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Using a flywheel associated to PV power plant in order to increase the integration of PV into island electrical grid

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Abstract. In a context where renewable energies from both wind and solar energy have low predictability, low controllability and strong variability, their massive integration into power systems may cause instabilities for these grids. The use of storage energy system is a promising solution. In the present article, we propose to focus on a detailed photovoltaic model in order to test flywheel energy storage system (FESS) models. FESS is used to smooth photovoltaic energy for power quality. A 17-kW photovoltaic grid connected power plant is modelled with Matlab/Simulink/SimPowerSystems.

Key words

Flywheel, storage, photovoltaic, smoothing, microgrid

1. Introduction

Most of islands are in the world highly dependent on importation of fossil fuel for energy. Due to the tourist attraction, during summer period, the total number of inhabitants is multiplied by around three in Corsica. Generally, tourism is a very important source of income for island territories. This parameter has to be taken into consideration in energy production and quality. During summer period, the solar energy resource increases and may contribute to the risk of instability of the grid. Indeed, photovoltaic energy (as wind and swell energy) is an intermittent energy. Its massive deployment on electrical grid may cause instability. Moreover, a limit of 30% on the grid has been fixed by a French regulation. This technical problem is a limitation to the development of these “fatal” energies, and hence to energy autonomy. The limit of 30% has been reached in Corsica since May 2012 [1].

The regulatory framework in the different countries around the world is evolving quickly and we could see, in the next months/years, the adoption of different technical constraints that impose to smooth and/or control the production. These probable regulatory frameworks tend to encourage the integration of Energy storage systems (ESS) into power systems at the power plant location in order to provide such a control of the production.
First studies on the subject have shown a strong interest for powerful energy storage systems with discharge duration between 1 hour and 15 min for coupling an energy storage system with renewable energy sources such as PV or Wind. Among the different ESS, the flywheel technology appears to be well scaled for such an application [2]-[3]-[4].
In the same time, an ESS at the power plant location may offer the opportunity to use it for ancillary services. Among the different services, frequency/voltage regulation and power quality services appear to be interesting in terms of potential revenue and may be consider as such.

Flywheel Energy Storage Systems (FESS) are competitive with chemical batteries in applications like transportation or improving power quality, which involve many charge-discharge cycles and little in the way of long-term storage. Particularly, FESS can be used to smooth the photovoltaic energy production. Photovoltaic energy can vary a lot on an island, where the weather can change very quickly. A smart grid, called PAGLIA ORBA, with photovoltaic generation, with energy storage system and with real loads (offices and accommodations), is on the way to be built in Corsica (Ajaccio). Particularly, the microgrid will have a 3-phase 17-kW photovoltaic power plant and a 3-phase 15-kW/300-kWsecond FESS.

With the 15-kW FESS, we would like to test these applications on the real system. The FESS is controlled in real time with a close-loop. Hardware-in-the-Loop simulation is needed to develop the control algorithm and to optimize these different factors: cost, duration, safety and feasibility.

First, the state-of-the-art of the coupling between a PV system and a FESS is given. Then, the simulation results of a PV system model are shown. At the end, a description of flywheel energy storage systems is handled.

2. State-of-the-Art

With large integration of photovoltaic energy in a grid of an island such as Corsica, stability of the electrical network becomes an important issue. Some researches were made on one hand about the coupling of photovoltaic power plant and storage systems, and on the other hand about the forecasting of photovoltaic energy production.

The possibility of the photovoltaic energy smoothing was examined by an Asian researcher group [4]. They used Electric Double Layer Capacitor (EDLC) and Flywheel system to "suppress the power variation".

In the context of microgrid, in this paper [5], the stability of a microgrid was studied in islanded mode and grid-connected mode with a flywheel. According to the mode, either PQ control (fixed active and reactive power control) or Droop control or Frequency/Voltage are used. Simulation results show how the flywheel uses PQ control only when the MicroGrid is operated in grid-connected mode. During islanded mode, the control scheme of the flywheel has to be switched from PQ control to Droop control or Frequency/Voltage.

Forecasting researches have been done both in photovoltaic production side [6]-[7]-[8]-[9]-[10]-[11]-[12]-[13]-[12] and load side [14].

3. Photovoltaic (PV) power plant

A. The SimPowerSystems detailed model

A detailed model of the 17-kW_{AC} photovoltaic power plant, located in Ajaccio is proposed here. The photovoltaic system is connected the island electrical grid. The toolbox SimPowerSystems is a toolbox of Matlab/Simulink for power applications. This tool fits well for the photovoltaic modeling.
The diode characteristic is given as [15]:

$$I_d = I_S \left(\exp\left(\frac{qVQ_d N_{scell} N_s}{kT_c}\right) - 1 \right) \tag{1}$$

Where:
I_s: diode saturation current (A)
I_d: diode current (A)
T_c: cell's working temperature (K)
k: Boltzman constant = $1.3806e^{-23}$ J.K-1
q: electron charge = $1.6022e^{-19}$ C
Q_d: diode quality factor
N_{scell}: number of series-connected cells per module
N_s: number of series-connected modules per string

This cell model is used for Maximum Power Point Tracking (MPPT). The MPPT is necessary to draw the maximum power from the PV module. There are many algorithms used to find the maximum power point (MPP) [16].
The incremental conductance algorithm is chosen. The advantage is that the derivative of the power with respect to the voltage at the MPP is zero, the derivative at the left of the MPP is positive and negative at the right.

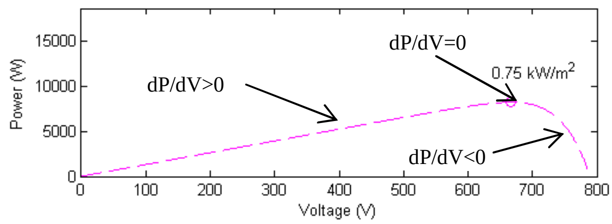

Figure 1: P-V Characteristics at 25°C

The power at the output of the PV array is:

$$P = VI \tag{2}$$

The incremental conductance algorithm is based on the differentiation the PV array power versus voltage curve:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} \tag{3}$$

The MPP will be found when:

$$\frac{dP}{dV} = 0 \tag{4}$$

$$-\frac{I}{V} = \frac{dI}{dV} \tag{5}$$

I/V represents the instantaneous conductance of the PV array and dI/dV is the instantaneous change in conductance.

By varying the duty cycle of the DC/DC converter inside the PV inverter, the point of operation of the PV array is modified. In our study, the SMA Sunny Tripower 17000TL inverter is used. This inverter has two DC inputs. On the first input there are three parallel strings. Each string has twenty one Tenesol series-connected modules (see the following table for the module specifications). On the second input, there are seventeen Tenesol series-connected modules. The total DC power is 19 600 Wp. The modules are tilted by 30 ° and directed southward.

Fig. 2 gives a view of the PV power plant SimPowerSystems.

Characteristics	Specifications
Typical peak power (P_p)	245 W
Voltage at peak power (V_{pp})	29.8 V
Current at peak power (I_{pp})	8.3 A
Short-circuit current (I_{sc})	8.7 A
Open-circuit voltage (V_{OC})	37.4 V
Temperature coefficient of open-circuit voltage	-266.4 mV/°C
Temperature coefficient of short-circuit current	1.837 mA/°C
Maximum power temperature coefficient	-1.075 W/°C
Diode quality factor (Q_d)	1.2
Diode Saturation current (I_{sat})	$6.3567e^{-9}$ A
Light-generated phot-current (I_{ph})	5.8683 A
Series resistance (R_s)	0.12264 Ω
Parallel resistance (R_p)	859.93 Ω

Table 1: Tenesol TE2200 specifications (1kW/m², 25°C, Am 1.5)

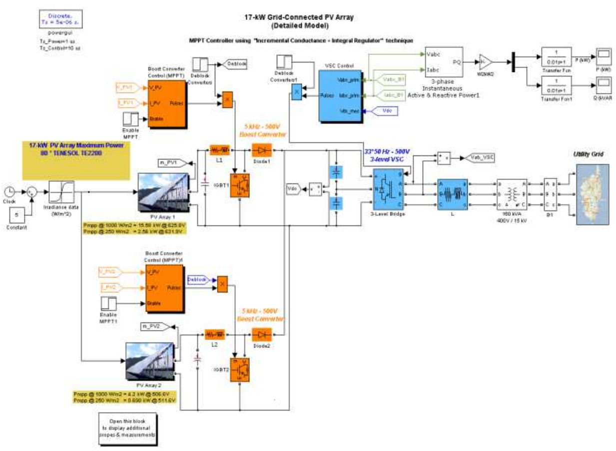

Fig. 2: SimPowerSystems model of the 17-kW Photovoltaic power plant

B. The simulation results

The PV production of two different days is simulated (1st August and 17th September 2012). The data at the model input are irradiation data from a pyranometer tilted by 30° and directed southward (one-minute time step).

The simulation results depend on the simulation stop time which can be set in Simulink. The bigger is the stop time, the better are the simulation results (Fig. 3 and Fig. 4). The elapsed time can be measured by using the commands tic and toc of Matlab.

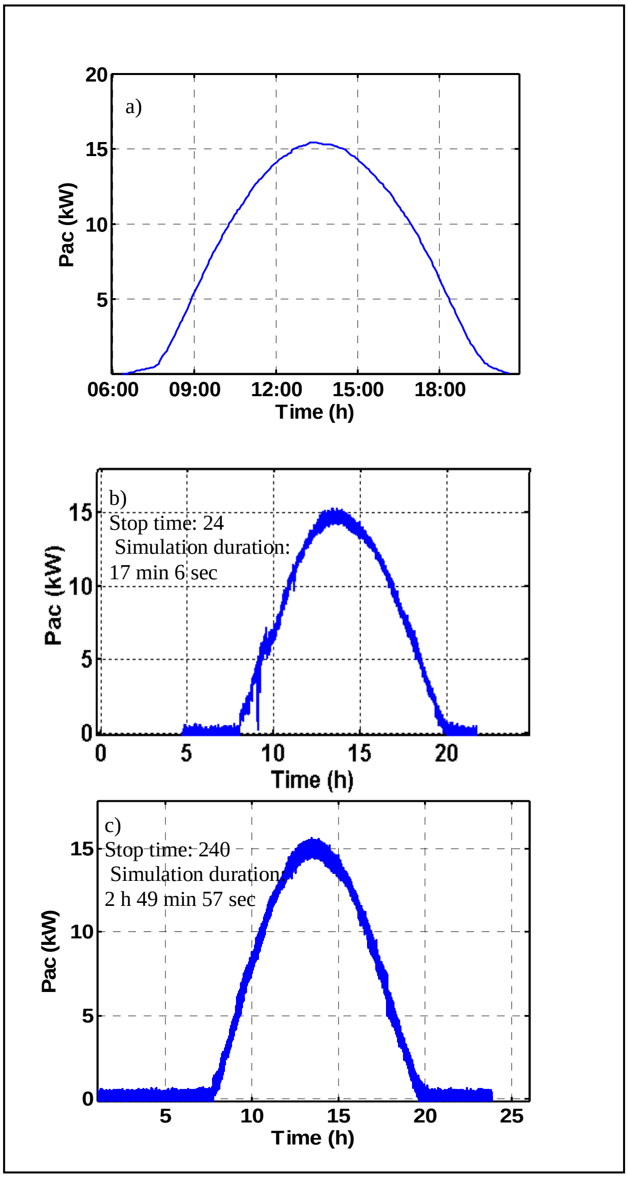

Fig. 3: a) Output of the real 17-kW_{AC} Photovoltaic power plant
b) Simulation of the PV output (Stop time: 24)
c) Simulation of the PV output (Stop time: 240)
1st August 2012 (Ajaccio, Corsica)

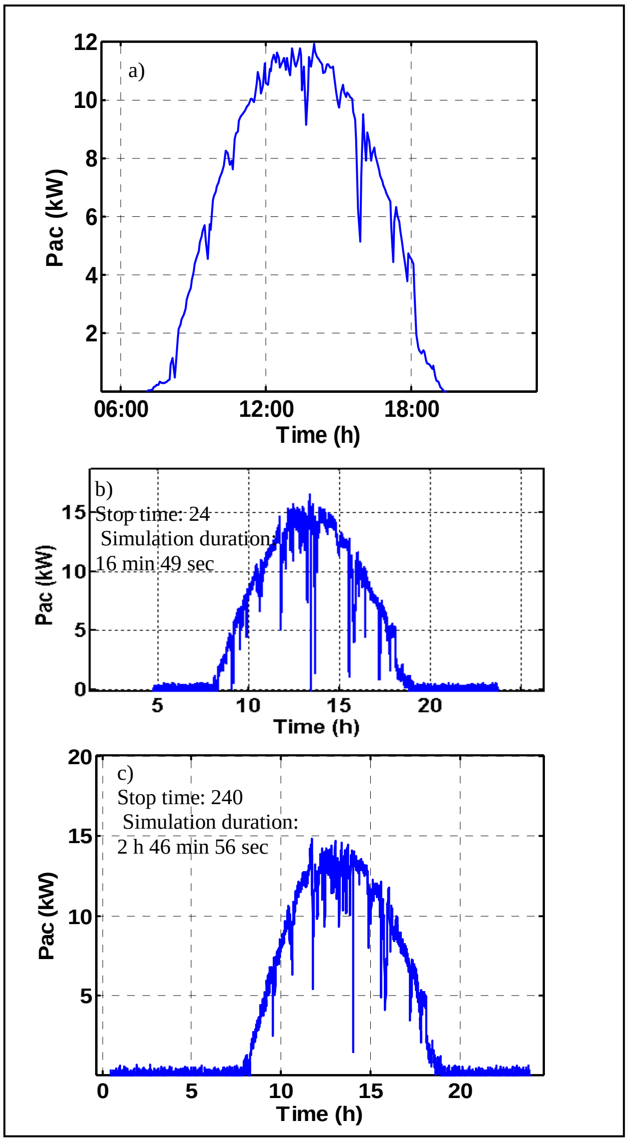

Fig. 4: a) Output of the real 17-kW$_{AC}$ Photovoltaic power plant
b) Simulation of the PV output (Stop time: 24)
c) Simulation of the PV output (Stop time: 240)
19th September 2012 (Ajaccio, Corsica)

4. Flywheel Energy Storage System

Flywheel Energy Storage Systems (FESS) store kinetic energy in a rotating mass (rotor). Depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. Kinetic energy is transferred in and out of the flywheel with an electrical machine that can function either as a motor or generator. When acting as motor, electric energy supplied to the stator winding is converted to torque and applied to the rotor, causing it to spin faster and gain kinetic energy. In generator mode kinetic energy stored in the rotor applies a torque, which is converted to electric energy.
Fig. 5 shows the basic layout of a flywheel energy storage system. For high speed flywheel (speed > 10 000 rpm), inside the containment, there is vacuum (or very low pressure).

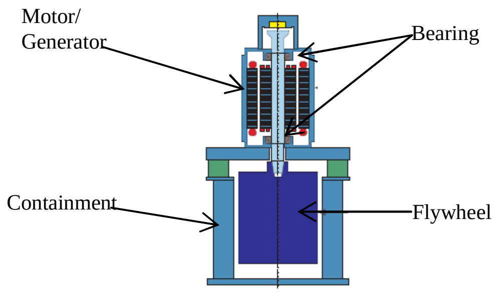

Fig. 5: Basic layout of a flywheel energy storage system [17]

Power electronics is required for the connection to the grid and to control the electrical machine of the FESS: control of the power in- and output, the speed, the frequency (see Fig. 6).

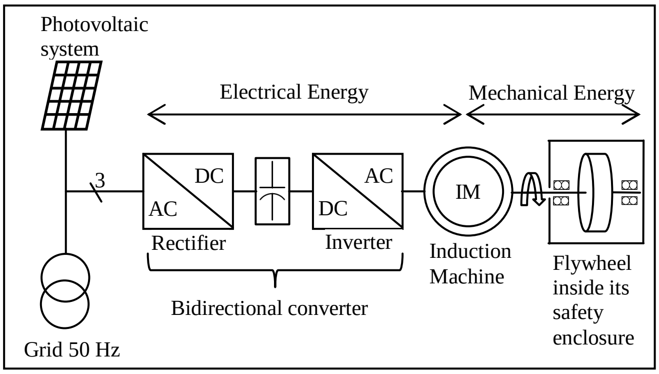

Fig. 6: A FESS connected to the grid and to a photovoltaic system

The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed according to the equation (2):

$$W_{max} = \frac{1}{2}.J.\Omega_{max}{}^{2} \qquad (6)$$

J: Flywheel moment of inertia (in kg.m²)
Ω: Flywheel speed (in rad.s^{-1})

In reality, a FESS works between a maximal speed, limited by the mechanical capacities of the rotating cylinder, and a minimal speed below which the energy recovery loses its efficiency. Thus, the recoverable energy becomes:

$$W_c = \frac{1}{2}.J.(\Omega_{max} - \Omega_{min})^2 \qquad (7)$$

5. Conclusion

Simulating the PV system outputs (AC voltages and currents) allows testing FESS models and the control laws of the FESS in off-line mode. Once the control laws are validated, it can be tested on the real FESS. The optimum stop time of the simulation must be found in order to have the best results and the smallest simulation duration. High irradiation data frequency (one-second time step) can be used to study the dynamic behavior of the FESS.

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