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Renewable Electricity conversion and storage: Focus on Power to Gas process, EMR modelling and simulation

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Abstract

Nowadays, the world attends an energy transition, which is motivated by the massive use of fossil energies that is at the origin of greenhouse gas emissions, in particular carbon monoxide/dioxide. Therefore, this energy transition promotes the large-scale use of renewable energy sources. The intermittence and the fluctuation of these sources make their integration difficult; this is why the incorporation of energy storage can provide additional beneficial features and aid in its further growth. This paper gives an overview about the electrical energy conversion and storage. A particular attention is paid to Power to Gas.

To perform an optimized sizing of power to gas system, there must be a modeled, which approximates the behavior of the real physical system. To do this multi-physics modeling is required. The macroscopic energy performance will be used in modeling each system component. EMR is a graphical modeling tool that facilitate understanding of the model of the energy chain. EMR modeling approach is a reliable option for real-time energy management of energy system macroscopically.

1. Introduction

All around the world the energy production and consumption model admits its limits. The intensive use of fossil energies has led to increasing greenhouse gas emissions, which enhanced the development and the use of Renewable Energy Sources (RES) and waste recovery at the expense of oil and natural gas. In 2012 [1], oil remains the most solicited source with an average rate of 40.7%. Electricity is the second-largest energy source with an average rate of 18.1%. The renewable electricity production reached 4699.2 Twh per year, exceeding 20% of the total electricity production but fossil fuels remain the core of global production. Even if the RES seem the most adapted solution to overcome the pollution problems, they also have limits. More than their availability problems, the most critical point is the time shift between the power generation and the consumption needs (peak PV production at midday while the peak demand is mainly in the evening) [2], [3]. Therefore, the step of electrical energy storage is compulsory.

The majority of primary energies can be stored easily, however it is very difficult to store electrical energy in large quantities. In this case, the energy storage consists in converting the electrical energy supplied by different sources or power grids into other forms of intermediary energy. The stored energy can be directly used or transformed again into electrical energy to support the power grid when other sources are unable to respond to high demands, when the cost of generation is high or in case of failure of other means of production [4], [5]. The storage duration is limited due to losses associated with Energy Storage systems (ESs).

2. Power to gas process

Against global warming caused by the massive greenhouse emissions, the Power to gas (PtG) appears as a pragmatic solution, which allows valorizing the CO_2.
PtG can be a one-step or two-steps process:
One step: $\text{electrical power} \xrightarrow{\text{Water electrolysis}} \text{Hydrogen (H2)}$
Two steps: $\text{electrical power} \xrightarrow{\text{Water electrolysis}} \text{Hydrogen (H2)} \xrightarrow{\text{Methanation}} \text{Methane (CH4)}$
The one-step process consists in converting electrical power (electricity that can be generated by renewable energy sources) into H_2 by Water Electrolysis (WEL). The two-steps process consists in converting the H_2 produced by the one-step process into CH_4 by methanation process; it consists in combining the H_2 with recovered CO_2. As illustrated by Fig.1, several applications are possible. These produced gases can be used directly or converted into electricity via fuel cells or gas turbines. The efficiency of PtG is 60%-70% [6]. Concerning the discharge phase (conversion from gases to electricity), the losses are higher compared to other electrical energy storage systems. However, the discharge time and storage capacity are the most interesting. Furthermore, it is possible to enhance the performance by recovering the waste heat, which may offers other opportunities of application. Furthermore, the establishment of a methodology for the energy management can also improve the system performance. Several techniques exist for energy management in distributed smart grids such as multi-agents systems or fuzzy logic for example. Therefore, the dynamic model of the system is compulsory because it allows taking into account the transient behavior. Hence, the simulation results will be closest to the real system behavior. In this work, EMR (Energetic Macroscopic Representation) has been used as modelling tool.

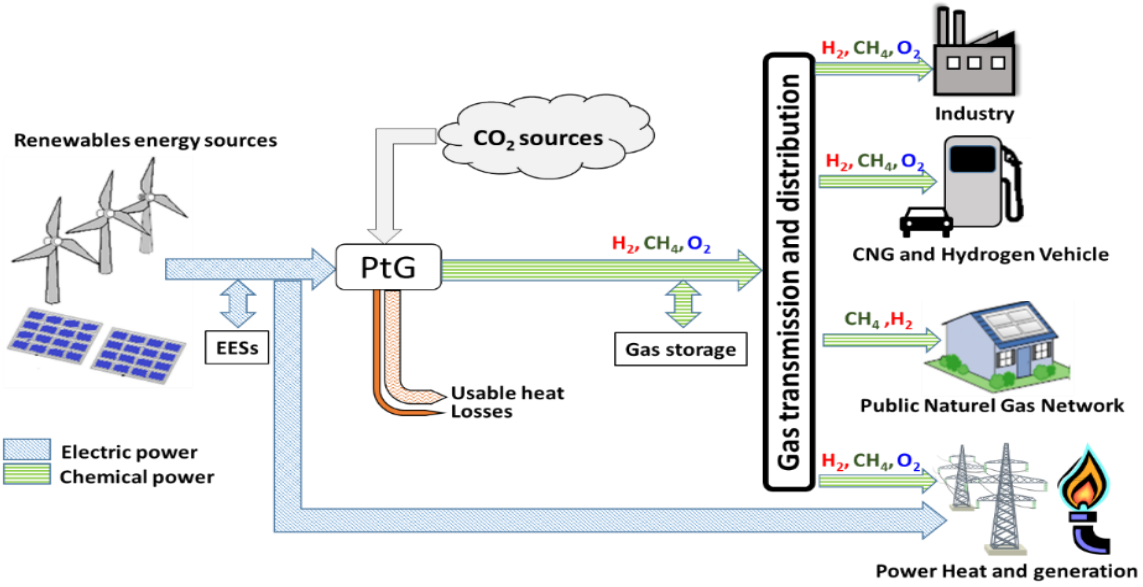

Fig. 1. Power to Gas process and its applications

3. The energetic macroscopic representation EMR

The energetic macroscopic representation is a synthetic representation for complex and multi-physical systems, based on the principle of action and reaction. Considering its control predilection, the EMR admits only the physical causality “integral causality”. It consists of three types of symbols (the source elements, the Multi/Mono physical conversion elements, the accumulation elements, Multi/Mono physical domain coupling device) Fig.2 [7], [8].

It therefore allows following the different steps of conversion undergone by the power supplied to a system. The variables of action / reaction linking each transition between two elements shows the state of the transmitted energetic flow. To simulate the EMR model, we used the EMR library created under Matlab/Simulink. This library is available on the website of EMR [7], [9], [10].

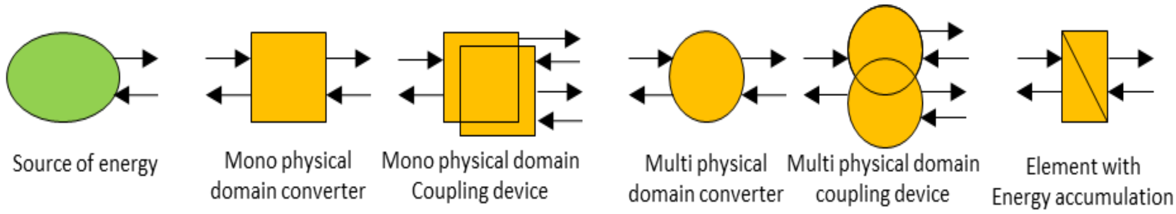

Fig. 2. EMR basic pictograms

In this article, the system to be modeled is a stationary system, which consists in supplying hydrogen to a methanation reactor. This hydrogen is produced by an electrolyzer powered by photovoltaic source. All the generated electricity is converted into hydrogen. Fig.3 is a synoptic of the power to gas system.

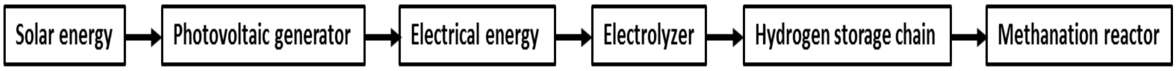

Fig. 3. Synoptic scheme of the system

3.1 Photovoltaic generator

The electricity produced is the result of coupling the thermal and radiometric domains. A dynamic modelling requires the inclusion of these two quantities. In this EMR model, thermal phenomena are involved. As for the radiometric domain, just the intensity of illuminance is represented. For more details of the radiometric modelling, please refer to [7].

The photovoltaic generators is a nonlinear source. For this work, a moderate complexity model is used. The relations describing the photovoltaic system are [7], [11]:

$$I_{PV} = I_L - I_D = I_L - I_{sat}\left[\exp\left(\frac{V_{PV} + IR_S}{nV_T}\right) - 1\right] \tag{1}$$

$$\text{with } V_T = \frac{kT_{PV}}{q} \tag{2}$$

V_{PV} is the output voltage and R_s is the series resistance. n is the ideality factor, k the Boltzmann constant and q is the charge of the electron. I_L is the irradiance current, it can be calculated as:

$$I_L = \left(\frac{E}{E_{ref}}\right)\left[I_{L,ref} + \mu_{I,sc}\left(T_{PV} - T_{PV,ref}\right)\right] \tag{3}$$

E is the solar irradiance and E_{ref} is the solar irradiance at the reference temperature $T_{PV,ref}$ (Temperature in the standard operating conditions). $\mu_{I,sc}$ is the variation coefficient of the short circuit current which depends on the temperature.

All the constants in the above equations could be determined using the photovoltaic panel datasheet and data from the characteristics curves. A portion of the solar radiation received by the module is converted into electricity, while the rest is dissipated in the module environment as heat [7], [12], [13], [14]. The dynamic of thermal activity within the module can assess the time course of the module temperature. To do this, all input and output heat flows of the module are considered such as:

$$C_{PV}\frac{dT_{PV}}{dt}=\sum \dot{Q}_{in}-\sum \dot{Q}_{out} \tag{4}$$

C_{PV} is the thermal capacity of the module, $\dot{Q}_{in}$ and $\dot{Q}_{out}$ are respectively the input and output heat flows. The main source of input thermal energy is the one from the solar irradiance. It may be expressed as follows:

$$\dot{Q}_{in}=S_{PV}E(1-\eta_{PV}) \tag{5}$$

S_{PV} is the module surface and η_{PV} is the module efficiency. We can consider the exchange of heat flow between the module and the environment as a convective flow, such as [15]:

$$\dot{Q}_{env/PV}=\frac{1}{R_{env/PV}}(T_{PV}-T_{amb}) \tag{6}$$

$R_{env/PV}$ is the thermal resistance and T_{amb} is the ambient temperature. The convective heat loss is calculated as [12]–[20]:

$$R_{env/PV}=\frac{1}{hS_{PV}} \tag{7}$$

Considering the thermal inertia, the module can be seen as a heat accumulation element. In order to calculate the thermal capacity, the module is considered as three layers of material. A flat sheet of PV cells laminated within a Polyester / Tedlar trilaminate, behind a glass face. The heat capacity of the module is the sum of the capacities of the three layers of material [12]–[25]:

$$C_{PV}=\sum_{PV} S_{PV}.d_{PV}\,.\rho_{PV}.c_{PV} \tag{8}$$

d_{PV},ρ_{PV}, c_{PV} are respectively the dimension, the density and the heat capacity of each photovoltaic module.

The photovoltaic generator is not connected directly to the DC bus because of the fluctuation of the produced electricity. Therefore, the addition of an CL filter is necessary. This filter is represented by the following equations:

$$I_{PV}-I_l=C\frac{dV_{PV}}{dt} \tag{9}$$

$$V_{PV}-U_l=\ L\frac{dI_l}{dt}+ri_l \tag{10}$$

An MPPT (maximum power point tracking) algorithm controls the DC-DC converter at the output of photovoltaic generator.

3.2 Hydrogen production unit

A PEM (Proton exchange membrane) electrolyzer provides the production of hydrogen, the electrolysis of water decompose it into H2 and O2 molecule. This method of producing hydrogen is considered as the cleanest method with 98% of gas purity at output. To ensure electrochemical reaction, a DC voltage is applied at both electrodes. The electrolyzer uses a part of this electrical energy to overcome potential of the Gibbs free energy. During this operation, heat is generated due to various losses. In this article, the electrolyzer will be represented by a simple EMR model. For a complete study of the PEM electrolyzer please refer to [10]. The equations used are [26]–[34] :

$$V_{EL} = E + V(I_{EL}) \tag{11}$$

V_{EL} is the DC voltage applied at both electrodes, E is the voltage that is assigned to the free energy of Gibbs. $V(I_{EL})$ Represents the sum of the overvoltage, which are related to the current I_{EL} that crosses the electrolyser. Regarding the thermal model, a total energy balance is established and which is expressed by the equation:

$$C_{EL}\frac{dT_{EL}}{dt} = \dot{Q}_{th} - \dot{Q}_{EL/env} - \dot{Q}_{EL/water} \tag{12}$$

$\dot{Q}_{th}$ is the thermal power generated by the reaction, $\dot{Q}_{EL/env}$ and $\dot{Q}_{EL/water}$ are respectively the exchanged flow with the external environment and exchanged flux with the feed water.

3.3 Hydrogen storage system

The produced hydrogen is intended to supply methanation reactor. For the system stability, an intermediate storage step is necessary. For this power to gas, the storage by compression is chosen because it is currently the most simple, the most used and the most effective for storing hydrogen until 200 bars.

The moto-compressor is constituted by a compression stage driven by an electric motor (permanent magnet motor). The EMR model of moto- compressor that comprises two parts, one part for the electric motor and a part for the compression stage, which is quasi-static. The equation, which links between these two parts is [9]:

$$P_{Mec} = \frac{P_{mec}}{\Omega_{shaft}}\,\dot{m}_{in}\,C_p\,T_{in}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} - 1\right) \tag{13}$$

P_{mec} is the mechanical power of the moto-compressor, Ω_{shaft} is the drive speed and C_p is the Thermal capacity of the hydrogen.

In order to maintain the pressure stable within the storage system, the use of a pressure regulator is required. The regulator ensures the control of the pressure based on a reference pressure. Regarding the tank, it is characterized by the following equation [9]:

$$\dot{m}_{BT}(t_0 + \Delta t) = \int_0^{t_0+\Delta t} \dot{m}_{BT}(\tau)\,d(\tau) + \dot{m}_{BT}(t_0) \tag{14}$$

Fig.4 is the EMR model of the whole system. In this paper, the methanation reactor is considered as a load.

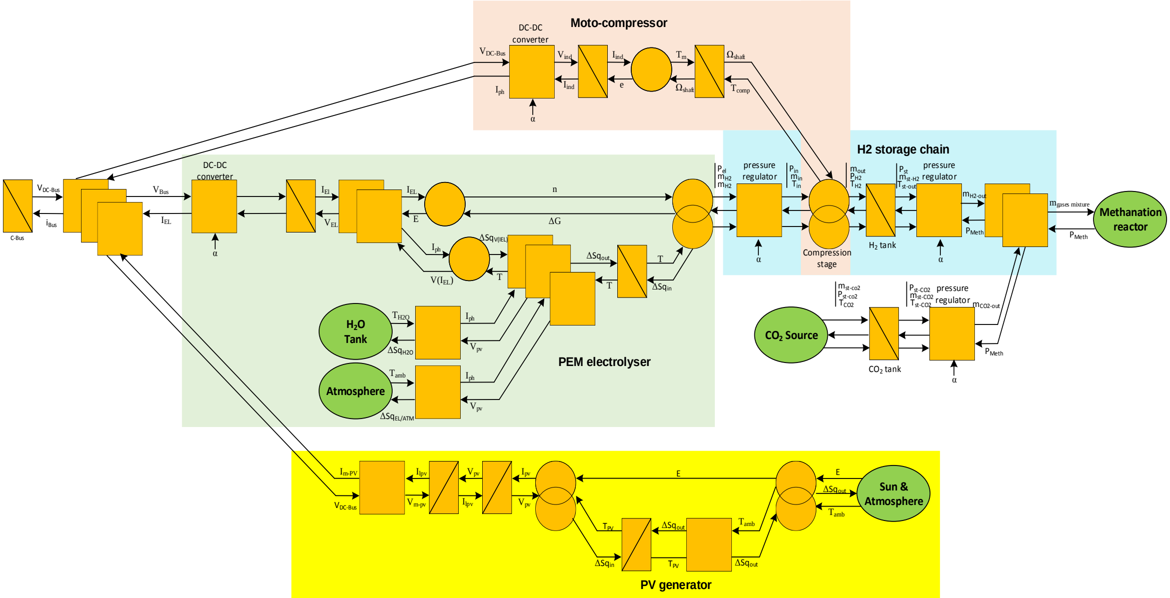

Fig. 4. EMR of the whole system

4. Simulation results of EMR model

Fig.5 illustrates the simulation results of a PV module made by BP Solar (BP485). It also shows the influence of irradiance and temperature on the electrical parameters of the module. The module power curve shows that the use of a control algorithm is required to obtain the optimal point.

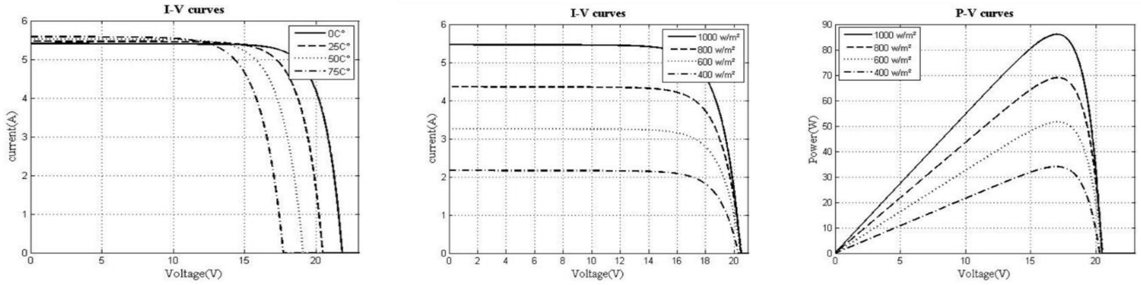

Fig. 5. Photovoltaic module

Fig. 6 illustrates the dynamic behavior of the PEM electrolyzer which is composed by 10 stacks. The electrolyzer is powered by a current of 10 A during 4000 seconds. For the same current and different values of temperature, the stacks voltage decreases when the temperature increases.

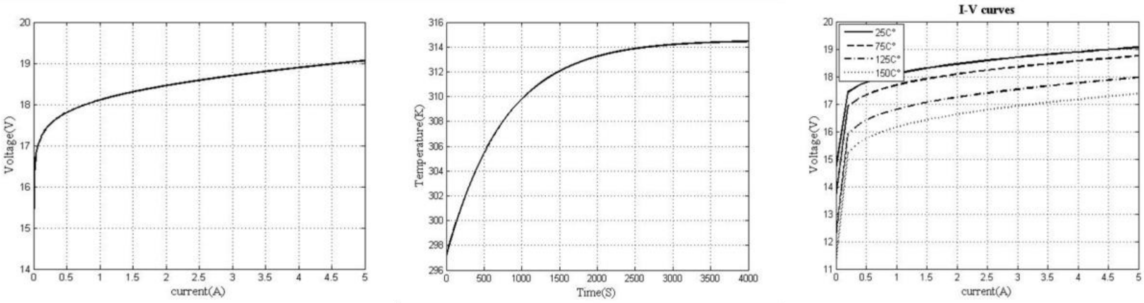

Fig. 6. Electrical curves and temperature behavior of PEM electrolyzer

5. Conclusion

This paper gives a short overview about the electrical energy conversion and storage, and then focus on power to gas (PtG) process. This process has been analyzed and modelled using the Energetic Macroscopic Representation. The EMR modelling approach is useful and provides in this work an adaptable model. Regarding the photovoltaic model, the interaction between temperature and electrical parameters allowed to obtain simulation results similar to the real photovoltaic module behavior. This modeling approach will allows us to develop a strategy for the energy management of the whole system. This strategy will be based on the technique of multi-agent systems and will be presented in a future paper.

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