NA4.2 – Autonomous and Grid-connected Photovoltaic Systems Modelling for Simulation Purposes

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What is the importance of simulating PV systems?

- It allows for real system dimensioning and design
- Prediction of realistic system behaviour under various disturbances (irradiance, temperature, power demand etc.)
- It can help pinpoint possible operation problems related to factors like partial shading, overload, battery overcharge etc.
- Capability of testing alternative, novel technologies such as different Maximum Power Point Tracking algorithms
- System evaluation under static and dynamic conditions in the short or the long term

Different methodologies and model categorization (system's point of view)

Modelled power components in grid-connected systems:

- PV cells and modules
- PV inverters (with their control strategies)
- Grid models

Stand alone systems and microgrids:

- PV cells and modules
- PV inverters
- Battery cells
- Battery inverters and/or chargers
- Diesel generators
- Active/reactive power loads
- Grid models
- Other Renewable Sources, Storage or Distributed Energy Resources

PV cells and modules simulation models

Static operation

- Parametric model
- Equivalent circuit
- Interpolation model
- Other models

Dynamic operation

- Models that take into account dynamic characteristics such as the impedance of a PV cell

Parametric model for a PV cell

$$I_{cell} = I_{L,cell} - I_{o,cell}\left[exp\left(\frac{V_{cell} + I_{cell}R_{S,cell}}{n_{cell}V_T}\right) - 1\right] - \frac{V_{cell} + I_{cell}R_{S,cell}}{R_{SH,cell}}$$

<u>where</u>:

V_T: Thermal Voltage given by V_T=kT/q ($V_{T,27^oC}$=25,85mV)

k: Boltzmann's constant (1.38x10^{-23}Joule/Kelvin)

T: cell temperature in ^{o}K

q: electron's charge (1.6022x10^{-19}Cb)

n_{cell}: correction coefficient. Value ranges between 1 and 2.

I_{cell}: Cell's output current

V_{cell}: Cell's terminal voltage

Parametric model for a PV Cell (cont'd)

$$I_{cell} = I_{L,cell} - I_{o,cell}\left[exp\left(\frac{V_{cell} + I_{cell}R_{S,cell}}{n_{cell}V_T}\right) - 1\right] - \frac{V_{cell} + I_{cell}R_{S,cell}}{R_{SH,cell}}$$

where:

$I_{L,cell}$: Light-generated current created by the incidence of light onto the cell.

$I_{o,cell}$: Internal p-n junction saturation current. Varies from 10^{-4} to 10^{-15}A

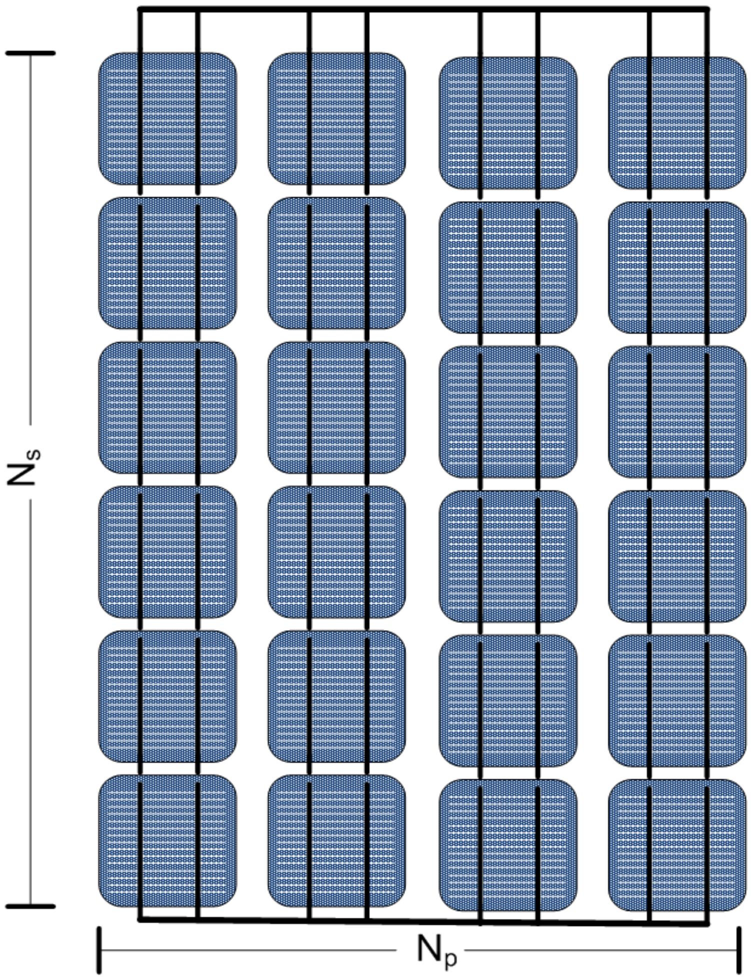
$R_{S,cell}$: Cell's series resistance. Includes all the factors of resistance to the carriers' movement. It ranges to values less than 1Ω.

$R_{SH,cell}$: Cell's shunt resistance. Represents leakage of carriers due to recombination in different parts of the cell, like p-n junction, crystal singularities etc. Its value is usually more than 1kΩ.

Implementation of parametric model in a PV module

Consider one panel of PV cells which consists of N_p parallel strings with N_s cells per string.

Based on the previous mathematical model and assuming that all the cells have the same characteristics we obtain an equation set describing the panel operation



Parametric model-equation of module

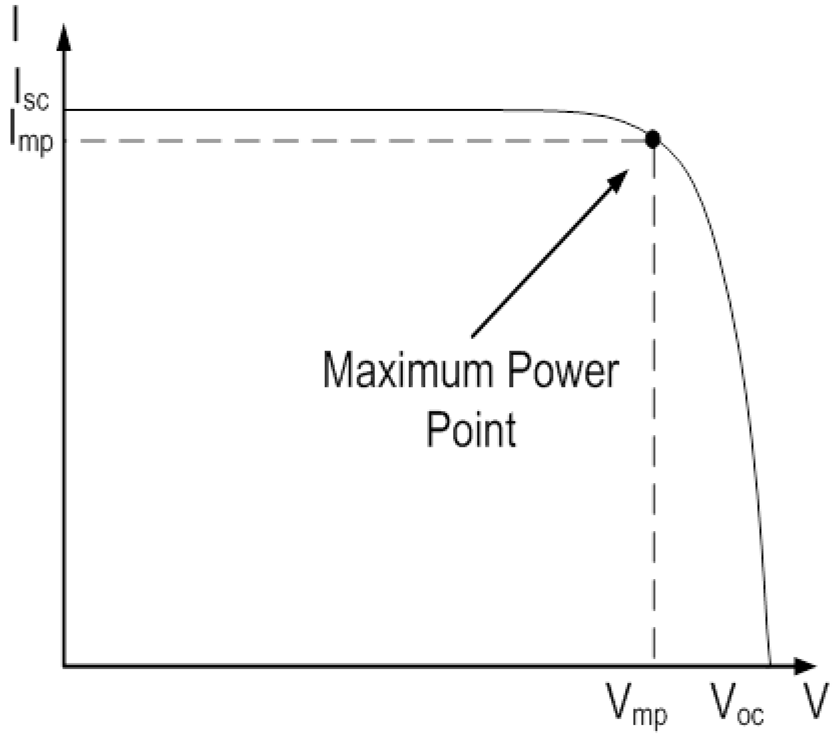
$$I = I_L - I_o\left[exp\left(\frac{V + IR_S}{nV_T}\right) - 1\right] - \frac{V + IR_S}{R_{SH}}$$

Where:

$n=N_S n_{cell}$	Correction coefficient
$I= N_P I_{cell}$	Module's current
$V=N_S V_{cell}$	Module's voltage
$I_L=N_P I_{L,cell}$	Equivalent light current
$I_o=N_P I_{o,cell}$	Total equivalent saturation diode current
$R_S=(N_S/N_P)R_{S,cell}$	Equivalent series resistance
$R_{SH}=(N_S/N_P)R_{SH,cell}$	Equivalent shunt resistance

The Current-Voltage characteristic and final equation set

I-V curve



Equation set

$$I \approx I_L - I_o\left[exp\left(\frac{V + IR_S}{nV_T}\right) - 1\right]$$

$$V \approx -IR_S + nV_T\left[ln\left(\frac{I_L - I}{I_o}\right) + 1\right]$$

$$I_{sc} \approx I_L - I_o\left[exp\left(\frac{IR_S}{nV_T}\right) - 1\right]$$

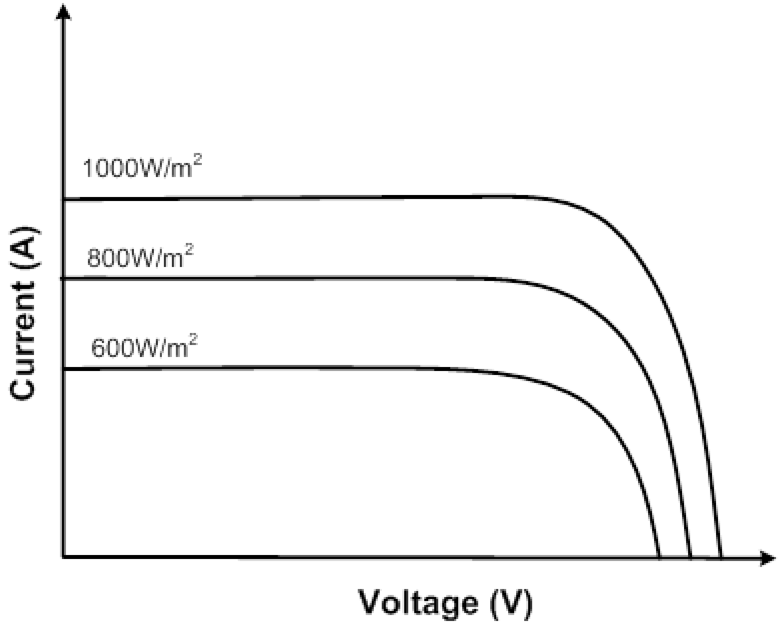
$$V_{oc} \approx nV_T\left[ln\left(\frac{I_L}{I_o}\right) + 1\right]$$

Dependency of parametric model on irradiance and temperature

Irradiance:

Affects the quantities I_L and V_{oc}

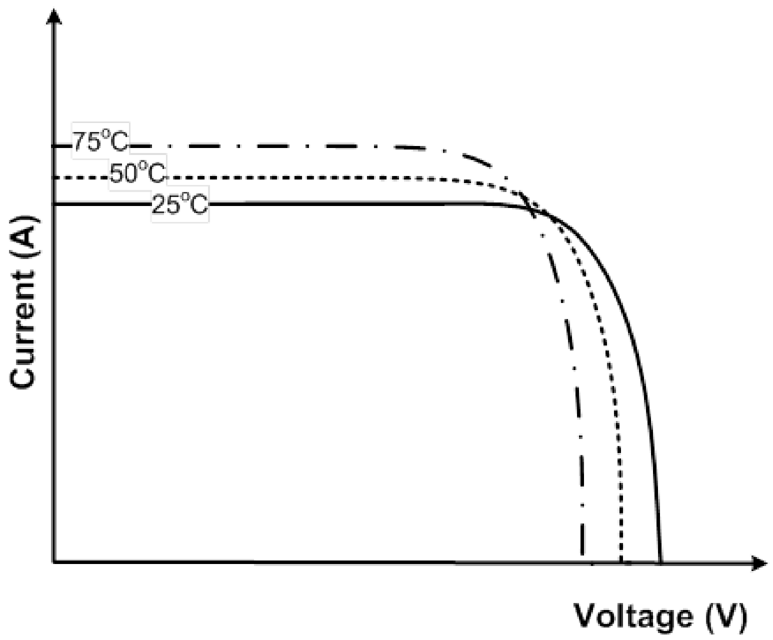
$$I_L^{GW/m^2} = \frac{G}{1000} I_L^{1000W/m^2}$$



Dependency of parametric model on irradiance and temperature (cont'd)

Effects of temperature increase:

- Slight open-circuit voltage (V_{oc}) decrease
- Slight short-circuit current (I_{sc}) increase
- Maximum power (P_{mp}) decrease



Dependency of parametric model on irradiance and temperature (cont'd)

Modified parameters:

$$I_{sc}^{(25+dT)^{o}C} = I_{sc}^{25^{o}C}\left(1 + \frac{C_{TI}}{100}dT\right)$$

$$V_{oc}^{(25+dT)^{o}C} = V_{oc}^{25^{o}C} - \frac{C_{TV}}{1000}dT$$

$$I_{L}^{(25+dT)^{o}C} \approx I_{L}^{25^{o}C}\left(1 + \frac{C_{TI}}{100}dT\right)$$

$$V_{T}^{(25+dT)^{o}C} = \frac{k\big(273 + (25 + dT)\big)}{q}$$

where:

C_{TI} : I_{sc} coefficient representing the change of I_{sc} for each degree

C_{TV} : V_{oc} coefficient representing the change of V_{oc} for each degree

dT : temperature change

Dependency of parametric model on irradiance and temperature (cont'd)

$$I_o(T) = I_o(T_r)\left(\frac{T}{T_r}\right)^{\frac{XTI}{n_{cell}}} exp\left(-\frac{1}{n_{cell}k}\left(\frac{E_g(T)}{T} - \frac{E_g(T_r)}{T_r}\right)\right)$$

$$E_g(T) = N_S E_g(0) - \frac{N_S C_{EG1} T^2}{C_{EG2} + T}$$

where:

XTI : Temperature coefficient for the I_O for the panel

$E_g(0)$: Energy gap for T=0°C (~1.17eV for Si)

C_{EG1} : Temperature coefficient (~4.73x10^{-4}eV/°K)

C_{EG2} : Temperature coefficient (~636°K)

Parametric model-Estimation of unknown parameters

- Algebraic or sequential method

  In this case selected measurements and reasonable assumptions are used. Through these data, analytical relationships for the unknown parameters can be determined.

- Iteration or optimization method

  In this case a measurement data set is required. These data are used in an iteration algorithm which leads to the optimum vector of parameters which minimize an error function. Moreover, an initial estimation is necessary.

Algebraic method

Required measurements:

V_{oc}, I_{sc}, V_{mp}, I_{mp}, V_{min}, I_{max}, V_{max}, I_{min}

Calculation of parameters:

STEP 1:

$$R_{SH} \approx R_{SHO}\left(\frac{V_{min}}{I_{sc} - I_{max}}\right)$$

STEP 2:

$$n \approx \frac{1}{V_T}\frac{V_{mp} + I_{mp}R_{SO} - V_{oc}}{\left[ln\left(\frac{(I_{sc} - I_{mp})R_{SH} - V_{mp}}{I_{sc}R_{SH} - V_{oc}}\right) + \frac{I_{mp}}{\left[I_{sc} - \frac{V_{oc}}{R_{SH}}\right]}\right]}$$

where:

$$R_{SO} = \frac{V_{oc} - V_{max}}{I_{min}}$$

Algebraic method (cont'd)

STEP 3:

$$I_o \approx \frac{\left[I_{sc} - \frac{V_{oc}}{R_{SH}}\right]}{exp\left(\frac{V_{oc}}{nV_T}\right)}$$

STEP 4:

$$R_S \approx R_{SO} - \frac{nV_T}{I_o exp\left(\frac{V_{oc}}{nV_T}\right)}$$

STEP 5:

$$I_L = I_{sc}\left(1 + \frac{R_S}{R_{SH}}\right) + I_o\left[exp\left(\frac{I_{sc}R_S}{nV_T}\right) - 1\right]$$

Iteration method

Minimization of an error function:

$$E(R_S, R_{SH}, n, I_L, I_o) = \frac{1}{N}\sum_{i=0}^{N-1}\left[\frac{V_{Mi} - F(I_{Mi}, V_{Mi}, R_S, R_{SH}, n, I_L, I_o)}{V_{Mi}}\right]^2$$

Or chi-square function:

$$\chi^2 = \sum_{i=1}^{N}\left(\frac{y_i - y(x_i, a_1 \dots a_M)}{\sigma_i}\right)^2$$

Commonest iteration method: Levenberg-Marquardt

Implementation of parametric model-parameters' calculation[1]

Model	*MSX77*	$\mathbf{P_{MAX}}$	*77.00W*	$\mathbf{I_{sc}}$	*5.0A*	CTI	*(0.065±0.015)%/°C*
Manufacturer	*Solarex*	$\mathbf{V_{mp}}$	*16.90V*	$\mathbf{V_{oc}}$	*21.0V*	CTV	-(0.5±0.05)mV/°C
		$\mathbf{I_{mp}}$	*4.56A*				
Standard Test Conditions			*1kW/m²*		AM1.5		*25°C*

Algebraic

I_L=4.985458

n=47.19563

R_s=0.178211

R_{SH}=609.444

I_o=1.477415e-07

Iteration

I_L=4.98

n=47.07

R_s=0.174

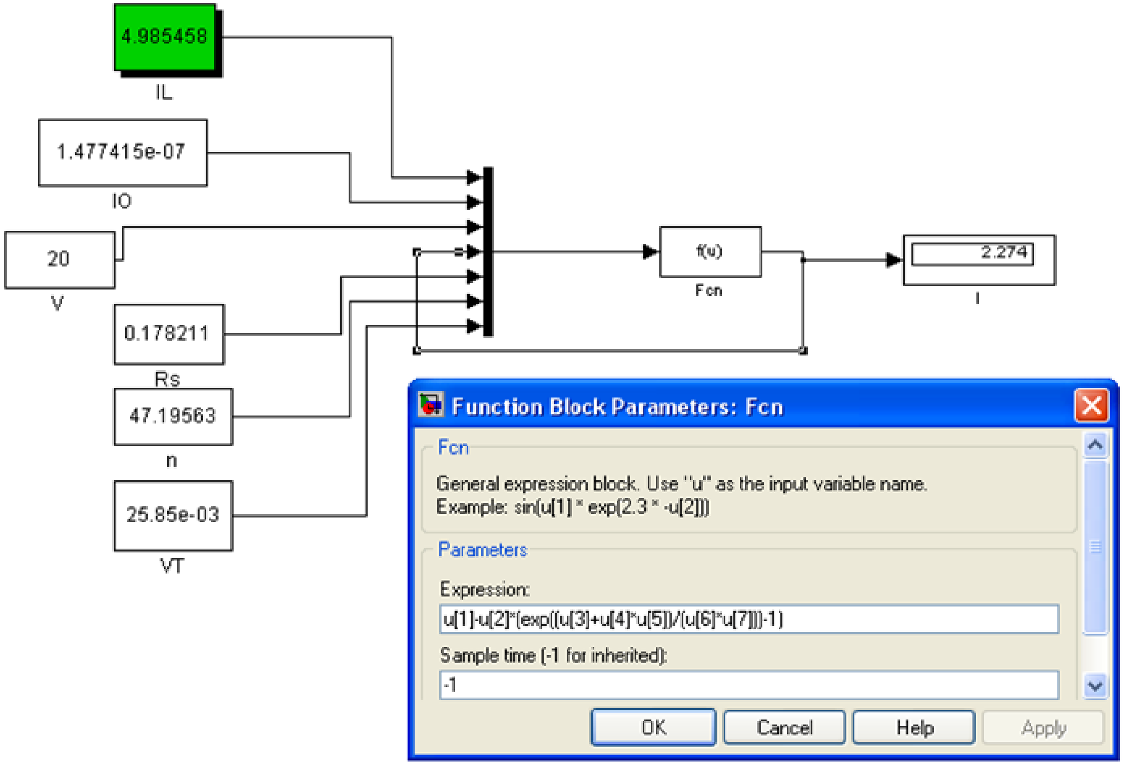
R_{SH}=610.0

I_o=1.40e-07

[1]Project title: "Techno-economic comparison and development of high-frequency single-phase inverters, integrated in crystalline-silicon PV modules, for direct connection to the grid", Project Leader, Emmanuel K. Tatakis, Department of Electrical & Computer Engineering, University of Patras, Rio-Patra, 26500, Tel.: +30-2610-996412

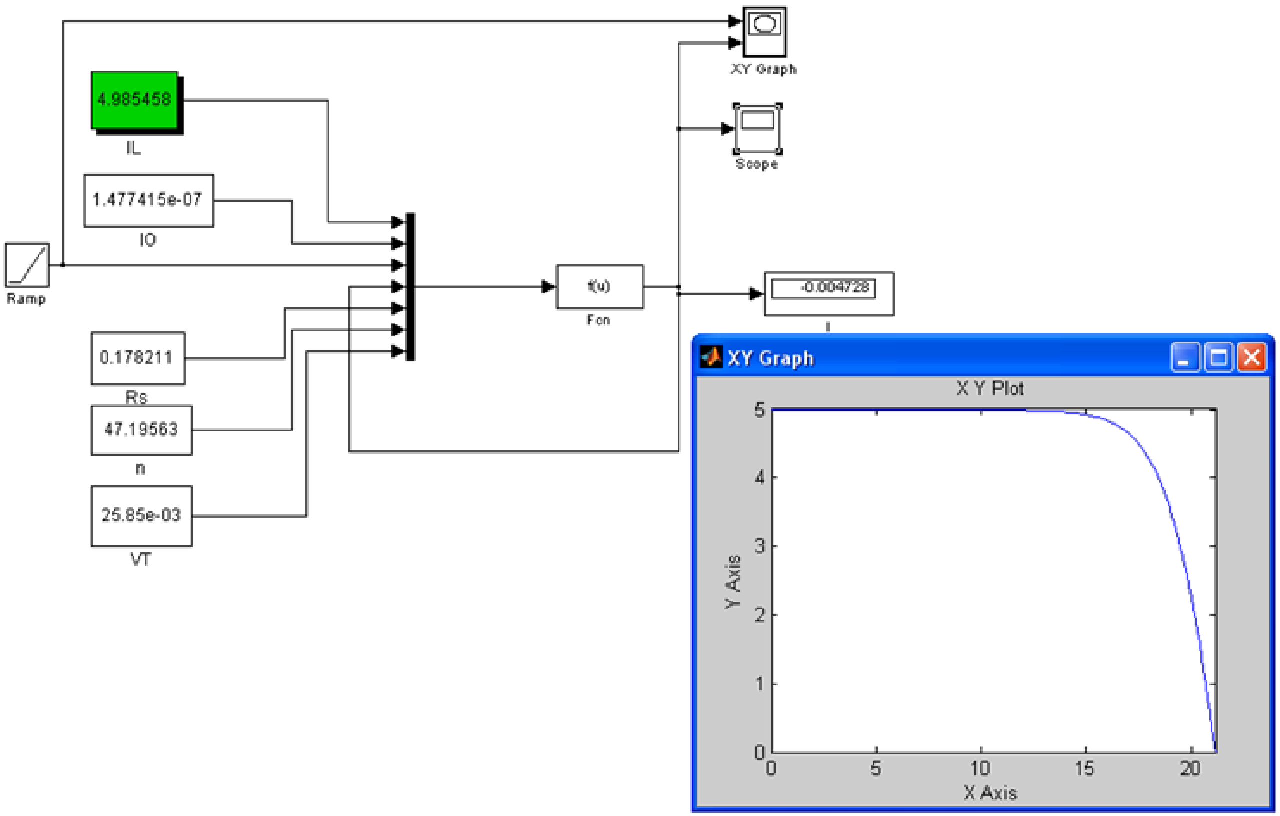
Examples

Example 1: Development of Simulink model for current calculation as a function of voltage by using the parametric model



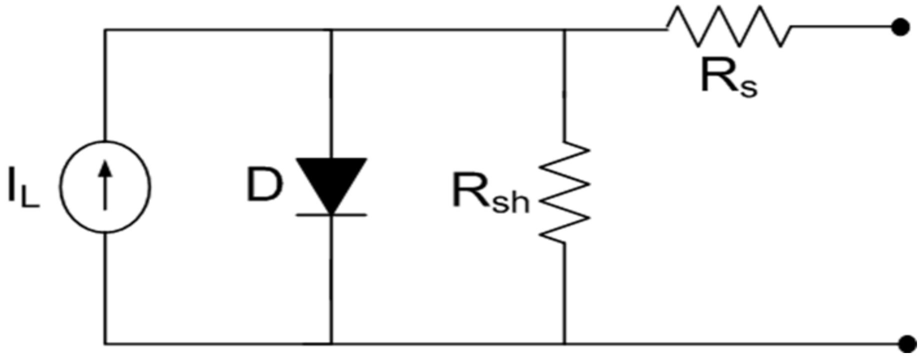
Examples (cont'd)

Example 2: I-V curve reproduction



Equivalent circuit model

Equivalent circuit:



Advantages

- Suitable for electric circuit simulation programs like PSPICE
- Simplified and proper for use when rough approximation of PV behaviour is needed
- Suitable for non-symmetrical operating conditions due to non-uniform irradiance and temperature and due to different parameter values

Disadvantages

- Not suitable for dimensioning simulation
- Absence of an analytical diode model in some simulation platforms
- Computational time increases when large number of such sub-circuits is used

Interpolation model

Main advantages :

- It does not require knowledge of the technological parameters set by the parametric model
- It requires only three operation points of data which are always given by a manufacturer’s datasheet
- It incorporates in a simplified and easy to use way the temperature and irradiation changes

Disadvantages:

Less accuracy compared with the very detailed parametric model

Interpolation Model-equation set

STEP 1:

$$C_2 = \left(\frac{V_{mp}}{V_{oc}} - 1\right) \Big/ ln\left(1 - \frac{I_{mp}}{I_{sc}}\right)$$

STEP 2:

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) exp\left(-\frac{V_{mp}}{C_2 V_{oc}}\right)$$

STEP 3:

$$D_I = C_{TI} \frac{G}{1000}(T - T_{ref}) + I_{sc}\left(\frac{G}{1000} - 1\right)$$

STEP 4:

$$V_R = V + C_{TV}(T - T_{ref}) + R_S D_I$$

Interpolation Model-equation set (cont'd)

Current equation:

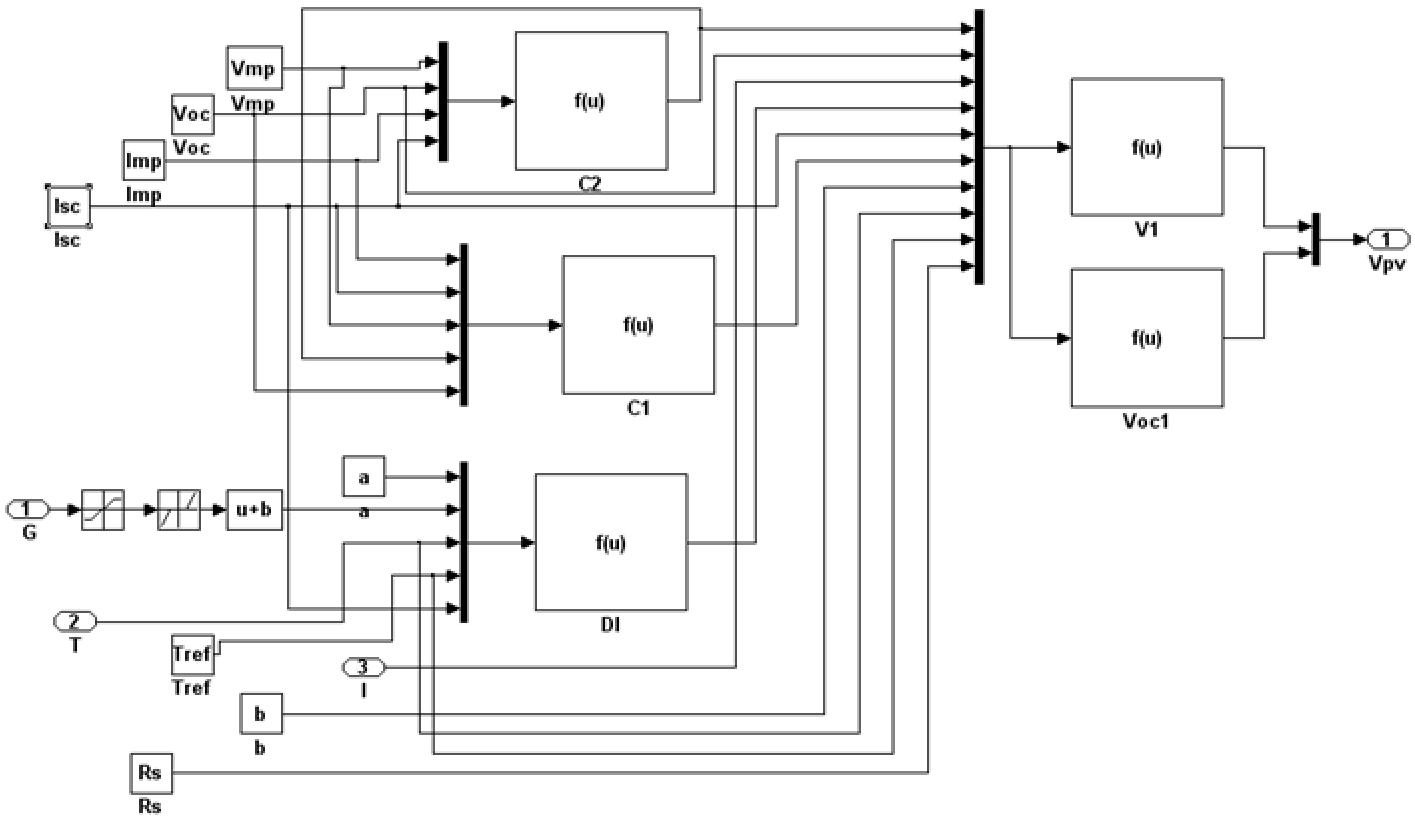
$$I = I_{SC}\left[1 - C_1\left(exp\left(\frac{V_R}{C_2 V_{oc}}\right) - 1\right)\right] + D_I$$

Voltage equation:

$$V = C_2 V_{oc} ln\left(\frac{1 - (I - D_I)/I_{sc}}{C_1} + 1\right) - C_{TV}(T - T_{ref}) - R_S D_I$$

Example

Example 3: Simulink model creation for calculation of voltage across the PV module as a function of current by using the interpolation model.



Other static PV models

- Point-by-point methods
  - Anderson's method

$$I_2 = \left(\frac{G_2}{G_1}\right)\frac{I_1}{\left(1 + C_{TI}(T_2 - T_1)\right)}$$

$$V_2 = \frac{V_1}{\left(1 + C_{TV}(T_2 - T_1)\right)(1 + ln(G_2/G_1)kT/q)}$$

  - Bleasser's method

$$I_2 = I_1\left(\frac{G_2}{G_1}\right)\left(1 + C_{TI}(T_2 - T_1)\right)$$

$$V_2 = V_1 - R_S(I_1 - I_2) + \frac{kT}{q}\ln\left(\frac{G_2}{G_1}\right) + \mathrm{C_{TV}}(T_2 - T_1)$$

Other static PV models (cont'd)

- IEC-891 procedure

$$I_2 = I_1 + I_{SC}\left(\frac{I_{SR}}{I_{MR}} - 1\right)C_{TI}(T_2 - T_1)$$

$$V_2 = V_1 - R_S(I_2 - I_1) - kI_2(T_2 - T_1) + C_{TV}(T_2 - T_1)$$

- Analytical models

Bi-exponential

$$I = I_L - I_{o1}\left[exp\left(\frac{V + IR_S}{n_1 V_T}\right) - 1\right] - I_{o2}\left[exp\left(\frac{V + IR_S}{n_2 V_T}\right) - 1\right] - \frac{V + IR_S}{R_{SH}}$$

Useful tips for PV systems' modeling

- Use of one single model for the array when the system operates uniformly and symmetrically
  - 👌 Minimisation of the computational time due to minimum calculations
  - 👎 Modification of the modules' number is not always easy
- Use of separate models for each module in order to study asymmetric operation
  - 👎 It increases the simulation time due to the large number of equations required to be solved
  - 👎 Special attention is needed if the modules are modelled either as current or as voltage sources (e.g. in Matlab simulation conflicts occur when voltage sources are connected in parallel or current sources in series)
- System solving using phasors instead of instantaneous values when it is feasible
  - 👌 Minimisation of computational time because the calculated quantities change slower than the instantaneous values

Modeling of PV inverters

- The model complexity depends on the focus of the required study

- Long-term analysis: It requires modeling and simulation of the system in a frame of hours-days-months

- Short-term analysis: Simulation of the system in a range less than 1sec

- The implementation of detailed models which take into consideration the switching operation is not recommended when long term studies are conducted

Modeling of PV inverters (cont'd)

- Power stage:
  - Power converter either in analytical (switches) or in simplified (linear current or voltage source) form
- Control stage:
  - Maximum Power Point Tracking algorithm
  - Anti-islanding protection
  - Power factor correction
  - Grid synchronization
  - Ancillary services functions like P-f/Q-V droop control
  - Switches driving

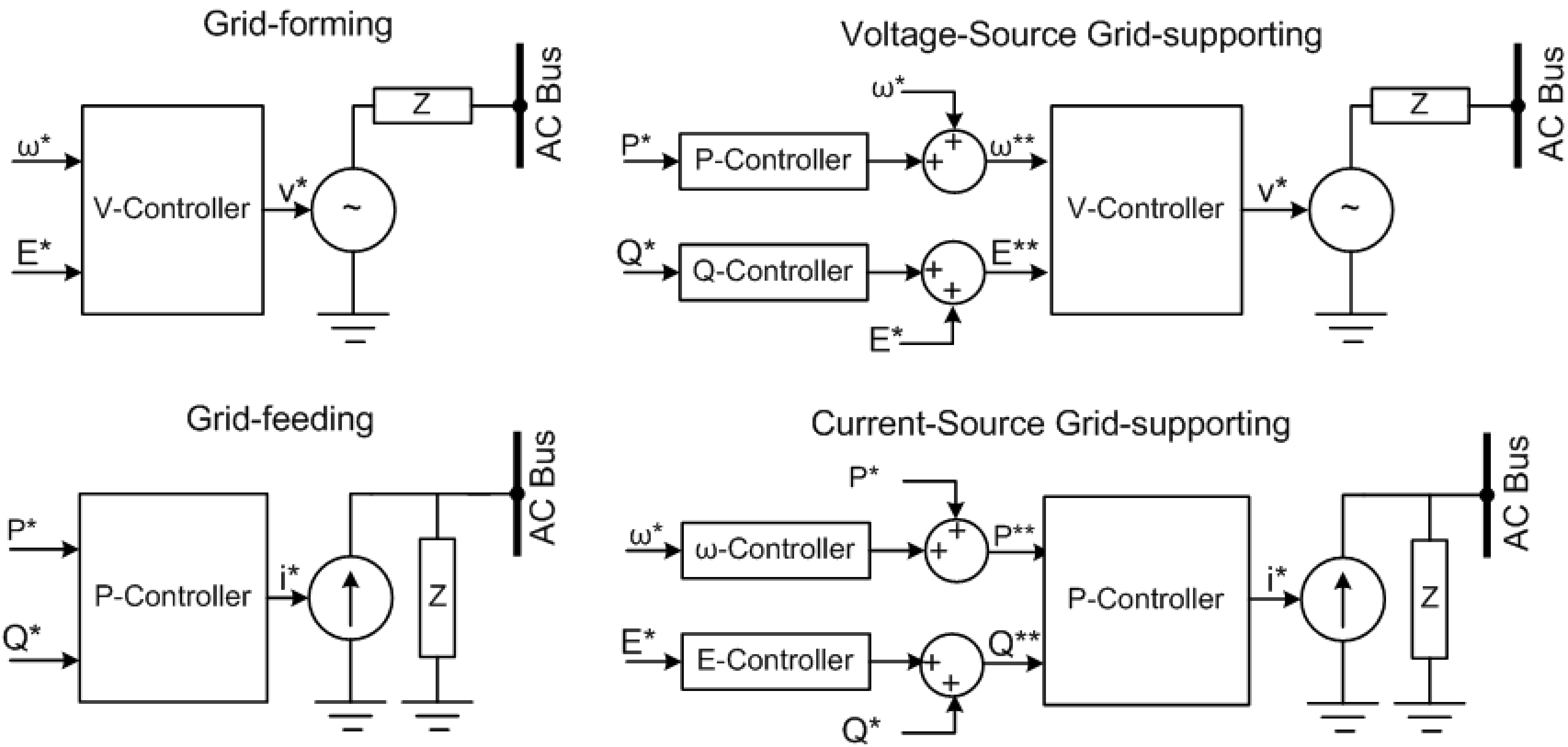
Modeling of PV inverters (cont'd)

Assumptions-simplifications:

- Use of linear current sources instead of analytical converter topology when possible
- Loss modeling based on the efficiency curves given by the manufacturer's datasheet (Maximum efficiency, european efficiency, efficiency curves)
- This leads to substantial reduction of simulation time due to elimination of switching behaviour

Grid-connected Inverters

Main types of grid-connected inverters



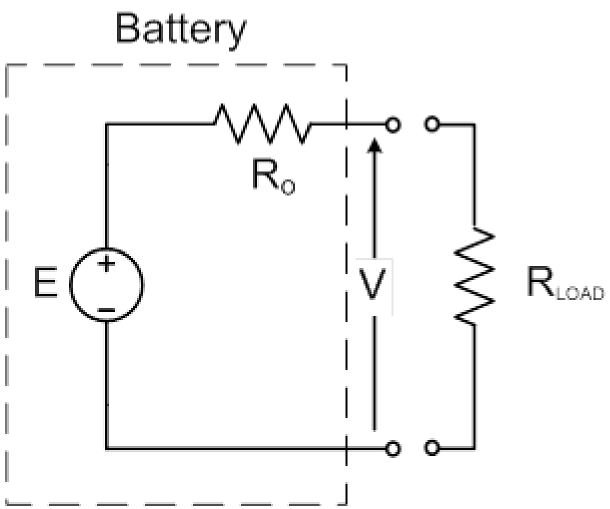
Stand-alone systems and microgrids modeling

- Use of the same models for PV modules and inverters
- In specific cases the PV inverter is modeled as voltage source without an MPPT algorithm
- Modelling of battery storage and inverter or charger
- Modelling of diesel generators
- Modeling of additional RES or DER included in the System-under-Test

Battery model

kinetic battery model:

Equivalent circuit:



The characteristic quantities of the battery described by the kinetic model are:

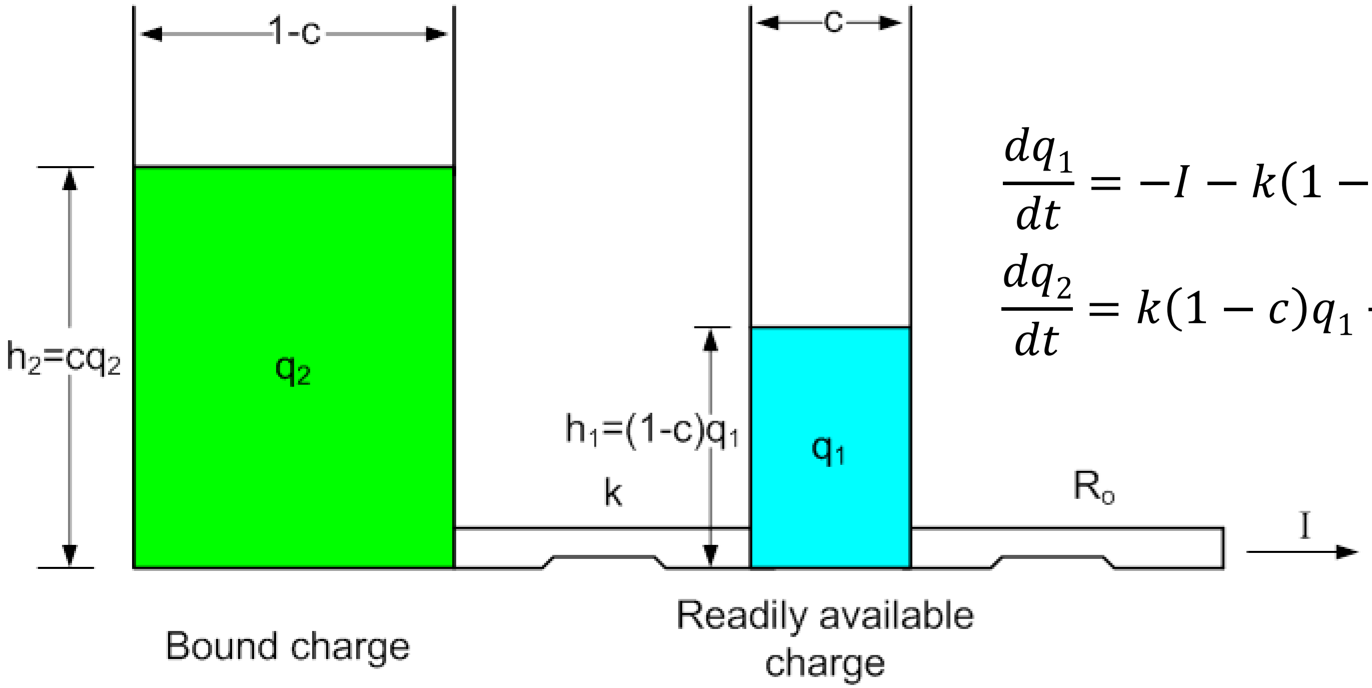
- Remaining capacity
- Terminal voltage
- Charge transfer
- Loss model
- Battery lifetime model

Remaining Ah calculation

Total charge = readily available + bound charge

$q = q_1 + q_2$

Equivalent representation of battery charge



$$\frac{dq_1}{dt} = -I - k(1-c)q_1 + kcq_2$$

$$\frac{dq_2}{dt} = k(1-c)q_1 - kcq_2$$

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Remaining Ah model

Assuming a constant battery current in a time interval Δt:

$$q_1 = q_{1,0}e^{-k\Delta t} + \frac{(q_0kc - I)(1 - e^{-k\Delta t})}{k} - \frac{Ic(k\Delta t - 1 + e^{-k\Delta t})}{k}$$

$$q_2 = q_{2,0}e^{-k\Delta t} + q_0(1-c)(1 - e^{-k\Delta t}) - \frac{I(1-c)(k\Delta t - 1 + e^{-k\Delta t})}{k}$$

Maximum charge

$$q_{max}(I) = \frac{q_{max}kc(q_{max}(I)/I)}{1 - e^{-k\left(\frac{q_{max}(I)}{I}\right)} + c\left(k\left((q_{max}(I)/I)\right) - 1 + e^{-k(q_{max}(I)/I)}\right)}$$

Battery Terminal Voltage

Terminal voltage:

$$V = E - IR_{bat}$$

Internal EMF:

$$E = E_o + AX + \frac{CX}{(D - X)}$$

where:

<u>Charge</u>

$$X = \frac{q}{q_{max}(I)}$$

<u>Discharge</u>

$$X = \frac{(q_{max} - q)}{q_{max}(I)}$$

Parameters calculation

- Voltage-current measurement for specific charging/discharging cycles
- Constant charging/discharging current
- Use of iteration method for the unknown parameters calculation

Simplified battery model (1)

State-of-Charge: $$SOC(t) = SOC(0) + \int_0^t \left(I_{battery}(t) - I_{gas}(t)\right) dt$$

Losses: $$I_{gas}(t) = I_{G0} e^{C_U\left(U_{battery}(t) - U_0\right) + C_T\left(T_{battery}(t) - T_0\right)}$$

Recommended parameter values:

- $C_U = 11.531 V^{-1}$
- $U_0 = 2.23 V/cell$
- $C_T = 0.0693 K^{-1}$
- $T_0 = 20^oC$
- $I_{G0} = 50mA/100Ah$

Modeling of battery inverters/chargers

- Same guidelines as in PV inverters regarding power stage are usually followed
- Control stage includes characteristics given by the manufacturer (like charging phases, SOC calculation, temperature compensation etc.)
- The inverter can be modelled either as voltage or as current source depending on the operation (grid-forming, grid-feeding, grid-supporting mode)

Diesel Generator Performance Model

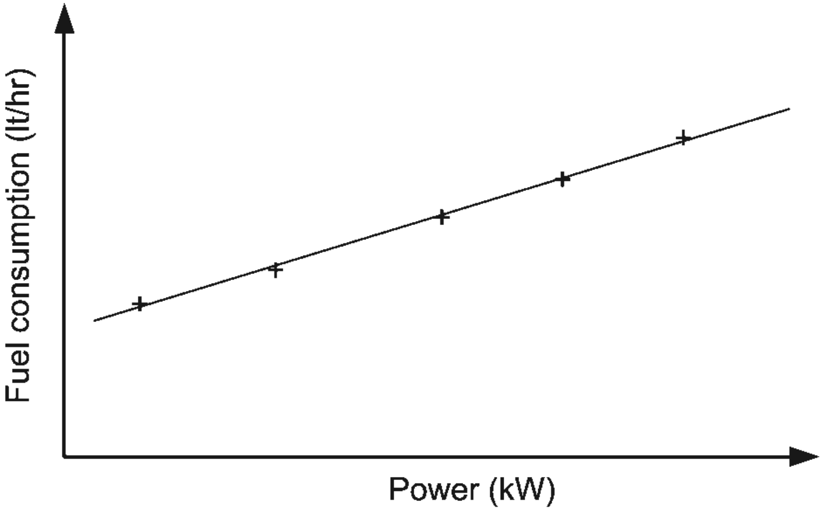
- Linear fuel vs. Power curve

$$F = a + bP$$

Where:

a=No load fuel consumption, fuel units/hr,

b=Slope of fuel vs. power, fuel units/kWh



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