A Step-Up Controller Based on Fuzzy Logic Strategy to be Implemented in Photovoltaic Systems.

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Abstract. This paper applies an artificial intelligence or fuzzy logic strategy to improve the performance of photovoltaic systems with regard to variations of I-V and P-V characteristics resulting from irradiance and temperature variations that in turn create maximum power point (MPPT) variation, resulting in fluctuation of the DC voltage at the input of the boost step converter. A fuzzy logic controller is used to regulate this output voltage that can cover a wide operating range and does not require exact mathematical modelling, thus being cheap to develop. The performance of the DC converter based on the application of the fuzzy logic strategy was tested using MATLAB/Simulink for different values of input DC voltage within the PV system. The results show a good stabilising ability during irradiation changes and smooth signal output from the converter.

1. Introduction

The urgent need to decrease the effects of environmental damage and global climate warming has motivated the researchers to develop alternative power systems to replace fossil fuels; one such renewable source is solar power using photovoltaic systems [1]. These systems are generally suitable for countries with a high solar power density such as Iraq, which currently depends almost entirely on oil to meet its energy demands, and this replacement can be implemented in multiple systems such as power plants, lighting, traffic lights sign, camera surveillance systems, and water pumps. These PV systems have many advantages, such as low cost, high efficiency, and flexibility of installation, yet along with their advantages, PV systems have several drawbacks such as nonlinearity. The nonlinearity of these systems is generally a consequence of temperature and insulation fluctuations, and many papers have thus presented various means to overcome these, such as increasing the conversion efficiency of the PV systems, increasing the output power of the PV systems, or implementing new technologies that decrease the cost of the PV systems, many using an MPPT based on tracking the maximum power point of the PV system using online or off-line algorithms or techniques to move the operating point of the system toward an optimal condition [2], [3]. Another approach to overcoming such fluctuations is to use pulse width modulated converters [4], in particular fuzzy logic controllers (FLC) [5].

As illustrated in Fig. 1, one of the main parts of a photovoltaic system is the DC-DC converter, the control procedure that stabilises the output of the converter regardless of variations in PV module output voltage caused by solar irradiation and the temperature change, as seen in Fig. 2. The effect of solar radiation on a photovoltaic panel is generally considered under a fixed temperature of 25 °C and the effect of that temperature under fixed radiation (1,000 W/m²) [6], [7].
Many researchers have proposed control techniques for converters [8], [9], [10], [11], [12]. In this work, a fuzzy logic control technique to improve the performance of the step-up converter is considered. This technique is based on the linguistic description for the system, including in-depth knowledge of the plant, which means there is no need to develop a mathematical model to obtain a fast and stable response.

![Figure 1. Photovoltaic system [6].](image1)

![Figure 2. Effects of solar radiation and temperature on PV [6].](image2)

2. Design of the proposed converter

The photovoltaic system shown in Fig 1. has multiple components, including the PV module, regulating device or DC-Dc converter, control circuit, storage battery, and mechanical and electrical connections. In this paper, a step up converter based on a fuzzy logic algorithm is applied to develop an efficient conversion algorithm in response to sudden radiation and temperature changes, thus decreasing the cost and time performance of the PV system [13], [14]. The module considered consists of several PV cells connected in series or parallel to form an array; each PV cell generates around 0.5 to 0.8 volts, and the panels are connected in parallel or series as required to produce an adequate array [15]. The basic circuit of the set up DC-Dc converter is shown in Fig. 3 [12]:
The most important values of the components in the circuit are the minimum inductance and minimum capacitance (1), (2), which can be calculated as

\[
L_{\text{min}} = \frac{D R_L (1 - D)^2}{2 f_s} \quad (1)
\]

\[
C_{\text{min}} = \frac{V_o D}{f_s \Delta V_o R_L} \quad (2)
\]

where \(D\) is the duty cycle (\(D = \frac{T_{\text{on}}}{T}\)), \(R_L\) is the load, \(f_s\) is the switching frequency, \(V_o\) is the resulting voltage, and \(\Delta V_o\) is the ripple voltage, which is 5% of \(V_o\).

The most important feature of a successful fuzzy logic controller is the use of linguistic variables instead of numerical variables, which decreases the nonlinearity of the system and the uncertainties of unmodeled physical quantities [16], [17]. Fuzzy sets written in natural language do not depend on a mathematical model but are instead based on the knowledge of the plant obtained by the fuzzification process, which transforms crisp input to linguistic variables based on defined membership functions. Any control decisions are carried out at the rule’s inference stage. Finally, the linguistic-based data is converted back to crisp data (defuzzification). Multiple defuzzification methods can be implemented with varying degrees of accuracy and computational intensity, such as centre of gravity (used in this paper), centre of gravity for singletons, mean maxima, or bisector of area. The main stages of FLC are:

1. **Fuzzification**, where the real values of the input (error and change in error), obtained as in equation (3), are transformed into fuzzy variables.

\[
e(k) = V_{\text{ref}} - \beta V_o (k)
\]

\[
Ce(k) = e(k) - e(k-1)
\]

\[
D(k) = D(k-1) + h\Delta D(k) \quad (3)
\]

where \(e(k)\) is the error, \(V_{\text{ref}}\) is the reference voltage, \(\beta V_o (k)\) is the \(k^{th}\) sample of the converted digital output voltage, \(Ce(k)\) is the change in error, \(e(k-1)\) is the previous value of the error, and \(D(k)\) is the duty cycle.

The output in this case is the change in duty cycle; these inputs, and output can be represented in terms of linguistic variables however, with VN being very negative, MN being minimally negative, N being zero, MP being minimally positive, and VP being very positive, as shown in Fig. 4, which demonstrates the membership functions for the input and output variables.
Figure 4. Error, change in error, and output membership functions.

2. **Inference stage**, where, depending on DC-DC converter behaviour, the following statement can be used:

   *If $e$ is VN and $Ce$ is MP, then output is MP.*

   where the error ($e$), change of error ($Ce$), represent the degree of membership ($\mu$), and output, respectively. To obtain the control decision, a max-min inference method can be used where the AND operator describes the minimum function and the OR operator describes the maximum function, as shown in **Table 1**.

   **Table 1. Fuzzy rules.**

   | Error ($e$) | VN | MN | N  | MP | VP |
   |------------|----|----|----|----|----|
   | VN         | N  | N  | VN | VN | VN |
   | MN         | N  | N  | MN | MN | MN |
   | N          | MN | N  | N  | N  | MP |
   | MP         | MP | MP | MP | N  | N  |
   | VP         | VP | VP | VP | N  | N  |

The inference stage thus introduces a function to generate the membership variable acting, as fuzzy information; however, the converter needs an adequate control signal for input, so this fuzzy information must be converted to deterministic information.
2- **Defuzzification**, the conversion process, which can utilise multiple methods such as Mean of Maxima, Max Criterion, and Centre of Area. The Centre of Area is the method used in this paper to determine the change of duty ratio, $\Delta D$, as follows:

$$
\Delta D_o = \frac{\sum_{i=1}^{n} \mu(D_i) * D_i}{\sum_{i=1}^{n} \mu(D_i)}
$$

(4)

The change in duty cycle ($\Delta D_o$) represents the output of FLC, which is converted to the duty ratio $D(k)$ as

$$
D(k) = D(k - 1) + \Delta D(k) \cdot h
$$

(5)

Computing the new duty cycle can thus be done by using one of two methods:

1. The first method is discrete time integration of the fuzzy controller output, which decreases the steady state error. The input of the FLC, the error signal, is added to the change of error, then the output is scaled by gain $h$ (this value must be small to avoid voltage oscillation of the steady state) and added to the previous sampling period to form the new duty cycle as shown in **Fig.5 a**. Here, the integrator is connected in series with FLC.

![a.](image1)

![b.](image2)

**Figure 5.** Methods of computing duty cycle.

2. In the second method, the output of the FLC is increased by the gain of $h$, then added to the output of the parallel integrator, which is increased by $K_i$, as seen in **Fig.5 b**:

$$
d(k) = K_i I(k - 1) + h \Delta d(k)
$$

(6)

where $I(k)$ is the discrete time integration of the error $e(k)$, and $h$, $g_0$, and $g_1$ are scaling factors that generate suitable responses. This type of integrator (parallel) is used to eliminate steady state error.

The fuzzy flow chart can be seen in **Fig.6**, where fuzzy inference is generated using Mamdani’s method, thus controlling the duty cycle, which is fed to the PWM circuit to control the switching process using the fuzzifier equation.

3. **Analysis and Discussion**

Based on results from the tested model for the Solar PV given in **Fig. 3**, a simulation process was achieved using MATLAB/SIMULINK (see **Fig. 7**), with component values as follows: input voltage ($V_i$) = 20 to 24 v, capacitance ($C$) = 230 μF; inductance ($L$) = 200 μH; switching frequency ($f_s$) = 200 kHz; average load resistance ($R_l$) = 48Ω; and desired output voltage ($V_o$)=48V. The maximum voltage drawn from the PV module was 24V, though normally when a step-up converter is connected to the
output of a PV panel, it draws about 48V (converter gain equal to 2). The DC converter is capable of regulating the output DC voltage and of regaining equilibrium after step changes in the load. The results were compared with other works such as [16], [17], and differences between conventional converters, as in Fig. 8; PID converters, as in Fig. 9; and the fuzzy converter, as in Fig. 10 were noted. Referring to Fig. 2, the change in temperature can be translated into a change in the voltage supplied to the converter, and this voltage change (20 to 24 V) with a step of 2V was used in simulation process, as shown in figures Figs. 8, 9, and 10 (blue curve), with the resultant voltage from the three converters shown as a red curve. From these figures, the best overshoot is approximately zero, with steady state reached at about 0.03 sec in the FLC, with minimum ripple, indicating that the overall efficiency of the proposed converter is around 90%. Based on examining different cases in Simulink, the fuzzy technique was found to be effective in reducing the effects of various perturbations such as load changes and input voltage changes; this technique thus offers powerful alternative to conventional techniques.

![Fuzzy flow chart](image)

**Figure 6.** Fuzzy flow chart.
Figure 7. Step-up model using FLC.

Figure 8. Conventional controller.
Figure 9. PID controller.

Figure 10. FLC Controller.

Table 2 shows the major specifications of the converter under investigation, highlighting the favourable comparison between the FLC and conventional and PID controllers.
Table 2

| Type       | Overshoot | Rise time    | Settling time |
|------------|-----------|--------------|---------------|
| Conventional | 25% | 651.758μs     | 0.6426         |
| PID        | 10%       | 1.2*10^-5    | 0.05          |
| FLC        | 0.86%     | 1.5*10^-6    | 0.03          |

4. Conclusion

Wide demand for solar energy in the fields of lighting, commercial devices, and everyday residential applications, particularly in regions where there are no alternative electricity sources, has spurred researchers and manufacturers to implement multiple approaches to improving photovoltaic systems. One of the important components of such systems is the converter, represented by the MPPT circuit that generates the maximum possible power based on tracking the maximum power point in the PV system. In this manuscript, a high efficiency, high gain setup converter implementing the fuzzy logic technique was proposed to control the duty cycle in order to reduce on-state drops across the switch. Multiple test cases were examined via simulation using MATLAB/SIMULINK to demonstrate that this technique is capable of reducing the effect of such disturbances, whether from source variation or load changes, proving that the fuzzy control offers an effective alternative to conventional controls. The examined controller also improves start up, transient, and steady states, offering a rapid and stable response. Finally, this controller demonstrated excellent ability to track MPP, taking less than 0.1 second to respond when the PV was subjected to sudden changes in irradiation and temperature, as well as being relatively easy to implement.

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