SIMUGRID

Seville, July 2019

Preface

Simμgrid is a $Matlab/Simulink^{TM}$ library, which includes mathematical models of the main elements of a microgrids: batteries, fuel cell, electrolyzers, renewable generation, etc. Most of them are simple, configurable and non-linear models, whose main objective is to help in the design of microgrids [3] energy management systems, allowing the tests of controllers in simulation.

Simμgrid is a companion toolbox of the book "Model Predictive Control of Microgrids" of the authors C. Bordons, F. García Torres and Miguel A. Ridao, published by Springer Nature Switzerland (ISBN 978-3-030-24569-6 and 978-3-030-24570-2 (eBook)).

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Simμgrid is freely provided under the following conditions:

1. all rights of the software remain with the authors.
2. the authors decline any liability related to the use of Simμgrid software.

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Chapter 1

Introduction

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1.1 Installation

Simμgrid is a library of Simulink blocks and does not require an specific installation, beyond the actions required to be used by Matlab/Simulink, as follows:

1. Uncompress the file Simugrid in your computer. It includes the library file ”SimugridLib.slx” and several folders with data, images and examples.
2. Add the folder including the above files and all its subfolders to the Matlab path.
3. Open a new Simulink to create a new microgrid or open one of the provided examples.

Chapter 2

Elements of Simμgrid Library

2.1 Timeseries Arrays

The generation and demand input data and the time evolution of the simulation variables use time series objects in Matlab. Thos section sumarizes the creation of timeseries matlab files, to be used in Simμgrid generation and demand blocks.

In order to create a .mat input file, if raw data are in vector format, a time series data object must be created.

Example:

Let consider a vector with power data (dimension 1x2412) corresponding to a 30 seconds time interval, named "Powerdata". First, a time vector with same dimension must be created:

$>> time = 0 : 30 : 72359$

Create the time serie with the desired variable name (i.e. ts_power) :

$>> ts\_power = timeseries(Powerdata, time,' Name',' Power');$

Save the created timeserie object ts_power in a .mat file with the desired name:

$>> save('MyPowerFile.mat',' ts\_power');$

A simple visualization of the timeserie object can be obtained with the plot command:

>> *plot*(*ts_power*)

2.2 Solar Generation

Solar generation is read from a .mat file which must contain enough data for the whole time simulation windows. Data are given in time series format. Two alternatives are available: a file with the generated power or a file with the irradiance.

2.2.1 Solar Generation - power data

Figure 2.1: Solar Power Generation Block

This is a input data block, and consequently there are not inputs. The block has the power as an unique output, as can be seen in the following table:

Outputs		**Units**
1	Power	watts

Data are read from a .mat file with the power generated in the photovoltaic plant in watts. This power can be scaled with a multiplicative factor. These elements can be introduced in the block parameter windows (See Fig. 2.2).

2.2.2 Solar Generation - irradiance data

This block provides the power output of a photovoltaic plant, as in the previous one, but computing it from irradiance data. Now, the main parameters of the

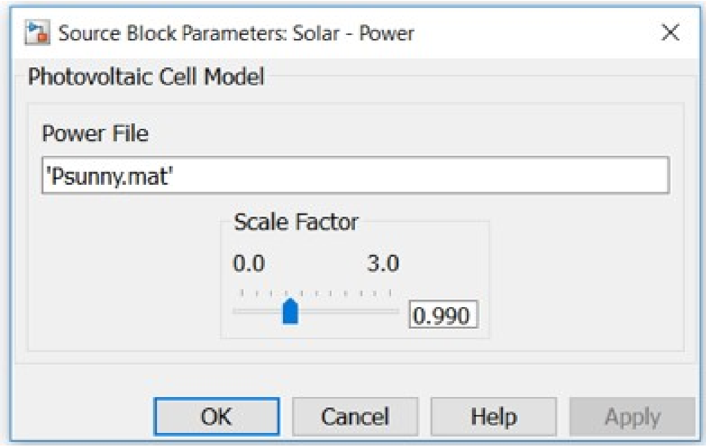

Figure 2.2: User Interface of the Solar Power Generation Block

Figure 2.3: Solar Irradiance Generation Block

Outputs		Units
1	Power	watts
2	Plant Current	amps

phototovoltaic plant are needed. The block also provides the plant current as a secondary output:

The model of a photovoltaic plant consists of the following equations:

Thermal voltage (U_t) is defined as:

$$U_t = \frac{k \cdot T_{pv}}{q} \tag{2.1}$$

where k is the Boltzman's constant T_{pv} is the temperature of the cell and q is the electron charge.

The characteristic equation of a cell is obtained as a function of the parameters shortcut current (I_{sc}) and open circuit voltage (U_{oc}), normally supplied by the manufacturer :

$$I_{pv} = I_{sc,pv} \cdot \left(1 - \exp\left(\frac{V_{pv} - V_{oc} + I_{sc}R_s}{V_t}\right)\right) \tag{2.2}$$

$$I_{sc} = \frac{I_{sc,n} \cdot G}{1000} \tag{2.3}$$

In this model, a panel can be composed of several cells and a number of panels can be connected in parallel or series. The required parameters are shown in Fig. 2.4.

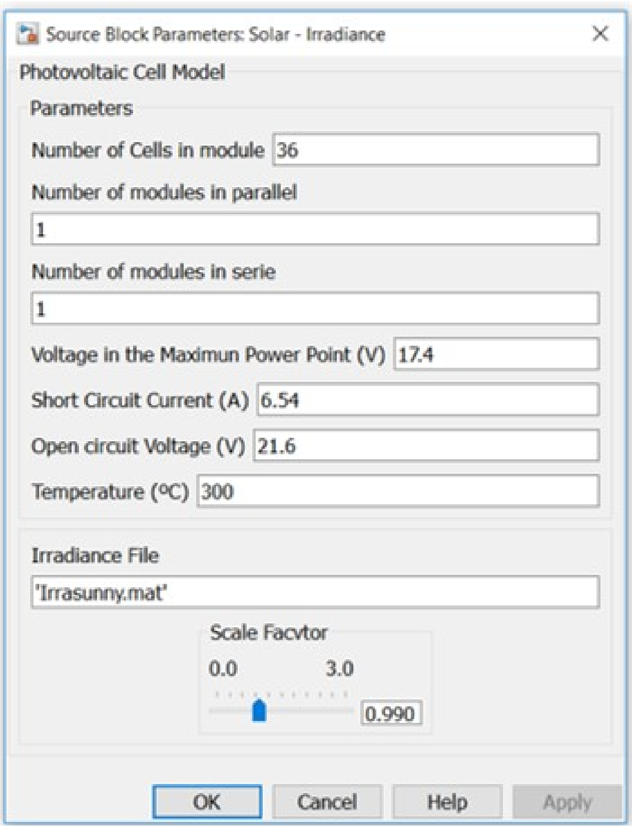

Figure 2.4: User Interface of the Solar Irradiance Generation Block

Note: Other parameters, as the resistor R_s are not available in the mask, but can be change editing the mask, in the *Initialization* section.

2.3 Wind Generation

There are also two blocks dedicated to provide wind data. The first one, power data are obtained directly from a .mat file, while the second one computes the power from a file with wind velocity data. Again, timeseries objects are used.

2.3.1 Solar Generation - power data

Figure 2.5: Wind Block

This block has only one output:

Outputs		Units
1	Power	watts

The .mat file with wind generation power can be selected in the mask of the block. As in previous blocks, the values can be scaled (Fig. 2.6).

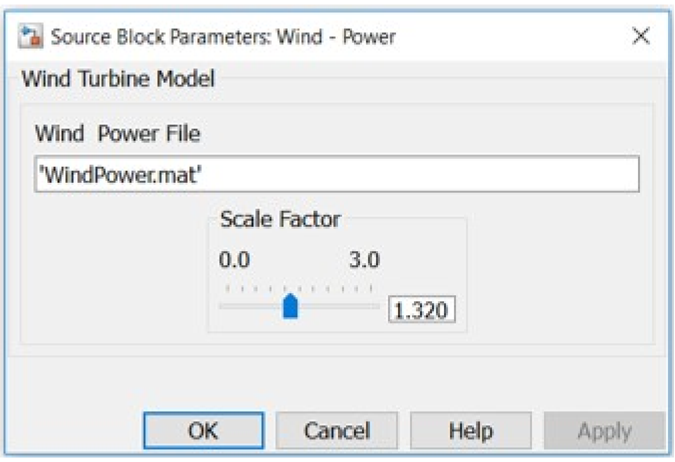

Figure 2.6: Mask of the wind power generation block

Figure 2.7: Wind velocity Block

2.3.2 Solar Generation - wind velocity data

This block provides the power output of a wind turbine, as in the previous one, but computing it from wind velocity data. Now, the main parameters of the wind turbine are needed.

The output is identical to block defined in the previous subsection:

	Outputs	**Units**
1	Power	watts

The following equation computes the output power of the wind turbine:

$$P_{wind} = 0.5 \cdot \pi \cdot \rho \cdot R_{blade}^2 \cdot v_w^3 \cdot C_p \tag{2.4}$$

where ρ is the density of air, R_{blade} represents the turbine radius, i.e., the blade length, v_w is the wind speed and C_p is the power coefficient. This coefficient can be obtained as a function of the pitch angle of the rotor θ and the tip speed ratio λ. In order to simplify the model, it will be assumed that C_p has a constant value. These data are introduced with the block mask (Fig. 2.8)

2.4 Gas Turbine

As opposed to wind or solar generation, gas turbine generation is controllable, and consequently the microgrid controller has to provide a power set-point generation, which is the input of the block. The block has two output, the fuel flow and the power that the gas turbine is able to produce. Notice, that the model in this tool are very simple, and the power output is the power limit but saturated with the maximum power of the turbine. The Table 2.1 summarizes the inputs and outputs of the block.

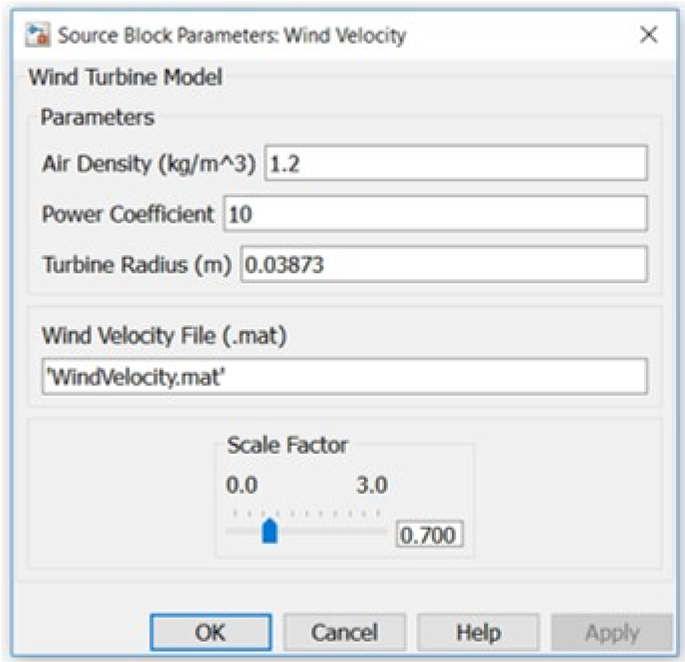

Figure 2.8: Mask of the wind velocity generation block

Figure 2.9: Gas Turbine Block

The mathematical model of the gas turbine is defined as follows. The generated mechanical power P_{gt} that produces the complete cycle is given by the following expressions:

$$P_{gt} = \dot{m}_a \cdot [C_{ph}(T_3 - T_4) - C_{pc}(T_2 - T_1)] \tag{2.5}$$

where $\dot{m}_a$ is the air flow, and C_{ph} and C_{pc} are the specific heat of air at constant pressure when air is at hot (T_3) and cold (T_1) temperatures respectively. The pressure ratio of the cycle is defined as:

Inputs		**Units**
1	Power Set-point	watts
Outputs		**Units**
1	Power Output	watts
2	Fuel flow	Kg/s

Table 2.1: Inputs and outputs of the Gas Turbine Block

$$PR = \frac{p_2}{p_1} = \frac{p_3}{p_4} \tag{2.6}$$

If γ_h and γ_c denote the ratio of specific heats at hot and cold temperatures, the relation between pressures and temperatures in the isentropic processes can be expressed as follows:

$$\frac{T_{2s}}{T_1} = PR^{\frac{\gamma_c - 1}{\gamma_c}} = x_c \tag{2.7}$$

$$\frac{T_3}{T_{4s}} = PR^{\frac{\gamma_h - 1}{\gamma_h}} = x_h \tag{2.8}$$

Then, temperatures can be obtained as follows:

$$T_2 = T_1 \left(\frac{x_c - 1}{\gamma_c} + 1 \right) \tag{2.9}$$

$$T_3 = T_2 + \eta_{comb} \frac{\dot{m}_f}{\dot{m}_a} \frac{H}{C_{ph}} \tag{2.10}$$

$$T_4 = T_3 \left[1 - \left(1 - \frac{1}{x_h} \right) \eta_t \right] \tag{2.11}$$

where η_c and η_t are the compressor and turbine efficiencies, η_{comb} is the combustor efficiency, $\dot{m}_f$ is the fuel flow and H is the lower heating value of fuel.

The mask of the block is shown in Fig. 2.10. All the constant of the above equation are defined in the *Initialization* section of the mask (Option Edit Mask).

This block has to be complemented with the Fuel Tank block. This block is just an integrator of the fuel flow. The output of this block (tank level) has to be considered by the controller to decide on the use of the gas turbine. Fig. 2.11 shows the connection of those blocks.

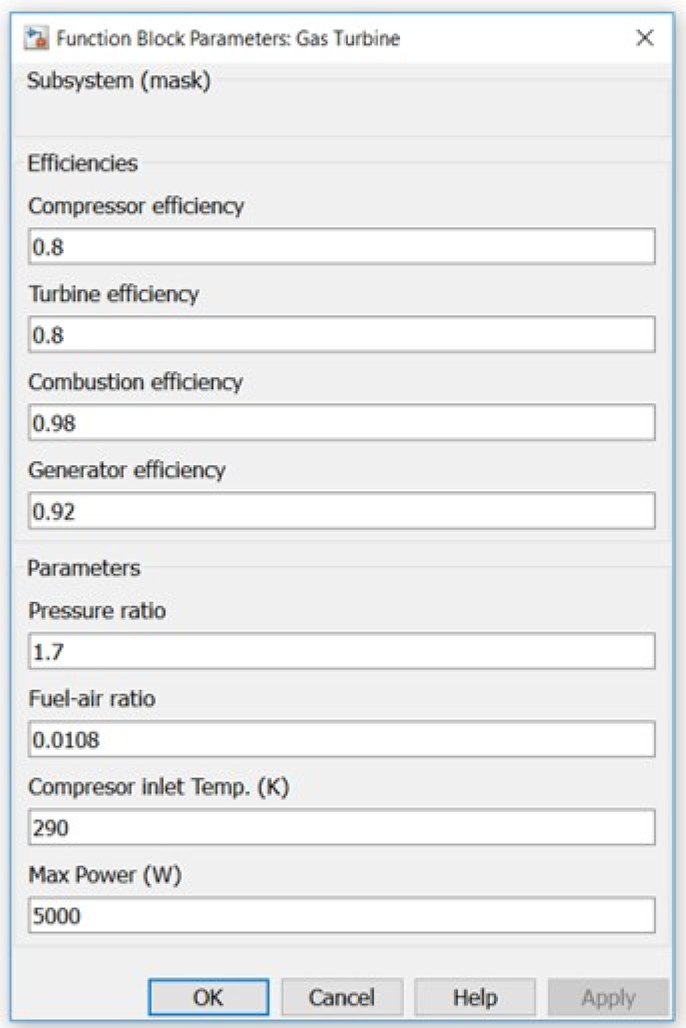

Figure 2.10: Mask of the wind velocity generation block

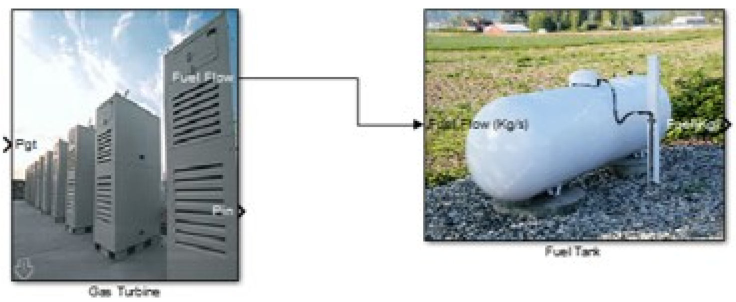

Figure 2.11: Mask of the wind velocity generation block

2.5 Demand

This input block read from .mat file the load consumption power in a time series format. The use of the block is identical to the power generation blocks. Again,

Figure 2.12: Demnand Block

there is only one output in the block:

Outputs		Units
1	Power	watts

Fif. 2.13 shows the mask of the Demand block. The name of the .mat file with the load power time serie ands a scale factor are the required parameters. When the number of points in the demand time serie is low, a stepped curve is obtained. If the option *Interpolate* is selected, a smoother curve will be used.

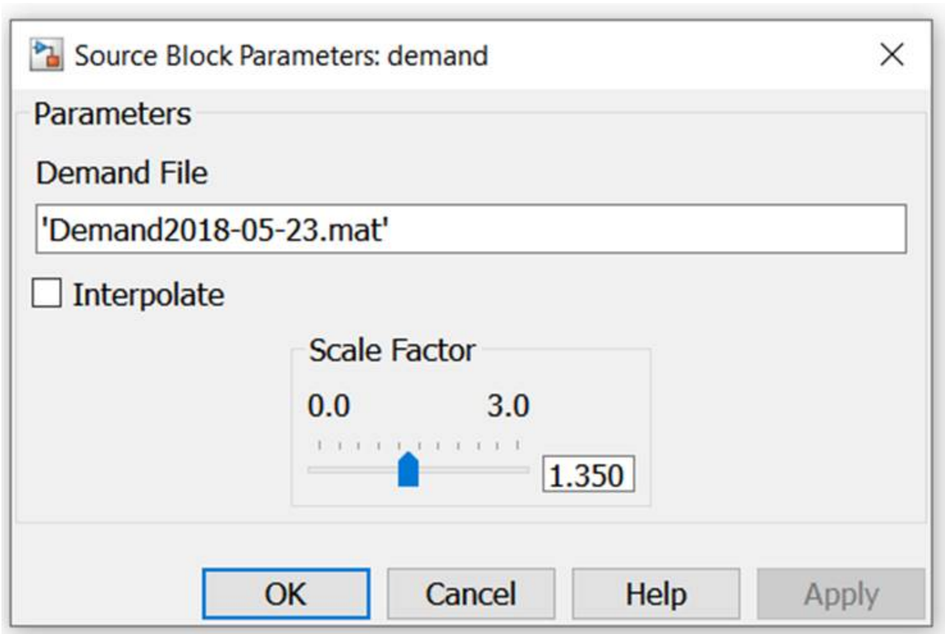

Figure 2.13: Mask of Demand block

Figure 2.14: Battery Block

Inputs		**Units**
1	Power Set-point	watts
Outputs		**Units**
1	Output Voltage	volts
2	Output Current	amps
3	Output Power	watts
4	State of Charge	%

Table 2.2: Inputs and outputs of the Battery Block

2.6 Batteries

The block has one input and four output, as can be seen in Table 2.2. The input is the power set-point send by the controller, and the State Of Charge (SOC), the voltage and current of the battery and the charge/discharge power (in this simple model is the power set-point saturated by the operational limits of the battery). It is important to notice the sign criteria used in this software: discharge power is positive and charge power is negative.

The mathematical model of the batteries is based on a simple model of a voltage source and an internal resistor [5].

$$V_{bt} = V_{bt,int} - R_i I_{bt}$$

Charge and discharge are modeled in a different way. When the battery is charging:

$$V_{bt,int} = V_{bt,0} - K_{bt}\frac{C_{120,bt}}{C_{120,bt}-C_{out,t}}Ibt - K_{bt}\frac{C_{120,bt}}{C_{120,bt}-C_{out,t}}Cout,t + A_{bt}e^{-B_{bt}C_{out,t}}$$

On the other side, during discharging:

$$V_{bt,int} = V_{bt,0} - K_{bt}\frac{C_{120,bt}}{C_{120,bt}-C_{out,t}}Ibt - K_{bt}\frac{C_{120,bt}}{C_{out,t}+0.1C_{120,bt}}Cout,t + A_{bt}e^{-B_{bt}C_{out,t}}$$

and

$Cout,t = \int_0^t I_{bt} dt$

In these equations, $V_{bt,0}$ is the open circuit battery voltage (V), $C_{out,t}$ is the current capacity of the battery (Ah), A_{bt} is the amplitude of the exponential zone (V), B_{bt} is the inverse of the time constant in the exponential zone (Ah_{-1}), K_{bt} is the polarization constant (V) and $C_{120,bt}$ is the maximum capacity of the battery (Ah).

All this parameters must be supplied to the clock using the block mask (see Fig.2.15). Default parameters correspond to the lead-acid battery installed in Hylab microgrid in University of Seville ([1]).

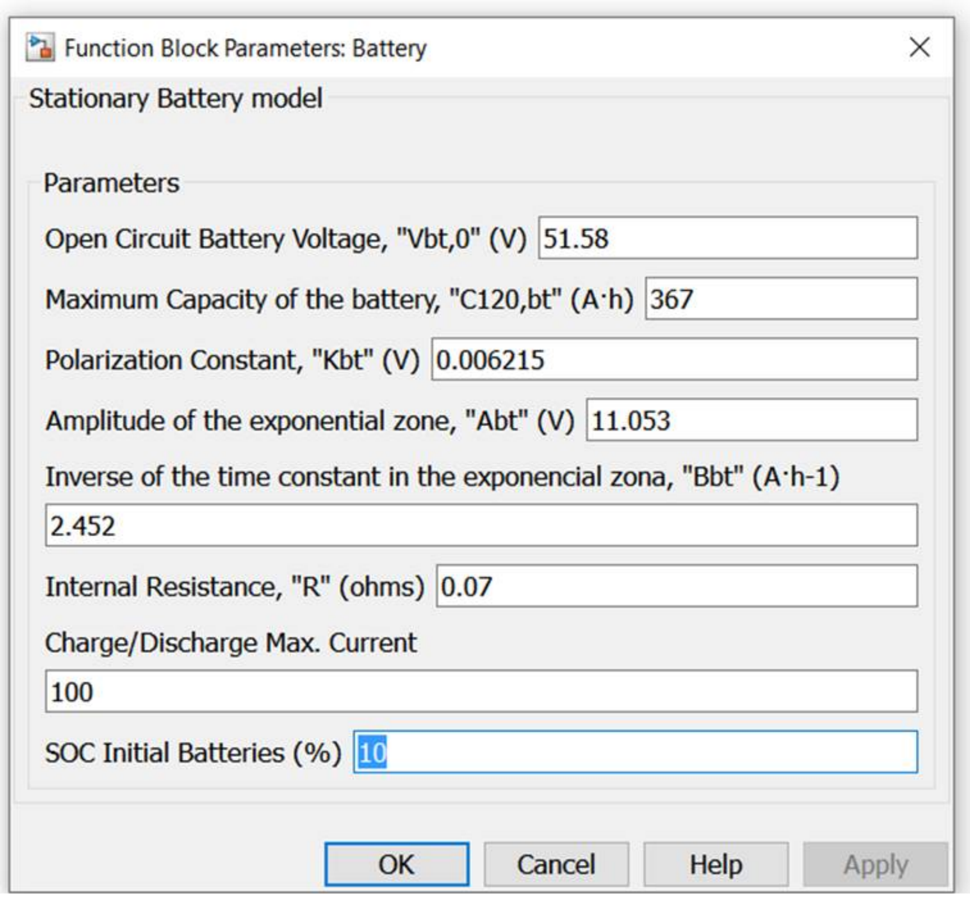

Figure 2.15: User interface of Battery block

Additionally to the above battery parameters, the maximum current of charge/discharge of the batteries and the initial State Of Charge must be introduced.

Inputs		**Units**
1	Power Set-point	watts
Outputs		**Units**
1	Output Voltage	volts
2	Output Current	amps
3	Output Power	watts
4	State of Charge	%

Table 2.3: Inputs and outputs of the Ultracapacitor Block

2.7 Ultracapacitors

Figure 2.16: Battery Block

Tha block has identical inputs and outputs as in the battery model, as can be seen in Table 2.3. The input is the power set-point send by the controller, and the State Of Charge (SOC), the voltage and current of the battery and the charge/discharge power. Notice the sign criteria used in this software: discharge power is positive and charge power is negative.

Classical equations of a capacitor has been used to model ultracapacitors. They are based on the ultracacitor models in [2], where a simple equivalent circuit with a capacitor and a resistor in series is used.

A bank of capacitors with several identical elements connected in series or parallel can be implemented in this software. As can be seen in Fig. **??**, capacity and the internal resistor are the parameters of the capacitor elements. The number of these elements connected in series or parallel also must be provided. Two operational constraint limits (voltage and current) are also included, and finally the user must introduce the initial State of Charge.

The equivalent internal resistor and capacity are computed in the mask (*Initialization* section).

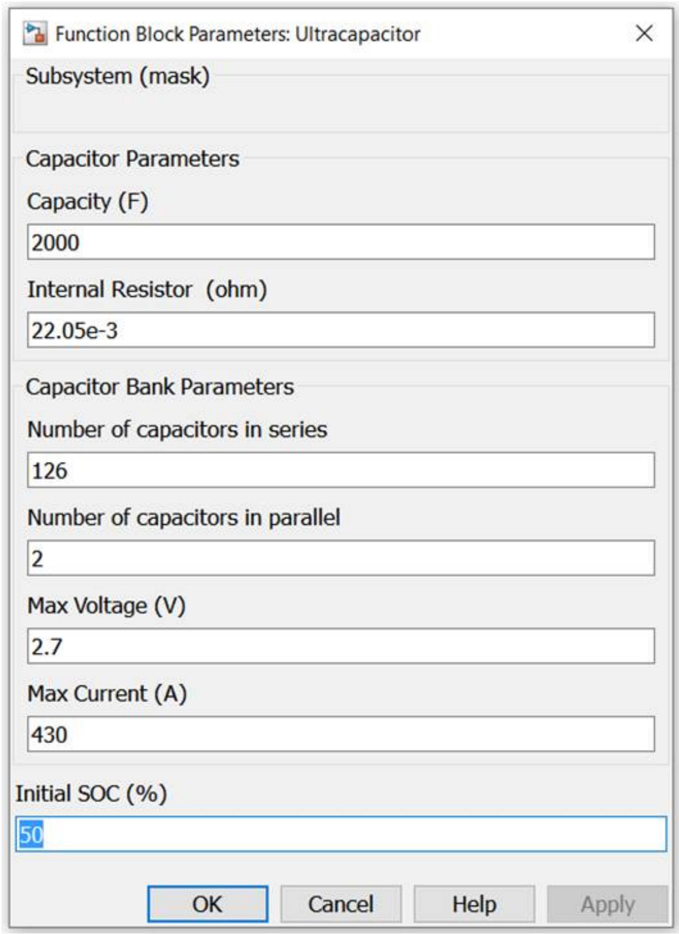

Figure 2.17: Mask of the ultracapacitor block

2.8 Fuel Cell

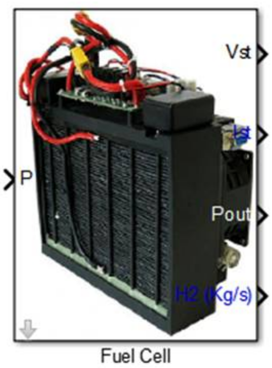

Figure 2.18: Fuel cell Block

Fuel cells are electrochemical devices whose function is to produce electricity from flows of hydrogen and oxygen. The simulation block has one input, as in previous block, the power set-point computed in the controller, and four output:

Inputs		**Units**
1	Power Set-point	watts
Outputs		**Units**
1	Stack Voltage	volts
2	Stack Current	amps
3	Power	watts
4	Hydrogen consumption	kg/s

Table 2.4: Inputs and outputs of the fuel cell Block

voltage and current of the stack, the power that the fuel cell can apply (set-point limited by constraints), and the flow of hydrogen, as can be seen in Table 2.4.

The mathematical model is based on a simplified model of the works in [1] and [4].

A fuel cell stack is composed of several cells N_{fc}^{cell} connected in series. The stack voltage $U_{fc}(t)$ can be expressed as:

$$U_{fc}(t) = N_{fc}^{cell} \cdot U_{fc}^{cell}(t) \tag{2.12}$$

The voltage of a single cell can be modeled as:

$$U_{fc}^{cell}(t) = U_{fc,o}^{cell}(t) - U_{fc,act}^{cell}(t) - U_{fc,ohm}^{cell}(t) - U_{fc,conc}^{cell}(t) \tag{2.13}$$

where $U_{fc,o}^{cell}$ is the reversible potential or "Nernst" voltage, $U_{fc,act}^{cell}(t)$ is the activation overpotencial, $U_{fc,ohm}^{cell}(t)$ is the ohmic overvoltage and $U_{fc,conc}^{cell}$ are the losses due to concentration mass. Hence, the voltage drop is a sum of four terms that can be expressed by the following expressions:

$$U_{fc,o}^{cell}(t) = U_0 + K_{1t}(T_{fc}(t) - T_{fc}^{o}) \tag{2.14}$$

with U_0 the reversible cell potential, K_{1t} is a constant, T_{fc} is the stack temperature and T_{fc}^{o} is the nominal temperature.

The activation losses in the fuel cell can be modeled as a function of two constant coefficients $K_{1,act}$ and $K_{2,act}$ and the current density of the stack i_{fc}

$$U_{fc,act}^{cell}(t) = -K_{1,act} \cdot (1 - e^{-i_{fc}/K_{2,act}}) \tag{2.15}$$

The ohmic losses can be modeled as a function of the equivalent ohmic resistor of the cell R_{ohm} and the stack current I_{fc}:

$$U_{fc,ohm}^{cell}(t) = R_{ohm} \cdot I_{fc}(t) \tag{2.16}$$

The concentration losses can be modeled as a function of two constant coefficients $K_{1,conc}$, $K_{2,conc}$ and the current density of the stack.

$$U_{fc,conc}^{cell}(t) = K_{1,conc} \cdot e^{K_{2,conc} \cdot i_{fc}(t)} \tag{2.17}$$

All these parameters can be introduced in the mask of the block (see Fig. 2.19).

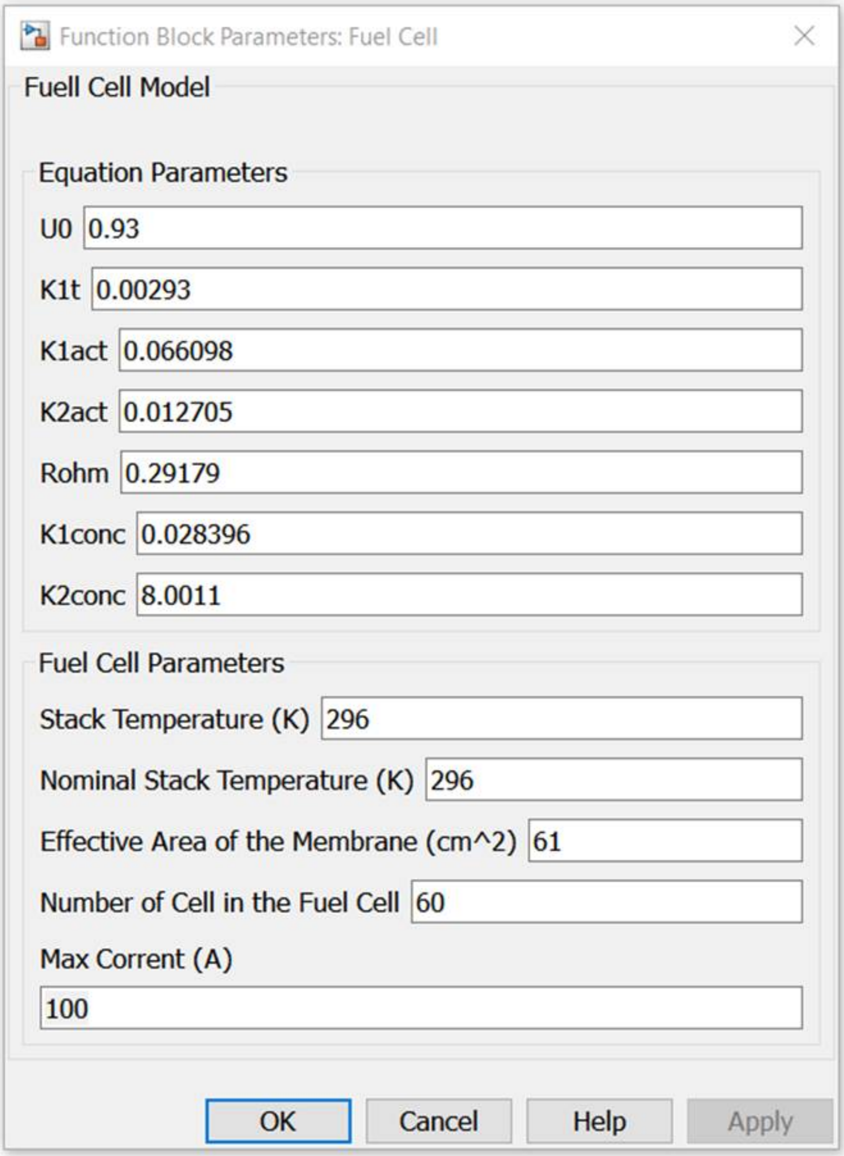

Figure 2.19: Mask of the fuel cell block

Additionally, the effective area of the membrane is needed to obtain the current density and also operational constraint on the stack current.

Inputs		**Units**
1	Power Set-point	watts
Outputs		**Units**
1	Stack Voltage	volts
2	Stack Current	amps
3	Power	watts
4	Hydrogen generation	kg/s

Table 2.5: Inputs and outputs of the Electrolyzer Block

2.9 Electrolyzers

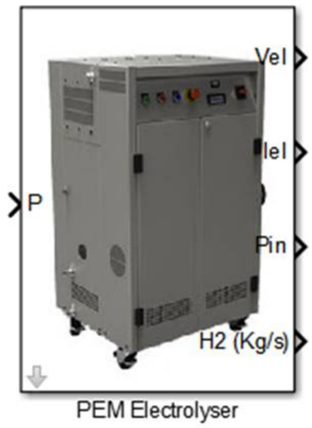

Figure 2.20: Electrolyzer Block

Electrolyzers are electrochemical devices which are able to separate hydrogen and oxygen from water molecules when a direct current is applied.

Inputs and outputs of the block are similar to the fuell cell block, one input, the power set-point computed in the controller, and four output: voltage and current of the electrolyzer, the power that electrolyzer can really apply (set-point limited by constraints), and the generated flow of hydrogen (See Table 2.5).

Mathematical model is a simplification of the equations presented in [1, 5].

The stack voltage of the electrolyzer $U_{elz}(t)$ (V) can be expressed as the product of the number of electrolysis cells N_{elz}^{cell} and the voltage of a single cell U_{elz}^{cell}.

$$U_{elz}(t) = N_{elz}^{cell} \cdot U_{elz}^{cell}(t) \tag{2.18}$$

The voltage of a single cell can be expressed by the following equation:

$$U_{elz}^{cell}(t) = U_{elz,o}^{cell}(t) + U_{elz,act}^{cell}(t) + U_{elz,ohm}^{cell}(t) \tag{2.19}$$

where $U^{cell}_{elz,o}$ is the reversible potential or "Nernst" voltage, $U^{cell}_{elz,act}(t)$ is the activation overpotencial and $U^{cell}_{elz,act}(t)$ is the ohmic overvoltage. Hence, the voltage drop is the sum of he following terms:

$$U^{cell}_{elz,o}(t) = E^o_{elz} + K_{1n}\left(T_{elz}(t) - T^o_{elz}\right) + \frac{2.3 \cdot R \cdot T_{elz}(t)}{4F} \ln\left(p^2_{H_2}(t) \cdot p_{O_2}(t)\right) \tag{2.20}$$

$$U^{cell}_{elz,act}(t) = \frac{R \cdot T_{elz}(t)}{F}\left[\sinh^{-1}\left(\frac{I_{elz}(t)}{2 \cdot A_{elz} \cdot i_{a_o,elz}}\right) + \sinh^{-1}\left(\frac{I_{elz}(t)}{2 \cdot A_{elz} \cdot i_{c_o,elz}}\right)\right] \tag{2.21}$$

$$U^{cell}_{elz,ohm}(t) = R_{ohm} \cdot I_{elz}(t) \tag{2.22}$$

where T_{elz} is the temperature of the electrolyzer, R and F are the known ideal gas and Faraday's constants, p_{O_2}, is the oxygen partial pressure, p_{H_2} is the hydrogen partial pressure, I_{elz} is the electrolyzer current, $i_{ao,elz}$ and $i_{co,elz}$ are the anode and cathode current densities.

Taking into account the reaction produced in the electrolysis stack the hydrogen mass flow can be modeled with the next expression:

$$W^{H_2,pro}_{elz}(t) = N^{cell}_{elz}\frac{I_{elz}(t)}{F} \tag{2.23}$$

The parameters must be introduced in the mask (see Fig. 2.21). Defoult data correspond th the Hylab electrolyzer [1].

2.10 Hydrogen Storage

This block has two inputs: H2_IN, that will be typically connected to the electrolyzer block, and H2_OUT, that must connected to the fuel cell block. The units of both of them are kg/s. The block has only one output, the Level Of hydrogen (LOH) in %.

Two parameters are needed to configure the block: The capacity (in kg) and the initial LOH (%).

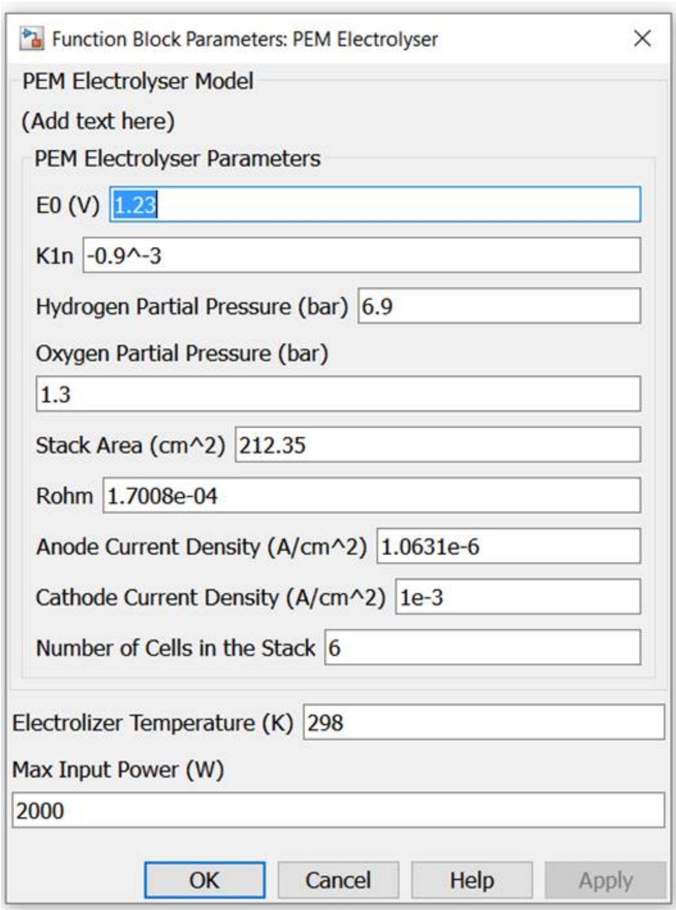

Figure 2.21: Mask of the fuel cell block

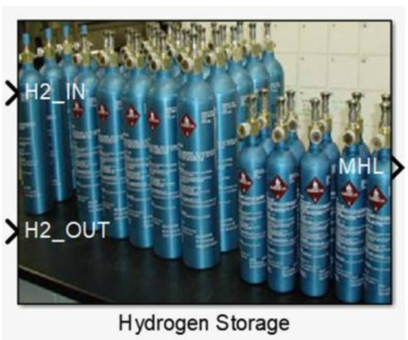

Figure 2.22: Hydrogen Storage Block

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