/V_{OC.REFERENCE}$

then its distribution is likely to be a Gaussian like spread with a peak and Std Dev which quantify the mode module tolerance and spread as percentages of reference values rather than fixed voltages which would be number of series cell dependent.

4) Deriving coefficients for the LFM from an IV measurement

Measure the IV curve(s) of a module with date+time, plane of array irradiance of the closest match reference cell (to minimise AOI and spectral corrections) and $T_{AMBIENT}$ and T_{MODULE}.

Also record Windspeed WS, Air Mass AM, Angle of Incidence AOI, Beam Fraction BF (= 1 - Diffuse Fraction) for further corrections where needed.

Figure 1 illustrates how the LFM's 6 Loss Factors (nI_{SC}, nR_{SC}, nI_{MP}, nV_{MP}, nR_{OC} and nV_{OC}) are derived from the measured IV curve.

(The MMF is Module Mismatch factor which affects the I_{SC} of the module but for a well-matched reference cell this can be ignored and isn't considered further in this paper). Spectral corrections will be introduced later to the LFM.

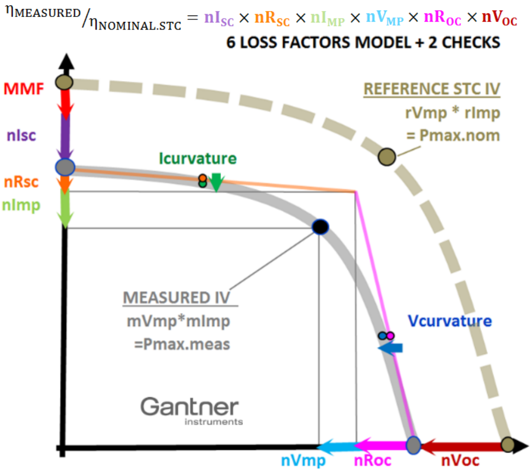

Fig 1: 6 Derived LFM parameters n*** from measured vs. reference IV values with 2 curvature check values (nI_C and nV_C)

5) Monitoring LFM Values with time and data smoothing

Figure 2 illustrates weather parameters irradiance (*100 kW/m^2 green), module(red) and ambient(orange) temperatures (C) and 6 derived LFM values (bottom) over a typical morning from sunrise to just after noon with mostly clear but some intermittent cloud events in September in Arizona.

Before 07:00 (A) the sun was below the horizon so there was only a little diffuse irradiance meaning some unusual values particularly for nI_{SC} and nV_{OC}.

From 07:00 to 13:00 the LFM values for steady irradiance were all smooth and between 85% and 115% as expected.

When there were sharp changes in irradiance (B) there are sometimes some glitches in LFM parameters away from the steady state values. Note that as everything is normalised it is easy to remove glitches when deriving modelled performance as is shown in the sanitised data A' and B'.

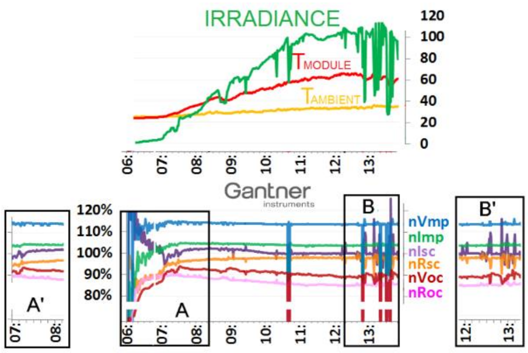

Fig 2: Raw Weather parameters (top) and LFM values(bottom) for a mostly clear morning. A' and B' are sanity checked (good, non-transient measurements) data.

6) Which LFM parameters cause efficiency to vary with irradiance?

Figure 3 illustrates how the 6 parameters vary vs. irradiance for measurements of a typical well behaved TF module. These shapes are typical for all well-behaved PV modules. Because nV_{OC} depends heavily on T_{MOD} it is best to show it as temperature corrected nV_{OC_T}.

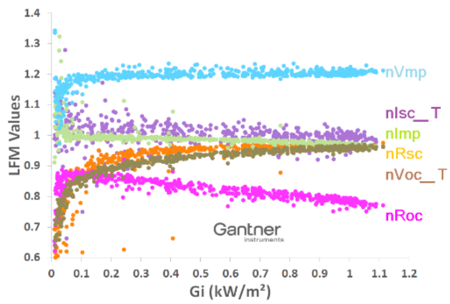

Fig 3. LFM parameters vs. irradiance for a typical well behaved CdTe module

The 6 LFM parameters depend on the following effects

nI_{SC_T}	Soiling, Air Mass, Angle of incidence and reflectivity. It will usually have the largest scatter of the LFM parameters.
nV_{OC_T}	~ logarithmically dependent vs Gi, dependent on T by the factor $beta_{VOC}$
nR_{SC}	Rising with Gi (has a worse loss at low light levels) R_{SHUNT}
nR_{OC}	Falls with Gi (has a worse loss at high light levels) R_{SERIES}
nI_{MP}	Quite flat vs Gi
nV_{MP}	Quite flat vs Gi

Figure 4 plots the two curvature parameters nI_C (identifies IV curve steps due to mismatch cracking shading) and nV_C (identifies Rs problems e.g. due to Schottky contact rollover).

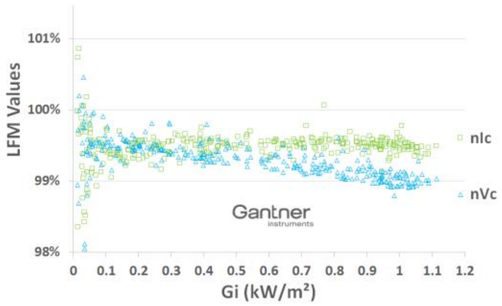

Fig 4: LFM curvature parameters vs. irradiance for a well behaved CdTe module.

Note the change in y-scale from fig 3 as these values are much closer to 100%. Absolute values will depend somewhat on the module technology but for a good measurement on an undegraded and unshaded module they should be smooth and quite flat from around 0.1 to 1.0kW/m². Any changes in cell cracking or shading will cause the nIc to fall at high light level. Incidences of rollover or increasing series resistances will cause nVc to change.

Because the PR_{DC} depends on the product of all 6 parameters then Low light efficiency performance depends mostly on which parameters fall there i.e.

nV_{OC_T} - ~log dependent, falls at low light

nR_{SC} – As I_{SC} ~ $I_{SC.STC}$ * G then R_{SHUNT} has a higher effect at lower light levels. R_{SHUNT} usually rises near exponentially at low light but its loss effect is usually greater at low light)

The High light performance depends mostly on

nR_{OC} (which depends on ~ $I^2.R_{SERIES}$)

Most of the differences between the low and high light efficiency of different technologies can be understood by characterising these three parameters.

7) Characterising the module temperature dependency with LFM parameters

Plot all of the 6 LFM parameters vs. temperature as in figure 5. Preferably select clear sky conditions with low angle of incidence and reasonably high T_{MOD} to get a better fit.

The apparent temperature coefficient is the gradient of each of the parameters below.

Gradient = d/dT_{MOD}	Coeff
nV_{OC_U}	bV_{OC}
nI_{SC_U}	aI_{SC}
(nI_{SC_U} * nR_{SC} * nI_{MP})	aI_{MP}
(nV_{OC_U} * nR_{OC} * nV_{MP})	bV_{MP}
Note :	
aI_{MP} + bV_{MP} =	Gamma

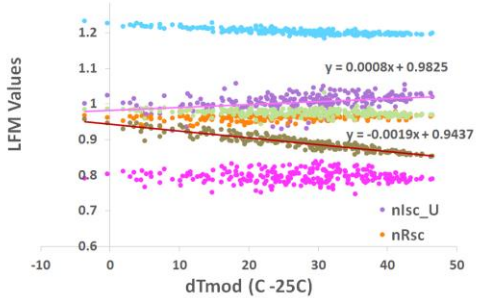

Fig 5: LFM parameters vs. module temperature with coefficients aIsc and bVoc for a well behaved CdTe module [Gantner instruments data]

8) LFM coefficients vs. PV technologies - c-Si, Thin Film

Some of the 6 LFM coefficients can be seen to differ by PV technology

- c-Si usually has lower R_{SERIES} (as it's due to tabbing related rather than TCO) meaning a better nR_{OC} particularly at high light levels when current is high
- Some thin films appear to have "better low light response" because they have "High light R_{SERIES} loss" meaning their nR_{OC} fall faster at high light level
- The efficiency of some thin films can collapse at low light levels and these can be characterised by the amount of nV_{OC} or nR_{SC} drops.

9) Quantifying Degradation at different conditions due to different LFM parameters

LFM can show which of the 6 parameters is causing any changes rather than just "Eff vs time" e.g. changes in nR_{SC} or nR_{OC} may indicate R_{SHUNT} or R_{SERIES} (respectively) related problems

The LFM can determine if the efficiency drop depends on conditions e.g. low light efficiency might drop at different rates than at high light levels

Figure 6 plots the changes in two LFM parameters nR_{SC} and nR_{OC} over time (years 2010 – 2016 are marked by different colours) for an abnormally bad TF module which is falling at ~3%/year.

The nR_{OC} appears to be degrading about 1%/y at all light levels, the nR_{SC} is degrading faster at low light levels (-2%/y) than at high light levels (-0.5%/y) indicating a non ohmic component of R_{SHUNT}.

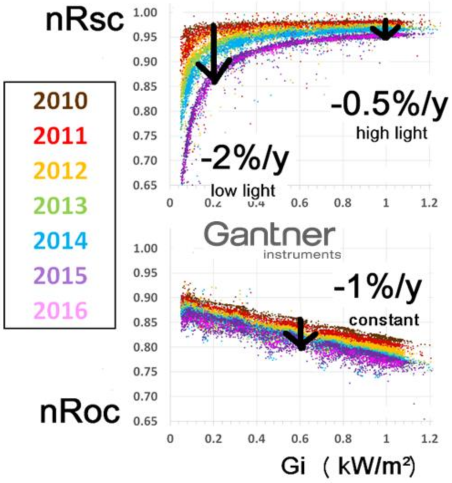

Fig 6: A degrading module shown by plots of changing nR_{SC} and nR_{OC} vs. irradiance (x – axis) vs. time (year)

Seasonal annealing (which can occur in some devices) would appear as an oscillation in one or more of the LFM parameters with time.

The magnitude and phase of the change with respect to season or recent weather conditions (e.g. average module temperature for the previous month) can be used to identify and quantify the effect.

10) Curve fitting

Several different methods (to be described) can be used to fit LFM curves depending on their shape as in figures 3. These include the following dependencies

Linear	$y = m * GI + c$
Logarithmic	$y = a * Log(GI)$
Power series	$y = 1 – GI^n$

Combinations with empirical parameters can be fitted as in [4] and are shown in fig 7.

$$nLFM= C_0 +C_1*Log(Gi) -C_2*Gi^2$$

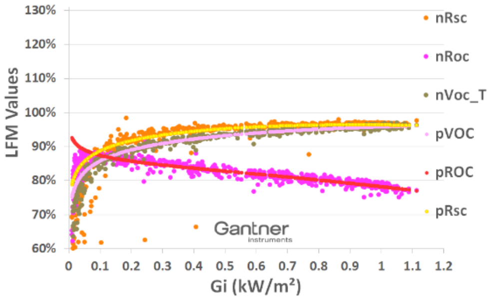

Fig 7: nLFM fits using a constant, log and power term.

These are then used for Fault diagnostics (if the performance differs from expected) and Energy Yield prediction (using expected climate data).

Appendix A gives Python Format code and definitions with links to measurement data from GI. This model is being added to PVLIB.

11) References

[1] Gantner Instruments Web portal

[2] PVPMC www.pvpmc.org

[3] Sutterlueti et al "Improved PV Performance Modelling by Combining the PV_LIB Toolbox with the Loss Factors Model (LFM)" 42nd PVSC 2015

[4] Stein et al 28th PVSEC Paris 2013

[5] Sellner et al 27th PVSEC Frankfurt 2012

Appendix A) LFM Equations (in Python code format)

```
# GLOSSARY OF PARAMETER NAMES AND EQUATIONS TO BE USED FOR PVPMC/PVLIB
# SRCL and Gantner Instruments
# Ver : 170407t17_1 yymmddthh_tz
# Nomenclature *default if missing)
# Prefixes
#   m* measurement
#   r* reference
#   n* normalised
#   a* alpha current temperature coefficient
#   b* beta voltage temperature coefficient
# Suffixes (if more than one use in alphabetical order e.g. _AST)
#   _U uncorrected (default if missing)
#   _T corrected for Tmodule
#   _A corrected for angle of incidence
#   _S corrected for spectrum
#
# Variable names
# Gi   = Plane of array irradiance kW/m2
# PRDC = DC Performance ratio or MPR = Efficiency.measured/Efficiency/nominal
# POA  = Plane of array
# LLEC = Low light efficiency coefficient
# mTAMB = measured Ambient temperature
# mTMOD = measured Module temperature
# YA = dc Energy yield "kWh.DC/kWp"

# DEFINITIONS AT STC
TSTC = 25 # C
GSTC = 1 # kW/m2
WSSTC = 1 # ms^-1
# GET THE PV DATASHEET REFERENCE VALUES r* AND TEMPERATURE COEFFICIENTS
# rIsc, rImp, rVmp, rVoc
# aIsc_Ref, bVoc_Ref, Gamma_Ref
#
# MEASURE THE CONDITIONS AND IV CURVE(S), DERIVE THE FOLLOWING #
# dt                                    # DATE+TIMES
# Gi                                    # POA irradiance kW/m2
# mTamb                                 # Ambient temperature
# mTmod                                 # module temperature

# mIsc, mRsc                            # from curve fit near V=0
# mImp, mVmp                            # from curve fit near max(I * V)
# mRoc, mVoc                            # from curve fit near I=0
#
# mI2 = I @ Vmp/2                       # cell mismatch, shading ?
# mV2 = V @ Imp/2                       # rollover from non ohmic back contact?
#
#                                                        Colour     #RGB
# DERIVE CURVATURE PARAMS
nIc = mI2/(mIsc-mVmp/2/mRsc)            # I@Vmp/2        LightGreen EAF5DC
nVc = mV2/(mVoc-mImp/2*mRoc)            # V@Imp/2        LightBlue  C8F0FF

# CALCULATE  (mIr, mVr) WHERE RSC and ROC LINES CROSS to make maths easier
mIr=(mIsc*mRsc-mVoc)/(mRsc-mRoc)        # calc I @ Rsc-Roc intercept
mVr=mRsc*(mVoc-mIsc*mRoc)/(mRsc-mRoc)   # calc V @ Rsc-Roc intercept

# now calculate normalised LFM parameters unit %
nIsc_U = mIsc/rIsc/Gi                   # U=Un temp corr  Purple     #AB73D5
nRsc   = mIr/mIsc                       #                 Orange     #FF8409
nImp   = mImp/mIr*rIsc/rImp             #                 Green      #BEE296
nVmp   = mVmp/mVr*rVoc/rVmp             #                 Blue       #5BD2FF
nRoc   = mVr/mVoc                       #                 Pink       #CC00CC
nVoc_U = mVoc/rVoc                      # U=Un temp corr  Brown      #948A54

nIdc_U = mImp/rImp/Gi                   #                 MidGreen   #D3ECB9
nVdc_U = mVmp/rVmp                      #                 MidBlue    #93E1FF

# can also can correct by temperature _T
nVoc_T = nVoc_U * (1-bVoc_Ref*(mTmod-Tstc))    # Temp correct by bVoc
nIsc_T = nIsc_U * (1-aIsc_Ref*(mTmod-Tstc))    # Temp correct by aIsc
```