Operation strategy for grid-tied DC-coupling power converter interface integrating wind/solar/battery

H L Jou1,4, J C Wu2, J H Lin1, W N Su3, T S Wu3 and Y T Lin3

1Department of Electrical Engineering National Kaohsiung University of Applied Sciences Kaohsiung, Taiwan
2Department of Microelectronics Engineering National Kaohsiung Marine University Kaohsiung, Taiwan
3Institute of Nuclear Energy Research, AEC, EY, Taiwan

E-mail: hljou5519@gmail.com

Abstract. The operation strategy for a small-capacity grid-tied DC-coupling power converter interface (GDPCI) integrating wind energy, solar energy and battery energy storage is proposed. The GDPCI is composed of a wind generator, a solar module set, a battery bank, a boost DC-DC power converter (DDPC), a bidirectional DDPC power converter, an AC-DC power converter (ADPC) and a five-level DC-AC inverter (DAI). A solar module set, a wind generator and a battery bank are coupled to the common DC bus through the boost DDPC, the ADPC and the bidirectional DDPC, respectively. For verifying the performance of the GDPCI under different operation modes, computer simulation is carried out by PSIM.

1. Introduction

The conventional fossil fuels have resulted in the problems of greenhouse emissions and climate change and thus damaged the earth’s environment seriously [1,2]. Paris agreement on global reduction of greenhouse emissions to relieve the climate change has promoted to use the renewable energies worldwide [3]. The wind energy and solar energy are the most attractive renewable energy sources now. However, the wind energy and solar energy have the characteristics of instability, intermittence and hard to be predicted. Battery energy storage can be integrated to make the energies of wind generator and solar module set more stable and reliable [4-7].

Power converter interface is one of the key technologies for the applications of the wind energy and solar energy effectively. The power converter interface for integrating wind energy, solar energy and battery energy storage can be divided into the AC-coupling topology [8,9] and DC-coupling topology [8-12]. Figure 1 shows the diagram of AC-coupling topology, and the diagram of DC-coupling topology is shown in figure 2.

As seen in figure 1, it consists of a wind generator, a solar module set, a battery bank, an AC-DC power converter (ADPC), a DC-DC power converter (DDPC), a bidirectional DDPC and three DC-AC inverters (DAIs). The output AC voltage of wind generator is rectified by an ADPC, and a DAI for converting the DC power to AC power injecting into the grid or supplying to the load. The module set is connected to a DDPC and a DAI connecting in cascade for converting the solar power to AC power injecting into the grid or supplying to the load. A combination of a bidirectional DDPC and a DAI is
used for charging or discharging the battery bank. In this circuit, three individual DAIs are needed to couple the energies of wind energy, solar energy and battery energy storage at the AC grid. It is known as AC-coupling topology.

![Diagram of AC-coupling topology for integrating the wind/solar/battery.](image1)

![Diagram of DC-coupling topology for integrating the wind/solar/battery.](image2)

As seen in figure 2, it consists of a wind generator, a solar module set, an ADPC, a DDPC, a bidirectional DDPC and a DAI. The output of wind generator is converting to the DC power by an ADPC. A DDPC has the function of regulating the voltage and the output power of solar module set. The battery bank is connected to a bidirectional DDPC for charging or discharging the battery power. The outputs of ADPC, DDPC and bidirectional DDPC are connected to a common DC bus of DAI which is operated as an interface to the grid or the load. It is known as DC-coupling topology. In this circuit, only a DAI is shared by three energy sources.

As can be seen in figures 1 and 2, it can be found that six power converters are required in AC-coupling topology and only four power converters are used in the DC-coupling topology. Hence, it can save two DAIs in the DC-coupling topology although the capacity of DAI should be enlarged slightly. Moreover, the energy is only processed by two power conversion stages in the DC-coupling topology but is processed by four power conversion stages in the AC-coupling topology when the charging power of battery bank is from the output powers of wind generator and solar module set. Therefore, the DC-coupling topology has the advantages of simplified hardware, lower cost and higher energy efficiency.

In this paper, operation strategy for small-capacity grid-tied DC-coupling power converter interface (GDPCI) integrating the wind energy, solar energy and battery energy storage is presented. The output powers of wind generator, solar module set and battery bank are coupling to the common DC-bus of a simplified five-level inverter through an ADPC, a boost DDPC and a bidirectional DDPC, respectively. The performance of GDPCI under different operation modes is validated by the simulation of PSIM.

2. Circuit topology

Figure 3 is the power circuit for the proposed small-capacity GDPCI integrating the solar energy, wind energy and battery energy storage. It is composed of a permanent magnetic synchronous generator (PMSG), a solar module set, battery bank, an ADPC, a boost DDPC, a bidirectional DDPC and a bidirectional five-level DAI. The ADPC is connected to PMSG, and it is comprised of a three-phase rectifier and a boost DDPC due to the consideration of cost in the application of small-capacity wind power generator. The bidirectional DAI is a five-level inverter which can save two power electronic switches as compared with the conventional five-level T-type power converter.

3. Operation strategy
The operation of proposed small-capacity GDPCI can be divided into five operation modes based on the charge/discharge of battery bank. Modes 1, 2, 3 are the charging modes, and modes 4 and 5 are the discharging modes. Table 1 shows the conditions of different modes. The power flow diagrams for five operation modes are shown in figures 4-8.

Table 1. Conditions of different operation modes.

| mode | conditions | charge/discharge |
|------|------------|------------------|
| 1    | \( P_{\text{wind}} + P_{\text{solar}} \leq P_{\text{bat}} \) | charge          |
| 2    | \( P_{\text{bat}} + P_{\text{load}} < P_{\text{wind}} + P_{\text{solar}} \) | charge          |
| 3    | \( P_{\text{bat}} + P_{\text{load}} < P_{\text{wind}} + P_{\text{solar}} \) | charge          |
| 4    | \( P_{\text{load}} + P_{\text{wind}} + P_{\text{solar}} < P_{\text{bat}} \) | discharge       |
| 5    | \( P_{\text{load}} < P_{\text{wind}} + P_{\text{solar}} + P_{\text{bat}} \) | discharge       |

**Figure 3.** Power circuit for proposed small-capacity GDPCI.

**Figure 4.** Power flow diagram for mode 1.

**Figure 5.** Power flow diagram for mode 2.

**Figure 6.** Power flow diagram for mode 3.
3.1. Charge

- **mode 1:**
  The generated power of wind solar is smaller than the demanded power of battery bank. In this condition, the insufficient charging power is supplied by the grid. The power flow diagram of the GDPCI is shown in figure 4.

- **mode 2:**
  The generated wind power and solar power is larger than the demanded power of battery bank but smaller than the demanded power of battery bank and the load. In this condition, the generated wind generator and solar module set is charged to the battery bank, and the additional generated power is supplied to the load. The insufficient demanded load power is supplied by the grid. The power flow diagram of the GDPCI is shown in figure 5.

- **mode 3:**
  The generated power of wind and solar is larger than the demanded power of battery bank and the load. In this condition, the generated wind power and solar power is charged to the battery bank and supplied to the load, and the additional power is fed to the grid. The power flow diagram of the GDPCI is shown in figure 6.

3.2. Discharge

- **mode 4:**
  The demanded power of load is larger than the generated power of wind and solar power and the output power of the battery bank in this condition. The generated power of wind and solar as well as the output power of the battery bank is supplied to the load, and the grid supplies the insufficient demanded power of load. The power flow diagram of the GDPCI is shown in figure 7.

- **mode 5:**
  The generated power of wind and solar power and the output power of the battery bank are larger than the demanded power of the load in this condition. The generated wind power, solar power and the output power of the battery bank are supplied to the load, and the additional power is fed to the grid. The power flow diagram of the GDPCI is shown in figure 8.

4. Simulation results

Computer simulation by PSIM is used to validate the function of the GDPCI under different operation modes. The battery bank is charged by the hybrid constant-current (CC)/constant-voltage (CV) strategy. The value of CC is 15 A, and the value of CV is 270 V.

Figure 9 shows the simulation result during the transient from mode 1 to mode 2. The demanded load power is 5 kW, the output power of wind generator is 1 kW and the output power of solar is 1.5 kW. It can be found that the battery bank is charged by 15 A before 3.47 s. The battery voltage reaches
270 V at 3.47 s, and the battery bank is changed from the CC to the CV. The generated power of wind and solar is charged to the battery bank when the generated power is small than the charging power of battery bank. The current charging to the battery bank is decreased gradually when the battery bank is charged by CV. The demanded power of the battery bank is then smaller than the generated power of wind and solar at about 3.52 s. And then, the additional generated power is supplied to the load and the grid supplies the insufficient load power. The operation of GDPCI is changed from mode 1 to mode 2.

Figure 9. Simulation result during the transient from mode 1 to mode 2, (a)$v_{\text{inv}}$, (b)$i_{\text{grid}}$, (c)$i_{\text{inverter AC}}$, (d)$i_{\text{load}}$, (e)$i_{\text{Rwind AC}}$, (f)$i_{\text{solar}}$, (g)$i_{\text{bat}}$, (h)$v_{\text{bat}}$, (i)$V_{\text{dc bus}}$.

Figure 10. Simulation result during the transient from mode 1 to mode 3, (a)$v_{\text{inv}}$, (b)$i_{\text{grid}}$, (c)$i_{\text{inverter AC}}$, (d)$i_{\text{load}}$, (e)$i_{\text{Rwind AC}}$, (f)$i_{\text{solar}}$, (g)$i_{\text{bat}}$, (h)$v_{\text{bat}}$, (i)$V_{\text{dc bus}}$.

Figure 10 shows the simulation result during the transient from mode 1 to mode 3. The demanded power of load is 1 kW, the output power of wind generator is 1 kW and the generated power of solar is 1.5 kW. It can be found that the battery bank is charged by CC 15 A before 3.47 s. The voltage of battery bank reaches 270 V at 3.47 s, and the battery bank is changed from CC to CV. The battery current is decreased gradually when the battery bank is charged by the CV. The demanded power charged to the battery bank is smaller than the generated power of wind and solar at about 3.52 s. Then, the additional generated power t is supplied to the load. The charging power of the battery bank is still decreased gradually, and the additional generated power after absorbing by the load is fed to the grid at about 3.6 s. The operation of GDPCI is changed from mode 1 to mode 3.

Figure 11 shows the simulation result for mode 4. The demanded load power is 5 kW. The output power of wind generator and solar module set are respectively 1 kW and 1.5 kW and the power discharging by the battery bank is 2 kW. The generated wind power, and solar power as well as the discharging power of battery bank are supplied to the load, and the grid supplies the insufficient load power. The power of battery bank is turned off while the voltage of battery bank reached 200 V for protecting over-discharging of battery bank.

Figure 12 shows the simulation result during the transient form mode 1 to mode 5. The demanded load in this condition is 2 kW. The output power of wind generator is 1 kW, and the output power of solar module set is 1.5 kW. The battery bank is charged by a constant current of 15 A before 2.6 s, and the GDPCI is thus operated in mode 1. The battery bank is changed from CC charging of 15 A to constant power (CP) discharging of 2 kW at 2.6 s. The operation of GDPCI is changed from mode 1 to mode 5.
5. Conclusions
The number of power converters using in the grid-tied AC-coupling GDPCI for integrating wind energy, solar energy and battery energy storage is six, and that using in the GDPCI is only four. Besides, the number of power conversion stages for charging the battery bank by the wind energy or solar energy is four in the AC-coupling topology, and that is only two in the DC-coupling topology. Therefore, the DC coupling topology is superior to the AC-coupling topology due to the advantages of simplified hardware, lower cost and higher energy efficiency.

The operation of GDPCI integrating small-capacity wind energy, solar energy and battery energy storage are divided into five operation modes based on the charge/discharge of battery bank. Three modes are for charging battery bank, and two modes are for discharging battery bank. Computer simulation verifies the operation strategy of the GDPCI under different operation modes.

Acknowledgments
The authors would like to express their acknowledgments for the financial support of Institute of Nuclear Energy Research Atomic Energy Council under the contract NL1060284. This paper is commissioned to study, but the paper does not represent the opinions of the commission unit.

References
[1] Pendergast D 2006 Kyoto and beyond: Development of sustainable policy IEEE EIC Climate Change Technol 1-3
[2] Arai J, Iba K, Funabashi T, Nakanishi Y, Koyanagi K and Yokoyama R 2008 Power electronics and its applications to renewable energy in Japan IEEE Circuits and Syst Mag 8 52-66
[3] Dimitrow R S 2016 The Paris agreement on climate change: Behind closed doors Global Environ Politics 16 1-11
[4] Manimekalai P, Harikumar R and Raghavan S 2013 An overview of batteries for photovoltaic (PV) systems Int J of Computer Appl 82 28-32
[5] Díaz-González F, Sumper A, Gomis-Bellmunt O and Villafáfila-Robles R 2012 A review of energy storage technologies for wind power applications Renew and Sust Energy Reviews 2154-72
[6] Simões M G, Busarello D T C, Bubshait A S, Harirchi F, Pomilio J A and Blaabjerg F 2016
Interactive smart battery storage for a PV and wind hybrid energy management control based on conservative power theory *Int J of Control* 89 850-70

[7] Masaud T M, Lee K and Sen P K 2010 An overview of energy storage technologies in electric power systems: What is the future? *North American Power Symposium (NAPS)* pp 1-6

[8] Nejabatkhah F and Li Y W 2014 Overview of power management strategies of hybrid AC/DC microgrid *IEEE Power Electron Society* 30 7072-89

[9] Badwawi R A, Abusara M and Mallick T 2015 A review of hybrid solar PV and wind energy system *Smart Sci* 3 127-38

[10] Zhang F G, Chen X Y, Yin X J and Wang Z S 2013 An improved capacity ratio design method based on complementary characteristics of wind and solar *Electr Mach and Syst (ICEMS)* 405-408

[11] Valenciaga F and Puleston P F 2005 Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy *IEEE Trans on Energy Conver* 20 398-405

[12] Zhang Y, Jia H J and Guo L 2012 Energy management strategy of islanded microgrid based on power flow control *IEEE PES Innovative Smart Grid Technol (ISGT)* 1-8