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A BI-DIRECTIONAL DC/DC CONVERTER FOR HYBRID WIND GENERATOR/BATTERY SYSTEM WITH STATE MACHINE CONTROL

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ABSTRACT
This paper presents a bi-directional dc/dc converter used in a hybrid wind generator(WG)/lead-acid battery power system with state machine control. State machine control strategy is used to control the system power flow and load sharing and it can also raise the system power capacity. The battery is charged or discharged through the bi-directional dc/dc converter. By adjusting the duty cycle of the power converter, multi-stage current charging control of batteries is realized and the efficiency of charging is improved. The proposed control method can be easily extended to other renewable energy conversion systems.

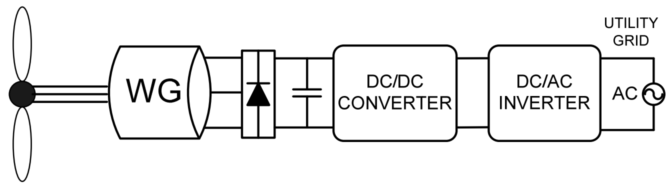
KEY WORDS
Wind generator, state machine, hybrid system, battery

1. Introduction

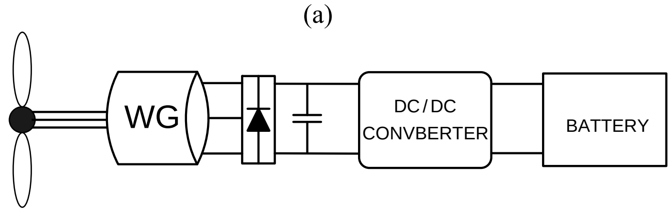
Human beings had used wind energy for many purposes such as for pushing a ship since five thousands years ago. Currently, people pay much attention to the issues related to environmental problems especially global warming. With a view to saving and protecting the environment, renewable energy resources are used generally and wind energy becomes a popular choice among numerous renewable energy resources. Wind energy is wildly used in autonomous systems for power supplying remote loads and grid-connected systems or other applications.

For recent years, the intensity of wind turbine blade as well as the structure of the machines have been strengthening gradually due to the rapid development of industrial technology. Because of increasing the length and volume of the blade, the capacity of generator has been raised and power cost has been decreased relatively. Furthermore, variable speed operation is applied to increase the wind energy which is produced in the process of generating. There is no doubt that the technology of power electronic has been advanced a lot. Compared with other renewable energy recourses, wind power can be used to generate efficiently with the mature technology[1].

Since wind energy possess the unstable and intermittent properties, the power electronic interface which connects the generator with load handles the power conversion and adjusts system parameters.



(a)



(b)

Figure 1 (a) Grid-connected application (b) Stand-alone application

There are two kinds of wind energy conversion systems: 1) Fig. 1(a) shows the block diagram of a wind power system in grid-connected applications. The system is used to take advantage of the wind generator with large capacity as energy source in general. The ac voltage generated with a wind generator is regulated with the rectifier and adjusted with a dc/dc converter, and then the dc/ac inverter inverses the dc voltage to ac output voltage and feeds it into utility line[2]. 2) Fig. 1(b) shows the block diagram of a stand alone wind power conversion system. This kind of system generally uses small wind turbine generator as the power source. The generator output is regulated by the rectifier and adjusted by a dc/dc converter. The output dc voltage charges up the battery as a load[3].

As the wind speed is low, the efficiency of wind generator becomes much lower because of the non-linear relationship between generator rotor speed and output power. Hence, maximum power point trackers are settled in wind power systems to increase the generating efficiency commonly.

As shown in Fig. 2, this paper presents a hybrid power system which composes of a wind generator, a lead-acid battery, a dc/dc boost converter and a dc/dc bi-directional converter. The structure of the system owns the

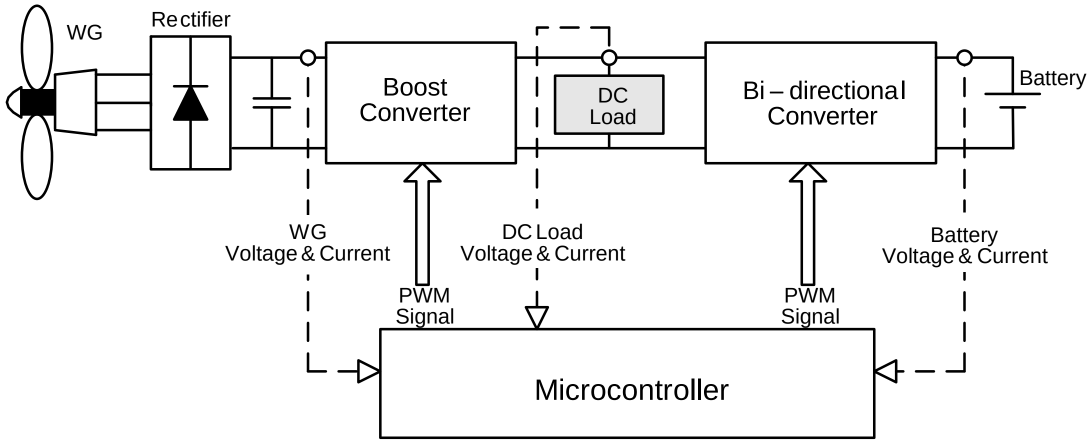


Figure 2. Block diagram of the proposed system

the characteristics of the power systems mentioned above. The state machine control is used to control the dc/dc bi-directional converter and manage the power produced by a wind generator so that the wind energy is used efficiently.

2. WG Characteristics

The energy in moving air is given by the following equation:

$$P_{wind} = \frac{1}{2}\rho A V^3 \qquad (1)$$

where ρ is the air density (typically 1.25 kg/m^3), A is the area swept by the rotor blades (m^2), and V is the velocity of the air (m/s).

The generator input power which means the mechanical power produced with the blade of wind turbine is given by the following expression:

$$Pm = \frac{1}{2}\pi R^2 \rho C_P V^3 \qquad (2)$$

where R is the blade radius (m), C_p is the wind-turbine power coefficient.

The maximum value of C_P is theoretically about 59% which is affected by the variation of generator tip-speed-ratio as follows:

$$TSR = \frac{\Omega R}{V} \qquad (3)$$

where Ω is the WG rotor speed of rotation (rad/s).

Assuming the generator efficiency is η, and then the total output power produced by the generator is

$$P = \eta Pm \qquad (4)$$

Theoretically, there is a generator maximum power point that corresponds to a value of TSR in different wind speed. Therefore, it shows a non-linear relationship between generator output power and rotor speed when the

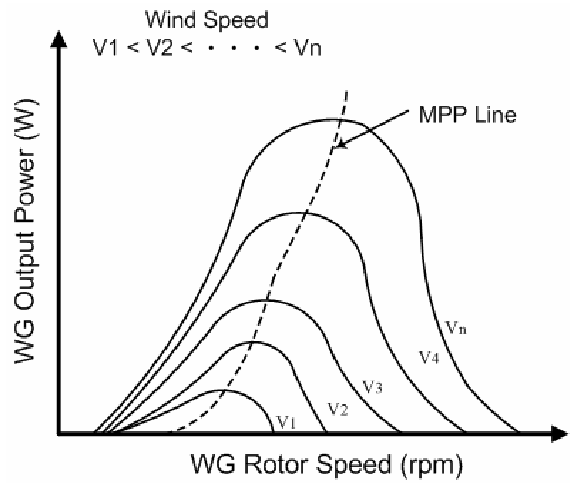


Figure 3 The WG output power curves at various wind speed

wind speed is fixed. The value of maximum output power is called the maximum power point[4]. Fig. 3 shows the power curve between generator rotor speed and output power.

Variable speed operation of wind generator enables the system to reduce the mechanical stress on generator blades and gears effectively. Besides, the design of system structure and control strategy has great effect on the system performance and the output power of generator.

3. Structure of the Proposed System

Fig. 4 shows the circuit diagram of the proposed system. The ac output of WG is converted to dc by using a three-phase full-bridge rectifier first. A boost dc/dc converter is used to raise the dc input voltage to a higher and fixed voltage level. The output dc voltage of boost converter is delivered to the dc load and provides the energy for battery charging as the WG generates enough power. On

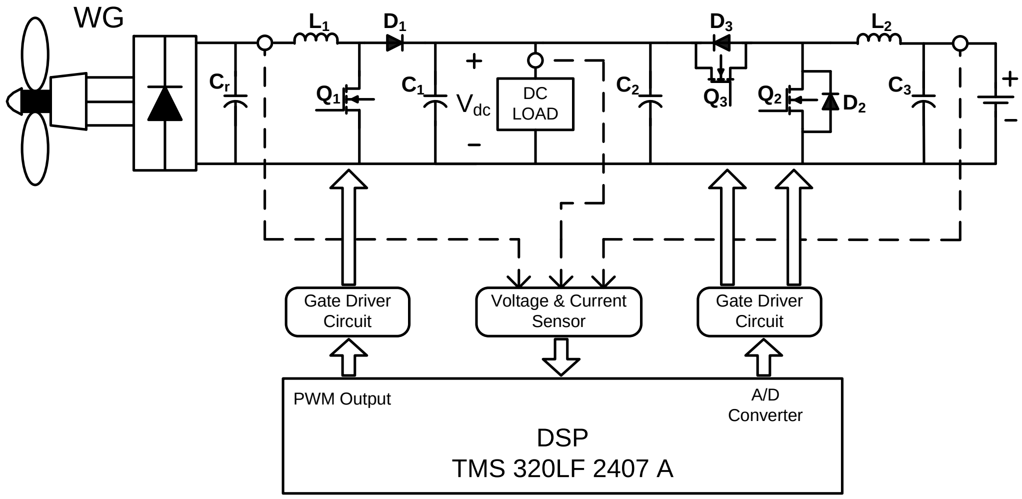
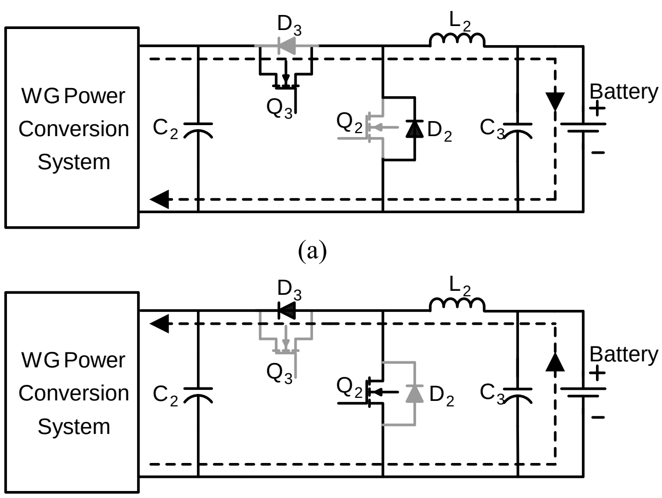


Figure 4. Circuit diagram of the proposed system

the other hand, the battery discharges through the bi-directional dc/dc converter to provide power compensation when the WG capacity is less than the load capacity.



(a)

(b)

Figure 5. The operation mode of the proposed system
(a) buck mode (b) boost mode

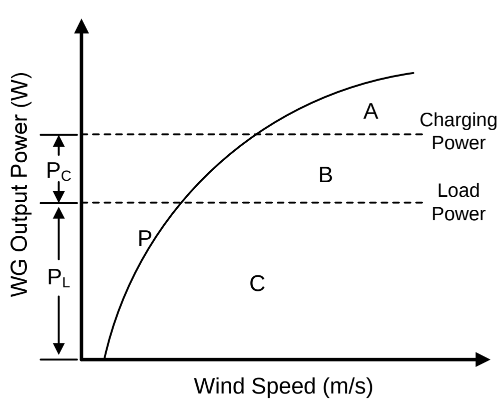


Figure 6. The relationship between WG output power and load required power

The operation mode of bi-directional dc/dc converter is shown in Fig. 5. The bi-directional dc/dc converter has two main switches (Q_2 and Q_3) and two main diodes(D_2 and D_3). It can operate as:

(1) Buck converter (Q_3 and D_2 on, Q_2 and D_3 off), which charges the battery from dc bus.

(2) Boost converter (Q_2 and D_3 on, Q_3 and D_2 off), which supplies energy to the load when the WG output is less than required load power.

The power inductors L_1, L_2 and the output capacitor, C_1 and C_3 respectively are calculated as follows[4]:

$$L_1 \geq \frac{V_{dc} D_{\min} (1 - D_{\min})^2}{2 f_S I_{OB}} \tag{5}$$

$$L_2 \geq \frac{V_{bat} (1 - D_{b,\max})}{f_S \Delta I_{L2}} \tag{6}$$

$$C_1 \geq \frac{I_{OH} D_{\max}}{f_S \Delta V_{dc}} \tag{7}$$

$$C_3 \geq \frac{V_{bat} (1 - D_{b,\max})}{8 f_S L_2 \Delta V_{bat}} \tag{8}$$

where f_S is the dc/dc converter switching frequency of the proposed system, V_{dc} is the output voltage of the boost converter, $D_{\min}$ and I_{OB} are the minimum duty cycle value and the minimum output current of the boost converter, respectively, V_{bat} is the output voltage or the battery voltage, $D_{b,\max}$ is the maximum duty cycle of the bi-directional dc/dc converter when operating in the buck mode, ΔI_{L2} is the peak-to-peak ripple current of the inductor L_2, $D_{\max}$ is the maximum duty cycle, I_{OH} is the maximum output current of the boost converter, ΔV_{dc} is the ripple of boost converter output voltage, ΔV_{bat} is the ripple of bi-directional dc/dc converter output voltage when working in the buck mode.

4. System Control Strategy

4.1 State Machine Control Strategy

Fig. 6 shows the relationship between the WG output power and the required load power. Assuming the non-linear variation of WG output power is ignored, the WG output power P increases when the wind speed rises. P_L and P_C represent the required power by the dc load and the power for charging the battery, respectively. Regions A, B and C indicate the states of load capacity and generator capacity under different wind speeds.

In region A, the WG output power generates enough power for delivering to the load and charging the battery. In region B, the WG output power is enough to for the load but unable to charge the battery with maximum charging current. This means the bi-directional converter must execute the MPPT algorithm during the charging process. The battery has to discharge for compensation because the WG output power is less than the required load power in region C.

The diagram of state machine control strategy is shown in Fig. 7. The circles represent the regulation modes (state) and the arrows mean changes from one regulation mode to another (events). The state machine control strategy chooses only one regulation mode and the bi-directional dc/dc converter operates only one control objective at any time. If the system works at region C as mentioned above, the battery discharges (DCB mode). When the system works at region A, multi-stage current charging method is used to charge the battery (MCB mode). If the system works at region B, the WG MPPT algorithm applies (CMPPT). If the battery voltage is lower than the preset minimum voltage level and the WG output is not enough for the required load power, the system shuts down.

4.2 Multi-stage Current Charging Method

Fig. 8 depicts the V-I curve of multi-stage current charging method. The initial charging current is set to C/10, where C is the battery capacity in ampere-hours. The battery voltage is measured and when it reaches the preset voltage, denoting an overcharging condition, the maximum battery charging current is decreased. This process repeats until the maximum battery charging current is reduced to below C/100. Then it means a 100% state of battery charge[5].

Fig. 9 shows the flowchart of multi-stage current control method. The program variables are initialized and the microcontroller detects the charging current and the battery voltage first. If the battery voltage rises above the preset voltage level, the maximum charging current is reduced to protect the battery from overcharging. Charging process won't stop until the maximum charging current is lower than the C/100 level, meaning a 100% battery state of charge. If the charging current can not reach the required maximum current level, then the program enters the MPPT process to increase the WG output power and charging efficiency. In addition, the maximum charging current is initialized if the battery voltage is below the minimum voltage level.

Advantages of multi-stage current charging method are:

(1) Avoid overcharging to extend battery lifetime by presetting a limit voltage level.
(2) Increase the charging efficiency by using multi-stage current charging method and maximum power point tracking algorithm alternatively.

4.3 MPPT Technique

If the MPPT process begins, the duty cycle of bi-directional dc/dc converter is adjusted as follows[6]:

$$D_n = D_{n-1} + \Delta D_{n-1} \tag{9}$$

$$\Delta D_{n-1} = K \cdot sign\,(\Delta D_{n-2}) \cdot sign\,(P_{b,n-1} - P_{b,n-2}) \tag{10}$$

where ΔD_{n-1} is the duty cycle change of bi-directional dc/dc converter at step $k - 1$; $P_{b,n-1}$ and $P_{b,n-2}$ are the bi-directional converter input power levels at step $k - 1$ and $k - 2$, respectively; K is a constant which controls the speed and accuracy of the convergence to the MPP. The function $sign(x)$ is defined as

$$sign(x) = 1, \quad \text{if } x \geq 0$$
$$sign(x) = -1, \quad \text{if } x < 0. \tag{11}$$

Fig. 10 shows the diagram of WG power maximizing process. Since the duty cycle is adjusted continuously to move to the top of WG power curve, the duty cycle is

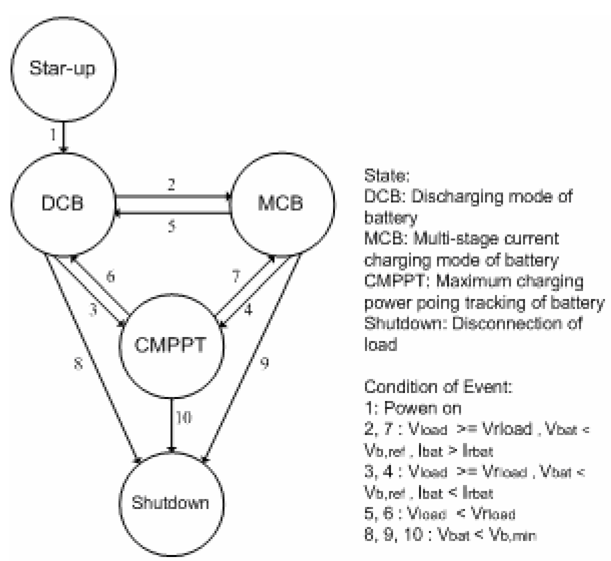


Figure 7 The diagram of state machine control strategy

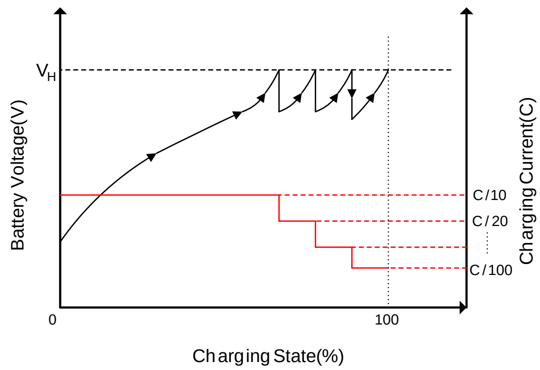


Figure 8 The V-I curve of multi-stage current charging

increased to the left side of power curve, resulting in a reduction of WG rotor speed and power increase. The process won't stop until the steady state operating region is reached. On the contrary, when the starting point is on the right side, decreasing the duty cycle results an increase of WG rotor speed and power raise. The process won't stop until the steady state operating region is reached.

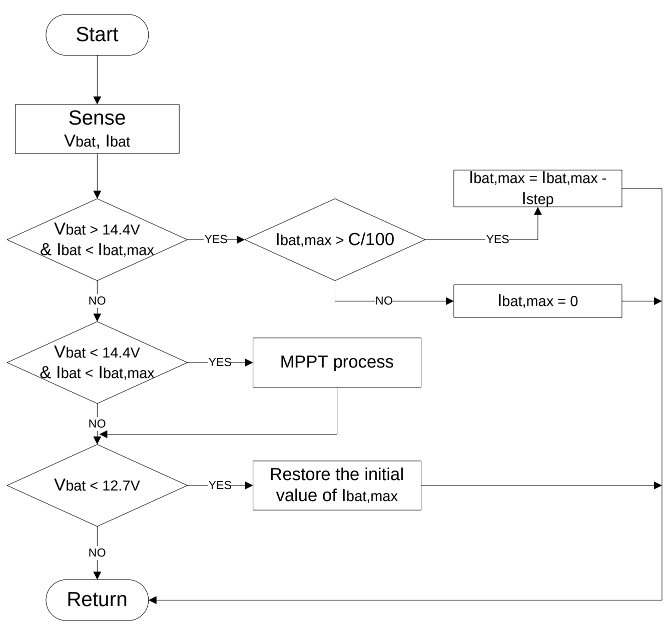


Figure 9 The flowchart of multi-stage current control

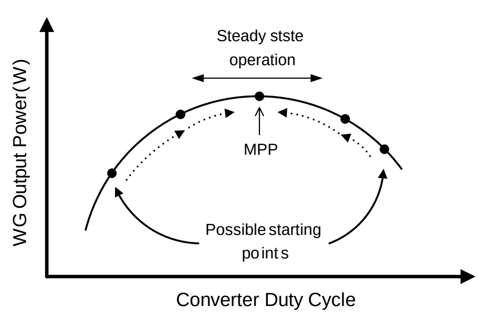


Figure 10 The diagram of MPP tracking process

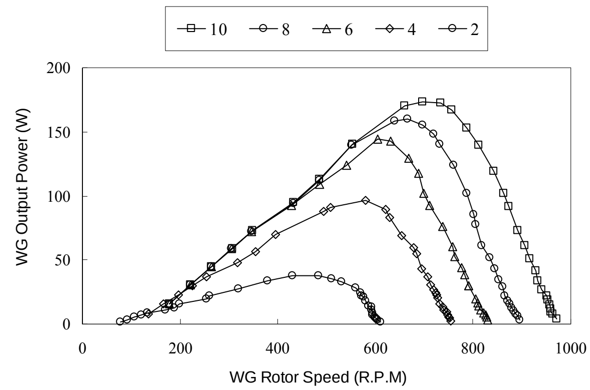


Figure 11 Experimental result of WG output power curves at various wind speed

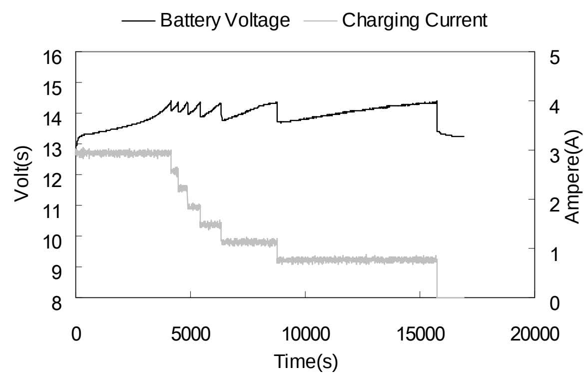


Figure 12 The V-I curve of multi-stage current charging control

5. Experimental Results

A WG simulator which connects with a PC is used to perform the experiments. The rated output power of WG simulator is 200W. A servo motor works to drive the generator. The control interface of WG simulator provides an option of numbers from 0 to 10 which represents the magnitude of drive signal for the servo motor. The bigger the number is, the faster the wind speed is. Once the number of drive signal is fixed, the wind speed is fixed as well.

The real time wind speed information is difficult to measure because the WG is a simulation system. Therefore, the integral number will be used to represent the wind speed magnitude in the following experimental results.

Fig. 11 shows the WG output power curves at various wind speed. The WG output power increases first and then decreases when the wind speed is fixed. The maximum values of curves represent their maximum power points.

The V-I curve of multi-stage current charging method is shown in Fig 12. A 12V, 50Ah lead-acid battery is used in charging experiments. The initial charging current is set to be 3A and it is decreased when the battery voltage reaches 14.4V. This process is repeated until the maximum value of battery charging current is lower than preset value.

Fig. 13 shows a 10-min system operating test and the data are sampled per 5 seconds. A 50Ω-1kW resister is used as the load and the load voltage (boost converter output voltage) is fixed at 60V. The charging current is set at 3A. At various wind speeds, the system can measure the change of load voltage, the load current, the output current of boost converter and the input current of bi-directional converter at load side (positive at buck mode and negative at boost mode).

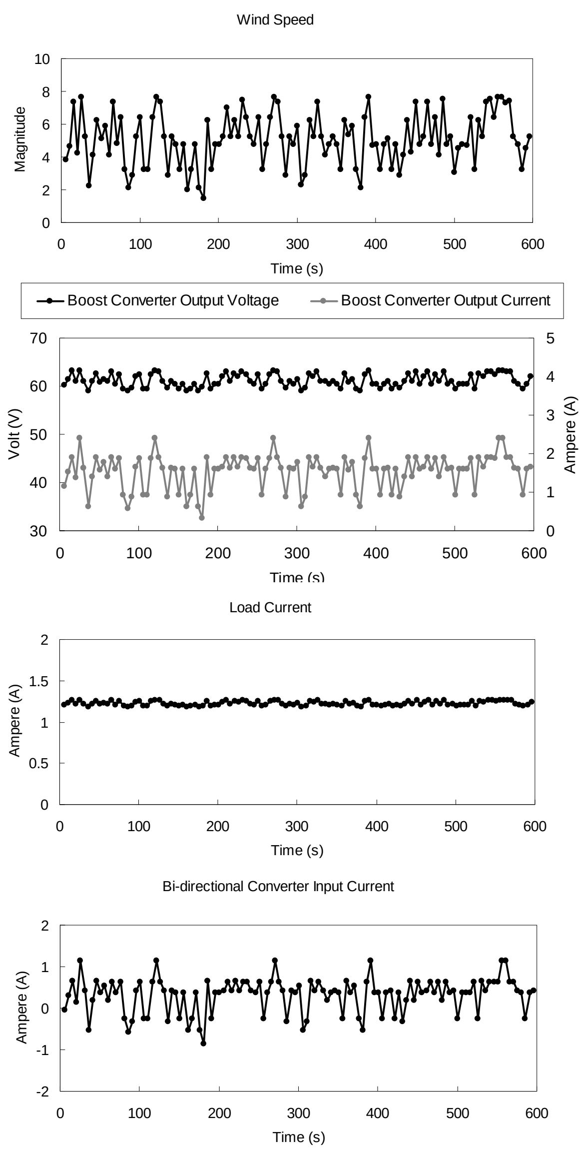


Fig. 13 Wind speed, load voltage, load current, output current of boost converter and input current of bi-directional converter versus time.

6. Conclusion

This paper presents a bi-directional dc/dc converter used in a hybrid wind generator (WG)/lead-acid battery power system with state machine control. State machine control strategy can be used not only to control the system power flow and load distribution, but also raise the system power capacity. The battery is charged or discharged through the bi-directional dc/dc converter. By adjusting the duty cycle of the power converter, multi-stage current charging control of batteries is realized and the efficiency of charging is improved by maximum power point tracking algorithm. The proposed control method and system structure can be easily extended to other renewable energy conversion systems.

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