International Journal of Research in Engineering and Innovation (IJREI)

journal home page: http://www.ijrei.com

ISSN (Online): 2456-6934

Dynamic control of power flow in DC microgrids with the participation of photovoltaic power generation and battery using power converters

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Abstract

This paper designs a hybrid system with the participation of photovoltaic power generation and battery that can regulate flows of power in a two-source DC microgrid. A center of measuring and hybrid dynamic control basing on analyzing power-flow cases and characteristic of the generation is constructed to hold voltage at DCbus at a fixed value and make power ratio delivered from each source track the reference value to resolve demand-side management program. Power converters are used as main blocks to harness maximum available power from the generation and regulate flows of power in whole DC microgrid. An experimental model is also designed including power and control circuits and the center of hybrid dynamic control to observe working states or change the working modes as natured or required. Experimental results prove the good adaptability to different tasks of the center of hybrid dynamic control and the good capability to analyze power flow in whole system as designed. They also prove that the proposed structure and center of hybrid dynamic control are able to apply to meet demand-side management problem in large systems when combined with forecasting systems of load and available power of photovoltaic power generation in considered period time.

Keywords: Demand-side management, DC microgrid, hybrid control system, power-flow control, photovoltaic power generation, power converter.

1. Introduction

Photovoltaic power generation (PVG) can be harnessed in isolated or grid-connected systems. It is also coupled with energy storage (ES) such as battery, fuel cell, supercapacitor, or other generations to construct hybrid systems. In these systems, power converters play an important role to extract energy at maximum power point (MPP), synchronize with the utility, and regulate power flow as required or dispatched and meet intelligent requirements at each node in the smart grid [1-5].

The IB-AVC method is a new approach that helps to extract all available power of PVG. Because of combining the iterative and bisectional technique in the maximum power point tracker (MPPT), the average voltage control technique and using information provided by a pyrometer (PYR) and temperature sensor (Temp), IB-AVC method can help to bring dynamic control of power flow from PVG at any variation of power of solar irradiance (G) and p-n junction temperature (T). Because it actively calculates parameters at MPP before creating control pulse to regulate DC/DC converter, it can help to reduce power loss in the circuit and avoid losing control signal when predicting wrong movement of working points caused by the variation of (G, T) or value of voltage at DCbus as traditional methods. For this reason, IB-AVC is one of best method to exploit all available energy of PVG [6].

DC/DC converters (buck, boost, buck-boost, one or bidirectional) and DC/AC converters (single or three phases) are often used in systems harnessing PVG. Input terminals of DC/DC converters are directly connected to PVG and their output terminals are connected to an ES or utility. Power from PVG goes through DC/DC converters, charges ES, directly provide for AC load in isolated system or deliver to

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utility. So, DC/AC converters convert DC current/voltage to AC current/voltage that has the suitable frequency for AC load and utility. Controllable switches (SW) placed in above converters must be changed on and off states in each duty cycle to conduct flows of power as calculated by controllers [1-5].

Value of exchanged power at each node can be required by dispatchers or continuously provided by demand-side management (DSM) program to harness optimal capacity of all blocks [7-9]. In two-source DC hybrid microgrids, an working schedule in considered period time will be created basing on rated, measured and predicted information to provide expected values to controllers and balance sources on power. Moreover, flow of power from each source in this microgrid can change depending on natured or required mode. For natured mode, the difference between values of voltage and capacity of sources decides the distribution of power in these system. For required mode, the amount of power or proportion of power (POP) can be set up by the operator or DSM program. For this reason, a center of hybrid control system (HCS) at each node must be designed by collecting all controllers to optimize flows of power in whole system. Due to the variation of (G, T) and electrical load, HCS also execute dynamic control of power flow at any time to meet electrical load and solve DSM program. Moreover, flows of power are often analyzed as natured depending on impedance or the difference of voltages [7], [8] so there has not had any deep study yet to give out a clear method to accommodate as required. With the participation of PVG, the power-flow distribution becomes more complexly and it needs to build a method to accommodatethe time of charging/discharging for ES and make a working plan in long time. According to the advantages of power electronic, control of power flow in DC microgrids can be done completely by using DC/DC converters.

To overcome above problem, this paper will design a system and a center of measuring and HCS to supply electric for AC load in an isolated microgrid. This system has two sources, where one source has the participation of PVG and another source characterizes for a balanced source. HCS will gather problems of harnessing MPP of PVG and controlling flows of power in a DC microgrid using power converters to adapt the DSM program. The second section will introduce the scheme system including general structure, power sharing control strategy and control scheme. The third section will represent an experimental model that helps to distribute flows of power as natured or required. Experimental results will be shown in the fourth section. The last section will represent some conclusions, contributions and future study.

2. Scheme system

2.1 Organization

The considered a microgrid has two sources, where source 2 plays a role of balancing power and source 1 is a combination of PVG and ES. SWs in DC/DC_{pv}, DC/DC_{s1}, DC/DC_{s2} converters are controlled by a center of measuring and HCS. General structure of the system is represented in Fig. 1.

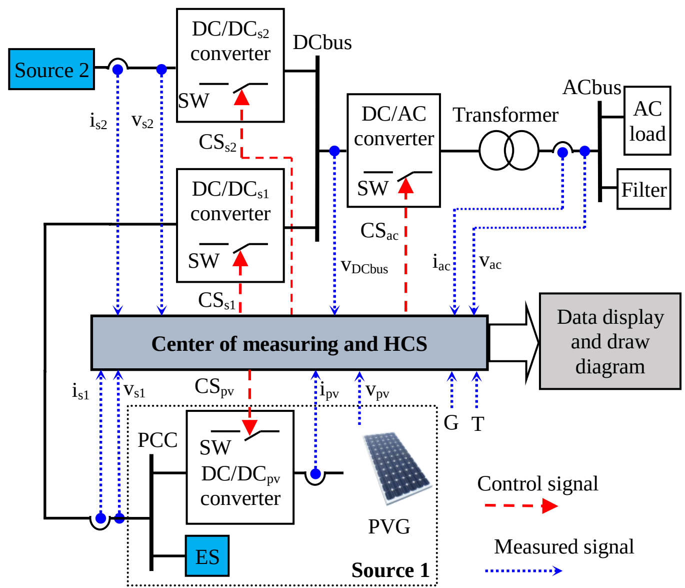


Figure 1: General structure

The center of measuring collects information measured by sensors to dispatch and draw diagrams, including:

- Current sensors provide instantaneous values of currents about i_{s1} and i_{s2} generated from sources, i_{ac} at ouput terminals of DC/AC converter, i_{pv} generated from PVG.
- Voltage sensors provide instantaneous values of voltages about v_{s1} and v_{s2} at output terminals of sources, vac at output terminals of the transformer, vpv at output terminals of PVG and v_{DCbus} at DCbus.
- PYR provides instantaneous value of G and temperature sensor provide instantaneous value of T.

Center of HCS includes 4 different controllers for DC/DC_{pv}, DC/DC_{s1}, DC/DC_{s2} and DC/AC converters. Controllers that create control signals CS_{pv}, CS_{s1}, CS_{s2} and CS_{ac} co-ordinates to each other to execute requirements of the operator or DSM program.

2.2 Power sharing control strategy

In two-source system with the participation of PVG as depicted in Fig. 1, information about a reference value of POP_{ref} (proportion of power between power from source 1 and source 2) or working mode (natured or required) can be set up. Center of HCS collects all measured information to work power-flow cases in whole system as represented in Fig. 2.

Where: p_{pv}, p_{ES}, p_{s1}, p_{s2} are instantaneous values of power from PVG, ES, source 1 and source 2. Continuous lines show the positive value of power, dash lines show the zero value of power.

Power in whole system will be distributed and controlled by the center of HCS in the following rules:

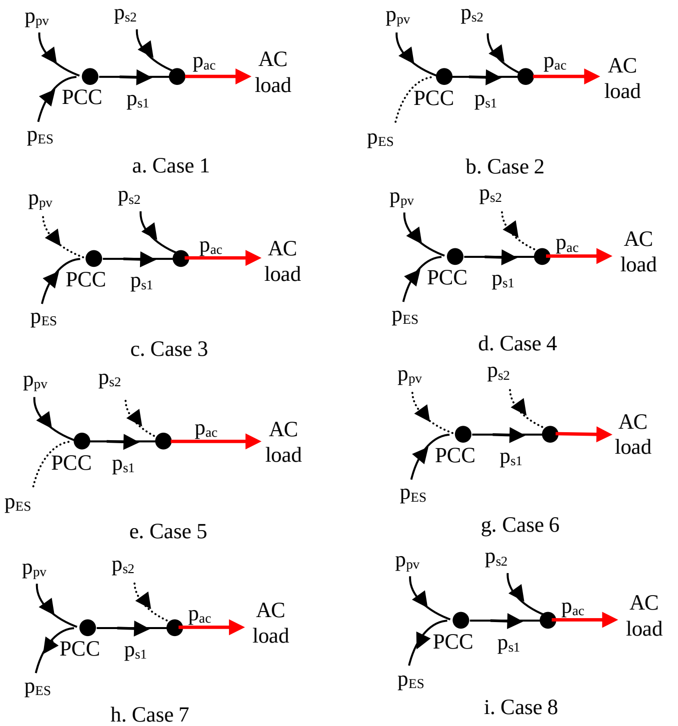


Figure 2: Power-flow cases

- Power harnessed at MPP of PVG goes through the DC/DC_{pv} converter to point of common coupling (PCC) in source 1 as depicted in case 1 (Fig. 2a), case 2 (Fig. 2b), case 4 (Fig. 2d), case 5 (Fig. 2e), case 7 (Fig. 2h), case 8 (Fig. 2i).
- Power P_{s1} from source 1 can be the sum of both PVG and ES as depicted in case 1 (Fig. 2a) and case 4 (Fig. 2d) when power at output terminals of the DC/DC_{pv} converter is smaller than p_{s1} or only PVG as depicted in case 2 (Fig. 2b) and case 5 (Fig. 2e) when power at output terminals of the DC/DC_{pv} converter is equal p_{s1} or only ES as depicted in case 3 (Fig. 2c) and case 6 (Fig. 2g) when there is not any power from PVG (value of G is too small).
- Power of AC load can be supplied by both sources as depicted in case 1 (Fig. 2a), case 2 (Fig. 2b) or case 3 (Fig. 2c) when POP_{ref} is set up by the operator or DSM program.
- Power of AC load can be only supplied by source 1 as depicted in case 4 (Fig. 2d), case 5 (Fig. 2e), case 6 (Fig. 2g) as required by the operator or DSM program (source 2 is to reserve).
- There is redundant power from PVG that charges ES after supplying power P_{s1} as depicted in case 7 (Fig. 2h) and case 9 (Fig. 2g).

Above analysis shows that PVG, the DC/DC_{pv} converter and ES will be merged to become source 1. Flows of power in this source depend on required power that must be mobilized from source 1 at each time. Moreover, power from source 1 or source 2 depends on the requirement of AC load, ability to generate power of PVG and working mode (change control signal of CS_{pv}, CS_{s1} to control SWs placed in DC/DC_{pv} and DC/DC_{s1} converters). Voltage at DCbus is controlled to maintain at a reference value $V_{DCbusref}$ by sending control signal CS_{s2} to drive SW placed in the DC/DC_{s2} converter. Furthermore, control signal CS_{ac} is determined to change on and off states of SWs placed in the DC/AC converter in each duty cycle to create AC signal (frequency is 50 Hz) at output terminals [10], [11], [12]. Power flow (p_{ac}) going through the DC/AC converter is power of AC load and loss in the transformer and switching loss.

Control strategy for center of HCS is represented in Fig. 3.

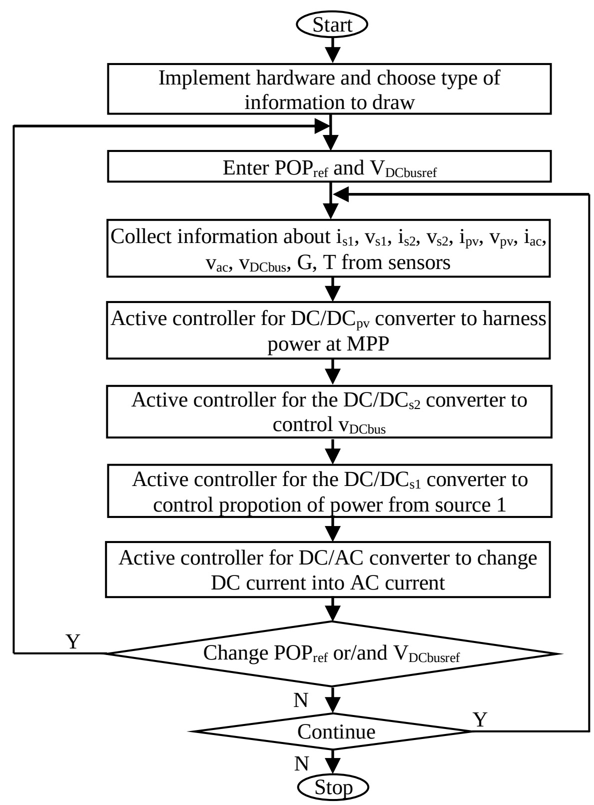
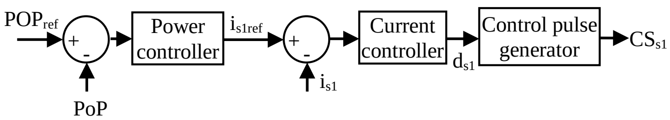


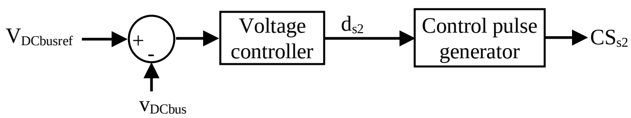
Figure 3: Control strategy for center of HCS

2.3 Control scheme

As above analysis, IB-AVC method is one of the best method to harness power at MPP for PVG. Using information about (G, T), value of voltage at MPP is always accurately determined by the IB technique in MPPT to provide a desired destination for the controller of the DC/DC_{pv} converter. Value of P_{mpp} determined by MPPT is used to compare with instantaneous value of p_{pv} to evaluate the ability to track MPP at any working condition. The controller for the DC/DC_{pv} converter using the IB-AVC method was tested and evaluated very carefully to highly meet the dynamic requirement for the process of harnessing MPP [6]. So, designing controllers for DC/DC_{s1} and DC/DC_{s2} converters is an important task to control flows of power. The principle to design the control structure is that controller for the DC/DC_{s2} converter considers source 2 as a large and stable source to regulate voltage at DCbus at value of $V_{DCbusref}$ (set up by the operator) and the controller for the DC/DC_{s1} converter regulates the value of $p_{s1}$to reach value of POP_{ref}. Control structure to regulate $V_{DCbusref}$ and POP_{ref} is represented in Fig. 4.



a. For DC/DC_{s1} converter



b. For DC/DC_{s2} converter

Figure 4: Control structure for DC/DC_{s1} and DC/DC_{s2} converters

3. Experimental model

3.1 Implementation of the experimental model

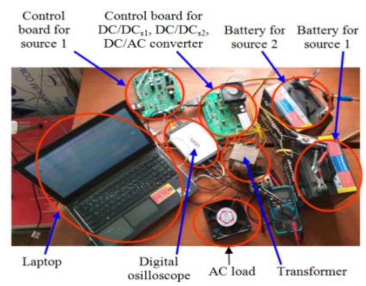
An experimental model is designed to test the ability to control flows of power in the DC microgrid in accordance with the DSM program. Main blocks in the experimental model are:

- A SV-55 panel (a production of Scott-Gemany). Parameters of SV-55 panel defined in STC is shown in Table 1.

Table 1. Parameters of a SV-55 panel

Type of parameters	**Value**
Short-circuit current (A)	3.25
Open-circuit voltage (V)	22.14
Voltage at MPP (V)	18.4
Current at MPP (A)	3.06
Temperature coefficient of I_{SC} (mA/^{0}C)	4.7
Temperature coefficient of V_{OC} (mV/^{0}C)	-0.743
Temperature coefficient of power (%/^{0}C)	-0.451
Photo-generated current (A)	3.2502
Reversed saturation current (A)	$1.623x10^{-8}$
Thermal voltage at p-n junction (V)	1.141
Series resistor (Ω)	0.151
Parallel resistor (Ω)	1675.9

- Sensor to measure G is PYR-BTA (a production of Vernier), sensor to measure T is LM-35 (a production of National Semiconductor).
- A power and control board for the DC/DCpv converter, a power and control board for DC/DC_{s1}, DC/DC_{s2} and DC/AC converters. ATMega328U microprocessors are placed in above boards to calculate and decide before sending control signal to pulse driver.
- Batteries are used in this model to characterize for source 2 and ES in source 1. Their capacity is 35 Ah and nominal voltage is 12V (a production of Dong Nai branch).
- AC load is an electric motor. The nominal power is 40W and the nominal voltage is 220V.
- A power transformer is used in this model to stepvoltage up and filter harmonic. Winding ratio of high side and low side is 760/28. Diameter of high voltage side winding is 0.45 mm and diameter of low voltage side is 2.1 mm.
- OWON digital oscilloscope is used to measure voltage waveform of high and low voltage side of the transformer.The implementation of the model is depicted in Fig. 5.



a. Power and control circuit

b. PVG and PYR

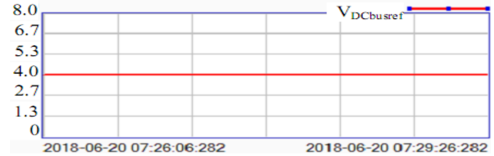
Figure 5: Implementation of the experimental model

Center of HCS is combined by the program for DC/DC_{pv} converter to regulate PVG and the program for DC/DC_{s1}, DC/DC_{s2} and DC/AC converters. A control/management program is designed by the Kingview 6.5 software in the laptop to observe instantaneous information and send control signal to the board. Measured information is transfered from boards to laptop by RS232 communication. The operator directly sets value of POP_{ref} and $V_{DCbusref}$ up and selects working buttons (called auto and manual buttons) in the control/management program that help to study natured and required distribution.

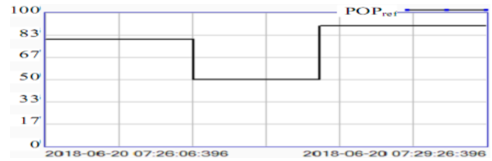
4. Experimental results

The first and the second sample tests were executed in 20 June 2018 to study flows of power in the natured mode. In these tests, the operator switches to the auto button in the program. The first sample test, from 7:26:06 to 7:29:26 (T was near a constant and approximately 35^0C), the value of $V_{DCbusref}$ was hold at 4 V (constant) while value of POP_{ref}changed in three levels (decreased from 80% to 50% and then increased up to 90%). The second sample test, from 7:50:48 to 7:54:08 (T was near a constant and approximately 44^0C), value of POP_{ref} was hold at 90% while value of $V_{Dcbusref}$was changed in three levels (increased from 4 V to 6 V and then decreased to 5 V). The experimental results in these sample test are represented in Fig. 6 and Fig. 7. These results show that values of i_{s1}, i_{s2}, p_{s1}, p_{s2} can not be affected by values of POP_{ref}. Corresponding to the variation of (G, T), power from PVG tracked MPP correctly (p_{pv} diagram coincided P_{mpp} diagram) and power delivered to PCC was smaller than ppv due to the power loss in the DC/DC$_{pv}$ converter). Because value of voltage on source 1 is always higher than it on source 2 and there has the participation of PVG, almost p_{ac} power always provided by source 1. In both these two sample tests, The controller for the DC/DC$_{s2}$ converter helped to drive v_{DCbus} to $V_{DCbusref}$ accurately and flow of power from source 2 only occupies a small ratio even when AC load increases (accordance with increasing $v_{DCbusref}$). It means that the controller for the DC/DC$_{pv}$ converter worked very well in the extraction process to harness all maximum power from PVG and flows of power between sources distributed naturally.

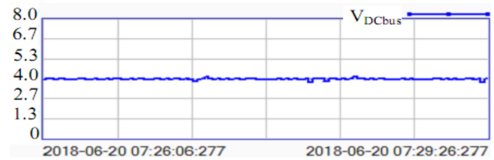
The third and fourth sample tests were also executed in 20 June 2018 to study the required mode. In these tests, the operator switches to the manual button in the program. The third sample test, from 9:59:16 to 10:02:36 (T was near a constant and approximately 46^0C), the value of $V_{DCbusref}$was changed in three levels (increased from 5 V to 6 V and then decreased to 5 V) while value of POP_{ref} was also changed in three levels (decreased from 80% to 50% and then increased up to 90%). The fourth sample test, from 10:32:14 to 10:35:34 (T was near a constant and approximately 43^0C), the value of $V_{DCbusref}$ was changed in four levels (decreased from 7 V to 6 V and then increased to 7.5 V and finally decreased to 6 V) while value of POP_{ref} was hold at 60%. The results in these sample test are represented in Fig. 8 and Fig. 9. These results show that values of i_{s1}, i_{s2}, p_{s1}, p_{s2} are highly affected by values of POP_{ref} and $v_{DCbusref}$. Similar to the first and second sample test, power from PVG tracked MPP correctly (p_{pv} diagram coincided P_{mpp} diagram) and power delivered to PCC was smaller than p_{pv} due to the power loss in the DC/DC$_{pv}$ converter). The controller for the DC/DC$_{s2}$ converter helped to drive v_{DCbus} to $V_{DCbusref}$ accurately although v_{DCbus} must be taken a short time to track $V_{DCbusref}$. Power from sources changed correctly in accordance with the increase or decrease of POP_{ref}. It means that flows of power in this model distributed very exactly as required, help to well prove the ability to regulate power flow in the DC microgrid using power converters.



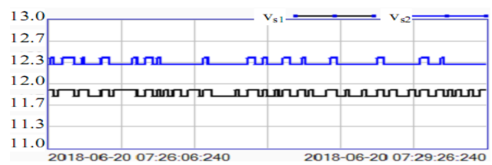
(a) Diagram of $V_{DCbusref}$



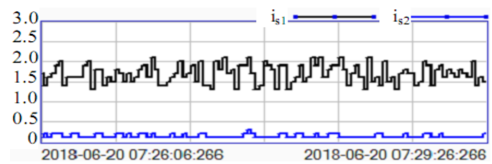
(b) Diagram of POP_{ref}



(c) Diagram of v_{DCbus}



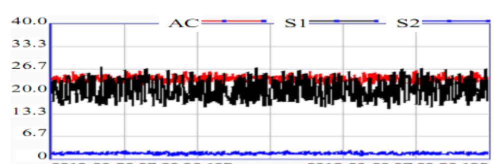
(d) Diagrams of v_{s1} and v_{s2}



(e) Diagrams of i_{s1} and i_{s2}

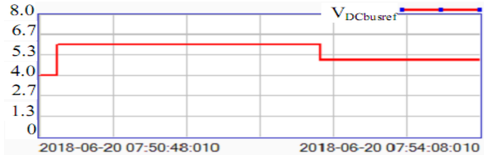
(g) Diagrams of G

(h) Diagrams of P_{mpp}, p_{pv}, p_{DCbus}

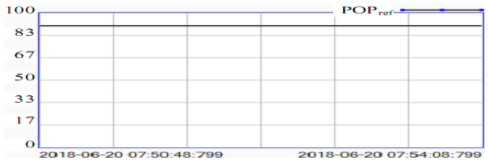


(i) Diagrams of power through DC/AC converter and p_{s1}, p_{s2}

Figure 6: The first sample test

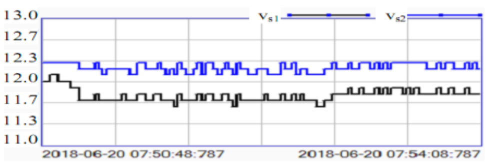


(a) Diagram of $V_{DCbusref}$

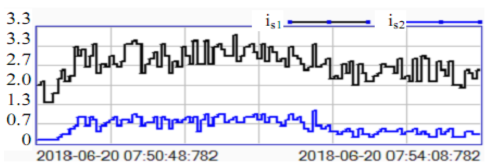


(b) Diagram of POP_{ref}

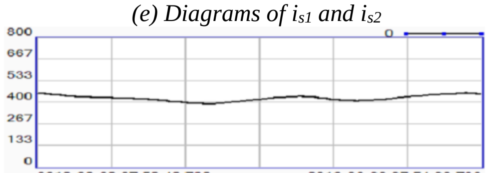
(c) Diagram of v_{DCbus}



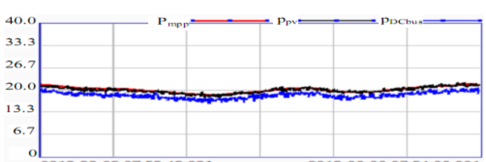
(d) Diagrams of v_{s1} and v_{s2}



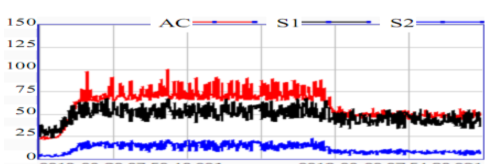
(e) Diagrams of i_{s1} and i_{s2}



(g) Diagram of G

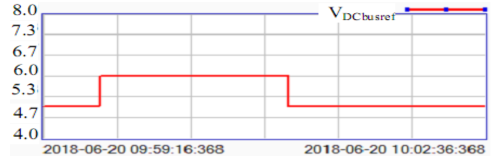


(h) Diagrams of P_{mpp}, p_{pv}, p_{DCbus}



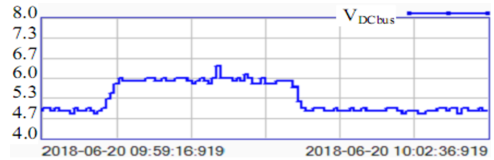
(i) Diagrams of power through DC/AC converter and p_{s1}, p_{s2}

Figure 7: The second sample test



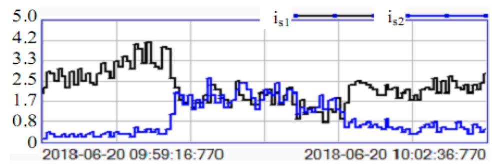
(a) Diagram of $V_{DCbusref}$

(b) Diagram of POP_{ref}

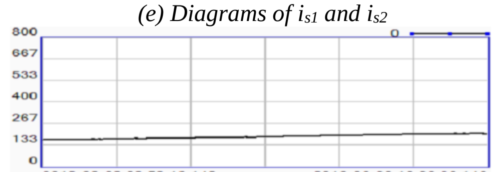


(c) Diagram of v_{DCbus}

(d) Diagrams of v_{s1} and v_{s2}

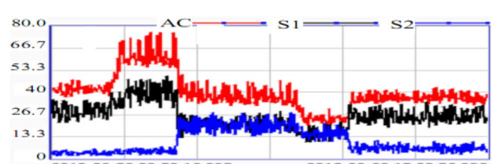


(e) Diagrams of i_{s1} and i_{s2}



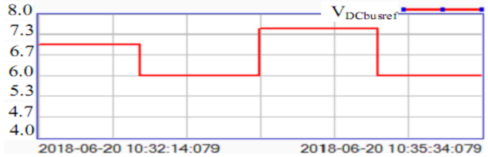
(g) Diagram of G

(h) Diagrams of P_{mpp}, p_{pv}, p_{DCbus}



(i) Diagrams of power through DC/AC converter and p_{s1}, p_{s2}

Figure 8: The third sample test

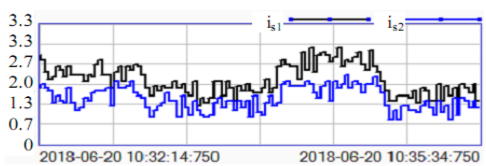


(a)Diagram of $V_{DCbusref}$

(b) Diagram of POP_{ref}

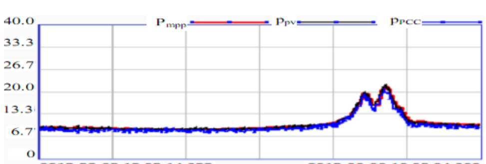
(c) Diagram of v_{DCbus}

(d) Diagram of v_{s1} and v_{s2}

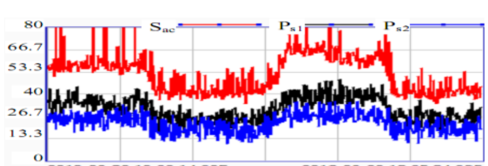


(e) Diagram of i_{s1} and i_{s2}

(g) Diagram of G



(h) Diagrams of P_{mpp}, p_{pv}, p_{DCbus}



(i) Diagrams of power through DC/AC converter and p_{s1}, p_{s2}

Figure 9: The fourth sample test

Using OWON digital oscilloscope, wave forms of AC voltage signal at terminals of the transformer (red line for low voltage side and yellow line for high voltage side) are represented in Fig. 10. Wave form of AC voltage signal contains high harmonic content at the low voltage side and low harmonic content at the other side because the transformer plays an important role of filtering harmonic. It can help to reduce harmonic before providing electric for AC load. Moreover, the controller for the DC/AC converter worked very well because it provided the standard frequency (50 Hz).

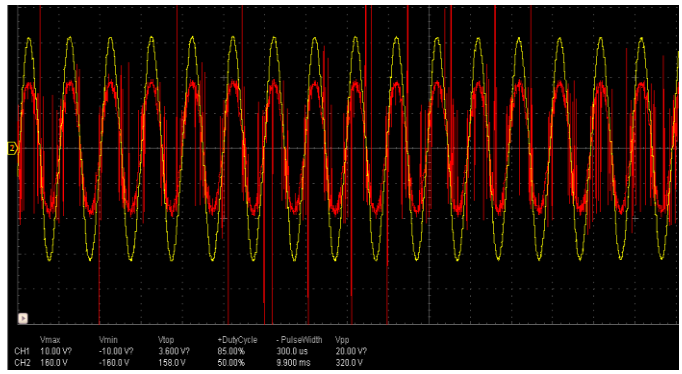


Figure 10: Wave forms of AC voltage signal

5. Conclusion

This paper proposed a hybrid system that has the participation of PVG and designed a center of measuring and HCS. Flows of power in whole system can be analyzed as natured or required by the operator or DSM program using power converter. The center collected all measured information and determined suitable control pulse for DC/DC_{pv}, DC/DC_{s1}, DC/DC_{s2}, DC/AC converters. All controllers in HCS correctly coordinated to harness power at MPP of PVG, regulate values of $V_{DCbusref}$ and POP_{ref} and create a suitable AC signal to provide electric for AC load.

An experimental model including power and control circuits, motor load, transformer, batteries, SV-55 panel and computer was designed to depict the proposed system. Experimental results showed the capacity of analyzing power flow as natured or required. For natured, mobilized power from each source depends on the power generating from PVG and the voltage difference of sources. For required, the mobilized power from each source always accurately track the reference value not depending on power from PVG. It showed the flexibility of HCS in a complex system that have the participation of multi generations. Due to the participation of PVG, voltage at PCC (source 1) was always higher than voltage of source 2. It showed the correct characteristic of the battery when it has a power delivered to its input terminals.

Experimental results in sample tests show the experimental model is suitable to operate a hybrid system in DSM problem using power converters. The study of control design for power converters in the hybrid system represents a correct direction to harness power at MPP and regulate power flow in whole system and create AC signal to adapt AC load in isolated systems. It also shows the correct approach and feasibility of DSM problem in system harnessing renewable energy. This model can be enlarged and developed to apply in large system to enhance the capacity of devices and make intelligent for each bus in whole system.

Acknowledgement

This study is partly supported by Science research project (ID: DH2018-TN02-02), Thai Nguyen University, Viet Nam

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