Analysis and comparison of nonlinear control for DC/DC buck converter in PV system

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Abstract. The use of DC power systems is increasingly widely used, so we need a system to convert DC power systems, one of which is a buck converter. The buck converter system requires a controller so that the output voltage generated is as desired without any disturbance when the buck is operating. This study examines improvements in buck converter performance using backstepping and SMC controllers. Backstepping controller and SMC are able to maintain stability where it can be shown by looking at the output voltage value of the buck converter. The results of a comparison of the simulation implementation of the backstepping controller and the SMC show that the recovery time of the SMC is faster than backstepping. From this comparison it is also seen that the amount of SMC voltage deviation is smaller than backstepping.

1. Introduction

In this modern era, almost all electronic device systems require a DC source. DC voltage is widely used in low-voltage electronic systems to high-voltage electrical systems. Including for DC electric motors, maximum power tracker (MPPT), battery charging, and so on. Therefore, the use of a DC power supply system requires a system that is able to convert DC voltage from one DC voltage level into another DC voltage level. In the industrial world, DC conversion systems are widely used to improve system efficiency [1]. There are different types of DC voltage conversion designs that have different capabilities. The types of energy conversion devices include a boost converter, buck converter, buck-boost converter, zeta converter, cuk converter, DC-DC bidirectional and others [2].

DC-DC converters have a DC voltage input and an output DC voltage. The output voltage can be greater or less than the input voltage. The buck converter is used to convert a large input voltage into a smaller output voltage. This type of converter is very suitable to be used to provide voltage to a load where the load requires a smaller voltage than the DC source it has. In the voltage converter that converts a DC quantity to another DC quantity, there is a step called regulating which has the function of regulating the output voltage, increasing or decreasing the value of the voltage. The output DC voltage of PV system depends on irradiation and ambient temperature such that it has unstable output voltage. Therefore, DC voltage does not only have to be regulated by the equipment we install. So, we need a DC voltage control, so that the equipment we install works in accordance with its capabilities [3-7].

From the description above, there are problems that occur with the buck converter. First, it is difficult to control the current because it has a large enough ripple. The second is the transient output voltage at
the start of the system which causes the length of time $T_s$ (Time Settling). This transient symptom cannot be eliminated, but its impact can be minimized by controlling the PWM on the buck converter. In the buck converter, control can be done with various controlling techniques such as PID, linear quadratic regulator (LQR), sliding mode controller (SMC), backstepping, and many more controlling techniques that can be used [8-11].

In this paper, a study of buck converter control was carried out using backstepping controllers and sliding mode controllers. Mathematical model of buck converter is used to help learning and understanding the operating principles of the buck converter [12]. The backstepping control was chosen because the output of the buck converter with backstepping control was displayed using the parameters listed in the journal, which has a fast output voltage setting time and low overshoot [13]. As a comparison, this research uses Sliding Mode Controller (SMC) control. The SMC was chosen because it was able to force the system output to move according to its surface path [14], besides that in the research written by Uçak and Günel [15] the output of the buck converter using the SMC was shown with interference only with the load. In this research, a simulation of disturbance testing was carried out in the form of a load change, input voltage change, and the change of voltage reference. The purpose of comparing the two nonlinear controls is so that we can see which of the two controllers is best used to regulate the output voltage of the buck converter. In this study also examine the durability these two controls kind of interferences. The interferences are given to compare which method is the most efficient for buck converter.

2. Mathematical model of buck converter

Buck converter is a power electronic converter with DC input voltage and DC voltage output where the output voltage value can be smaller than the source voltage. This converter is included in a switching type converter which works by opening and closing electronic switches. This converter uses inductors, diodes, capacitors and a MOSFET or IGBT which functions as an electronic switch. The buck converter circuit is shown in Figure 1.

![Figure 1. Block diagram of proposed system.](image)

When the switch is closed, the diode is reverse bias as shown in Figure 2. In accordance with Kirchhoff’s voltage law, the loop passes through the closed source, inductor, and switch. By analyzing the voltage and current that passes through the inductor, it can be determined by the kirchoff voltage law and kirchoff current law, which the calculation will also be used to make the equation of inductor current ($i_L$) and capacitor voltage ($V_C$) as,

\[
\frac{di_L}{dt} = \frac{V_{in} - V_C}{L}
\]

![Figure 2. The equivalent circuit when the switch is ON.](image)
\[
\frac{dv_c}{dt} = \frac{1}{C} (i_L - \frac{V_c}{R})
\]

When the switch is open as shown in Figure 3, the inductor current does not change instantaneously, the diode is biased forward to provide a path for the inductor current. It is assumed that the output voltage \( V_o \) is constant.

![Figure 3. Block diagram of proposed system.](image)

The value of the voltage and current that passes through the inductor when the switch is open can be determined by the following equation.

\[
\frac{di_L}{dt} = -\frac{V_c}{L}
\]

\[
\frac{dv_c}{dt} = \frac{1}{C} (i_L - \frac{V_c}{R})
\]

By using state space averaging modeling, the converter equation is simplified as equation,

\[
\dot{x} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -1 \end{bmatrix} \times \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} d_L \\ 0 \end{bmatrix} \times [\text{Vin}]
\]

So that we can get the state space average value of the buck converter current (\( \dot{X}_1 \)) and voltage (\( \dot{X}_2 \)).

\[
\dot{X}_1 = -\frac{X_2}{L} + \frac{dV_{in}}{L}
\]

\[
\dot{X}_2 = \frac{X_1}{C} - \frac{X_2}{RC}
\]

3. Sliding mode control design

In order to obtain the desired output voltage, it is necessary to make an error function in SMC, the error function can also be interpreted as sliding surface. The error function is based on the current output of buck converter. In designing sliding surface, current, voltage and power can be used, but in reality, power is difficult to control so the reference that is often used is current. The proposed sliding surface is given by,

\[
\sigma = K_1 e + \dot{e}
\]

where \( e \) is the error of inductor current and \( K_1 \) is positive gain for sliding surface. The derivation of sliding surface is derived to reach its equilibrium system.

\[
\dot{\sigma} = -K_1 \dot{X}_1 + \frac{1}{L} \dot{X}_2
\]

The equivalent control \( U_{eq} \) is obtained as (4) by substituting (2) into (3).

\[
U_{eq} = \frac{1}{V_{in}K_2C} x_1 - \frac{x_2}{V_{in}} \left( -K_2CR + 1 \right)
\]

The first step to deriving \( U_n \) is to employ the Lyapunov function.
\[ V = \frac{1}{2} \sigma^2 \]
\[ \dot{V} = \sigma \dot{\sigma} \]

By considering a positive definite Lyapunov function, it is defined

\[ \sigma \left( \frac{K_2 V_{in} U_n}{L} \right) < 0 \]

The signal of natural control \( U_n \) is determined as

\[ U_n = K_3 \left( \frac{L}{K_2 V_{in}} \right) \text{sign}(\sigma) \]

The input control \( U \) is defined by \( U_{eq} + U_n \) and, therefore, it can be obtained as,

\[ U = \frac{1}{V_{in} K_1 C} X_1 + \frac{V_d}{V_{in}} \left( -\frac{1}{K_1 C R} + 1 \right) + K_3 \left( \frac{L}{K_2 V_{in}} \right) \text{sign}(\sigma) \]

4. Results and analysis

The research was conducted to see the output voltage generated by the buck converter, then given a controller so that the regulated voltage is better as shown in Figure 4. In buck converter, there are several parameters that must be known and set. The buck converter specifications studied are given in Table 1.

![Figure 4. Block diagram of proposed system.](image)

| Parameter        | Symbol | Value     |
|------------------|--------|-----------|
| Input Voltage    | \( V_{in} \) | 15-24 V   |
| Inductor         | \( L \)  | 2 mH      |
| Load Resistor    | \( R \)  | 30 Ω       |
| Capacitor        | \( C \)  | 6 μF       |
| Frequency        | \( f \)  | 15 kHz    |

Table 1 shows the specifications and values used. The input voltage uses a value of 15 V, which is adjusted to the value of most photovoltaic outputs, which is around 12 V to 14.7 V. The output voltage generated by the buck converter is 5 V, this voltage is commonly used in battery charging systems starting from the battery. to the device.

In order to find out the success rate of the plant and controller in producing an output voltage that is in accordance with what is required by the load and to know the resistance of the controller when there
is a change in input voltage, a change in the loading side, and a change in reference voltage. The proposed controller is compared by backstepping controller [13] as a nonlinear control and the parameters are defined in Table 2.

### Table 2. Parameters of controller.

| Types of controllers | Parameters          |
|----------------------|---------------------|
| Backstepping         | \( C_1=3000 \) \( C_2=10000 \) |
| Proposed Method      | \( K_1=100 \) \( K_2=10 \) \( K_3=100 \) |

#### 4.1. Input voltage change

In this test the input voltage will be varied to be greater than the initial input voltage, the magnitude of the change is 0%, 25%, 50%, 75% and 100% while the reference voltage and load are made constant. Then we look at the output of the two control systems as presented in Table 3.

### Table 3. The buck converter responses when the input voltage changes.

| No | \( V_{in} \) (V) | R (Ω) | \( V_{ref} \) (V) | \( t_{rec} \) (s) | \( \Delta V \) (V) | \( t_{rec} \) (s) | \( \Delta V \) (V) |
|----|------------------|-------|-------------------|------------------|-----------------|------------------|-----------------|
| 1  | 15               |       |                   | -                | -               | -                | -               |
| 2  | 18.75            |       |                   | -                | -               | -                | -               |
| 3  | 22.5             | 30    | 5                 | -                | -               | -                | -               |
| 4  | 26.25            |       |                   | -                | -               | -                | -               |
| 5  | 30               |       |                   | -                | -               | -                | -               |

Based on Table 3, the results of the backstepping and SMC controllers are able to maintain a steady state even though the input voltage increases. It can also be seen from the \( t_{rec} \) and \( \Delta V \) values where there is no change in the output voltage. For more details, the test results are shown in Figure 5.

![Figure 5. Output voltage and output current when input voltage is changed into 30V.](image)

#### 4.2. Load resistor change

In this second test, the load resistor will vary, while the input voltage and reference voltage are kept constant. The performances are presented in Table 4, the results of the backstepping controller is not able to maintain quickly a steady state when the load conditions increase. It can also be seen from the \( t_{rec} \) and \( \Delta V \) values where the changes that occur in the output voltage are able to return to steady conditions with relatively small \( t_{rec} \) and \( \Delta V \) values.
Table 4. The buck converter responses when the load resistor changes

| No | $V_{in}$ (V) | R (Ω) | $V_{ref}$ (V) | Backstepping | SMC |
|----|--------------|------|---------------|--------------|-----|
|    |              |      |               | $t_{rec}$ (s) | $\Delta V$ (V) | $t_{rec}$ (s) | $\Delta V$ (V) |
| 1  | 15           | 30   | 5             | 0            | 0    | 0            | 0 |
| 2  | 37.5         | 45   | 0             | 0.0012       | 0.305 | 0            | 0 |
| 3  | 45           | 5    | 0             | 0.0013       | 0.501 | 0            | 0 |
| 4  | 52.5         | 60   | 5             | 0.0013       | 0.638 | 0            | 0 |
| 5  | 60           | 0    | 0             | 0.00128      | 0.739 | 0            | 0 |

Figure 6 depicts the output of the buck converter with backstepping control and SMC which is given interference in the form of a change in the value of the load by 100%. The system with backstepping control has an overshoot at 0.01 seconds of 5.97 V and has a time recovery 0.00114 s and using SMC has no overshoot.

4.3. Voltage reference change

In order to determine the performance of the two types of nonlinear controllers used, a third test is carried out. The last examination is conducted on this system by changing the reference voltage of the buck converter under constant load and input voltage. From the results of Figure 7, it can be seen that the time required for a system with an SMC controller to reach the desired value is faster than a system with a backstepping controller. The change in reference voltage in 0.01 seconds makes the backstepping controller have a very large voltage overshoot or deviation. This shows that using the backstepping controller causes the system to become unstable for about 0.006 seconds.

Figure 7. Output voltage and output current when reference voltage is changed into 9V.
5. Conclusion
In uncontrolled condition, the buck converter is not able to generate the desired output voltage and it is not robust against the interferences. By using backstepping and SMC, the buck converter when there is a change in input voltage is able to generate the output voltage as a reference and is able to eliminate overshoot. Voltage deviation occurred in backstepping control when load is changed. It is less able to follow the reference voltage compared with SMC. Backstepping control is not able to reach the reference voltage when it changes. It is proved that Buck Converter with SMC generates controlled output current and constant output voltage.

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