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Fuzzy logic control approach of a maximum power point employing SEPIC converter for standalone photovoltaic system

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Abstract

This paper presents a new fuzzy logic controller as a maximum power point tracker employing single-ended primary-inductor (SEPIC) converter. The new controller improves perturb and observe search method with rules to fuzzify and eliminate its drawbacks. An accurate and fast converging to maximum power point is offered by fuzzy logic tracker during both steady-state and varying weather conditions compared to conventional maximum power point tracking methods. The performance of the proposed maximum power point tracker is demonstrated in both simulation and experiment at different operating conditions.

Keywords: Fuzzy logic controller (FLC), Maximum power point tracker (MPPT), Photovoltaic (PV)

1. Introduction

Due to its output gain flexibility, single-ended primary-inductor converter (SEPIC) acts as a buck-boost DC/DC converter, where it changes its output voltage according to its duty cycle. Unlike the conventional buck-boost converter, SEPIC converter has a non-inverted output and it uses a series capacitor to isolate input from output [1]. The buck and buck-boost converters lose half of their input power due to input current series switching; for that reason, the two types of converters should be excluded from maximum power applications. The boost converter has continuous input current, but the output voltage is always larger than the input which may not achieve maximum power transfer operation

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in some cases, such as when the maximum power voltage is less than input. Regarding Ćuk converter, it is not widely used because of stability difficulties. To operate properly, it needs a complex compensation circuit which causes slow response. The maximum power point tracking (MPPT) technique tracks the maximum power via increasing or decreasing voltage and current. Therefore, the use of SEPIC converter is effective as it increases or decreases voltage at current’s expense and it is also able to exploit all the existing power from PV due to its continuous input current.

MPPT algorithm represents optimal load for photovoltaic (PV) array, producing opportune voltage for the load. The PV panel yields exponential curves for current and voltage, where the maximum power occurs at the curve’s mutual knee [2], [3]. The PV power and voltage characteristics are nonlinear and affected by the irradiance and temperature variations. The applied MPPT uses a type of control and logic to look for the knee, which, in turn, allows the SEPIC converter to extract the maximum power from the PV array. The tracking method provides a new reference signal for the controller and extracts the maximum power from the PV array. Literature has proposed many MPPT techniques. The incremental conductive method is based on the derivative of power over voltage being zero at the MPP, positive on the left of the MPP, and negative on the right. This method requires complex computation to give good performance under rapid weather conditions change. Furthermore, the tracking time is relatively long for small step size [4]. Hill climbing method works by perturbation of the PV system which changes the power converter duty cycle and observes it on the output power, and then deciding the new direction of the duty cycle to extract maximum power. The hill climbing method has slow response especially under varying weather conditions because the MPPT gives the decision directly for the duty cycle by declaring a controller of error signal. The voltage-based MPPT method uses the fact that the ratio between the maximum power voltage and the open circuit voltage under different weather conditions are linearly proportional [5] and current-based MPPT approximates the ratio between the maximum power current and the short circuit current under different weather conditions [6]. Perturbation and observation (P&O) method is the commonly used due to its ease of implementation and low cost [7]. P&O works effectively under varying weather conditions where it can reach the error signal due to its separation between the MPPT method that controls the reference signal and the duty cycle resulting from changing the reference signal. Therefore, P&O employs the MPPT for the reference signal, while the power converter can be controlled separately.

Among different intelligent controllers, fuzzy logic is the simplest to integrate with the system. Recently, fuzzy logic controller (FLC) has received an increasing attention from researchers for converter control, motor drives and other process control as it provides better responses than other conventional controllers [8]-[13]. The imprecision of the weather variations that can be reflected by PV arrays can be addressed accurately using fuzzy controller. In order to take the advantages of fuzzy logic algorithm, the MPPT algorithm is integrated using FLC so that the overall control system can always provide maximum power transfer from PV array to the inverter side, in spite of the unpredictable weather conditions. The drawback of most of the fuzzy-based MPPT algorithms [14]-[18] is that the tracking point is located away from the maximum power point when the weather conditions change. Furthermore, the MPPT control depending on duty-cycle changes causes neglect in power converter error signal control. However, there is a need to control the duty cycle of the power converter and to track the maximum power point depending on reference signal not duty-cycle.
This paper presents a fuzzy-based P&O technique for MPPT standalone PV system. The proposed MPPT is capable of exploiting the advantages of the P&O method and eliminates its drawbacks. The MPPT is designed by converting the P&O algorithm into 17 fuzzy rules after the controller inputs and output have been divided to five fuzzy subsets. As the proposed method always transfers maximum power from PV arrays, it optimizes the number of PV modules. The proposed scheme is implemented in real-time using DSP board – TMS320F28335.

2. Conventional P&O Technique

The P&O algorithm is based on the following principle: if the voltage of the PV array is perturbed in a specific direction and the PV power increases, this means that the operating point has moved toward the maximum power and, therefore, the operating voltage must be perturbed in the same direction. Otherwise, if the power decreases, the operating point has moved away from the maximum power and, therefore, the direction of the operating voltage perturbation must be reversed.

P&O operates by changing the power converter voltage reference signal and observing its impact on the output power. The P&O is the most commonly used algorithm because of its simplicity, ease of implementation and low cost. However, it oscillates around the operating point which causes power losses, and the operating point moves away from the maximum power which loses the way during fast irradiance variations.

Fig. 1 (a) shows the behavior of the PV power using the conventional P&O MPPT method. The PV output power is enforced to move toward the maximum power point. After reaching the optimum point, the PV output power oscillates around the point. At 0.33 s, the solar radiation decreased; therefore, power diverges from the optimum value due to the drawback aforementioned.

3. The Proposed System

Change of voltage level fed to the inverter is the main function of the DC/DC converter. In this work, voltage level increases or decreases depending on the maximum power. Furthermore, the controller changes the voltage level by changing the duty cycle of the pulse width modulated (PWM) signal, which tracks the reference signal. A sinusoidal reference-signal is compared with the output signal to produce a supposedly zero error signal. Another reference signal is used to compare the SEPIC’s output to achieve the maximum power. This reference signal is adaptive, changing its shape according to weather
conditions. The SEPIC’s output signal is, thus, compared with the adaptive reference signal to feed the inverter with the most suitable power. The inverter’s input signal should be as smooth as possible, but the SEPIC MPPT generates a non-smooth signal, owing to its tracking of maximum power. This problem is not as big since the non-smooth signal can be enhanced by the inverter’s fuzzy controller and the low-pass filter connected to the inverter. So, even the input signal is not smooth, the exploitation of the maximum power is possible, as is the creation of a smooth output signal.

Fig. 1 (b) is the circuit diagram of the SEPIC DC/DC converter together with the MPPT and the fuzzy controller. The design of fuzzy controller was done using Mamdani method. The selection of the membership functions will be discussed in the next sections. The PWM changes its duty cycle according to the control signal, configuring a feedback from the output signal represented in voltage, current and power to get the reference signal, which is unpredictable and adapts itself depending on the maximum power.

4. P&O Fuzzy-Based Technique

In fuzzy logic controller design, one should identify the main control variables and determine the sets that describe the values of each linguistic variable. The proposed P&O searching algorithm is designed to achieve the advantage of P&O simplicity and eliminate all aforementioned drawbacks. The change in PV array output power and the change in PV array output voltage are the inputs of the FLC. The increment of the reference voltage is the output of the FLC where the increment is added to the previous reference voltage to produce the new reference voltage. The inputs and the outputs of the FLC are shown in the equations from (1) to (3)

\[
\Delta P = P(k) - P(k-1)
\]
\[ \Delta V = V(k) - V(k - 1) \]  
\[ \Delta V_{\text{ref}} = V_{\text{ref}}(k) - V_{\text{ref}}(k - 1) \]

The advantage of this modification in P&O is that the output of the FLC changes the reference voltage only. Therefore, the duty cycle of the SEPIC converter can further be controlled using specific controller. Furthermore, the SEPIC controller ensures that the PV output power does not diverge from the maximum power point during varying weather conditions or variable load.

The input variables of the FLC are divided into five fuzzy subsets which are: positive big (PB), positive small (PS), zero (Z), negative small (NS) and negative big (NB). These five fuzzy subsets for two input variables can generate twenty five fuzzy logic control rules, but the zero membership rules are shortened in one rule which is only generating total of seventeen rules, instead of twenty five. The membership functions of the output variables are seven-term fuzzy sets with classical triangular and trapezoidal shapes, negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB). The fuzzy method used here is Mamdani, where the maximum of minimum composition technique is used for the inference and the center-of-gravity method is used for the defuzzification process to convert the fuzzy subset reference voltage that changes to real numbers as presented in (4).

\[ \Delta V_{\text{ref}} = \frac{\sum_{i=1}^{n} \Delta V_{\text{ref},i} \mu(\Delta V_{\text{ref},i})}{\sum_{i=1}^{n} \mu(\Delta V_{\text{ref},i})} \]  

Where \( \Delta V_{\text{ref}} \) is the fuzzy output and \( \Delta V_{\text{ref},i} \) is the output membership function center of max-min inference composition.

The fuzzy rules mimic the behavior of P&O method. The fuzzification of the P&O technique with the rules is shown in Fig. 2 (a). The shapes and fuzzy subset partitions of the membership function in both input and output shown in Fig. 2 (b) depend on the behavior of the controller output and input signals.

The FLC deals with variable step size to increase or decrease the reference voltage; therefore, the tracking time becomes short and the system performance during steady-state conditions is much better than with conventional P&O technique. Moreover, the zero (Z) membership function keeps the system in the steady-state without oscillations once it achieves the maximum power point; this zero membership function is considered an overtaking on the P&O technique in solving the problem of oscillation.

5. Simulation and Experiment Results

5.1. Simulation Results

The results introduced in Fig. 3 (a) belonged to power, voltage and current under step radiation varying. It is clear that the drawback of the conventional P&O method appeared where the reference loses the optimum point at sudden radiation changing. Furthermore, at gradually radiation varying, Fig. 3 (b) shows that the conventional P&O lost the optimum point and caused oscillations in the steady state while these drawbacks have been solved for the proposed FLC-based MPPT technique. In both previous cases, the proposed FLC-based MPPT showed faster response in the transient response and stable steady state. Moreover, the oscillations disappeared, comparing with the conventional P&O method.
5.2. Experiment Results

The PV array was connected to the SEPIC converter, which used the controlled PWM generated by TMS320F28335 DSP with 8kHz carrier wave. Two 5mH inductors were chosen to keep the operating of the converter in continuous conduction mode. The values of the input capacitor $C_i$ and the output capacitor $C_o$ were 470μF and 2200μF, respectively. A prototype was developed to verify the performance of the proposed FLC-based SEPIC converter. The power electronic switches used in this paper were IGBT modules GT50J32S.

The experimental results of the SEPIC converter were tested under different operating conditions. The maximum power point was attained in a short time and had a small oscillation around the steady state. Moreover, the proposed controller forced the power to move to the new operating point when the weather conditions were varied. The experiment results of the proposed MPPT and the conventional P&O tracker are shown in Fig. 4 (a) and Fig. 4 (b), respectively. The riposte of Fig. 4 (a) verifies the efficacy of the proposed MPPT method over conventional P&O method.
6. Conclusion

This paper has introduced a new fuzzy logic controller as a maximum power point tracker employing single-ended primary-inductor (SEPIC) converter. The new controller improved P&O search method by rules fuzzifying. An accurate and fast converging to maximum power point has been presented by fuzzy logic tracker during both steady-state and varying weather conditions compared to conventional maximum power point tracking methods. The DSP board TMS320F28335 has been used to implement the real-time implementation for the proposed control scheme. The performance of the proposed controller has been found better than that of the conventional tracker. As compared to the conventional P&O tracker, results indicated that the proposed FLC scheme can provide faster response and fewer oscillations around the steady state. It is worth noting that the proposed MPPT FLC based SEPIC converter is a potential candidate for PV inverter applications.

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