Journal of the Korean Institute of Illuminating and Electrical Installation Engineers (2014) 28(12) : 18~29
http://dx.doi.org/10.5207/JIEIE.2014.28.12.018 ISSN 1229-4691(Print) ISSN 2287-5034(Online)

A Matlab/Simulink-Based PV array-Supercapacitor Model Employing SimPowerSystem and Stateflow Tool Box

Won-Pyo Hong*

Abstract

This paper proposes the integration of photovoltaic (PV) and energy storage systems for sustained power generation. In this proposed system, whenever the PV system cannot completely meet load demands, the super capacitor provides power to meet the remaining load. A power management strategy is designed for the proposed system to manage power flows between PV array systems and supercapacitors (SC). The main task of this study was to design PV systems with storage strategies including MPPT with direct control and an advanced DC-link controller and to analyze dynamic model proposed for a PV-SC hybrid power generation system. In this paper, the simulation models for the hybrid energy system are developed using Matlab/Simulink, SimPowerSystems and Matlab/Stateflow tool. This is the key innovative contribution of the research paper. The system performances are verified by carrying out simulation studies using practical load demand profile and real weather data.

Key Words : Photovoltaic system, Supercapacitor, PV-SC hybrid system, Matlab/Simulink model, Power management

1. Introduction

Ever-increasing energy consumption, soaring costs, the exhaustible nature of fossil fuels, and the worsening global environmental issues have taken all contributed to the viewing of renewable energy sources as promising solutions. Renewable energy systems (RES) including wind turbines, solar energy and fuel cells have experienced a remarkably rapid growth in the past ten years because they are pollution-free sources of power [1-3]. Abundance and sustainability of solar radiant energy are important factors that characterize the energy through the PV effect among the RES. But the power generated by a PV system is highly dependent on weather conditions. To overcome the intermittency of the solar energy source, energy storage systems (ESS) have to be coupled with short term storage devices like supercapacitors (SC), which enable charge/discharge cycles inferior to 10s with kW/kg specific power[4-5]. Recently, PV array

---

* Main author : Dept. of Building & Plant
Engineering, Hanbat National
University, Korea
Tel : +82-42-821-1179, Fax : +82-42-821-1175
E-mail : wphong@hanbat.ac.kr
Date of submit : 2014. 7. 30
First assessment : 2014. 8. 21
Second assessment : 2014. 10. 20
Completion of assessment : 2014. 10. 31

systems have been used in several electric power applications. Despite the high initial cost and low efficiency, the PV system has few operation and maintenance costs as it is a stationary source of energy fabricated from semiconductor materials. Compared with oil prices, solar energy is a feasible energy supply with great long-term benefits.

The combination of the PV system and SC bank is an attractive choice due to their high efficiency, fast load-response [6]. Attractive features of SC include its high capacitance, short duration peak power delivery capacity, i.e., high power density, reduced space, environmental safety, low power to weight ratio, and safe, long-lasting cycle life.

In solar energy conversion systems, SCs are operated when high power demand is requested or when the supplied electrical power needs adjustment [7]. As an example, they furnish significant power to overcome the initial inertia at solar pump start-up and allow quality power when operating with grid-connected photovoltaic inverters. Integration in microgeneration systems enables numerous applications [4]: road signs and lighting, bus schedule displays, parking fee machines, remote weather stations, system commands, automatic distributors, emergency lights, and compressors. Other uses of SCs fed by solar energy have been envisaged over the last decade as reviewed below.

An average multi-level representation of power electronic converters is used to design a dynamic model of an SC Bank for microgrid application [8]. Hong proposes Matlab/Simulink dynamic models of photovoltaic, micro turbine systems and SC. The simulation comparison results of the two systems, this is, with SC and without SC bank, were carried out [9]. Also, SCs have been implemented in stand-alone power generation stations with renewable energy sources. In this framework, the energy management of autonomous photovoltaic power stations has been modelled in the case of batteries or fuel cells combined with SCs for electricity storage [10]. Uzunoglu et al. employed blocks containing transfer function to simulate the power control of autonomous power station by taking into account intermittency in their simulation [11].

Tao Zhou et al. have studied a dc-coupled wind/hydrogen/ SC hybrid power system. The purpose of the control system is to coordinate these different sources, particularly their power exchange, in order to make controllable the generated power [12]. An energy storage model of a superconductor and PV array based on a Matlab/Simulink software environment was presented by W.P. Hong [13]. This paper focuses on developing a simulation model to design and analyze the overall system performance of a feasible PV/SC hybrid system in residential use. The simulation model can be used not only for analyzing the PV/SC hybrid system performance, but also for sizing and designing the hybrid system to meet the load demands for any available meteorological condition. In this paper, modeling and simulations are performed using MATLAB/Simulink, SimPowerSystems and Stateflow tool packages[13] and the results presented to verify the effectiveness of the proposed system during peak power demands or transient conditions. The detailed power converter controllers developed and turned to be reduced power fluctuations and the PV array for this simulation have been modeled with the 2D lookup table provided in the Matlab Toolbox and the controlled current source of SimPowerSystems. These methods offer effective data storage and the reduction of simulation time. The main contribution of this paper is to present a flatness-based control approach for a solar power generation system with an SC storage device.

2. Dynamic Modeling

2.1 PV System Model and MPPT

2.1.1 PV System Model

A PV system consists of many cells connected in series and parallel to provide the desired output terminal voltage and current. Solar insolation, temperature and output voltage of PV are essential factors that affect the output characteristics of the PV cell. Since the PV system exhibits a nonlinear I-V characteristic, it is vital to model the PV unit for MPPT (maximum power point tracking) in PV based power system[14]. M. Veerachary et al. introduced a verified model for a silicon solar PV panel [15]. Recently, detailed models that include nonlinear effects such as resistive losses, non-ohmic current and temperature have been developed to create a more accurate model [16]. The parameters used in the mathematical modeling of the PV system and the output voltage characteristic of the PV system may be expressed as Eq. (1)[17].

$$V_{PV} = \frac{N_s \alpha k T}{q} \ln\left[\frac{I_{sc} - I_{PV} + N_p}{N_p I_0}\right] - \frac{N_s}{N_p} R_s I_{PV} \qquad (1)$$

α	ideality or completion factor
I_0	PV cell reverse saturation current [A])
I_{PV}	PV cell output current [A]
I_{sc}	short-circuit cell current (representing insolation level [A])
k	Boltzmann's constant [J/_K]
M_V	voltage factor
N_p	the number of parallel strings
N_s	the number of series cells per string
q	electron charge [C]
R_s	series resistance of PV cell [U]
T	PV cell temperature [_K]
V_{MP}	PV cell voltage corresponding to maximum power [V]
V_{OC}	open-circuit voltage [V]
V_{PV}	terminal voltage for PV cell [V]

The manufacturer's datasheet provides necessary information for most of the parameters of Eq. (1) [17-18]. The current-voltage characteristics of the PV array can be obtained and analyzed by using Eq. (1). Using the current-voltage curves, the current-power curves can be obtained to operate with maximum efficiency and produce the maximum power output. The maximum power output of the PV array varies according to solar radiation or temperature. Therefore, an MPPT is needed to maintain the solar array more effectively as an electric power source [19]. In this paper, the PV array model with a 2D-Lookup table and a controlled current source is used for simulation time and computational efficiency [15]. The irradiance data and the I-V characteristic curve of PV array can be used for modeling the PV output power. Fig. 1 shows the PV array Matlab/Simulink model using the 2D-Lookup table and the controlled current source. The input data for the 2D Look-up table are irradiance data and output voltage of PV array.

To evaluate the performance of the whole system under the Matlab simulation environment, the IncCond method has also been developed by the Matlab/Stateflow tool as shown in Fig. 1. The IncCond method adjusts the PV operating point with small steps and uses an average value of 100 samples to avoid oscillation around the MPP. In this paper, the direct control of the MPPT algorithm is adopted for changing the duty cycle of a dc-dc converter. A PI controller can be used in general MPPT algorithms, but requires a control loop for regulating the current of MPP calculated by the MPPT algorithm. Fig. 1 also shows an IncCond

MPPT algorithm with direct control by the Matlab/Stateflow toolbox.

Compared with general MPPT algorithms, the direct control of the MPPT algorithm shown in Fig. 2 is simple and uses only one control loop in which the PI controller is excepted because it performs the adjustment of the duty cycle within the MPPT algorithm as shown in Fig. 2.

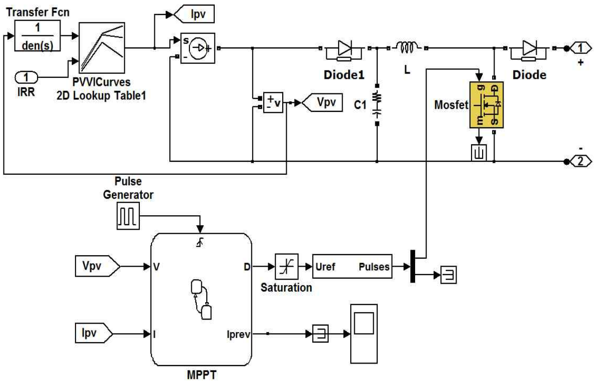
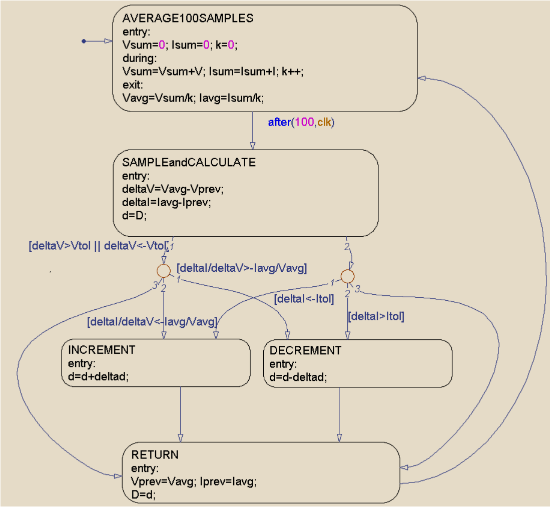


Fig. 1. The direct control model of PV system with dc-dc converter

2.1.2 Incremental Conductance Direct MPPT Method

Comparative studies [20-21] show that an incremental conductance method tracks faster the maximum power point under rapidly changing atmospheric conditions.

Conventional IncCond MPPT algorithms have two independent control loops to control the MPPT. The first control loop contains the MPPT algorithm, and the second one is usually a proportional (P) or P-integral (PI) controller. The IncCond MPPT method makes use of instantaneous and IncCond MPPT to generate an error signal, which is zero at the MPP. However, it is not zero at most of the operating points. The main purpose of the second control loop is to make the error from MPPs near to zero. However, the MPPT system of standalone PV is a nonlinear control problem due to the nonlinearity nature of PV and unpredictable environmental conditions, and hence, PI controllers do not generally work well [22].



```
AVERAGE100SAMPLES
entry:
Vsum=0; Isum=0; k=0;
during:
Vsum=Vsum+V; Isum=Isum+I; k++;
exit:
Vavg=Vsum/k; Iavg=Isum/k;

SAMPLEandCALCULATE
entry:
deltaV=Vavg-Vprev;
deltaI=Iavg-Iprev;
d=D;

INCREMENT
entry:
d=d+deltad;

DECREMENT
entry:
d=d-deltad;

RETURN
entry:
Vprev=Vavg; Iprev=Iavg;
D=d;
```

Fig. 2. Matlab/Stateflow chart of IncCond algorithm for direct control method

On the other hand, compared with the general MPPT algorithms, the direct control of the MPPT algorithm is simple and uses only one control loop as shown in Fig. 3. The PI controller of the MPPT is excepted because it directly performs the adjustment of the duty cycle within the MPPT algorithm. However, the direct INC MPPT has some drawbacks under the rapidly changing irradiation of a PV system because it uses a fixed iteration step size [18].

The PV array for this simulation has been modeled with a 2D lookup table provided in the Matlab Toolbox and the controlled current source of SimPowerSystems. These methods offer effective data storage and reduction of simulation time. To produce PV array power output by 2D Lookup table as shown in Fig. 1, the I-V values of PV arrays are utilized in accordance with various irradiance conditions. Fig. 5 represents the 3D figure obtained from data utilization of Fig. 4. This result is utilized effectively in practical applications.

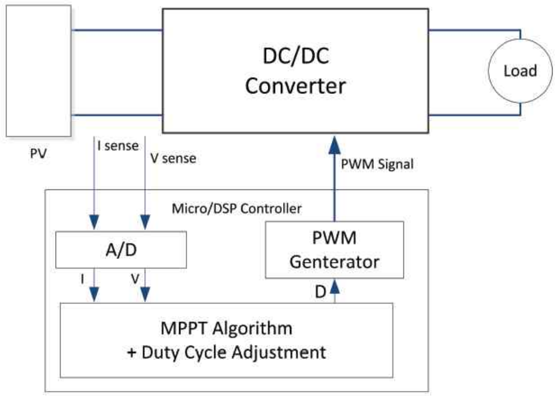


Fig. 3. Block diagram of MPPT with the direct control

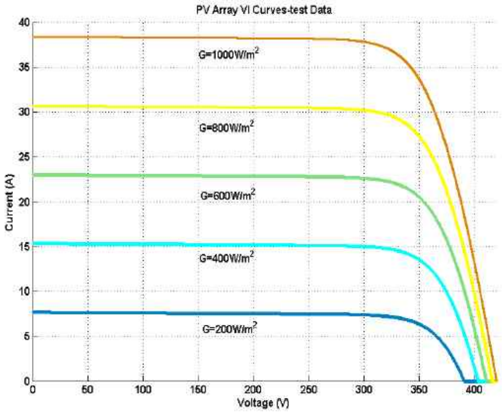


Fig. 4. Characteristic curve of current and voltage according to irradiance

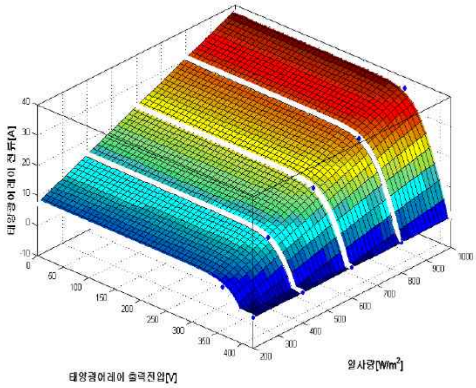


Fig. 5. 3D characteristic of PV array for variable irradiance

Fig. 6 shows the PV system model with dc-dc converter designed by Matlab/Simulink and SimPowerSystems.

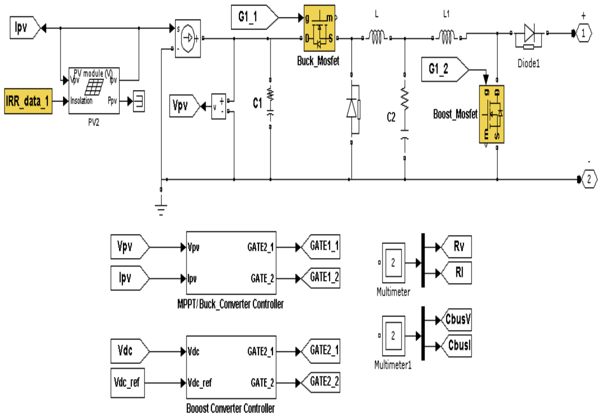


Fig. 6. PV system model with DC-DC converter

2.2 Supercapacitor (SC) Model

Capacitors that store energy within the electrochemical double-layer at the electrode:electrolyte interface are known under various names including trademarks or established colloquial names such as ‘doublelayer capacitors’, ‘supercapacitors’, ‘ultracapacitors’, ‘power capacitors’, ‘gold capacitors’ or ‘power cache’. ‘Electrochemical double-layer capacitor’ is the name that describes the fundamental charge storage principle of such capacitors. Electrical double layer capacitors (EDLCS) are popularly known as Ultracapacitors (UC) or Supercapacitors (SC). These devices are emerging rapidly as green energy storage devices in the field of Hybrid Electrical Vehicles and UPS systems, along with FACTS devices in power systems, electric drive applications and utility applications. Attractive features of SC are its high capacitance, short duration peak power delivery capacity, i.e., high power density, reduced space, environmental safety, low power to weight ratio, and safe, long-lasting cycle life. SCs are fabricated with two electrodes of carbon material and the distance between the two electrodes is so small that the operating voltage of SC is less than 3V. They are commercially available up to 30,000F. High voltage/ high current can be achieved by connecting a greater number of capacitors in series/parallels. SCs can be charged or discharged faster than batteries and have 10 to 20 times more power density than conventional batteries. The energy density offered by SCs is 10 to 100 times [25-26] that of conventional storage.

2.2.1 Considerations in choosing the proper model

In order to model the behavior of SCs, certain requirements are set before the formulation of equivalent circuit models of SCs.

So that the model can be as simple as possible, the model should describe the behavior of the SC accurately and parameters should be determined by using SC terminal measurements. As SCs have complex physical natures, it is very much preferable analyze SC based on a distributed parameter system. SCs are modeled based on three physical aspects: (1) electrochemistry of two different materials interfaced in different phases, which is modeled as an RC circuit. The resistive element depends on the resistance of electrode materials, resistance of electrolytic solvent, pore width membrane porosity, and quality of the connection electrode-collector. (2) Based on the theory of the interfaced tension in the double layer, the capacitance of the SC varies linearly with the capacitor terminal voltage. (3) Double layer charge distribution shows a certain self-discharge. In different states of discharge, there are some important features presented to be taken into consideration when establishing a conceptual model for an SC:

- Series resistance increases with decreasing temperature due to reduced mobility of ions in the electrolyte at low temperatures.
- At an SC with 16 cells, the variation (resistance with temperature) is twice as great as that of an SC with one cell.
- The resistance range is 3.7 times higher at -30℃ to the value measured at 40℃.
- Capacitance depends on the physical parameters of the SC, so it is not influenced by temperature.
- At higher currents, the voltage fluctuates greatly and cannot accurately determine the effects on capacitance (ions in the electrolyte migrate to the harder surfaces of carbon at low temperatures).
- Capacitance variation with voltage introduces a nonlinear component in the system (to increase voltage, the internal electric field attracts more ions and the concentration near the electrode increases).
- At the same voltage, at different temperatures, the capacitance varies more in the charging state. A possible explanation is that during the charging cycle, the diffusion and electrical forces are repelling and during the discharge cycle, they attract.

2.2.2 SC Model

An SC can be modeled by using standard circuit components as shown in Fig. 7. This circuit design is used because a similar circuit is presented in the data sheet for the SC banks from EPCOS [27]. The parameters used in the mathematical modeling of the SC bank are as follows:

C	Capacitance [F]
$C_{SC\text{-}total}$	The total SC system capacitance [F]

ESR, R	Equivalent series internal resistance [Ω]
E_{SC}	The amount of energy released or captured by the SC bank [Ws]
n_s	The number of capacitors connected in series
n_p	The number of series strings in parallel
$R_{SC\text{-}total}$	The total SC system resistance [Ω]
V_i	The initial voltage before discharging starts
V_f	The final voltage after discharging ends [V]

The model consists of a capacitance (C) and an equivalent series resistance (ESR, R) representing the charging and discharging resistance. An equivalent parallel resistance (EPR) represents the self-discharging losses. The ESR is important during charging and discharging since it represents internal heating in the capacitor. The EPR only impacts long term energy storage performance since it models a leakage effect.

The amount of energy drawn from the SC bank is directly proportional to the capacitance and the change in the terminal voltage given by

$$E_{UC} = \frac{1}{2}C\left(V_i^2 - V_f^2\right) \tag{2}$$

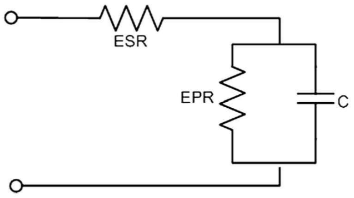


Fig. 7. Simplified SC model

When the SC bank is subject to supply a prescribed amount of energy, the SC terminal voltage decreases. Eq. (2) represents the voltage variation versus energy released or captured by the SC bank. If the SC bank releases energy to the load side, E_{SC} is positive. If energy is captured by the SC bank, E_{SC} is negative. The effective specific energy for a prescribed load can be satisfied by using various SC bank configurations. In practical applications, the required amount of terminal voltage and energy or the capacitance of the SC storage system can be achieved using multiple SCs in series and parallel. The terminal voltage determines the number of capacitors that must be connected in series to form a bank and the total capacitance determines the number of capacitors that must be connected in parallel in the bank. The total resistance and the total capacitance of the SC bank may be calculated as [24]

$$R_{UC-total} = n_s \frac{ESR}{n_p} \tag{3}$$

$$C_{UC-total} = n_p \frac{C}{n_s} \tag{4}$$

The equivalent model shown in Fig. 8 is chosen based on measurements analyzed in [23], developed to fit the curves obtained by processing precision measurements - RC series and parallel linear model in Simulink. An SC comprised standard circuit components, as shown in Fig. 8. (the model is provided in the manufacturer's data sheet) can be modeled as shown in Fig. 9 and Fig. 10, respectively. The circuit includes all components that are used in the base model. Because this is a conceptual circuit more than one that is effectively functional, neither the control of the switch onr of the capacitors is shown. The two variable capacities are nonlinear, dependent on the voltage applied to the entire circuit.

Capacitance C is the one on which depends the behavior of the entire circuit, determining the maximum state of charge of the SC. The amount of stored energy and the value of energy levels variation are determined mainly by the capacitance. Resistance R2, connected in parallel with the capacitor, represents the quantification of the auto discharge effect. Resistance R1 represents losses in the charge/discharge cycle, arising due to resistance of the conductor element; the process is not ideal.

Over voltage protection, provided by R3, is necessary to prevent damages to the elements of the SC, by balancing the voltage of the cells (otherwise, the voltage in an individual cell can increase more than the other values, leading to emission of gas or explosion). This difference in voltage can occur if one cell has a smaller capacitance than the other, which is reflected in the amount of stored energy [29]. Resistance Rp and Cp are included in the circuit to shape the fastest processes in the SC's behavior.

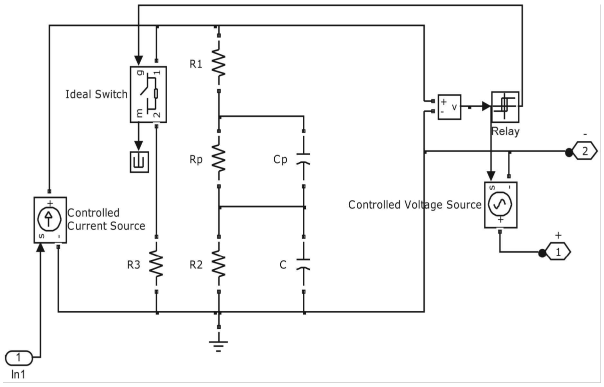


Fig. 8. The basic circuit model of SC for SimPowerSystem

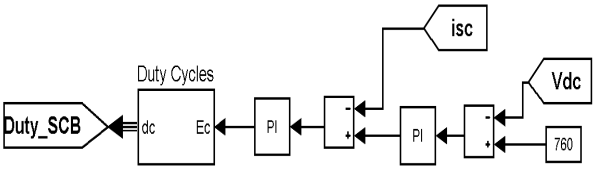


Fig. 9. Control architecture of the bidirectional converter

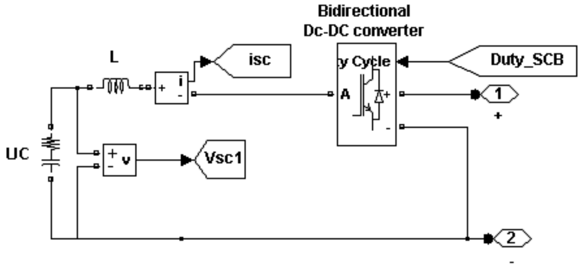


Fig. 10. Simplified UC model with bidirectional dc-dc converter

Simulink is used to create a first model of the SC according to the basic circuit described in Fig. 8. Initial model testing is done with a simple circuit consisting of a resistance in series with a capacitance and resistance in parallel. This base circuit manages to show the basic function of the SC [23]. By adding more components until the circuit described in Fig. 8 is achieved, the accuracy of the model is improved. The Simulink model that is used as the basic model of the SC is shown in Fig. 8. The relay block controls the switch that connects the balancing resistance R3 to the circuit [28].

3. System Model Configuration and Simulation Results

3.1 System model configuration

The proposed system for stand-alone application is shown in Fig. 11. Low-voltage, high-current (power) converters are needed because of the electrical characteristics of the PV cell and the SC bank. All the elements are connected to a DC bus with a DC-link voltage of 760V. The photovoltaic generator with boost converter is directly connected to the DC bus. The SC bank is always connected to the DC bus by means of a two quadrant dc/dc bidirectional converter. In this paper, the DC-link voltage controller is accurately modeled to maintain the dc-link voltage stably for control of the proposed hybrid source structure. The SC's DC voltage is applied to an IGBT two-level inverter generating 60Hz. The IGBT inverter uses PWM at a 20kHz carrier frequency. The circuit is discretized at a sample time of 1 (sec), and the load voltage is regulated at 1pu (380V rms) by a PI voltage regulator using abc to dq and dq to abc transformations.

The first output of the voltage regulator is a vector containing the three modulating signals used by the PMW Generator to generate the 6 IGBT pulses. The second output returns the modulation index. The Discrete 3-Phase PWM Pulse Generator is used as shown in Fig. 12.

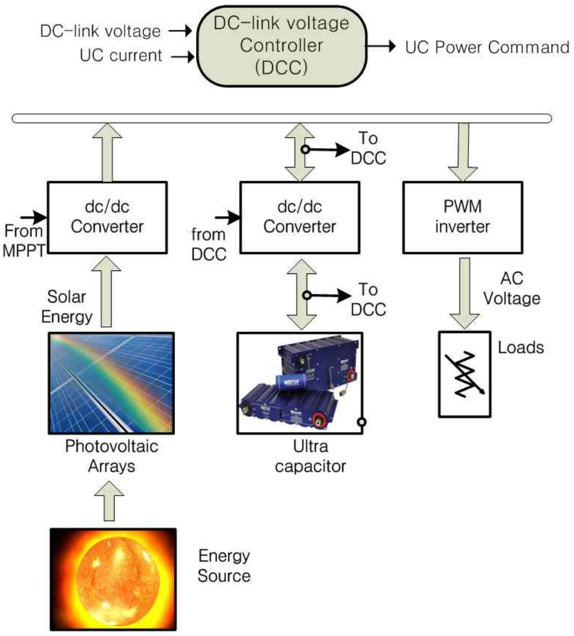


Fig. 11. Block diagram of the proposed system

3.2 Simulation Results

The PV panels used in this study are capable of delivering 12kW of power under maximal radiation conditions. The SC power is limited by the maximum current of 750A as recommended by the manufacturer. The SC can deliver large bursts of power as long as the current is lower than 750A. The initial voltage of the SC bank is set to be 48.6V. Fig. 12 shows the Malab/Simulink model for simulation and the parameters used in this simulation are shown in Table 1 and Table 2.

Fig. 13 shows the output power of the photovoltaic system by the proposed MPPT algorithm by the Matlab/Stateflow box and the charging and discharging power waveform of the supercapacitor bank is shown as in Fig. 14. The positive power region represents the discharge power by the SC bank and the negative power region represents the charge power of the SC bank. Fig. 15 represents the stable characteristics of the DC-link voltage. This is due to good operation of the new proposed dc kink controller and the effective role as a fast storage device. Fig. 16 shows phase voltage and current of load. This shows that the PV array is a good main source and that the SC functions as a buffer to compensate for the uncertainties of the PV source in both steady and transient states. This result verified the good performance of the LC filter.

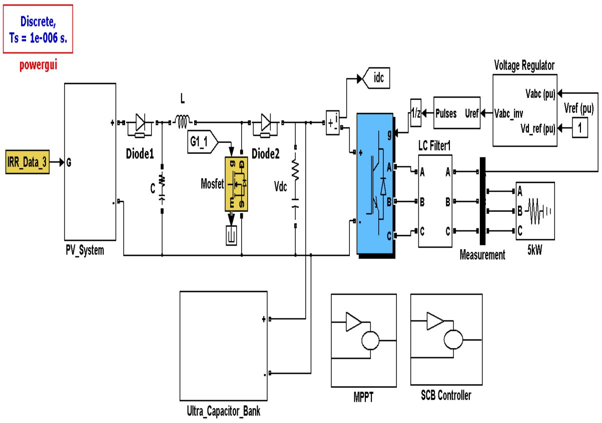


Fig. 12. The Matlab/Simlink model for simulation

Table 1. SC specification

specification	Value
Capacitance[F]	165
Internal series resistance(dc)[mΩ]	6.1
Leakage current[A]	0.0052,73h, 25℃
Operating temperature	-40℃ to 65℃
Voltage[V]	48.6
Short-circuit current[A]	4800
Power density[W/kg]	7900
Energy density[Wh/kg]	3.81
Volume[l]	12.6
Weight[kg]	14.2

Table 2. PV system model parameters

Parameter	Value
The number of series cells per string(Ns)	105
The number of parallel cells per strings(Np)	148
Ideality or completion factor(a)	1.9
Boltzmann's constant(k)	1.3805e-23[J/°K]
PV cell temperature(T)	298[°K]
Electron charge(q)	1.6e-19C
Short-circuit cell current(Isc)	2.926[A]
PV cell reverse saturation current(I0)	0.00005[A]
Series resistance of PV cell (Rs)	0.0277[Ω]

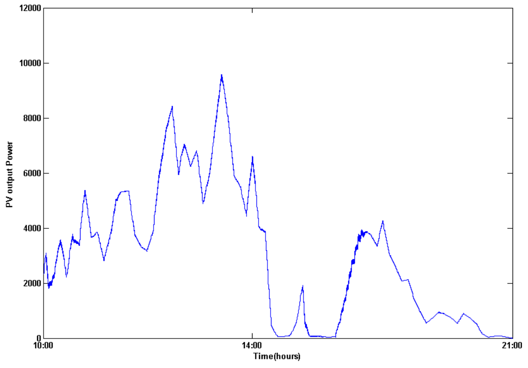


Fig. 13. The power of photovoltaic system by MPPT

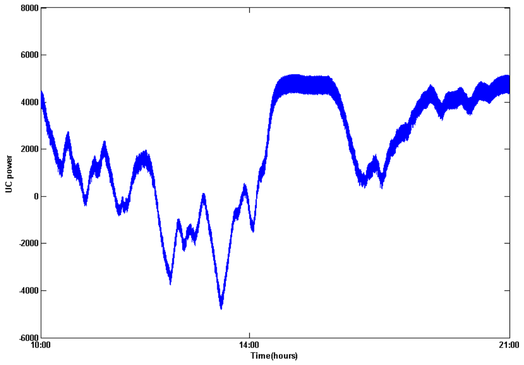


Fig. 14. SC bank charge and discharge power

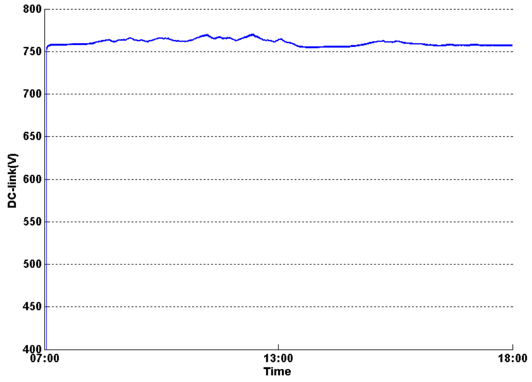


Fig. 15. DC-link voltage by SC bank

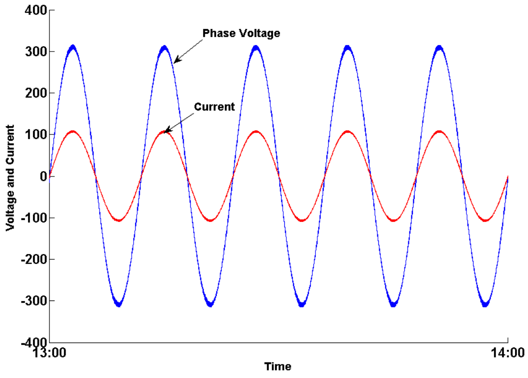


Fig. 16. Phase voltage and current of load

4. Conclusion

The PV-SC hybrid power system is designed and modeled for stand-alone building micro-grid users with appropriate power management controllers and power converters. A compact topology, suitable for high-power applications, is proposed. A behavioral model to simulate the PV energy storage by SCs is justified. The model consists of a code that enables the evaluation of the solar irradiance incident on a PV array, an equivalent electrical circuit for PV module, and an equivalent multi-branch electrical circuit for the set of the SCs with regulator switch and controller. This study integrated a PV system with a SC storage system using a new modeling method including a PV MPPT with direct control and an advanced DC link controller. The developed system and its control strategy exhibit excellent performance for the simulation of a complete day or for longer periods of time. In the future, simple or flexible models that consider the various characteristics of SCs and integrated optimal operation scheme of PV-SC sources will be analyzed for practical applications.

Acknowledgements

The authors would like to gratefully acknowledge the financial support of the KETEP under Grant 2013T100200078.

References

[1] Ulleberg O., "Stand-alone power systems for the future: optimal design, operation and control of solar-hydrogen energy systems," PhD dissertation, Norwegian University of Science and Technology, 1998.

[2] Chedid R, Rahman S., "A decision support technique for the design of hybrid solar-wind power systems," IEEE Transactions on Energy Conversion, Vol. 13, No.1, pp.79-83, 1998.

[3] Spyker R.L., Nelms R.M., "Analysis of double-layer capacitors supplying constant power loads," IEEE Transactions on Aerospace and Electronic Systems Vol. 36, No. 4, pp.1439-1443, 2000.

[4] R. K¨otz and M. Carlen, "Principles and applications of electrochemical capacitors," Electrochimica Acta, vol. 45, no. 15-16, pp. 2483-2498, 2000.

[5] V.A. Shah, et.al., "Improved Method for Characterization of Ultracapacitor by Constant Current Charging", International Journal of Modeling and Optimization", Vol. 2, No. 3, pp.290-294, June, 2012.

[6] Pierre-Olivier Logerais, et al., "Study of Photovoltaic Energy Storage by Supercapacitors through Both Experimental and Modelling Approaches", Journal of Solar Energy Volume 2013, Article ID 659014, pp.9 pages. 2013.

[7] A. Luque, et al., "Handbook of Photovoltaic Science and Engineering", JohnWiley and Sons, Chichester, UK, 2003.

[8] Tao Zhou and Bruno François, "Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration", IEEE Transaction on industrial Electronics, Vol. 58, No. 1, pp. 95-104, Jan. 2011.

[9] Won-Pyo Hong, et al., "Power Control modeling and Simulation of Hybrid Power System for Building Microgrid Connected Application", Journal of KIIEE, Vol.23, No.11, pp.85-93, November 2009.

[10] D. Lu, et al., "Application of Petri nets for the energy management of a photovoltaic based power station including storage units," Renewable Energy, vol. 35, No. 6, pp. 1117-1124, 2010.

[11] M. Uzunoglu, et al., "Modeling control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications," Renewable Energy, vol. 34, No. 3, pp. 509-520, 2009.

[12] Tao Zhou, et al., "Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration", IEEE Transactions on Industrial Electronics, Vol. 58, No. 1, 2011.

[13] W.P.Hong, "Power control and modeling of solar-ultra capacitor hybrid energy system for stand-alone applications", ICCAS 2010, Oct.27-30,2010 in Kintex, Gyeonggi-do, Korea.

[14] H. Patel, et al., "MATLAB-based modeling to study the effects of partial shading on PV array characteristics", IEEE Transactions on Energy Conversion 23, pp. 302-310, 2008.

[15] M. Veerachary, et al., "Voltage-based maximum power point tracking control of PV system," IEEE Transactions on Aerospace and Electronic Systems, Vol.38, Issue 1, pp. 262-270, 2002.

[16] Kashif Ishaque, et al., "Modeling and simulation of photovoltaic (PV) system durin g partial shading based on a two-diode model", Simulation Modelling Practice and Theory 19, pp. 1613-1626, 2011.

[17] Y. Sukamongkol, et al., "A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads," Renewable Energy, Vol.27, Issue 2, pp.237-258, 2002.

[18] Won-Pyo Hong, et al,. "A Variable Step Size Incremental Conductance MPPT of a Photovoltaic System Using DC-DC Converter with Direct Control Scheme", Journal of the Korean Institute of Illuminating and Electrical

Installation Engineers , Vol. 27, No. 9, pp. 74~82, 2013.
[19] K. H. Hussein, et al., "Maximum Photovoltaic Power Tracking : an Algorithm for Rapidly Changing atmospheric Conditions," IEE Proceedings-Generation, Transmission and Distribution, Vol.142, pp. 59-64, 1995.
[20] A. Pandey, et al., "Design issues in implementing MPPT for improved tracking and dynamic performance," in Proc. IEEE IECON 2006, pp.4387-4391, 2006.
[21] I. Houssamo, et al., "Maximum power tracking for photovoltaic power system: development and experimental comparison of two algorithms," Renewable Energy, Vol.35, Issue 10, pp. 2381-2387, 2010.
[22] F. Salem, et al., "An enhanced fuzzy-PI controller applied to the MPPT problem," J. Sci. Eng., Vol.8, No.2, pp. 147-153, 2005.
[23] E. Danila, et al., "MODELS AND MODELLING THE SUPERCAPACITORS FOR A DEFINED APPLICATION", Annals of the University Craiova, Electrical Engineering Series, No. 35, pp. 200-205, 2011.
[24] AHMED AL-JANAD, et al., "ANALYSING PERFORMANCE OF SUPER-CAPACITOR AND BATTERY IN LOW VOLTAGE ELECTRICAL DISTRIBUTION SYSTEMS," Journal of Theoretical and Applied Information Technology,. Vol. 61, No.1, pp. 99-106, 10th March 2014.
[25] H. Douglas and P. Pillay, "Sizing ultracapacitors for hybrid electric vehicles", 31st IEEE annual conference of industrial electronics, pp. 37-50, May 2000.
[26] Varsha A. Shah, et al., "Improved Method for Characterization of Ultracapacitor by Constant Current Charging", International Journal of Modeling and Optimization, Vol. 2, No. 3, June 2012.
[27] Data sheet for super capacitor from EPCOS with Part No.: B48621-S0203-Q288.
[28] Patrik Johansson, "Comparison of Simulation Programs for Supercapacitor Modelling : Model Creation and Verification", Master of Science Thesis, Electrical Engineering Department of Energy and Environment Division of Electric Power Engineering , CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden, 2008.
[29] Y. Cheng, "Assessments of Energy Capacity and Energy Losses of Supercapacitors in Fast Charging-Discharging Cycles", IEEE Trans. on Energy Conversion, vol. 25, No. 1, pp.253-261,2010.

Biography

Won-Pyo Hong

Won-Pyo Hong received a B.S. degree in Electrical Engineering from Sungsil University, Seoul, Korea, in 1978 and M.Sc. and Ph.D. degrees in Electrical Engineering from Seoul National University, Seoul, Korea, in 1980 and 1989, respectively. From 1980 to 1993, he was a senior researcher for the Korea Electric Power Research Institute at the Korea Electric Power Cooperation. He was a visiting professor at the UBC, Canada, from 2007 to 2008. He is a professor in the Department of Building and Plant Engineering of Hanbat National University, where he has taught since 1993. His main research interests are building energy and management systems, smart green buildings, fieldbus bus-based control and distributed energy systems.