A Study on Hybrid Storage Technology Based on Super-capacitor and Battery in Stand-alone Photovoltaic System

Huaizhong CHEN *

Zhejiang Industry Polytechnic College, Shaoxing, Zhejiang,312000, China.

***Abstract* — Energy storage systems are generally required for guaranteeing power supply stability and sustainability aiming at independent Photovoltaic, PV, power generation system. The system needs to absorb pulse power issued by photovoltaic cells for inhibiting DC bus voltage fluctuation and meeting the needs of providing load with short-term high power. A super capacitor is characterized by high power density and long cycle life, which is very suitable for combining it with battery for large energy density for jointly forming energy storage part of independent photovoltaic power generation system. In this paper, a mathematical model with parallel connection of battery and super capacitor is developed. Independent photovoltaic system structure with battery hybrid energy storage and super capacitor is constructed. A control strategy is then proposed for a hybrid energy storage by super capacitor and battery. The simulation experimental results show that hybrid energy storage mode by battery and super capacitor can improve the system on load, reduce charge and discharge cycle frequency, and prolong service life of battery.**

Keywords – photovoltaic (PV); hybrid storage; battery; super capacitor; control strategy

I. INTRODUCTION

Solar energy is popular in various countries due to its advantages of cleanness, carbon-free, inexhaustible and unlimited source, etc. Independent photovoltaic system is an important mode in solar energy photovoltaic power generation utilization. Power of photovoltaic power generation is greatly influenced by light intensity and environment temperature. Energy can not be stored synchronously. Therefore, batteries should be equipped for balancing system energy. Excessive solar energy can be stored in case of energy residual [1]. Load demand can be supplemented in case of energy insufficiency. Traditional battery energy storage mode has some shortcomings, such as short cycle life, low power density, large amount of maintenance, etc., thereby further increasing the cost of PV system. The super-capacitor has the characteristics of large power and long cycle life, which can improve the utilization ratio of the battery. Performance of energy storage system must be greatly improved by combining both super-capacitor and battery. They can solve problem of low power density, short service life, etc. during separate energy storage of battery. Technical performance and economic performance of energy storage system can be improved. In the paper, system model is established aiming at the feature that the system has three energy sources of photovoltaic cell, super-capacitor and battery. A hybrid energy storage solution for independent PV system is designed. Corresponding energy control method and energy management strategy are proposed. Different energy control strategies are adopted according to working states of PV cells and hybrid energy storage components [2,3]. Photovoltaic power converter is operated under the working mode set by the system. Therefore, three power supplies in the system can work coordinately.

II. HYBRID ENERGY STORAGE MODEL

A. Battery Model

Modeling analysis of the battery is the basis for analyzing the whole hybrid energy storage system. Batteries are used for independent photovoltaic energy storage device. The switching transition process of energy storage between charge and discharge is analyzed. Certain precision is required. Battery equivalent circuit model is shown in Fig.1.

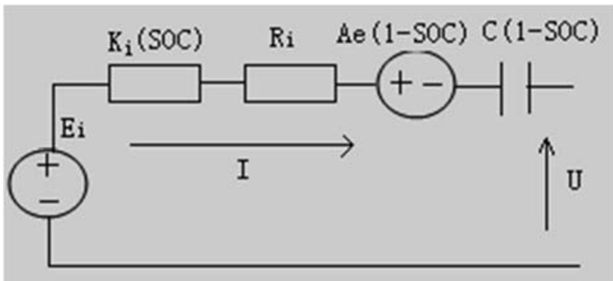

Figure 1. Battery equivalent circuit model.

Battery pack SOC (charged state) can be calculated by the following formula:

$$SOC = \frac{Q_0 - \int_0^t I(\tau)d\tau}{Q_{max}} \tag{1}$$

In the formula: Q_0 refers to battery pack initial capacity; Q_{max} refers to maximum capacity of battery pack; I refers to battery pack current, discharging is available for positive value, and charging is available for negative value. Terminal voltage of battery is shown as follows:

$$U = E_s + Ae^{-B(1-SOC)} - C(1-SOC) - K_i(SOC)I - R_i I \tag{2}$$

In the formula: $Ae^{-B(1-SOC)}$ is used for correcting rapid drop at the beginning of discharge; E_s refers to voltage at the beginning of battery discharge; C(1-SOC) refers to correction item introduced due to consideration of no-load voltage along discharging degree; K_i(SOC)I refers to voltage drop caused by electrode plate channel; R_iI refers to active voltage losses[4,5].

B. Super-capacitor Model

Super-capacitor is located on the intersection between electrodes and solution so that it can accommodate more charge. Since it does not have chemical change during charging and discharging, it is provided with stronger cycle use ability, which can be repeatedly charged and discharged for one hundred thousand times repeatedly with high charging and discharging service life. Super-capacitor equivalent circuit model is shown in Fig. 2.

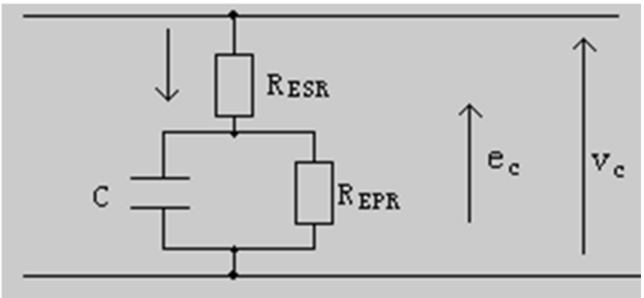

Figure 2. The equivalent circuit of super-capacitor

The model is mainly composed of ideal capacitor C, equivalent series internal resistance R_{ESR} and equivalent parallel internal resistance R_{EPR}. Wherein, C represents capacity of super-capacitor, R_{ESR} refers to total series internal resistance of super-capacitor, which can simulate internal loss due to charge and discharge. R_{EPR} is used for stimulating leakage current of super-capacitor, which mainly affects long-term process described by the following mathematical model:

$$R_{ESR} = \frac{\Delta V}{\Delta i} \tag{3}$$

$$R_{EPR} = \frac{t_1 - t_2}{C(\ln V_1 - \text{n} V_2)} \tag{4}$$

$$v_c = R_{ESR} i_c + \frac{1}{C}\int (i_c - \frac{e_c}{R_{EPR}}) d\tau + V_{c0} \tag{5}$$

Wherein, V_1 and V_2 represents self-discharge voltage value during t_1 and t_2 time sections; C refers to rated capacity; ΔV and Δi respectively represent variations of terminal voltage and current. Since super capacitors are mainly used for absorbing frequent power pulse at the time of charge and discharge, influence of R_{EPR} can be ignored, and the super-capacitor can be equivalent to the series mode of one capacitor and one resistor. The super-capacitor is not aging in the use process compared with batteries. It can be regarded as device capable of infinite charge and discharge in actual application. The super-capacitor not only can be charged like traditional energy storage component, but also can be charged in the mode of large pulse current [6].

C. Modeling Analysis of Battery and Super-capacitor

Super-capacitor and battery have strong complementarily in performance. Super-capacitor and battery can be mixed for use. Such circuit not only has advantages of high-density energy storage like battery, but also contains the advantages of Super-capacitor, such as high-speed charge and discharge performance, large power density, etc. Such mode can greatly reduce internal loss of power supply, thereby prolonging operation time of power supply. Battery is simplified into ideal voltage source, which is serially connected with equivalent internal resistance. The super-capacitor can also be simplified as the ideal capacity structure which is serially connected with internal resistance. Equivalent circuit of parallel model between super-capacitor and battery is shown in Fig.3.

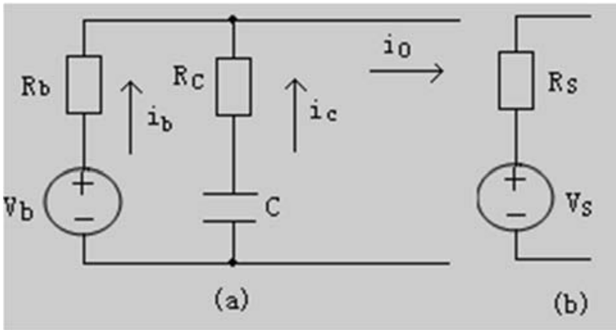

Figure 3. Equivalent model of hybrid power supply.

Components shown in Fig.3 respectively include: Super-capacitor equivalent series internal resistance R_s, battery equivalent series internal resistance R_b, super-capacitor branch current i_s, load current i_0, battery branch current i_b. Laplace transform processing is firstly implemented on Fig.3(a). After it is simplified by thevenin's theorem, equivalent simplified model can be obtained as shown in Fig.3(b). Analysis process is shown as follows in order to get specific parameters of the model more intuitively:

$$V_s = \frac{V_b}{S} + \frac{R_b}{R_b + R_c} \cdot \frac{V_{co} - V_b}{S + 1/(R_b + R_c)C} \tag{6}$$

In the formula: V_{CO} refers to initial voltage of ideal super-capacitor C.

$$R_s = \frac{R_b R_c}{R_b + R_c} \cdot \frac{S + 1/R_c C}{S + 1/(R_b + R_c)C} \tag{7}$$

Pulse cycle is set as T, duty ratio as D, current peak as I_0 aiming at pulsed power load, and the current i_0 (t) can be represented as follows:

$$i_o(t) = I_o \sum_{k=0}^{N-1} [\phi(t - kT) - \phi(t - (k + D)T)] \tag{8}$$

In the formula: $\phi(t)$ is a standard step function. Formula (8) undergoes Laplace transform for obtaining frequency domain expression formula of pulse load current as follows:

$$I_o(S) = I_o \sum_{k=0}^{N-1} [\frac{e^{-kTS}}{S} - \frac{e^{-(k+D)TS}}{S}] \tag{9}$$

Pulse electric current can produce pulse voltage drop $V_R(S)$ on super-capacitor and battery parallel equivalent internal resistance produces as follows:

$$V_R(S) = \frac{R_b R_c I_o}{R_b + R_c} \cdot J \tag{10}$$

$$J = \sum_{k=0}^{N-1} [\frac{S + 1/R_c C}{S + 1/(R_b + R_c)C} \cdot \frac{e^{-kTS} - e^{-(k+D)TS}}{S}] \tag{11}$$

The voltage drop $V_0(S)$ produced by pulse current on the load is shown as follows:

$$V_o(S) = \frac{V_b}{S} + \frac{R_b}{R_b + R_c} \cdot \frac{V_{co} - V_b}{S + 1/(R_b + R_c)C} - Q \tag{12}$$

$$Q = \frac{R_b R_c I_o}{R_b + R_c} \sum_{k=0}^{N-1} [\frac{S + 1/R_c C}{S + 1/(R_b + R_c)C} \cdot \frac{e^{-kTS} - e^{-(k+D)TS}}{S}] \tag{13}$$

Formula (12) undergoes Laplace inverse transform for obtaining time-domain expression formula of voltage drop on pulse load:

$$M = (1 - \frac{R_b}{R_b + R_c} e^{\frac{t-(k+D)T}{(R_b+R_c)C}} \phi(t - (k+D)T \tag{14}$$

$$Z = R_b I_o \sum_{k=0}^{N-1} [(1 - \frac{R_b}{R_b + R_c} e^{\frac{t-kT}{(R_b+R_c)C}} \phi(t - kT) - M)] \tag{15}$$

$$v_o(t) = v_b + \frac{R_b}{R_b + R_c}(V_{co} - V_b) e^{\frac{1}{R_b + R_c}} - Z \tag{16}$$

Current I_{bs} (t) of one battery branch during steady-state operation is introduced synchronously:

$$N = 1 - \frac{R_b}{R_b + R_c} e^{\frac{t-(k+D)T}{(R_b+R_c)C}} \phi(t - (k+D)T \tag{17}$$

$$I_{bs}(t) = I_o \sum_{k=0}^{N-1} [(1 - \frac{R_b}{R_b + R_c} e^{\frac{t-kT}{(R_b+R_c)C}} \phi(t - kT) - N)] \tag{18}$$

When $t = (k + D)T$, $I_{bs}(t)$ can reach the maximum value, namely:

$$I_{bpeak}(t) = I_o(1 - \frac{R_b e^{\frac{t-kT}{(R_b+R_c)C}}}{R_b + R_c} \frac{1 - e^{\frac{(1-D)T}{(R_b+R_c)C}}}{1 - e^{\frac{T}{(R_b+R_c)C}}}) = \frac{I_o}{\gamma} \tag{19}$$

In the formula: γ refers to system power enhancement factor. γ is larger, ability of outputting power is stronger. γ is related to load parameters, including duty cycle and cycle. γ is also associated with super-capacitor and battery parameters, including battery internal resistance, Super-capacitor internal resistance and capacitance[7].

It is obvious that when battery and super-capacitor are connected in parallel, the maximum output current branch is smaller than pulse load current amplitude. Load current of other parts is assumed by super-capacitor. Since specific power of super-capacitor is higher and current output ability is very strong so the power supply output ability is correspondingly increased.

III. SYSTEM DESIGN

A. *System Overall Structure Design*

Composite power supply energy storage independent PV system of battery and super-capacitor is adopted, which is mainly composed of photovoltaic array, Maximum Power Point Tracking(MPPT)control, charge control, battery, super-capacitor, bi-directional DC/DC converter, two-day Buck-Boost DC converter and load components as shown in Fig.4.

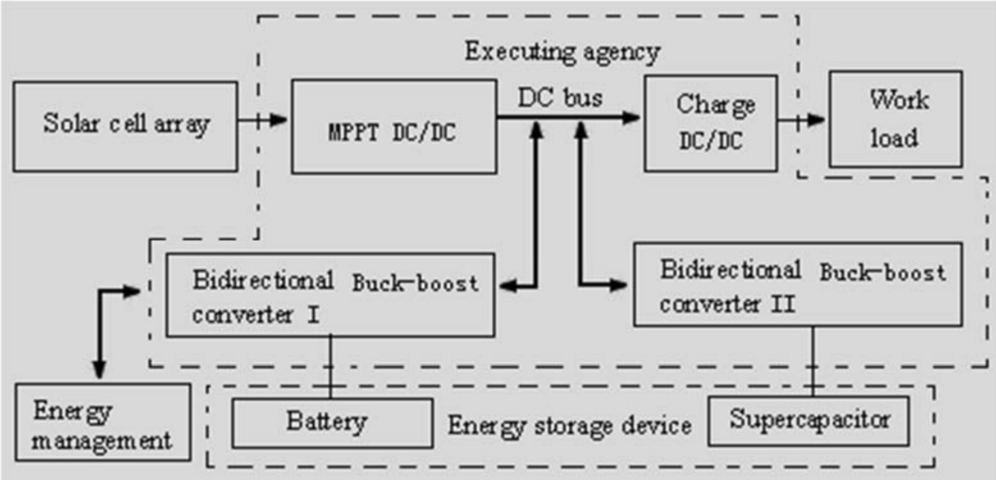

Figure 4. Hybrid energy storage stand-alone PV system structure diagram.

One-way DC/DC converter behind photovoltaic array is operated under MPPT mode. Photovoltaic power is maximally converted to DC bus side. The super-capacitor configured in the system has certain energy storage ability, which can reduce charge and discharge cycle frequency of battery. Output electricity of PV system also can be filtered, thereby optimizing discharge current of battery. Battery and super-capacitor can jointly provide required energy and power of DC load. Bidirectional converter I belongs to battery constant current charge and discharge controller. Constant current charge and discharge can greatly prolong the life of battery. Two-way DC/DC converter II belongs to super-capacitance voltage controller. Voltage regulation can be realized through controlling two-way flow of energy between the super-capacitor and DC bus. Energy management unit is the core of the system. Working mode of the system can be judged by testing bus voltage, super-capacitor voltage, battery voltage and other system variables. Corresponding logic control signals can be released. Charge and discharge of hybrid energy storage device can be realized through rational and effective control of the two converters, thereby achieving stable and reliable operation of independent photovoltaic power generation system[8].

B. *Two-way DC Converter Design*

Two-way Buck-Boost DC converter can make energy to flow in two ways, and the polarity of input and output voltage is not changed. Two-way converter I has the same circuit as the two-way converter II. Difference of duty ratio can be controlled according to energy management. Vi refers to DC bus terminal voltage, and Vo refers to terminal voltage of combined battery. The first category is Buck working mode. Its equivalent circuit is shown in Figure.5. When the DC bus voltage is higher than the set value, excessive energy can be delivered to battery by DC bus through Buck - Boost DC converter, thereby the DC bus voltage can be stabilized as set value, namely energy flows from Vi to Vo, and inductance current i_{tf} flows from left to right, which is recorded as $+i_{tf}$, and the equivalent circuit is shown in f Fig.5(a). When the switch S1 is conducted, its equivalent circuit is as shown in Fig.5(b). Then, i_{tf} can be increased. When S1 is stopped, its equivalent circuit is shown in Fig.5(c). S2 is conducted after one dead zone time. However no current flows through S2 due to D2 subsequent flow [9].

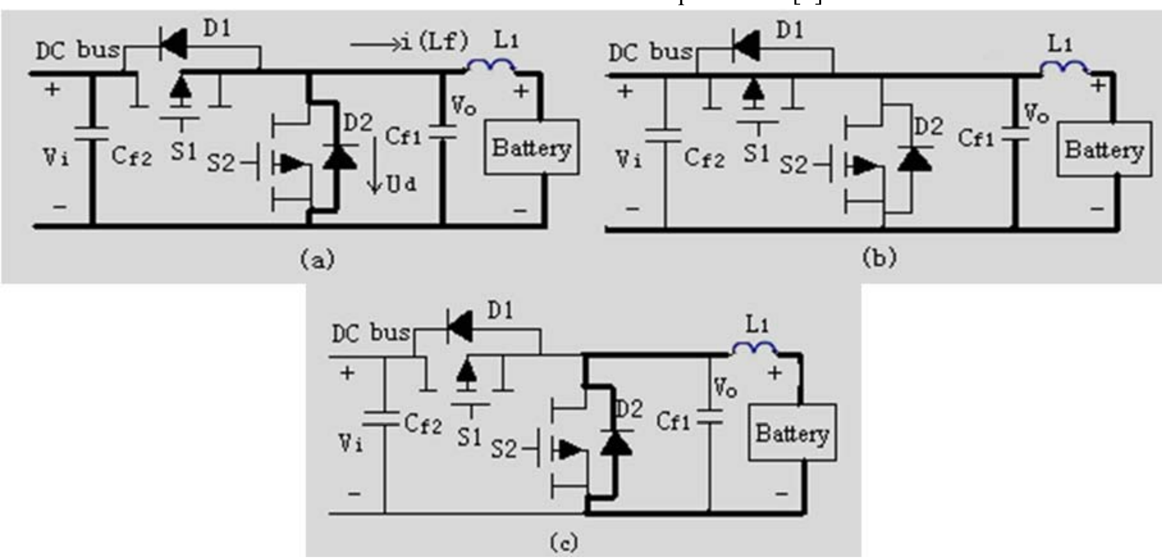

Figure 5. Equivalent circuit of Buck working mode.

The second mode is Boost working mode. Its equivalent circuit is shown in the Figure.6. When DC bus voltage is less than certain value, DC bus voltage can be stabilized at the set value, DC bus should absorb energy from combined energy storage device through two-way Buck-Boost DC converter, which is equivalent to energy flow from combined energy storage device s to DC bus, namely flowing from V_0 to Vi and inductance current i_{tf} flowing from right to left, which is recorded as $-i_{tf}$. Its equivalent circuit is shown in Fig.6(a). When the switch S2 is conducted, i_{tf} can be increased under V_0 effect. Its equivalent circuit is shown in Fig.6(b). When S2 is stopped, D1 has subsequent flow, and its equivalent circuit is shown in Fig.6(c). S1 is conducted after one dead zone time section. However, no current flows through S1 under the condition. Since D1 has subsequent flow, it flows to Vi end on the load side through D1 unless S is conducted again in next stage.

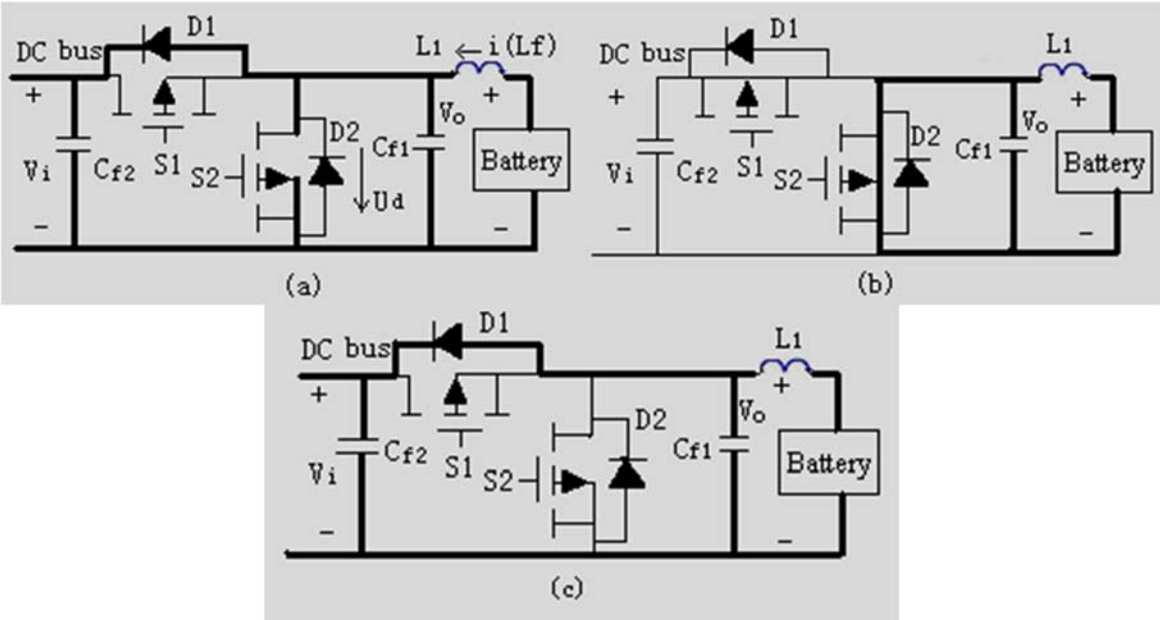

Figure 6. Equivalent circuit of Boost working mode.

The two-way DC converter is added between the DC bus and the battery, which is mainly for better control of the charge and discharge of the battery. According to the demand of the output and load of the photovoltaic cell, the current limit of the battery is controlled, so that it is always in a state of charge and discharge. At the same time, the two-way DC converter can reduce the charge and discharge current of the battery, improve working environment. If the battery is directly connected to the DC bus, and the DC converter connected to the super capacitor and the control need a certain response time, so the battery will take a certain time of the impact of the current. In addition, in this case, the battery terminal voltage does not need to maintain a strict matching relationship with the DC master, which can reduce the battery's configuration capacity.

IV. CONTROL STRATEGY

PV is the total source of system energy. Super-capacitor has the role of regulating voltage and storing energy. Power fluctuation in the system can be inhibited. Battery can be used for storing energy. After super-capacitor is fully charged and sufficiently discharged, the battery can realize energy balance in the system as energy storage device of charging and discharging. Through the reasonable configuration and energy management of photovoltaic cells, super capacitors and batteries, we can ensure the stable and reliable operation of the system. When the system PV output power is greater than the rated power load, excess energy through the converter in a battery and a super capacitor is stored [10]. When the output power is insufficient, the battery and super-capacitor discharge, and this control strategy can ensure stable power supply load. System energy management strategy has the following six operating modes :

Working mode I: Photovoltaic battery output power is greater than the load power, power in storage battery and super-capacitor is close to 100%. The battery is disconnected under the condition, power supply is provided for load directly by photovoltaic battery. Super-capacitor is connected to the circuit in order to improve the system peak power and reducing output current pulse. Photovoltaic system working mode is shown in Fig.7.

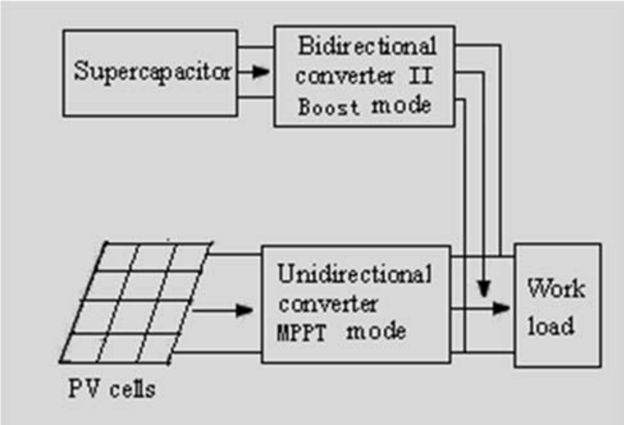

Figure 7. Work mode I.

Working mode II: Photovoltaic system working mode is shown in Fig.8.

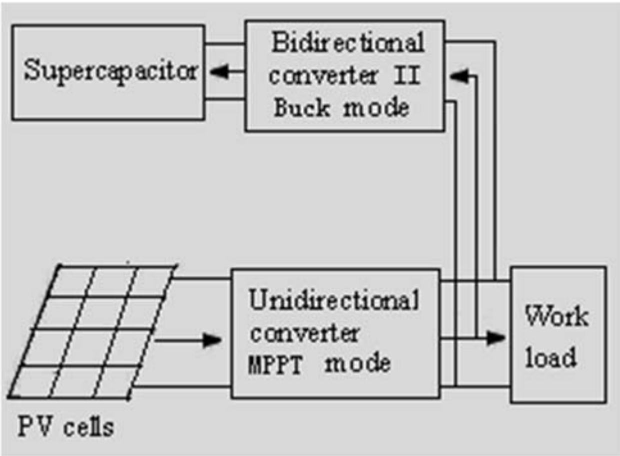

Figure 8. Work mode II.

Output power of photovoltaic cells is greater than the load power, battery power is close to 100%, and super-capacitor power is not full. When photovoltaic cells supply power to load, super-capacitor is charged synchronously, and the battery is kept disconnected.

Working mode III: The output power of photovoltaic cells is greater than load power, battery and super-capacitor are not fully charged. Power is supplied to load by photovoltaic battery, and battery can be charged synchronously under the condition according to principle of charging the battery followed by discharge. Super-capacitor is disconnected to make the battery to reach full power state as soon as possible. The system can automatically enter mode 2 after the battery is fully charged. Photovoltaic system working mode is shown in Fig.9.

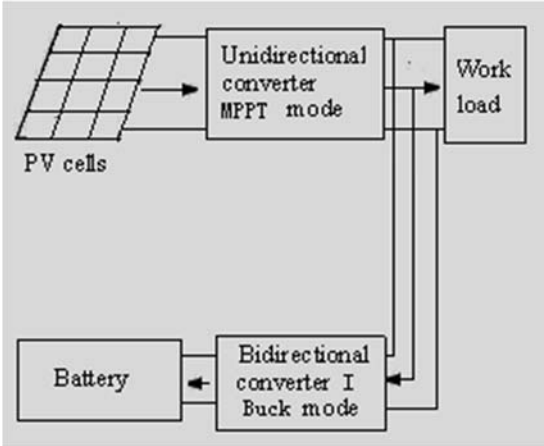

Figure 9. Work mode III.

Working mode IV: Photovoltaic battery output power is less than the load power. Super-capacitor electricity is lower than the set value. The battery is accessed to circuit under the condition. Photovoltaic cell, super-capacitor and battery can jointly supply power for the load. Photovoltaic system working mode is shown in Fig.10.

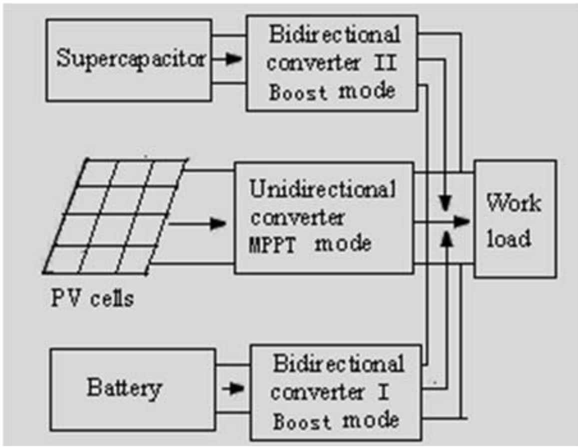

Figure 10. Work mode IV.

Working mode V: Photovoltaic cells have no output, one-way converter stops operation. Two-way converter 1 is operated in Boost mode, and the battery can separately supply power for the load, output voltage can be controlled, thereby ensuring stable voltage of bus. Photovoltaic system working mode is shown in Fig.11.

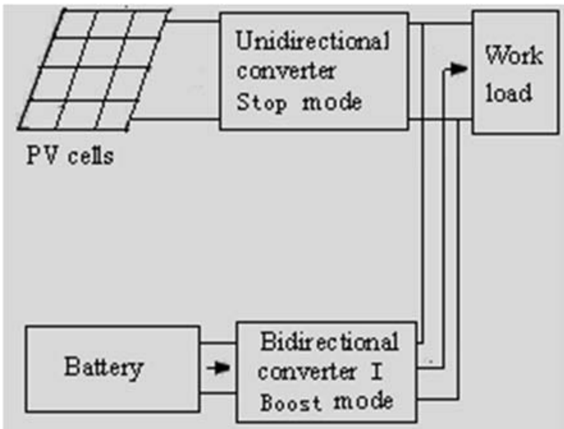

Figure 11. Work mode V.

DOI 10.5013/ IJSSST.a.17.25.36 ISSN: 1473-804x online, 1473-8031 print

Working mode VI: If the load power is suddenly changed under the condition of working mode 5, the super-capacitor can be started for discharging the load. Photovoltaic system working mode is shown in Fig.12.

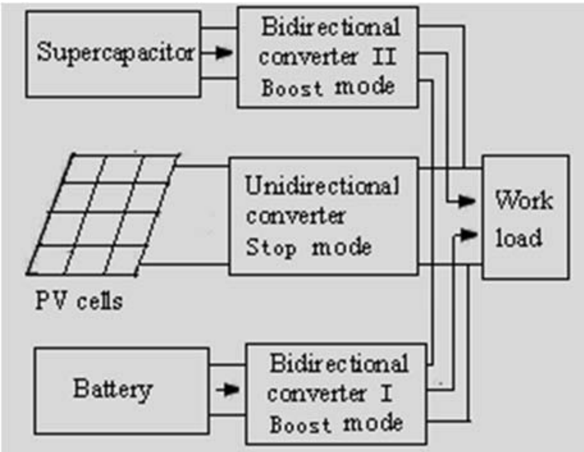

Figure 12. Work mode VI.

Super-capacitor is utilized to keep bus voltage stable. Advantages of super-capacitor are fully utilized, namely good rapidity and service life. When the system power is fluctuated, the super-capacitor is firstly operated for inhibiting fluctuation, thereby reducing discharge and discharge small cycle frequency of battery. In MPPT control circuit, super-capacitor is used for serially connecting with photovoltaic array through DC-DC power conversion circuit, features of super-capacitor can be fully utilized, namely large capacitance as well as repeated charge and discharge, thereby realizing tracking of the maximum power point, and improving the utilization efficiency of photovoltaic cells[11].

V. SIMULATION

MATLAB simulation is utilized for establishing simulation model on independent photovoltaic power generation system proposed in the paper, thereby implementing simulation verification. The upper limit value of charging voltage in super-capacitor in the system is 56V, and the lower limit value of discharge voltage is 48V. The upper limit value of charging voltage of battery is 52V, and the lower limit value of discharging voltage is 46V, and the expected value of DC bus voltage is 100V. Fig.13 shows photovoltaic cell output voltage V_p, DC bus voltage V_{bus}, battery discharge current i_b, super-capacitor discharge current i_c and current waveform on the load during load mutation when photovoltaic cell output energy is insufficient.

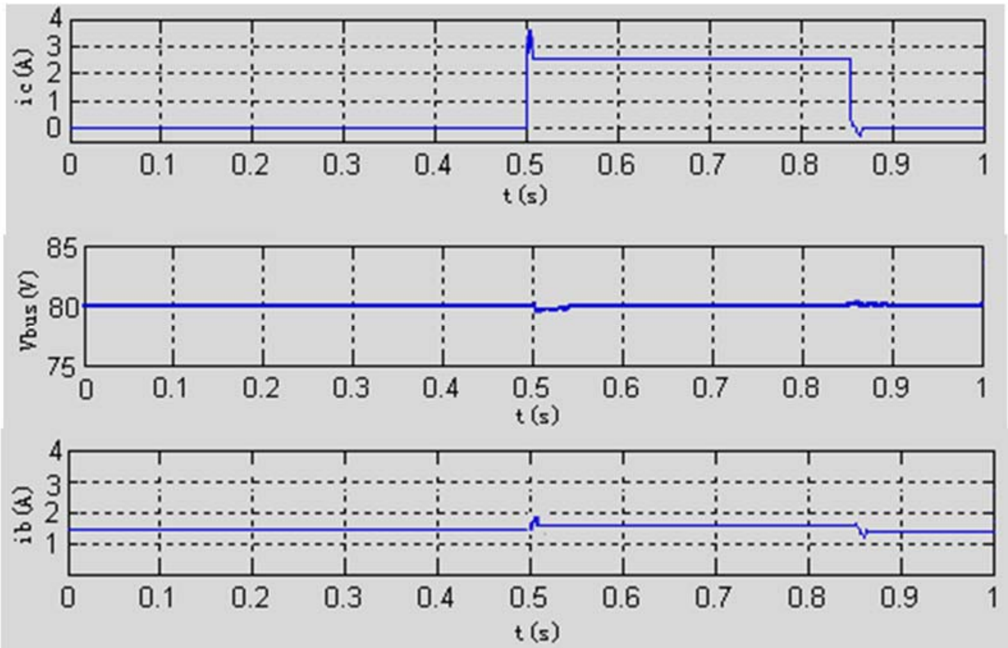

Figure 13. Working waveform when system load suddenly changing.

The Fig.13 shows that since photovoltaic battery output energy is insufficient, one-way converter is still operated under MPPT mode. Most impact power can be provided by super-capacitor during load mutation. Battery output current can reduce instant output power of battery according to set output of limiter. Insufficient energy can be continuously provided by battery after the load is stabilized[12].

VI. CONCLUSION

Hybrid energy storage system of battery and super-capacitor applied in PV power generation system, is proposed. Energy can be transmitted in two ways through a parallel-connected DC converter. Hybrid energy storage of super-capacitor and battery is used as independent PV power generation system of energy storage device. Both PV cell and energy storage elements can be operated coordinately under different conditions by controlling the two converters to work under different working modes. The system can be operated stably and reliably. When load pulse and input fluctuation are larger, super-capacitor can play certain filtration role. Charging and discharging current of battery can be kept at soother level. Features of PV cells-large capacitance as well as repeated charging and discharging are fully utilized, thereby realizing tracing of the maximum power points. Utilization rate of PV cells is improved, charging and discharging frequency of the battery is reduced, service life of battery is prolonged, thereby improving working efficiency of the whole system. Hybrid energy storage technology will be widely applied in new energy power generation system and other fields as constant progress of technology.

ACKNOWLEDGEMENTS

This work is supported by scientific research funded project of Science Technology Department of Zhejiang Province (2015C31128).

REFERENCES

[1] Zhou Lin, Huang Yong, "A survey of energy storage technology for micro grid, Power System Protection and Control, vol. 39, pp. 147-152, 2011.

[2] Dixon J W, Oriuzar M E, "Ultracapacitors DC-DC converters in regenerative braking system", IEEE Aerospace and Electronic Systems Magazine, vol. 17, pp. 16-21, 2002.

[3] Jones B W, Powell R, "Evaluation of distributed building thermal energy storage in conjunction with wind and solar electric power generation", Renewable Energy,vol. 74, pp. 699-707, 2015.

[4] M. E. Glavin, W. G. Huriey, "Optimization of a photovoltaic battery ultra capacitor hybrid energy storage system, Solar Energy", vol. 86, pp. 3009-3020, 2012.

[5] Cegnar E J, Hess H L, "A purely ultra capacitor energy storage system hybrid electric vehicles utilizing a based DC-DC boost converter", Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition,vol. 2, pp.1160-1164, 2004.

[6] Kumar K K, Bhaskar R, Koti H, "Implementation of MPPT Algorithm for solar photovoltaic cell by comparing short-circuit method and incremental conductance method", ProcediaTechnology, vol.12, pp. 705-715, 2014.

[7] Zhang Chunjiang, "A control strategy for battery ultra capacitor hybrid energy storage system" ,Transactions of China Electro technical Society, vol.129, pp. 334-340, 2014.

[8] Hang Y, "Application Research on a Stand-alone PV system with ultra capacitor battery Hybrid energy storage", Master degree thesis of Chongqing University, vol.19, pp.567-475, 2011.

[9] Ahmed J, Salam Z. "A maximum power point tracking for PV system using Cuckoo search with partial shading capability, Applied Energy", vol.119, pp.119-130, 2014.

[10] Li Shaolin, Yao Guoxing, "Research on ultra capacitor battery energy storage in wind/solar power system", Power Electronics, vol.44, pp.12-16, 2010.

[11] LIANG Shichun, "A Prediction algorithm of PV Power with hybrid Energy storage" Chinese Journal of Power Sources, vol.47, pp.24-27, 2014.

[12] Xie Shixiao, Yang Li, "A chance constrained programming based optimal configuration method of hybrid energy storage system", Power System Technology, vol.36, pp.79-84, 2012.