Intelligent voltage controller based on firefly algorithm for DC-DC boost converter

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ABSTRACT

DC-DC boost converter is one of the important tools of photovoltaic (PV) power plant. DC-DC boost converter can be used to adjust the voltage output of photovoltaic before going to the inverter. In addition, DC-DC boost converter can be used as additional devices to make the PV plant operated in maximum power point condition. To get the optimal voltage adjustment, an appropriate controller is essential. Generally, proportional-integral (PI) controller is commonly used to control the switching procedure of the boost converter. However, with uncertainty of the source (uncertainty of the PV output), PI controller is out of date. Hence designing PI controller based on the metaheuristic algorithm such as firefly algorithm is essential. This paper is proposed an intelligent voltage controller for DC-DC boost converter based on firefly algorithm (FA). From the simulation results it is noticeable that the PI based on FA could provide better control signal (indicated by the fastest settling time of the boost converter).

Keywords:
DC-DC boost converter
Firefly algorithm
Photovoltaic
PI controller
Renewable energy

1. INTRODUCTION

Indonesia has recently encountered a crisis on fuel oil, where the domestic petroleum used by motorized vehicles and other purposes exceeded the local production, making the country a gasoline importer. The limited fossil energy sources, such as fuel and coal, instigated the need for innovation to overcome contingent future challenges [1]. In Indonesia, the abundance of solar sources is also an alternative solution worth examining with other inexhaustible energy. This is because many renewable sources, including photovoltaic (PV) based solar energy, have recently been developed as a potential substitute for fuels and fossils [2]. One component of PV development is also used to manage voltage and output power, toward maximizing the generated electricity [3]. Furthermore, solar energy has emerged as a realistic alternative, which is developed as a sustainable power source regarding the advancements in battery and PV technology [4]. In photovoltaic applications, issues are observed with the performance of the DC-DC converter, where the generated voltage often varies due to the fluctuations of the PV temperature and the solar power radiation intensity [5], [6]. The power source of the converter is also the PV output voltage, which essentially requires modification through a control technique. In this condition, the voltage generated needs to meet all the required criteria for adoption [7].

In 2022, Ertekin et al. [8], a proportional-integral (PI) controller was used as the voltage output of the boost converter, in addition it is showing that its utilization caused the optimal operation of the booster's...
switching mechanism. The research of [9] also indicated the comparative analysis between the zeta and boost converters using a PI controller. In this condition, both converters had a better response with the addition of the control system. Based on [10], this controller still provided a good performance despite being used in a cascade-controlling mechanism. Irrespective of these great performances, deterioration is still observed with the consideration of the PV plant inanity. This shows the need for the optimal dens of PI, regarding the metaheuristic algorithm. In electrical engineering, the application of this algorithm is presently becoming favourable, specifically in power systems.

In 2021, Setiadi et al. [11], the application of the differential evolution algorithm was observed for tuning the PI controller of a six-pulse three-phase rectifier. In this case, the overshoot of the rectifier was damp by designing a PI controller through a differential evolution algorithm. The research of [12] also emphasized the design coordinated controller between the capacitor energy storage and dual-input power system stabilizer, regarding an improved differential evolution algorithm. Moreover, the application of the flower pollination algorithm was used in designing superconducting magnetic energy storage (SMES) for the enhanced dynamic stability of a power system [13]. In this process, the damping performance of the system was significantly enhanced by adding SMES, based on the flower pollination algorithm.

In 2018, Abdulkhader et al. [14], the application of particle swarm optimization (PSO) was observed for designing a multi-band power system stabilizer, with the adoption of FFO (fruit fly optimization) also used for developing virtual synchronous machine in [15]. Among all the numerous algorithms, FA (Firefly Algorithm) is still observed as the best model, regarding the simplicity and optimal results [16]. Therefore, this research aims to develop an intelligent voltage controller for DC-DC boost converter, using the firefly algorithm. Based on subsequent evaluations, the remaining parts of this report are organized as follows, section 2 provides the fundamental theory of PV, MPPT, and PI controller. By minimizing the goal function evaluated, the PID controller is designed to lower the settling time, maximum overshoot, and inaccuracy [17]. It also emphasizes system identification, fruit fly algorithm, and the design patterns of the MPPT-based FFA, section 3 describes the simulation results, and section 4 highlights the contribution and conclusions.

2. METHOD
2.1. DC-DC boost converter

The boost converter contains an inductor, a metal oxide semiconductor (MOSFET), diode and capacitor with its output voltage depending on the operating period. The output stress is also higher than the input voltage, with the working framework emphasizing the MOSFET switching functions. Figure 1 shows the open loop DC-DC boots converter electrical circuit. While Figure 2 shows the DC-DC electrical circuit in “ON” condition [18].

![Figure 1. Circuit of DC-DC boost converter](image1)

![Figure 2. Circuit of DC-DC Boost Converter in “ON” Condition](image2)
Based on Figures 1 and 2, the following equation is obtained,

\[ V_s = L \frac{di}{dt} \]  \hfill (1)

in this condition, the switch was connected for \( t_{on} \). When the following equations were applied, the change in the inductor current was assumed to be constant,

\[ V_s = L \frac{\Delta I}{dt} \]  \hfill (2)

\[ L \cdot \Delta I = V_s \cdot t_{on} \]  \hfill (3)

When the switch was open, the charging inductor began to discharge, leading to the system being the current source. The load was also supplied by two voltage sources, namely \( V_s \) and \( V_L \), causing greater output compared to the input power. Figure 3 depicts the DC-DC boost converter electrical circuits in “Off” condition [19], [20].

![Figure 3. DC-DC boost converter switching transistor is OFF](image)

With the switch opening at \( t_{off} \), the following equation was obtained,

\[ V_s + V_L = V_R \]  \hfill (4)

\[ V_s + \frac{\Delta I}{t_{off}} = V_R \]  \hfill (5)

2.2. DC-DC boost converter continuous conduction mode

Every power converter and its bilinear form was acquired in one of two methods which is creation of a list for all possible configurations and identification of transferable. The creation of a list for all possible configurations, with subsequent observation for prevalent bilinear structures. According to the preliminary analysis, a DC-DC Boost Converter operating in ccm likely used the following design in Figure 2, i.e., cases (a) and (b), where the switches (H) were on (\( h_1 = 1 \)) and off (\( h_2 = 1 \)), respectively. Since this is a DC-DC Converter example, the switching feature (\( u \)) was transformed into two patterns, i.e., \( u = h_1 = 1 - h_2 \).

Status variables also included inductor current (\( i_L \)) and capacitor voltage (\( V_C \)), with (6) representing the state space of DC-DC boost converter [21].

\[
\begin{align*}
u = 1; \quad &\quad i_L = \frac{E}{L} \quad V_C = -\frac{V_C}{RC} \\
u = 0; \quad &\quad i_L = \frac{E}{L} - \frac{V_C}{L} \quad V_C = i_L - \frac{V_C}{RC}
\end{align*}
\]  \hfill (6)

By switching the \( u \)-function, (6) was summarized in one form as described in (7), which was directly used for simulation, to represent \( h_1 \) and \( h_2 \) validation functions. This equation also ensured the production of specified bilinear structures [22].

\[
\begin{align*}
u = 1; \quad &\quad \dot{i}_L = \frac{E}{k} u + \frac{E-V_C}{L} (1 - u) \\
u = 0; \quad &\quad \dot{V}_C = \frac{-V_C}{RC} u + \left( \frac{i_L}{C} - \frac{V_C}{RC} \right)(1 - u) \\
u = 0; \quad &\quad \dot{i}_L = \left( 1 - \frac{(1-u)V_C}{k} \right) + \frac{E}{L}
\end{align*}
\]  \hfill (7)

In this situation, the (8) ensured the derivation of the following bilinear structure by (8).
\[
\begin{pmatrix}
\frac{\dot{i}_L}{V_C}
\end{pmatrix} = \begin{bmatrix}
0 & -\frac{1}{L} & \frac{1}{C} & 0 & 0
\end{bmatrix} \begin{pmatrix}
\frac{\dot{i}_L}{V_C}
\end{pmatrix} + \begin{bmatrix}
\frac{1}{L} & 0 & 0 & 0 & 0
\end{bmatrix} + \frac{E}{L} u + \frac{E}{L} \frac{d}{d}
\] (8)

With \(b = [0 \ 0]^T\), (8) can be written as state space representation as described in (9).

\[
\dot{x} = A.x + B.x.u + d
\] (9)

Based on identification of the transferable variables a state variable was initially selected, with \(i_L\) and \(V_c\) remaining similar as observed in the previous method. In this condition, the switch over parameters included the transistor voltage (\(V_H\)) and current (\(i_D\)), which were inputted as state variable functions as described in (10).

\[
V_H = \begin{cases}
0 & \text{if } H \text{ is turned on} \\
V_C & \text{if } H \text{ turned off} \\
i_L & \text{if } H \text{ turned off}
\end{cases}
\] (10)

By consequently applying the Kirchhoff voltage and current laws to express \(d\dot{i}_L/dt\) and \(dV_C/dt\), the equation describing the circuit compartment was obtained as shown in (11) [21].

\[
\begin{align*}
L.i_L &= E - V_H \\
C.V_C &= i_D - \frac{V_C}{R}
\end{align*}
\] (11)

The transferred variable was also expressed as an appropriate switching function, with an additional feature, provided in (12) and (13). In addition, Figure 4 shows the DC-DC converter operated in CCM.

\[
u = \begin{cases}
1 & \text{if } H \text{ is turned on} \\
0 & \text{if } H \text{ turned off}
\end{cases}
\] (12)

\[
\begin{align*}
V_H &= V_C(1 - u) \\
i_D &= i_L(1 - u)
\end{align*}
\] (13)

By substituting (13) into (12), new equation can be form as described in (14).

\[
\begin{align*}
\frac{i_L}{L} &= -\frac{(1-u)V_C}{L} + \frac{E}{L} \\
\frac{V_C}{C} &= (1 - u)i_L/C - \frac{V_C}{RC}
\end{align*}
\] (14)

The connection between the input and output circuits was also described by two dependent sources, due to its performance as an ideal DC transformer with a changeable external-regulated ratio. Furthermore, the one-of-a-kind program enabled the simulation of the system described (14). As modelled by Simulink®, the efficiency of the optimal thrust level was then in the phase shift of the duty cycle ratio [22].
2.3. Firefly algorithm

Firefly algorithms (FA) is a metaheuristic algorithm inspired by the characteristics of fireflies. It was also initially established by Dr. Xin-She Yang from Cambridge University in 2007. There are three important rules of FA [23].

- All fireflies are unisex, leading to great attraction levels regardless of their gender. In addition, the brightness of these organisms is also determined by the location of their objective functions.
- The attraction is proportional to the brightness, indicating that the fireflies with lower luminance often move towards those are brighter. This brightness is found to decrease as the distance increases. When none of these organisms has the brightness luminance, their movement are always in a random pattern.
- The fireflies’s brightness is determined by the location of their objective functions.

The population will be randomly initialized, and then some fireflies will be chosen as candidate solutions from among the many fireflies. After counting the cost of the candidate solution fireflies, the best candidate will be designated as the ‘center,’ and all other fireflies will ‘fly’ to that center. Each iteration will result in a penalty for each firefly. After the maximum number of iterations, the solution with the lowest penalty value will be chosen [24]. In FA, 2 important factors were considered, namely the light intensity variation and the attraction formula. For convenience, the attraction of fireflies was assumably defined by the light intensity brightness, \( I_{os} \), which varied regarding the inverse quadrant law [25], [26].

\[
I(r) = \frac{I_s}{r^2} \tag{15}
\]

\( I \) is the intensity of the original firefly light, which has a fixed absorption coefficient. This indicated that the light intensity (I) varied with the distance (r), causing the following [27].

\[
I = I_s e^{-\gamma r} \tag{16}
\]

\( I \) is the original light intensity to avoid the singular at \( r = 0 \), where the combined effect of the two opposites on the best quadrant law and absorption was approximated as Gaussian law [28].

\[
I_{os} = I_s e^{-\gamma r} \tag{17}
\]

The attraction of the fireflies was also proportional to the light intensity of those nearby. This was determined by the following formula [29].

\[
\beta = \beta_0 e^{-\gamma r^2} \tag{18}
\]

Where, \( \beta \) is the attraction when \( r=0 \). To simplify this equation, the following equation was used [30].

\[
\beta = \frac{\beta_0}{1 + \gamma r^2} \tag{19}
\]

In (29) and (30) are defined as the characteristic distance, \( I = \gamma^{-1/m} \). Where the change in attractiveness changes significantly from 0 to \( e^1 \). To simplify the implementation of the calculation can be generalized and become [30].

\[
\beta_0 e^{-\gamma r^m} \quad (m \geq 1) \tag{20}
\]

For constant conditions, the long characteristic can be described as (21).

\[
I = \gamma^{-1/m} \tag{21}
\]

The distance between 2 fireflies (i) at \( x_i \) and \( x_j \) also represents using Cartesian distance as (22).

\[
r_{ij} = \| x_i - x_j \| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{22}
\]

Furthermore, the movement of the fireflies (i) attracted by the lighter ones (j) was defined as (23).

\[
x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_j - x_i) + \alpha e_1 \tag{23}
\]
Where:
\( x_i \): Spatial of position-i
\( x_j \): Spatial coordinate of firefly-j
\( \alpha \): Random parameter
\( \epsilon_1 \): Random value of eigenvector between 0-1

### 2.4. Design concept

To determine the design specification, the input of the DC-DC boost converter was very essential. Table 1 shows the specification of DC-DC boost converter used in this research [31]. A metal oxide semiconductor called a MOSFET, as well as diodes, inductors, and capacitor are all components of a boost converter. The running time has an impact on the DC-DC Boost Converter’s output voltage. The input voltage is greater than the output stress. The DC-DC Boost Converter's working framework was focused on MOSFET switching capabilities.

These parameters emphasized the design of PI as a voltage controller of the FA-based boost converter. In this condition, the circuit and the firefly algorithm were designed and coded in Simulink and Matlab. The objective function of FA was also used to reduce the error of the boost converter’s voltage output, with the fitness function mathematically described using (23) [32], [33]. Table 2 shows the parameter of FA for optimizing the PI controller.

<table>
<thead>
<tr>
<th>Table 1. DC-DC boost converter parameter</th>
<th>Table 2. FA parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>12</td>
</tr>
<tr>
<td>Capacitor</td>
<td>10(^6)</td>
</tr>
<tr>
<td>Inductor</td>
<td>10(^2)</td>
</tr>
<tr>
<td>Resistor</td>
<td>100</td>
</tr>
</tbody>
</table>

\[
E = \int_{0}^{\text{time}} t|e(t)|dt
\]  

This design process included the following steps:
Step 1. Start the FA by initializing the numbers of fireflies, iteration, and optimized parameter,
Step 2. Randomly generate the position of the fireflies as the initial coordinates,
Step 3. Evaluate the objective function of each firefly’s position,
Step 4. Rank the fireflies based on the objective function and determine the best fitness,
Step 5. Update the firefly movement,
Step 6. Update the best fitness,
Step 7. When j is higher than i, evaluate the fitness function of each firefly and update the light intensity,
Step 8. Rank the fireflies and obtain the best solution,
Step 9. When the criterion is not satisfied, repeat step 4,
Step 10. Print the results (\(K_p\) and \(K_i\) value).

### 3. RESULTS AND DISCUSSION

To test the efficacy of the proposed method, two different case study are carried out. The first case study is investigating how the proposed controller reacted to the changing of the voltage input reference. In the second case study the variation of the load is carried out to deeply understand the efficacy of the proposed controller.

#### 3.1. Case study 1

In this section time domain simulation is carried out to evaluate the efficacy of the proposed controller. The controller is tested against different voltage references (25 volt and 20 volt). Figure 4 shows the time domain response of boost converter voltage output under 25-volt voltage reference. While Figure 5 shows the boost converter voltage output response under 20-volt voltage reference. It is noticeable that on both conditions, the voltage response of the system with proposed controller is better than the system using conventional controller. This is indicated by smaller overshoot and fastest settling time of the system with proposed controller method.
Tables 3 and 4 show the detailed features of time domain simulation in Figures 5 and 6. It is found that the proposed controller method is superior compared with conventional controller method. It is observed that the overshoot for two different conditions could be damp when the proposed controller is introduced in the boost converter. Similar with the overshoot, the settling time is also accelerated when proposed controller is added in the boost converter.

<table>
<thead>
<tr>
<th>Index</th>
<th>Overshoot (watt)</th>
<th>Settling time (second)</th>
<th>Final value (volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>1.5</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Intelligent based</td>
<td>0.5</td>
<td>1.3</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Index</th>
<th>Overshoot (watt)</th>
<th>Settling time (second)</th>
<th>Final value (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>4.18</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Intelligent based</td>
<td>2.41</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

3.2. Case study 2

In the second case study, the load is change from 100 Ohm to 90 Ohm. Figure 6 shows the response of the system with 20 volt and 90 Ohm. While Figure 7 depicts the response of the system with 25-volt input reference and 90 Ohm. It is observed that in Figure 8, both of the response (system with conventional controller and system with proposed controller) does not have any overshoot. In addition, from Figure 8 it is noticeable that the settling time of system with proposed controller have faster settling time compared to the system with conventional controller.

Different with response in Figure 7, response in Figure 8 indicated that both of the system have overshoot. However, system with proposed controller provide minimum overshoot. In addition, the settling time is also faster compared with the system with conventional controller. Furthermore, Tables 5 and 6 show
the detailed features of Figure 6 and Figure 7. Similar with the first case study, the best response is provided by DC-DC with the proposed method.

<table>
<thead>
<tr>
<th>Table 5. Detailed features of Figure 7</th>
<th>Table 6. Detailed features of Figure 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index</td>
<td>Overshoot (watt)</td>
</tr>
<tr>
<td>Conventional</td>
<td>-</td>
</tr>
<tr>
<td>Intelligent based</td>
<td>1.4</td>
</tr>
</tbody>
</table>

4. CONCLUSION

This paper proposes an intelligent design of DC-DC boost converter voltage controller based on FA. The simulation is carried out using MATLAB/Simulink environment. From the simulation results it is observed that the proposed controller method is superior compared to the conventional controller. This statement indicated by the smaller overshoot and faster settling time of the system with proposed controller method compared with conventional controller method. Further research need to be conducted by making the controller adaptive to any disturbance using artificial neural network or using machine learning technique.

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REFERENCES


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