Green electronics: ELEC 3202 – 2
Modelling of PV Systems

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2016-2017
A PHOTOVOLTAIC (PV) system and categories of model

• The PV system can be modelled in several stages:
  – Power from the Sun
  – PV Arrays
  – MPPT (Maximum power point tracking)
  – Power Conversion
  – Loads

• In this section of the course we will concentrate on:
  – System models of the PV array
  – Power from the sun
  – Abstract loads
**Modelling Principles**

- There are three basic approaches to modelling in this context
  - The first is a purely system level approach – which is how Matlab operates. Energy is not conserved, and signals are dimensionless
  - The second is to use electric analogies for all elements, and this is commonly implemented in Spice
  - The final approach is to use a true multiple domain approach, in Saber, VHDL-AMS or Verilog-AMS
Which approach to use?

- In general, Matlab is often used in this context, as it is simple to understand, and readily available.

- However, for the more detailed power systems analysis, SPICE or Saber should be used.

- The underlying principles of the models apply regardless of the modelling implementation.
Radiation from the sun

- The Radiation from the Sun reaches the earth in the wavelength range of a few hundred nm to several um.
- Depending on the location of the PV array (Space, mountain top, or sea level), the characteristics of the radiation will be different.
- There are two main distributions that are considered in systems analysis:
  - AM0 and AM1.5
The spectral response of a silicon solar cell under glass.
• At short wavelengths below 400 nm the glass absorbs most of the light and the cell response is very low.
• At intermediate wavelengths the cell approaches the ideal.
• At long wavelengths the response fall back to zero.
• Silicon is an indirect band gap semiconductor so there is not a sharp cut off at the wavelength corresponding to the band gap ($E_g = 1.12 \text{ eV}$)
The PV CELL: Spectral response

Why is the spectral response increasing towards the bandgap?

What would you do to improve the spectral response of this solar cell?
Spectral response is important since it is the spectral response that is measured from a solar cell, and from this the quantum efficiency is calculated. The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength. This gives:

\[ SR(A/W) = \frac{q\lambda}{hc} QE \]

or

\[ SR(A/W) = \frac{QE}{\lambda(nm)} \cdot 1239.8 \]

\[ SR(A/W) = \frac{QE}{\lambda(\mu m)} \cdot 1.2398 \]
Solar Radiation (Standard reference)

- The extra-terrestrial space, at the average distance between the Sun and the Earth, the irradiated solar energy is about 1.353 kW/m².

- On the Earth’s surface, the irradiation is approximately 1 kW/m² (this is a reference value only, as the net irradiation on Earth’s surface depends on many factors).

Spectral distribution of the black body radiation and the Sun radiation in the extraterrestrial space (AM0) and on Earth’s surface (AM1.5). Source: Möller
Solar Radiation ((Standard reference))

- PV devices are generally evaluated with reference to a standard spectral distribution.

- The American Society for Testing and Materials (ASTM) defines two standard terrestrial spectral distributions:
  - The direct-normal
  - The global AM1.5 \((\text{Air Mass}_x)\)
Solar Radiation ((Standard reference))

The direct-normal

• The direct-normal standard corresponds to the incident radiation that perpendicularly reaches a Sun-facing surface directly from the Sun.

The global AM1.5

• The global or total standard corresponds to the spectrum of the direct and diffuse radiations. Diffuse radiation is the radiation influenced by the atmospheric steam and the reflection on Earth’s surface.

Illustration of the AM1.5 path and the direct-normal and global incident radiations on a Sun-facing surface at 37° tilt.
Solar Radiation ((Standard reference))

The global AM1.5 ((Air Mass)\(x\))

- The AMx number indicates the length of the path of the solar radiation through the atmosphere.
- With longer paths more light deviation and absorption occur.
- These phenomena change the spectral distribution of the light received by the PV device.
- The length of the path of the sun rays (given in number of atmospheres) is indicated by the x coefficient of AMx defined as:

\[
x = \frac{1}{\cos \theta z}
\]

For \(x = 1.5\) \(\theta z = 48.19\) degrees
Solar Radiation ((Standard reference)

The global AM1.5 ((Air Mass)$_x$)

- The intensity and spectral distribution of the solar radiation depend on the geographic position, time, day of the year, climate conditions, composition of the atmosphere, altitude, and many other factors.
- Due to the factors that influence the solar radiation, the AM1.5 spectral distributions are only average estimates that serve as references for the evaluation and comparison of PV devices.
- **The AM1.5 distributions are used as standards in the PV industry.**
- **Datasheets** generally bring information about the characteristics and performance of PV devices with respect to the so-called **standard test condition (STC), which means an irradiation of 1000 W/m$^2$ with an AM1.5 spectrum at 25 °C**
**Solar irradiance**

- The actual irradiance is the integration over the wavelength (shown in microns) of all the individual spectral responses.

- For a PV installation, the overall irradiance is the important figure, and therefore this will be the source data to the model.
Solar irradiation profile

- In addition to the spectral response of the irradiance, there is in fact a profile over the daily cycle of the irradiance, called the irradiance profile.

- This is obviously location and calendar specific, and takes the form of the curve shown in the next figure.

This is a SPICE model, so note the timescale is 0-24, but using a simulation time, not a real 24 hour timescale.
Modelling the irradiance profile

The daily profile can be modelled using a simple Gaussian distribution curve, as a basis, with the equation:

\[ Irr = ae^{-\frac{(x-b)^2}{2c^2}} \]

Where:
- **B** is the offset from zero (say 12 noon)
- **C** is the width of the curve
- **A** is the maximum amplitude
Modelling the irradiance profile

- Obviously, each day will have a different profile, so each of the parameters \(a\), \(b\) and \(c\) can be characterized from the observed weather data to provide a complete model of the annual irradiance for system modelling.

We can use Matlab to model the irradiance function with the mathematical building blocks:
System design

Solar Radiation (Inclination)

- Clearly, the latitude of the PV location will have a profound impact on the efficiency of the overall system, and therefore it is useful to model this behaviour in the model.

- Data exists for the inclination requirements and effects on the system, depending on location.
Modelling of PV devices: Ideal PV Cell

The basic equation from the theory of semiconductors that mathematically describes the I–V characteristic of the ideal PV cell is:

\[ I = I_{pv,cell} - I_{0,cell} \times \left[ \exp\left(\frac{qV}{akT}\right) - 1 \right] \]

- \( I_{pv,cell} \): is the current generated by the incident light (it is directly proportional to the Sun irradiation)
- \( I_{0,cell} \): is the reverse saturation or leakage current of the diode
- \( Q \): electron charge
- \( k \): Boltzmann constant
- \( T \): temperature in Kelvin
- \( a \): is the diode ideality constant

Single-diode model of the theoretical PV cell and equivalent circuit of a practical PV device including the series and parallel resistances.
**Modelling of PV devices: Ideal PV Cell**

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Characteristic \( I-V \) curve of the PV cell.

The net cell current \( I \) is composed of:
- The light-generated current \( I_{pv} \)
- The diode current \( I_d \)
Modelling of PV devices: (PV Array)

\[ I = I_{pv} - I_0 \cdot \exp \left( \frac{(V+R_s I)/(v_t a)}{v_t a} \right) - 1 \right) + \frac{(V+R_s I)/(v_p)}{v_t a} \]

This equation originates the \( I-V \) curve below, where three remarkable points are highlighted:

- No voltage with short circuit \((0, I_{sc})\)
- Maximum power point with MPP \((V_{mp}, I_{mp})\),
- No current with Open circuit \((V_{oc}, 0)\).
There is a direct relationship between the temperature and the performance of the solar cell, and this can be included in the model

\[ I(T) = I \times \left(1 + TK1 \times \left[T - T_{mean}\right]\right) \]

In addition, the device (diode) also includes temperature dependence in circuit simulators such as SPICE or Saber.
Modelling of PV devices: Maximum power

With the IV characteristic shown in the basic model, there is a simple calculation of power (I*V) which shows the maximum power achievable from this PV cell:
System design

Modelling of PV devices: System Modelling of PV Arrays

- For the purposes of a system model, it is not always necessary to implement a circuit level model, and in fact a simple power output can be adequate in many system simulations.

- Using the Irradiance model as an input, simply defining an efficiency block as a gain, will give a realistic model of the power input to the system.
Modelling of PV devices: Maximum Power Point Tracking

- The goal of any PV system is to maximize the power output, and in this context that means modulating the voltage to obtain the maximum power output.

- As can be seen from the Maximum power graph, there is a very clear peak, and a quite narrow area of maximizing the power, so the incentive to do this is quite high.

- Also, losses incurred in the power point tracking process are relatively insignificant compared to the benefit of achieving the maximum power point in the system.
  - *More on this topic later*
Modelling of loads

- Loads are relatively simple to model as time based profiles of individual resistive or inductive elements.

- The cumulative loading can be presented as the sum of all the individual loads.
Modelling of loads: Example

Constant Loads
• These are power loads that are on all of the time, and can be considered effectively constant
• This might include a computer permanently turned on, or a freezer.

• It is worth noting that in detailed analysis, loads such as refrigerators may actually exhibit a cyclic behaviour as the compressor is only required to “boost” the refrigeration in a modern appliance

Peak Loads
• Individual appliances may have a dramatic “on/off” behaviour with a very high power demand, for a relatively short period
• Examples of this may include a Kettle, or other small appliance such as a Microwave.
• The Power demand may be several kW, but the duration is short (a few minutes)
• These can be modelled as a short pulse
Modelling of loads: Example

Predictable Loads
- Predictable loads are those where the domestic routine of a household will enable a highly regular pattern of behaviour
- For example:
  - Between 7am and 8am the electric shower will be used for 20 minutes
  - Between 7pm and 10pm, the TV will always be turned on
Modelling of loads: Modeling the Loads

Modelling these loads is a relatively simple matter in tools such as Matlab or SPICE.

Constant Loads
- Matlab – constant source
- SPICE – DC voltage source

Pulse Loads
- Matlab/SPICE – pulse source

Arbitrary Loads
- SPICE – PWL source
- Matlab -
Modelling of loads: Modelling the Loads

We can take these simple modelling techniques and begin to create a realistic load model.

Take a reduced domestic scenario of:
- Freezer (cyclic)
- Refrigerator (constant)
- Kettle (Pulse)
- Shower (Pulse)
- TV (Pulse)