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Characterization and Control of Supercapacitors Bank for Stand-Alone Photovoltaic Energy

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Abstract

In this paper, a simple scheme of the supercapacitor based on (RC) circuit is modeled and characterized using experimental methods. Then, computer simulations and experimental results showed very good agreement which demonstrates the accuracy of the adopted model. An example of hybrid photovoltaic/supercapacitor stand-alone system is considered in this paper. Dynamic model of photovoltaic system component is developed and validated with experimental results. In addition, the maximum power point tracking (MPPT) control for photovoltaic and the supercapacitor state of charge (SOC) control are also addressed in this work. Based on the dynamic component models, a simulation model for the considered hybrid energy system has been developed using MATLAB/Simulink. The simulation results show the primary role of the supercapacitor when the load changes rapidly.

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1. Introduction

A growing interest in renewable energy resources has been observed for several years. The alternative energy sources are non-polluting, free in their availability and continuous. These facts make the alternative energy resources attractive in rural or energy deficient areas where the cost of connection to the grid in remote locations cannot be justified [1]. Today, the most developed source of alternative energy systems are: the solar energy and the wind energy.

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Nomenclature

ESR	equivalent series resistance
L_{pv}	boost converter filter inductance
C	bus filter capacitance
L_{sc}	bidirectional converter filter inductance
V_{mpp}	voltage at maximum power point
I_{mpp}	current at maximum power point
V_{oc}	open circuit voltage
I_{sc}	short circuit current
P_{pv}	photovoltaic power
P_{bus}	load power
P_{sc}	supercapacitor power
V_{semax}	supercapacitor maximum voltage
SOC_r	supercapacitor state of charge reference
n_{bb}	bidirectional dc-dc convertor efficiency
D	duty ratio
D_r	reference duty ratio
i_{scr}	supercapacitor reference current
$v_{L,pv}$	boost converter filter inductance voltage
mes	measure value
ref	reference value

However, these renewable energy sources suffer from some deficiencies when used as stand-alone energy sources. The natural intermittent properties of wind speed and sunlight causes power fluctuations in wind turbine and photovoltaic panel systems. In addition it is difficult to store the power generated by wind turbines and photovoltaic panels for future use [2,3]. For these reasons, energy storage is required to manage the power flow and to maintain system instantaneous power balance. Generally, the energy storage systems in stand-alone renewable sources can be batteries or supercapacitors.

In comparison to standard batteries, the energy density of super-capacitors is lower by an average factor of 10. However, their energy density is compatible with a large range of power applications that need high instantaneous power during short periods of time. Another advantage in the use of super-capacitors rather than batteries is their life time and their number of cycles, which is at least 500 times more than that of standard batteries [4]. In addition super-capacitors are electrical energy storage devices that offer significantly better energy densities than conventional capacitors and can be constructed in

modular and/or stackable format [5–9]. The charge and discharge times of a super-capacitor varies from fractions of a second to several minutes while providing maintenance free operation. Super-capacitors provide the lowest cost per farad, extremely high cycling capability and are environmentally safe.

This paper is dedicated mainly to characterize the supercapacitors bank. Then, the simple model of supercapacitor called RC model is considered. An experimental test of the supercapacitors bank is performed and the results are discussed. An example of photovoltaic (PV)/supercapacitor (SC) hybrid system is considered in this paper. Then, the modeling and control of this system is represented. Dynamic models for the main system components, namely, PV energy conversion system and supercapacitors bank, are developed and validated by experimental results. The maximum power point tracking (MPPT) control for the PV system, and the state of charge control for the supercapacitor, are also addressed in this work. Based on the dynamic component models, a simulation model for the proposed hybrid system has been developed using MATLAB/Simulink. The overall power management strategy for coordinating the power flows among the two energy sources is discussed. Simulation studies have been carried out to verify the system performance under load and weather variation profiles. The results show that the overall power management strategy is efficient and the power flows among the different energy sources and the load demand is balanced successfully.

2. Supercapacitor modeling and characterization

Many models of the supercapacitors are proposed in the literature [10], the model developed by Zubieta and Bonert [11] can be used. This model takes into account a non-linear equivalent capacitance (C_o and C_u), a leakage resistor (R_l), a series resistor (R_s), and relaxation phenomenon ($R_1, C_1; R_2, C_2; \dots; R_n, C_n$). This model is known by its accuracy. However its implementation in Matlab/simulink software necessitates a very long time period which makes it impossible to apply. In this paper, the characterization of the supercapacitor is based on a simplified RC model, its consists of a non linear capacitance $C(v_{sc})$, an equivalent series resistance (ESR) and a rated capacitance C_{cd} , as shown in Fig. 1. This simplified model is suitable for applications where the energy stored in the capacitor is of a primary importance [10-11].

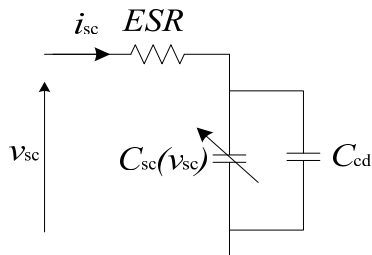


Fig. 1. Simplified RC circuit of the supercapacitor

The schematic diagram bench used to identify the parameters of the supercapacitor is showed in Fig. 2. The diagram is composed of a bidirectional dc-dc converter with its smoothing inductance, Maxwell BOOSTCAP units (BMOD Series), and a dSPACE 1103 card. The supercapacitor use non-water soluble electrolyte technology. The energy storage bank is composed of a branch with 7 supercapacitors under 105 V with a resistive balancing. According to the manufacturer's information, the branch of supercapacitors composes an 8.3 F – 105 V supercapacitor based energy storage unit. The configuration of the characterization bench system was implemented in the CRTT laboratory (Saint-Nazaire, France). The current and voltage sensors are used to measure the super-capacitor voltages and currents.

In this paper, the constant current tests method is used to determine the supercapacitor branch parameters. Constant current tests represent a basic and a widely used characterization method that is useful to determine the rated capacitance and the equivalent series resistance (*ESR*). Then, these parameters can be determined for charge or discharge and for different current levels and ambient temperatures [12].

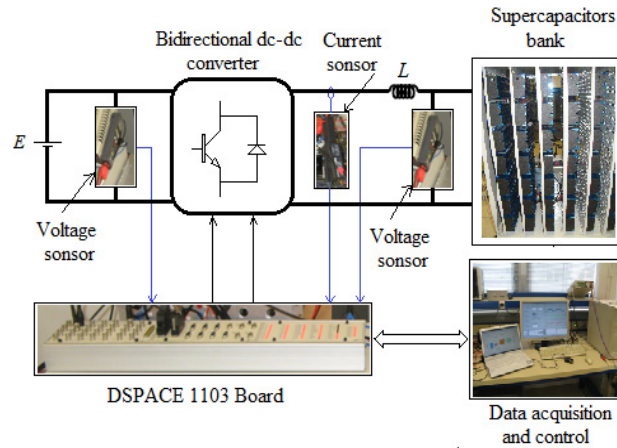


Fig. 2. Characterization bench

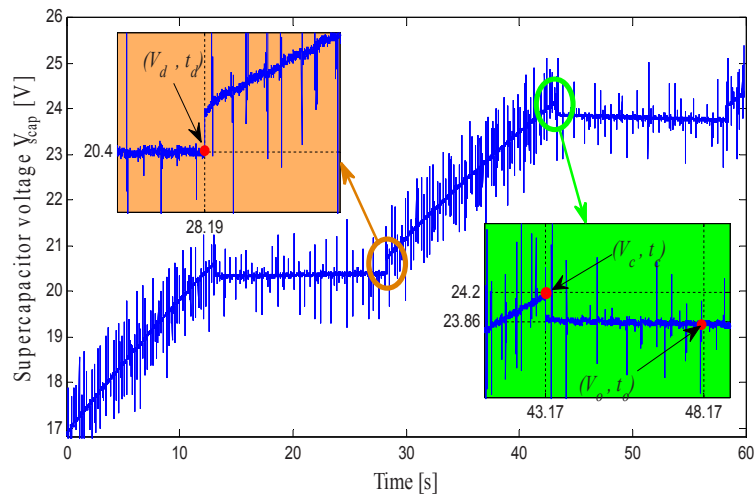


Fig. 3. Experimental response voltage cycles to 2 A test charge constant current.

This method is based on a succession of cycles, each made of a constant current charge from (V_d) up to (V_c) separated by a rest period ($t_d - t_c = 5$ s) during which the open-circuit voltage (V_o) is measured. Therefore, the use of Eqs. (1) and (2) allows for the calculation of the averaged rated capacitance (C_{cd}) and the averaged equivalent series resistance using the parameters showing in Fig. 3. This figure illustrates the evolution of the supercapacitor voltage measured at current switch-off after 2A constant current charge with an ambient temperature of 25 °C. This method allows the determination of averaged resistance (*ESR*) and averaged rated capacitance C_{cd} . Their values are given in Table.1.

$$ESR = \frac{1}{n \times I_{sc}} \sum_{i=0}^n V_{c_i} - V_{o_i} \tag{1}$$

$$C_{cd} = \frac{I_{sc}}{n} \sum_{i=0}^n \frac{tc_i - td_i}{V_{o_i} - V_{d_i}} \tag{2}$$

$$C(V_{sc}) = \frac{I_{sc}}{\frac{dV_{sc}}{dt}} \tag{3}$$

Fig. 4 shows the linear dependency of capacitance with voltage; the slope of the capacitance versus voltage curve is about 0.95 F V^{-1} . The effect of the non-linearity is taken into account in the model of the supercapacitor. Fig. 5 illustrates the evolution of the simplified model voltage compared to the measured voltage at 2 A constant current charge and discharge. The two sets of results give a good fit apart from the noise observed on the experimental voltage.

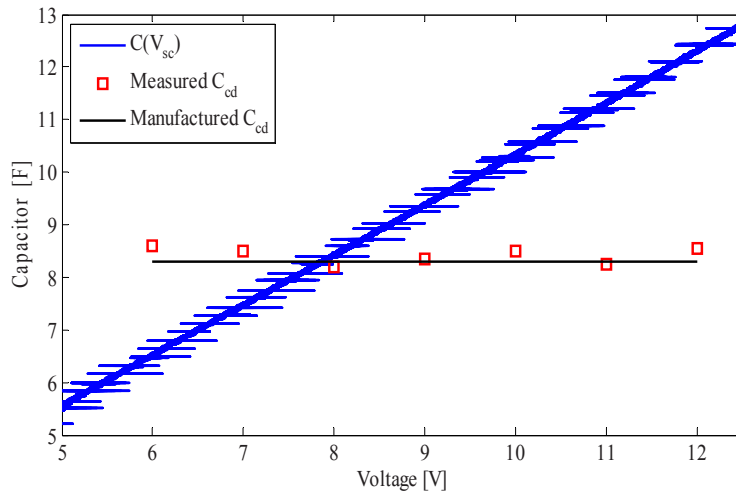


Fig. 4. Linear dependency capacitance with voltage and measured rated capacitance.

Table 1. Supercapacitor parameters

Parameters	Manufactured	Characterized
C_{cd} [F]	8.3	8.66
ESR [Ω]	0.15	0.17
K [F.V^{-1}]	-	0.95

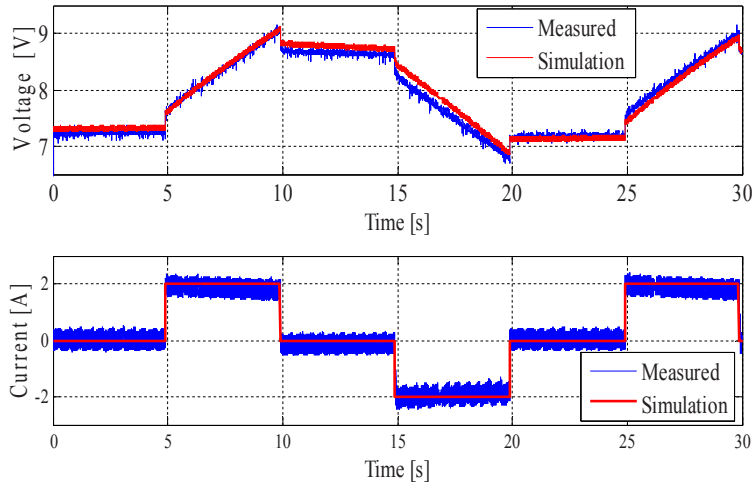


Fig. 5. Experimental and simulated responses of the supercapacitor branch.

3. Photovoltaic model

The most commonly used model for a PV cell is the one-diode equivalent circuit as shown in Fig. 6 [13, 14]. Since the shunt resistance R_{sh} is large, it normally can be neglected. The five parameters model shown in Fig. 6(a) can therefore be simplified into that shown in Fig. 6(b).

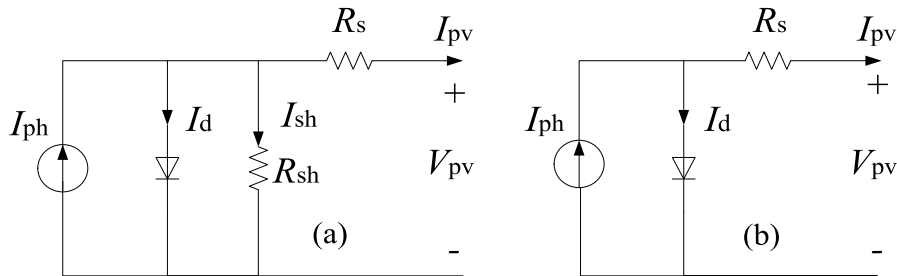


Fig. 6. One-diode equivalent circuit model for PV cell.

(a) five parameters model; (b) simplified four parameters model.

This simplified equivalent circuit model is used in this study. The PV cell model is generally represented by the following expressions

$$I_{pv} = I_{ph} - I_d \tag{4}$$

$$I_d = I_0 \left[\exp\left(\frac{V_{pv} - R_s I}{V_t}\right) - 1 \right] \tag{5}$$

$$I_{ph} = G / G_{ref} \left[I_{ph,ref} + \lambda_I (T_c - T_{c,ref}) \right] \tag{6}$$

Where I_{ph} is the light current, I_{pv} is the load current and I_0 is the saturation current. The V_{pv} is the output voltage, R_s is the series resistance, the V_t is the thermal voltage, G is the irradiation, T_c is the cell temperature and λ_l is the temperature coefficient. The main PV parameters are shown in Table.2.

Table 2. PV panel parameters

Parameters	Characterized
V_{mp} (V)	17.1
I_{mp} (A)	4.70
V_{oc} (V)	21.9
I_{sc} (A)	4.97
P_{max} (W)	80.0

4. Hybrid system control

In this section, a hybrid stand-alone PV/supercapacitor power generation systems is investigated. The system is controlled in a way that during a load transient the PV provides the steady-state load, and the supercapacitor will supply the transient load. The supercapacitor SOC is controlled to remain within a desired range. Meanwhile, the PV output power is controlled by MPPT device. The dynamic models for PV and supercapacitor, discussed in sections 2 and 3, are used in this section for simulation study. Fig. 7 shows the schematic diagram for the proposed PV and supercapacitor power generation system.

In order to allow the PV panel and the supercapacitor work efficiently, both the PV panel and the supercapacitor are connected to the DC bus through a converter, where a boost dc-dc converter is used for PV system to implement the MPPT technique and a bidirectional dc-dc converter is used to control the supercapacitor SOC.

The supercapacitor is allows operates at charge and discharge mode in different scenarios. Like the PV, the rating voltage of the supercapacitor is generally lower than the dc bus voltage. Or it's expected to be lower so that the volume and size of the supercapacitor can be made smaller and the costs are reduced. So when the power is transferred from the high-voltage dc bus to the low-voltage supercapacitor, a buck converter is demanded. When the power is delivered from the supercapacitor to the dc bus, the voltage is step up, and a boost converter is needed.

4.1. Supercapacitor control

The supercapacitor operating voltage can be maintained within a band by appropriate sizing of the supercapacitor and enforcing upper and lower bounds on the SOC. The rate of change in supercapacitor state of charge is proportional to the charging current i_{sc}

$$\frac{d}{dt} SOC = \frac{1}{C_{sc} V_{scmax}} i_{sc} \quad (7)$$

The power demand of the load is satisfied by sharing the current load demand between the photovoltaic panel and the supercapacitor energy storage system. In steady state, the current delivered by the bidirectional dc-dc converter from the supercapacitor can be expressed as [15]

$$i_{sc_b} = \frac{v_{sc}}{v_{pv}n_{bb}}i_{sc} = i_{bus} - i_{pv} \tag{8}$$

Thus, the reference of the supercapacitors SOC_r can be estimated using the following equation

$$\frac{d}{dt}SOC_r = \frac{v_{pv}n_{bb}}{C_{sc} V_{sc\max}V_{sc}}(i_{bus} - i_{pv}) \tag{9}$$

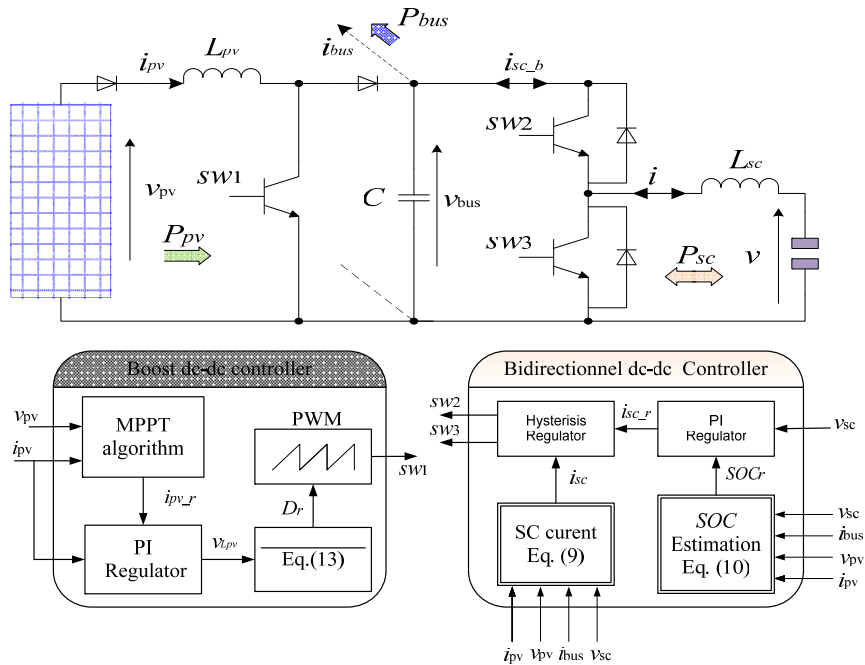


Fig. 7. PV panel and supercapacitor hybrid controller system scheme.

4.2. Photovoltaic system control

In order to extract the maximum available power from a PV array, it is necessary to operate the PV array at its maximum power point (MPP). The MPP tracker device is a high-frequency boost dc-dc converter inserted between the PV array and the dc bus, and it takes the dc input from the PV array, convert it to a different dc voltage and current to exactly match the PV array to the dc bus. The dynamic model of the boost dc-dc converter is given by the following equations

$$v_{pv} = L_{pv} \frac{di_{pv}}{dt} + (1 - D)v_{bus} \tag{10}$$

$$i_{pv}(1 - D) = C \frac{dv_{bus}}{dt} + i_{bus} \tag{11}$$

4.3. Simulation results

The PV panel works in a specific area to guarantee the optimum efficiency. If photovoltaic output power matches the requirement of the load, the photovoltaic will be the only source to supply the loads. If there is a difference between photovoltaic supply and the load demand, the supercapacitor will fill in the gap.

Fig. 8 shows that when ($i_{pv} - i_{bus} > 0$), there is an excess in power. The available power is used for supercapacitor charging. When ($i_{pv} - i_{bus} < 0$), the PV generated power is not sufficient to supply the load demand, the supercapacitors bank in discharging mode and PV panel operate together for produce the required power.

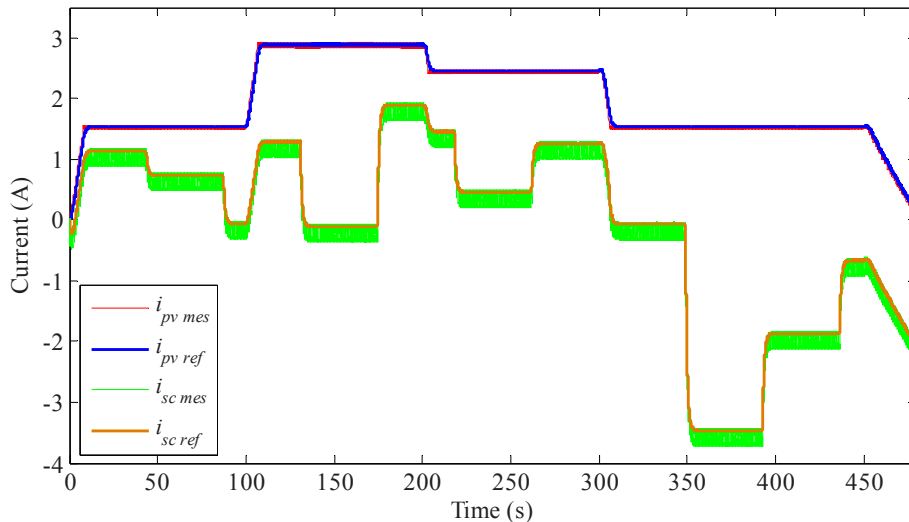


Fig. 8. PV panel and supercapacitor currents.

5. Conclusion

In this paper, a supercapacitor for stand-alone applications has been modelled and characterized. Moreover, a simple methodology based on the constant current tests has been used. Experimental results show that the developed model of the supercapacitor reproduces the dynamic characteristics. Adding, a supercapacitor auxiliary power sources to PV panels can reduce the PV's size and cost. With the further comparison among other alternative sources, the supercapacitor is selected as the auxiliary source to assist the PV panel because of its high power density, quick response and long life time.

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