Voltage control for variable speed wind turbine using buck converter based on PID controller

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Abstract. Currently, energy diversification is needed to overcome the limitations of fossil energy as a fuel for electricity generation. In Indonesia, one source of renewable energy that has great potential is wind energy. Wind energy conversion system is an environmentally friendly electricity generator with unlimited availability. However, the electrical energy produced depends on the fluctuating wind speed so that it produces a fluctuating voltage. Variable speed wind turbine is one of the most widely used wind turbine types because it has better efficiency but requires control to overcome the fluctuations in the voltage generated. This paper presents voltage control on a prototype variable speed wind turbine with a permanent magnet synchronous generator (PMSG) and buck converter. The output voltage generated by the PMSG will be rectified by a three-phase uncontrolled rectifier. Voltage control is done through the duty cycle settings on the buck converter that is connected to the battery for energy storage. PID controller is used to set the duty cycle of PWM pulses with a switching frequency of 31.5 kHz. The Proportional Integrator Differentiator (PID) controller is embedded in the microcontroller. Based on the test results, the resulting output voltage can be held constant at 14V by providing variations in wind speed changes which are simulated through PMSG speed changes. Transient responses with the fastest settling time of 1.2 s were obtained with the PID controller parameter values Kp = 0.6, Ki = 0.15 and Kd = 0.6.

1. Introduction
The use of wind energy as electrical energy generator is increasingly being used because it is environmentally friendly energy, free of CO2 emissions and unlimited availability [1-2]. Wind turbine technology continues to be developed to improve the efficiency of wind energy conversion. Wind turbines are needed to convert wind energy into electrical energy. One type of wind turbine system that is widely used is the variable speed wind turbine (VSWT). Compared to a fixed speed wind turbine, VSWT has higher efficiency. However, the electrical energy produced is highly dependent on fluctuated wind speed so that the electrical energy produced also fluctuates [2-5]. To overcome the fluctuation of electrical energy produced, VSWT is connected to a battery as energy storage. In addition, constant voltage control is needed so that battery charging becomes more efficient.

To improve the performance of the controller, a power electronic configuration for VSWT is required. The use of the dc-dc converter is widely used in wind turbine systems to increase efficiency [6-7]. Buck converter, boost converter and buck-boost converter are types of dc-dc converters which are
usually used in wind turbine systems. Two-phase buck converter has been applied to the small scale wind turbine system and produces good performance. Two single buck converters are connected in parallel so as to produce an output power twice as large as a single buck converter at currents below 4 A [8]. A buck-boost converter is also used in PMSG wind turbines and is connected to a DC link to maintain a constant supply voltage. Based on the simulation results, this converter provides low cost and good quality power conversion but has not been implemented in the prototype [9-10].

In this paper, voltage control is designed using a PID controller for a wind turbine system using PMSG. The voltage control will maintain the buck converter output voltage at 14 V through the duty cycle setting sent to the buck converter switching component. The PID controller is embedded in the microcontroller which sends a pulse width modulation (PWM) signal to the buck converter circuit through the MOSFET driver circuit.

2. Methods
Variable speed wind turbine in this paper consists of permanent magnet synchronous generator (PMSG), 3 phase uncontrolled rectifier, buck converter, driver converter, voltage and current detector, microcontroller and battery as energy storage. Figure 1 shows block diagram of variable speed wind turbine. PMSG will convert wind energy captured by the blade to be 3 phase voltage. PMSG has rating power of 500 Watt. 3 phase voltage will be changed to DC voltage by 3 phase uncontrolled rectifier. The greater the wind energy captured, the greater the PMSG rotation will be as well as the resulting output voltage. The rotation of the turbine causes the generator to induce and emits a three-phase AC voltage with a value depending on the rotation. The output voltage of the PMSG will be rectified by an uncontrolled rectifier circuit and the filter becomes a DC voltage. The voltage limit to be processed is 20-100 volts. If the voltage is less than or more than this limit, the relay will break the connection between the PMSG and the rectifier. The voltage that has been rectified will enter the Buck Converter. The microcontroller will adjust the output voltage of the buck converter to a constant 14V through the duty cycle setting of the PWM signal sent to the driver circuit. The output voltage of buck converter is depended by duty cycle value. The duty cycle setting uses a PID controller based on the battery voltage detected by the voltage detector as feedback. PID controller is embedded on microcontroller. The driver circuit functions as an interface between the microcontroller and the buck converter which will match the output voltage of the microcontroller and the MOSFET on the buck converter of 12V.

![Figure 1. Block diagram of proposed variable speed wind turbine.](image)

2.1. Design of voltage detector
Voltage detector will detect battery and rectifier voltage and generate output voltage that will send to microcontroller. Figure 2 shows voltage detector circuit that used voltage divide circuit.
Figure 2. Voltage detector circuit.

The voltage detector circuit is used to detect the PMSG output voltage and the buck converter output voltage to be displayed on the LCD via the microcontroller or as feedback to the controller. The voltage sensor circuit uses a voltage divider system with two resistors connected in series to convert a maximum voltage of 100 Volts to 5 volts so that it can be read by the microcontroller via the ADC pin. The resistors used have maximum power of 0.5 Watt so that maximum current and voltage are 5 mA and 100 V respectively. The resistance value used can be determined by:

$$\frac{V_{out}}{V_{in}} = \frac{R_1}{R_1 + R_2}$$  \hspace{1cm} (1)

Where $V_{out}$ is the output voltage of voltage detector with maximum value of 5 V. $V_{in}$ is the output voltage of PMSG with maximum value of 100 V. $R_1$ and $R_2$ is resistance value in voltage detector circuit. The total resistance is 30 kΩ, so that $R_1$ and $R_2$ is 28.5 kΩ and 1.5 kΩ respectively.

2.2. Design of buck converter

Buck converter is a type of switching converter that produces an output voltage that is lower than the input voltage. The buck converter can be operated in 2 modes, namely continuous conduction mode and discontinuous conduction mode. In continuous conduction mode, the current will continue to flow through the inductor, or in other words, the current in the inductor never reaches zero. Whereas in discontinuous conduction mode, the current flowing through the inductor will be zero for a certain period of time. The inductor value selected will determine which mode to use. The buck converter circuit consists of a MOSFET as a switching component, inductor, capacitor, and diode, as shown in Figure 3.

Figure 3. Buck converter topology.
In this article, the buck converter input voltage is the 3 phase rectifier output voltage. The buck converter circuit used is a modification of the basic buck converter circuit. The buck converter output voltage depends on the duty cycle of the PWM signal sent by the microcontroller to the Mosfet (M1). The lower the duty cycle, the lower the output voltage will be. The diode in Figure 3 is replaced by Mosfet 2 (M2) by providing a PWM signal with a duty cycle opposite to M1, as shown in Figure 4. When M1 gets a high pulse, M2 will get a low pulse. When M1 gets a high pulse and M2 gets a low pulse, the current will flow to the inductor and fill the capacitor. Otherwise, the inductor current will decrease and the input will be disconnected with the circuit.

![Figure 4. The Proposed buck converter.](image)

The switching frequency of the buck converter is designed at 31.5 KHz, the output voltage ripple is 4% and the maximum output current is 10A. Value of inductor (L) and capacitor (C) can be determined by:

\[ L = \frac{1}{f} \times (V_{in} - V_{out}) \times D \times \frac{1}{\Delta V_o} \]  

\[ C = \frac{V_{out} \times (1 - D)}{8 \times L \times \Delta V_o \times f^2} \]  

Where \( f \) is switching frequency, \( D \) is duty cycle, and \( \Delta V \) is voltage ripple. The inductor value used is 0.8 mH with a copper coil diameter of 0.9mm and two 10 \( \mu \)F capacitors are connected in series.

2.3. Design of PID controller

The PID controller is used to determine the duty cycle of the PWM signal sent to the buck converter driver circuit so that the buck converter output voltage can be maintained constant at 14V. The determination of the PID controller parameter value uses the Ziegler Nichols I method which can be determined by:

\[ K_p = 1.2 \times \frac{T}{L} \]  

\[ T_i = 2 \times L \]  

\[ T_d = 0.5 \times L \]  

Where \( L \) is delay time and \( T \) is settling time from open loop response. Based on value \( K_p, T_i \) and \( T_d \), \( K_i \) and \( K_d \) can be determined. In this paper, the value of \( K_p \) is 0.6, \( K_i \) is 0.15 and \( K_d \) is 0.6.

3. Experiment results

The performance of the prototype variable speed wind turbine with voltage control was tested experimentally. Figure 5 (a) shows the measurement results of the PMSG output voltage at a rotating
speed of 800 Rpm. The PMSG output voltage is an AC voltage of 200Vpp. The greater the rotational speed, the greater the PMSG output voltage. The PMSG output voltage is rectified into a DC voltage signal by a 3 phase uncontrolled rectifier. The comparison of the measurements results of the rectifier and PMSG output voltage is shown in Figure 5 (b). Measurement of PMSG and rectifier output voltage used an oscilloscope.

![Graph 1](image1.png)

**Figure 5.** Measurement result of PMSG and rectifier output voltage.

![Graph 2](image2.png)

**Figure 6.** Relationship between rectifier output voltage and rotor speed of PMSG.

Figure 6 shows relationship between rectifier output voltage and PMSG rotor speed. The rectifier output voltage is proportional and linear to the rotor speed of the PMSG. The greater the rotation of the rotor, the greater the output voltage generated by the rectifier. Figure 7 shows measurement result from voltage detector with input voltage range between 5 V – 50 V. The average error in testing of the voltage sensor is 1.66%.
Figure 7. Measurement result of voltage detector.

![Voltage Detector Measurement Result](image1)

Figure 8. Measurement result of buck converter output voltage.

![Buck Converter Output Voltage](image2)

Figure 9. Output voltage of buck converter with PID controller.

![PID Controller Output Voltage](image3)

Figure 8 shows the measurement results of the buck converter output voltage to changes in duty cycle. The greater the duty cycle, the greater the output voltage of the buck converter. The buck converter output voltage test is done by giving a change in duty cycle and the input voltage is kept constant at 37.5V. The PID controller can work well maintaining a constant voltage of 14V, as shown in Figure 9.
The system response has no maximum overshoot with a settling time of 1.2 s and a steady state error of 0.3%.

4. Conclusion
Voltage control for variable speed wind turbine using buck converter based on PID controller has been described in this paper. The prototype uses PMSG with a power rating of 500 Watt. The voltage generated by the wind turbine system is highly dependent on wind speed. The wind turbine system is connected to a battery, so to maintain a battery voltage of 14V, voltage control is needed. Voltage control using a PID controller embedded in the microcontroller. Based on the test results, the PID controller can work properly. With the controller parameter values $K_p = 0.6$, $K_i = 0.15$ and $K_d = 0.6$, the resulting transient response does not have a maximum overshoot with a settling time of 1.2 s and a steady-state error of 0.3%.

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