

2012 International Conference on Future Energy, Environment, and Materials

Research on a Stand-alone Photovoltaic System with a Supercapacitor as the Energy Storage Device

Jie Li^a, Yu Chen^b, Yunda Liu^b

^a*School of Information Engineering, Inner Mongolia University of Science and Technology Baotou, China*

^b*School of Information Engineering, Inner Mongolia University of Science and Technology Baotou, China*

Abstract

With the application and development of the supercapacitor energy storage (SCES) system, energy storage technology has been greatly improved in modern power systems. The SCES provides required energy buffer for a photovoltaic power system and plays an important role in improving the operation stability of a power system. This paper designs a stand-alone photovoltaic system with a supercapacitor as the energy storage device. In particular a Stand-alone PV system constituted by photovoltaic and supercapacitor sources is simulated in PSIM with DC to DC buck boost converter to prove that supercapacitor as a power supply device. The PSIM simulation results reflect that system stability was validated when the input power of photovoltaic array fluctuates greatly. The designed system offers a preferable reference for applications of the supercapacitor in the field of regeneration energy and quality improvement of electricity power.

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Keywords: Supercapacitor; energy storage; PSIM simulation; stand-alone PV system.

1. Introduction

In the field of electrical power systems, many works today focus on the use of renewable and innovative sources. The aim of the works is to show how renewable energy generators can efficiently replace non-renewable power sources. In this context, photovoltaic (PV) are playing an important role as new clean, long lasting, pollution and maintenance free sources. For this reason, the number of the studies on PV systems is rapidly increasing^[1-3].

A typical PV system is constituted by a PV source and a converter, able to match the source characteristics to the electrical requirements. Moreover, being the electrical performances of the PV source dependent on weather conditions, the system is traditionally equipped with an auxiliary storage device in stand-alone applications^[4].

Traditionally, the choice of the storing technology implies a trade off between techno-economical performances and environmental issues. Examining the relevant literature, which focuses in the largest

part of the applications on auxiliary sources constituted by electrochemical batteries, problems related to efficiency, availability and lifetime can be drawn [5]. In particular, we underline that (1) for stand-alone PV systems, typically used in remote locations with minimal power resources, the limited available PV charging source may be insufficient to provide a full charge to the battery; (2) conventional PV systems are still not able to maintain a float charging voltage at an optimum level to extend battery life; (3) in many cases the battery life time, achieved in uncontrolled environments, is much less than expected.

In this context, the option of using supercapacitor based auxiliary devices is a valid solution when the capability of storing energy can be limited. Compared with batteries, supercapacitors have one or two orders of magnitude higher specific powers, and much longer lifetime. Because they are capable of millions cycles, they are virtually free of maintenance. Their great rated currents enable fast discharges and fast charges as well. Their quite low specific energy, compared to batteries, is in most cases the factor that determines the feasibility of increasing power density and satisfying reliability requirements of PV power sources [6, 7]

2. Photovoltaic source model

A. Simplified Equivalent Circuit

A solar cell basically is a p-n semiconductor junction. When exposed to light, a current proportional to solar irradiance is generated. The circuit model of PV cell is illustrated in Fig. 1 [8].

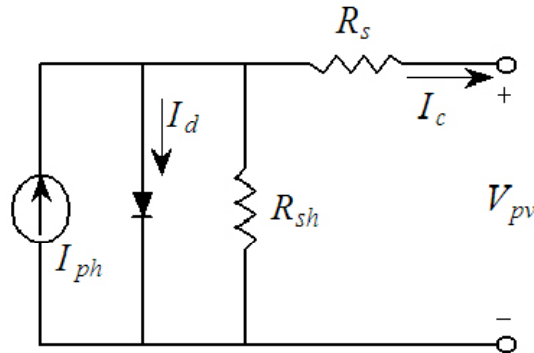


Fig. 1. Circuit model of a single photovoltaic battery.

B. Theoretical Mathematical Model

The equations that describe I-V characteristics of the solar cell based on simple equivalent circuit shown in Fig. 1, are given below;

$$I = I_{ph} - I_d \left(e^{\frac{qV_{PV}}{kT}} - 1 \right) \tag{1}$$

C. Practical PV Circuit Model.

A photovoltaic array can be regarded as the series-parallel connections of several photovoltaic batteries. Therefore, the output of a photovoltaic array will satisfy the following set of equations.

$$\begin{aligned}
 U_{all} &= N_s U_{cell} \\
 I_{all} &= N_p I_{cell} \\
 P_{all} &= N_s N_p P_{cell}
 \end{aligned}
 \tag{2}$$

Assume that we have two series connected batteries, the circuit model of the photovoltaic array will be as what is shown in Fig. 2.

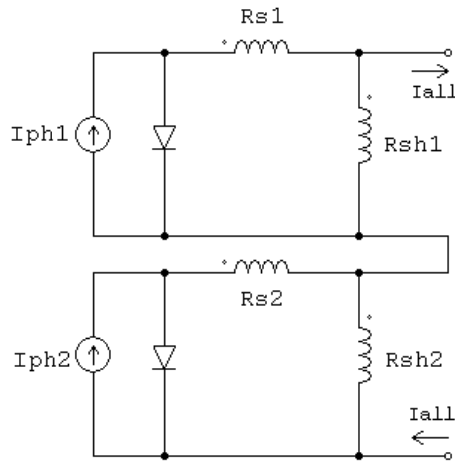


Fig. 2. Circuit model of the photovoltaic array.

In order to calculate the output current of the photovoltaic array and we then have

$$I_{all} = I_{sc} - I_0 \left(e^{\frac{q(V_{PV} + I_{all}R_s)}{AkT}} - 1 \right) - \frac{U + R_s I_{all}}{R_{sh}}
 \tag{3}$$

Where

$$I_0 = C_D T^3 e^{\left(-\frac{eE_G}{AkT} \right)}$$

From the above equation, we can obtain the direct current circuit model of the photovoltaic array as that in Fig. 3.

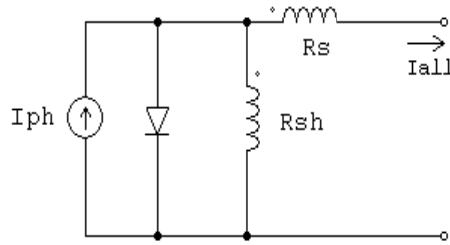


Fig. 3. Equivalent direct current circuit model of the photovoltaic array.

3. Simulation Model for the Photovoltaic Array

We use PSIM to simulate the photovoltaic array (Fig. 4) according to the mathematical models discussed previously. In Fig. 4, S, T, P and N are the ports that connect to the peripheral main circuit and they are responsible for the settings of illumination intensity, temperature and the output voltage of the photovoltaic array [9]. The core of the simulation model is the description of the nonlinear relationship between the voltage and the current of the photovoltaic array. It is realized by sampling the voltage, multiplying it by K and a^x to produce the corresponding reference current, and then generating the corresponding output current through C/P control and voltage control current source. In addition, the temperature has been calibrated in the simulation model.

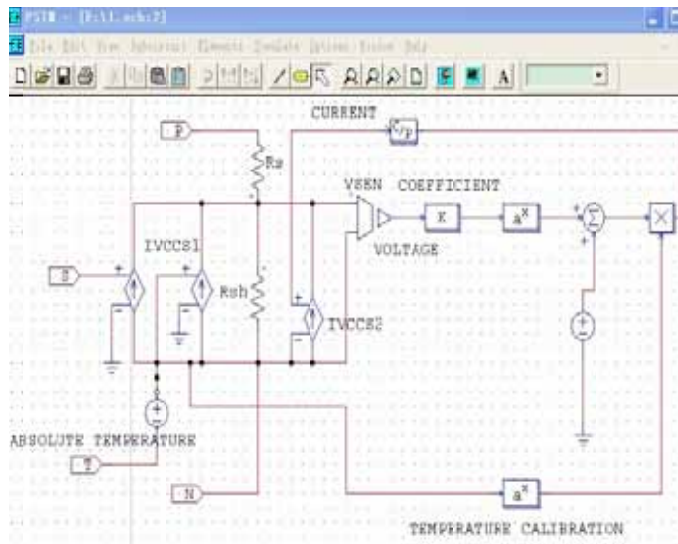


Fig. 4. Circuit model of the photovoltaic array in PSIM.

For analytical convenience, we describe the circuit model of the photovoltaic array as a sub-circuit shown in Fig. 5, where S is the input port for the illumination intensity, T is the input port for the temperature parameter, P is the positive electrode and N is the negative electrode of the output power respectively.

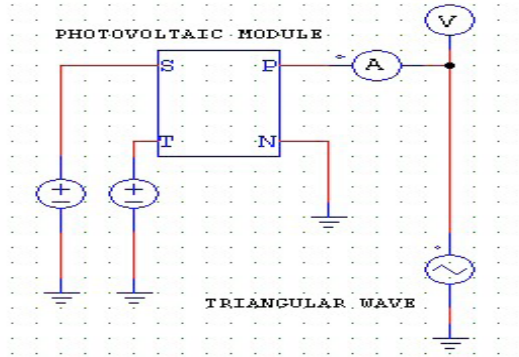


Fig. 5. Sub-circuit model of the photovoltaic array after encapsulation.

4. Design of the Charge Controller

The supercapacitor-based stand-alone photovoltaic system mainly consists of a photovoltaic array, a charge controller, a supercapacitor array and the loads.

As the power source of the system, the photovoltaic array is prone to be affected by the illumination intensity, temperature and the operation situation of the loads. Therefore, we design a charge controller to control the output energy of the photovoltaic array. Specifically, the charge controller in our system adopts the Buck-Boost converter as shown in Fig. 6. The circuit is implemented as a Buck converter followed by a Buck converter. The output voltage of the Buck-Boost converter can operate in a wide range and can be higher or lower than the input voltage. It thus enables the input voltage to vary in a wide range when the output voltage is required to be kept constant^[10, 11].

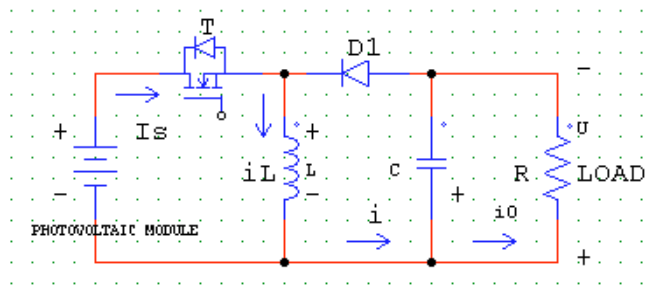


Fig. 6. Structure of the charging controller (Buck-Boost converter).

When the switch T is on, current I_s flows through the induction L , the current in the induction i_L increases and stores energy. When the switch T is off, i_L decreases, and the voltage drop in the induction is reversed. Diode D_1 is forward biased and turned on, the output voltage on the load is U , and the capacitor C charges and stores energy. C can discharge to the load and ensure that U is almost unchanged when the switch T is on.

The output of the Buck-Boost converter can be expressed as

$$U = \frac{D}{1-D} U_s \tag{4}$$

Where $D = \frac{T_{on}}{T_s}$ is the duty cycle, T_s , T_{on} are the switching cycle and the on-time respectively. We can thus obtain the desired voltage by changing the duty cycle.

5. Simulation Analysis

We build a photovoltaic system with the supercapacitor as the energy storage device based on the designed photovoltaic array model and the charge controller model (Fig. 7). We sample the operation current of the impulse load in a certain period, calculate its average as the reference for the output current of the charge controller, compare it with the actual output current to generate the error signal, and finally generate the PWM signal to control the MOS-FET in the charge controller via PI compensator.

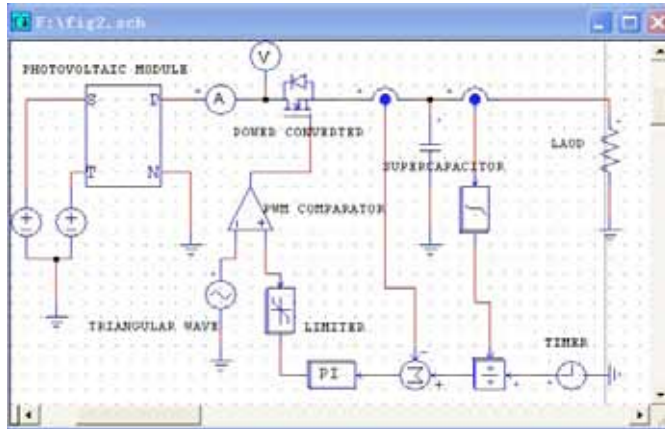


Fig. 7. System control model with the supercapacitor as the energy storage device.

Fig. 8 depicts the output current I_{pv} of the photovoltaic array after passing through the charge controller, the input current I_c of the supercapacitor array and the load current I_b in the steady state. As can be observed, when the output current fluctuates severely, the supercapacitor array can adjust its own charging and discharging current accordingly to make sure the current of the load to be relatively smooth.

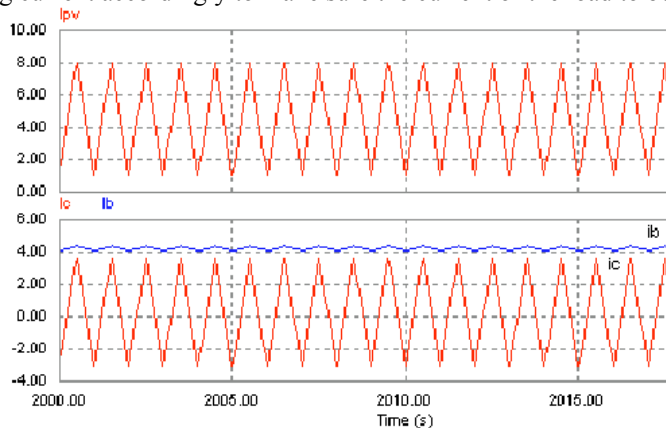


Fig. 8. Currents in the steady state.

We can thus observe that, in a photovoltaic system, although the output current of the photovoltaic array can fluctuate rapidly and widely influenced by the environmental factors such as the illumination intensity, the supercapacitor can greatly reduce such effect on the load due to its superior filtering capability.

From the simulation results, we can observe that adopting the supercapacitor as the energy storage device in a photovoltaic system can enhance the power capability of the energy storage device and can make the system to operate in more steady conditions. Since the lifetime of the supercapacitor and the charge controller is very long, we can realize a high improvement in the system performance by adding a little effort to the traditional structure of a stand-alone photovoltaic system. It has relatively good economical efficiency and realistic importance.

6. Conclusion

This paper uses the supercapacitor as the energy storage device, builds photovoltaic battery and stand-alone photovoltaic system models via PSIM and researches on the operation characteristics of the system. Simulation results show that the supercapacitor has strong resistance capacity to large fluctuations of the input power of a photovoltaic system. In addition, the results also show that the supercapacitor has many advantages such as high power density, high charging and discharging efficiency and long cycle life. Moreover, the design of the charge controller of the supercapacitor is very flexible and can be adjusted according to the specific system requirement. It is expected that, in the future, the supercapacitor, as the energy storage device, will play an important role in the fields such as regeneration energy systems and quality improvement of electricity power.

References

- [1]P. Thounthong, B. Davat, IEEE Power Energy 6 (2008) pp 69–76.
- [2]Phatiphat Thounthonga, Viboon Chunkag, “Energy management of fuel cell/solar cell/supercapacitor hybrid,” power source. 1 January 2011, pp. 313-324
- [3]Mohamed Rahmane, Chuck Iacovangelo, Job Rijssenbeek, Mike Vallance, Reza Sarrafi-Nour “Materials Development for Sodium Metal Halide Batteries” ASM/TMS Annual symposium, GE Global Research, Niskayuna, 2009
- [4]O.C. Onar, M. Uzunoglu, M.S. Alam, “Dynamic modeling, design and simulation of a wind/fuelcell/ultra-capacitor-based hybrid power generation system,”Journal of Power Sources 161 (2006) 707–722
- [5]N. Mutoh, T. Inoue, A Controlling method for charging photovoltaic generation power obtained by a MPPT control method to series connected ultra-electric double layer capacitors, in: Industry Applications Conference, 39th IAS, vol. 4, 2004, pp. 2264–2271
- [6]Chong Han, Alex Q. Huang, Ding Li, Haresh Mamath, Mike Ingram, Stanley Atcitty, Modeling and Design of a Transmission Ultracapacitor (TUCAP) Integrating Modular Voltage Source Converter with Ultracapacitor Energy Storage, 2006 IEEE
- [7]Chong Han, Alex Q. Huang, Ding Li, Haresh Mamath, Mike Ingram, Stanley Atcitty, “Modeling and Design of a Transmission Ultracapacitor (TUCAP) Integrating Modular Voltage Source Converter with Ultracapacitor Energy Storage,” 2006 IEEE.
- [8]Geoff Walker, “Evaluating MPPT converter topologies using a matlab PV model,” IEAust, Vol. 21, pp. 49-56, 2001.
- [9]Veerachary M, “PSIM circuit-oriented simulator model for the nonlinear photovoltaic sources”, Aerospace and Electronic Systems, IEEE Transactions on 2006 IEEE
- [10]Wangpei Bo, Zhang Jiancheng, bell cloud. Used to increase renewable energy power system voltage stability of the bi-directional DC / AC / DC Converter. North China Electric Power University, 2009
- [11]Koizumi, H, Mizuno, T .A Novel Microcontroller for Grid-Connected Photovoltaic Systems Industrial Electronics, IEEE, 2006.

APPENDIX A

A:	Ideality factor,
CD:	Manufacture constants,
Eg:	Energy band gap,
I:	Cell current (A),
I _{ph} :	Light generated current (A),
I _{sc} :	Short circuit current (A),
I _d :	Diode saturation current,
I _{all} :	Out current of the photovoltaic array,
I _{cell} :	Current of a single photovoltaic battery,
K:	Boltzmann constant (1.38×10^{-23} J/K),
N _s :	Number of batteries that are series connected,
N _p :	Number of batteries that are parallel connected,
P _{cell} :	Power of a single photovoltaic battery,
P _{all} :	Output power of the photovoltaic array,
Q:	Charge of electron 1.6×10^{-19} (coul),
R _S , R _{Sh} :	Cell series and shunt resistance (ohms),
T:	Cell temperature (K),
U _{cell} :	Voltage of a single photovoltaic battery,
U:	Load voltage,
U _{all} :	Output voltage of the photovoltaic array.