ICIC Express Letters
Part B: Applications
Volume **7**, Number **11**, November **2016**

ICIC International ©2016 ISSN 2185-2766
pp. 2443–2449

DESIGN AND IMPLEMENTATION OF AN ANALOG CIRCUIT WITH MINIMUM COMPONENT COUNT FOR DOUBLE-LINEAR-APPROXIMATION MPPT

Chih-Lung Shen[1], You-Sheng Shen[1] and Cheng-Tao Tsai[2]

[1]Department of Electronic Engineering
National Kaohsiung First University of Science and Technology
No. 1, University Rd., Yanchao Dist., Kaohsiung City 824, Taiwan
clshen@ccms.nkfust.edu.tw; u0415903@nkfust.edu.tw

[2]Department of Electrical Engineering
National Chin-Yi University of Technology
No. 57, Sec. 2, Zhongshan Rd., Taiping Dist., Taichung 41170, Taiwan

Received April 2016; accepted July 2016

Abstract. *A novel analog circuit to fulfill the maximum-power-point tracking (MPPT) based on double-linear approximation (DLA) criterion is proposed, which is able to quickly and accurately determine the maximum-power point (MPP) of a PV array. The proposed analog circuit has the least components while compared with other DLA MPPT circuits. Therefore, it has the merits of low cost, fast response, and high reliability. Once atmospheric conditions, that is, temperature and irradiation, have been detected, the optimal terminal voltage of PV array can be instantly determined without complicated calculation. In this paper, a boost dc/dc converter is built to demonstrate that the proposed circuit is capable of finding the maximum power point of PV arrays. Simulations and practical results have verified the feasibility and validity of the analog circuit.*
Keywords: MPPT, DLA circuit, PV arrays

1. **Introduction.** With the rapid growth in industry in many countries, greenhouse effect has been damaging the earth more and more and environmental conservation becomes a critically important issue. Therefore, it is urgent to seek a clean and safe energy to replace fossil fuels. Among all the renewable energies, solar energy provides the easiest access for power generation. In addition, PV array is easy to install. Therefore, the development toward PV power is of great worth.

The output power of a solar module varies with environmental conditions, including temperature and irradiation. Having the PV module set on the MPP enables us to retrieve the maximum power output. There are plenty of approaches to achieve MPPT, such as linear approximation method (LAM) [1,2], incremental conductance method (ICM) [3-6], perturb-and-observe method (POM) [7-11], voltage feedback method (VFM) [12], and power feedback method (PFM) [13]. Among them, POM is the most-used one, but it could cause unnecessary power loss when moving around the MPP.

The target of this study is to develop a simple analog circuit to find out the MPP of a PV array, based on double-linear approximation (DLA). The proposed circuit can accurately provide a reference voltage to controller for the regulation of the PV terminal voltage so as to draw maximum power from the array. In [14], the DLA analog circuit has to adopt five operational amplifiers and nine resistors, which results in disadvantages of high cost and low MPPT speed. Therefore, in this paper we propose a novel MPPT analog circuit to eliminate the mentioned disadvantages. The proposed circuit has the least number of discrete components, which makes significant improvement. Simulations and practical measurements are carried out for demonstration.

2. **Characteristics of PV Array.** The equivalent circuit of PV cell is shown in Figure 1, in which I_{ph} stands for the cell photocurrent source, and D_b and R_b represent the intrinsic diode and the nonlinear impedance of the *p*-*n* junction, respectively. In addition, the internal shunt resistance and series resistance of the PV cell are separately modeled by R_k and R_s. Compared with R_L, the value of R_s is relatively smaller than R_L, whereas the value of R_k is much greater than R_L. That is, the equivalent circuit illustrated in Figure 1 can be simplified by neglecting both resistances of R_k and R_s. Generally, the output power of PV module, P_{PV}, is equal to the voltage across the load, V_{PV}, times the required current of load, I_{PV}. To calculate the P_{PV} accurately, the equation for calculating P_{PV} is expressed as follows:

$$P_{PV} = I_{PV}V_{PV} = n_p I_{ph} V_{PV} - n_p I_{sat} V_{PV} \left[\exp\left(\frac{q}{kTA} \frac{V_{PV}}{n_s} \right) - 1 \right], \tag{1}$$

where q is electric charge and equals 1.6×10^{-19} C, I_{sat} is the reverse saturation current of PV module, k stands for the Boltzmann constant (1.38×10^{-23} J/°K), T denotes the module temperature, A means the ideal factor of PV module always between 1 and 5, and n_s and n_p represent the PV module number in series and in parallel, respectively.

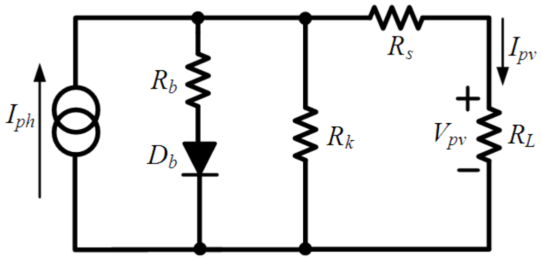

FIGURE 1. The equivalent circuit of a PV cell

TABLE 1. Electrical characteristics of the used PV module (AJP-M660-215B)

Model	AJP-M660-215B
Maximum Power ($P_{\max}$)	215 W
Voltage at Maximum Power (V_{mp})	29.94 V
Current at Maximum Power (I_{mp})	7.18 A
Open Circuit Voltage (V_{oc})	36 V
Short Circuit Current (I_{sc})	7.83 A
Temperature Coefficient of V_{oc}	−0.34 %/°C
Temperature Coefficient of I_{sc}	0.080 %/°C

The PV module used in this paper is AJP-M660-215B, and its electrical characteristics are listed in Table 1. At the fixed module temperature (25°C), simulated P_{PV}-V_{PV} curves under various irradiations are shown in Figure 2. In the case of constant irradiation (1 kW/m^2), Figure 3 depicts the relationship between P_{PV} and V_{PV} relating to different module temperatures. In Figures 2 and 3, the MPPs under different atmospheric conditions are addressed by color dots.

3. **The Proposed Circuit of DLA.** Figure 4 shows the relationship between maximum power P_{mppt} and the corresponding reference voltage V_{ref} at the irradiation $S = 1$ kW/m^2 while temperature varies from 25°C to 65°C. Figure 5 shows the trajectory of P_{mppt}-V_{ref} with an increasing on irradiation from 200 W/m^2 to 1 kW/m^2. Furthermore, the curves of V_{ref} versus T and V_{ref} versus S are shown in Figure 6 and Figure 7, respectively. From

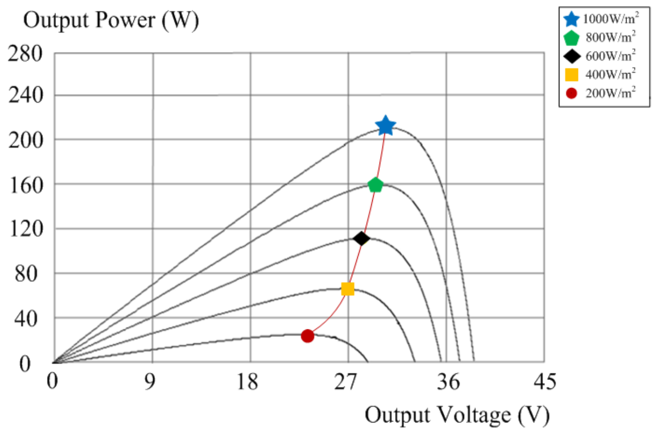

Figure 2. P-V curve at constant temperature (25°C)

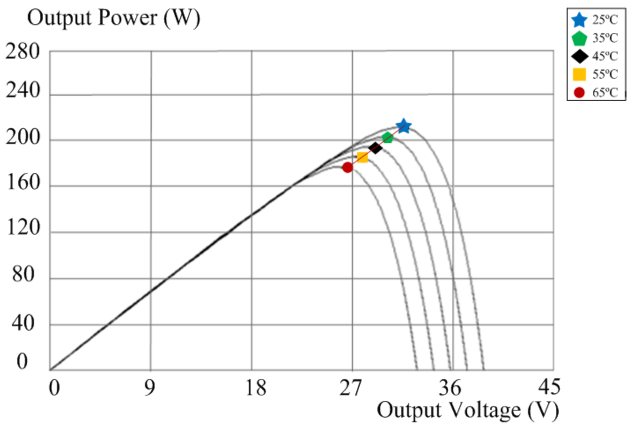

Figure 3. P-V curve under fixed irradiation (1kW/m^2)

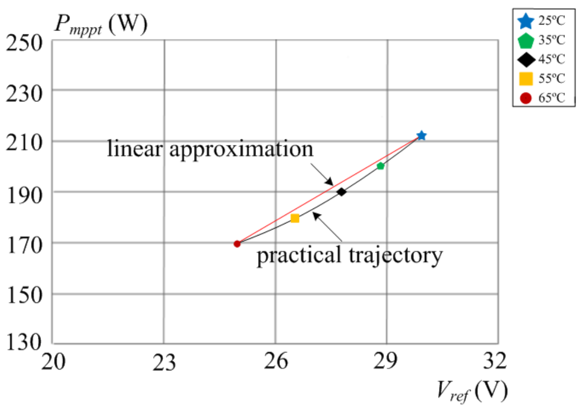

Figure 4. P_{mppt} and V_{ref} while module temperature increases from 25°C to 65°C

Figures 6 and 7, it can be seen that two straight lines can approximate both of curves. Once a V_{ref} is obtained, the MPPT can be readily achieved.

The DLA circuit consists of two operational amplifiers, one photodiode (PD), one thermistor, and three resistors, as shown in Figure 8. The PD is used to detect the magnitude of irradiation. When irradiation increases, the current I_{Re} will also increase. Then, a current flowing through R_f increases. The voltage at the node x can be expressed as

$$V_x = -\left(I_{Re} + \frac{E_{dc}}{R_1}\right) R_f. \tag{2}$$

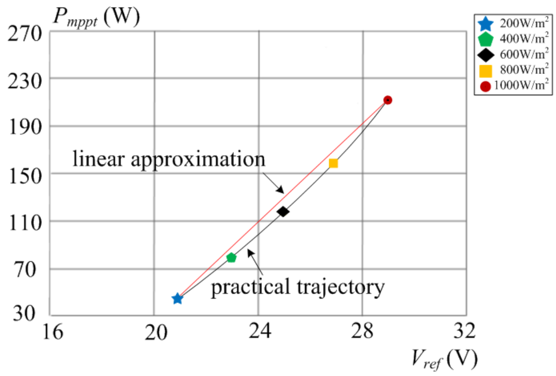

FIGURE 5. P_{mppt} and V_{ref} while irradiation increases from 200 to 1000 W/m^2

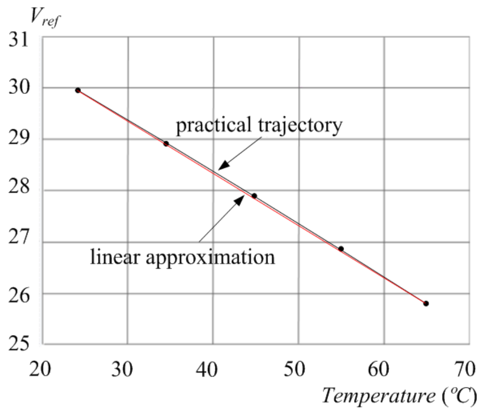

FIGURE 6. The trajectory of V_{ref} versus T

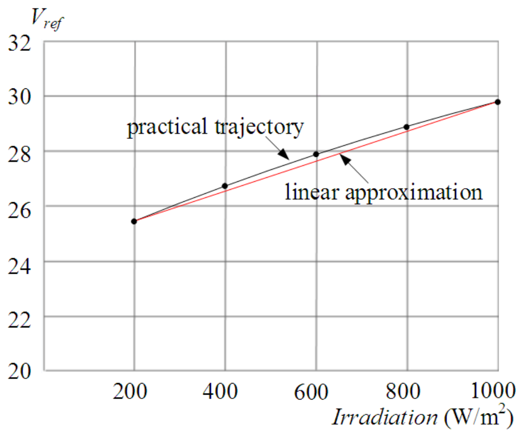

FIGURE 7. The trajectory of V_{ref} versus S

In addition, temperature of PV module is measured by thermistor R_3. After given V_x, the reference voltage V_{ref} is founded by

$$V_{ref} = -\left(\frac{V_x}{R_2}\right) R_3. \tag{3}$$

By substituting (2) into (3) and with simplifying, reference V_{ref} in terms of circuit parameters can be obtained as

$$V_{ref} = R_3 \left(I_{Re} + \frac{E_{dc}}{R_1}\right) \frac{R_f}{R_2}. \tag{4}$$

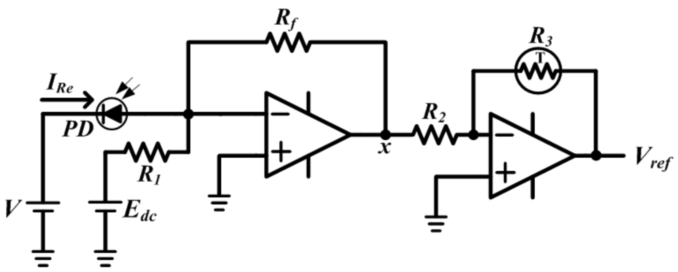

Figure 8. The proposed DLA circuit

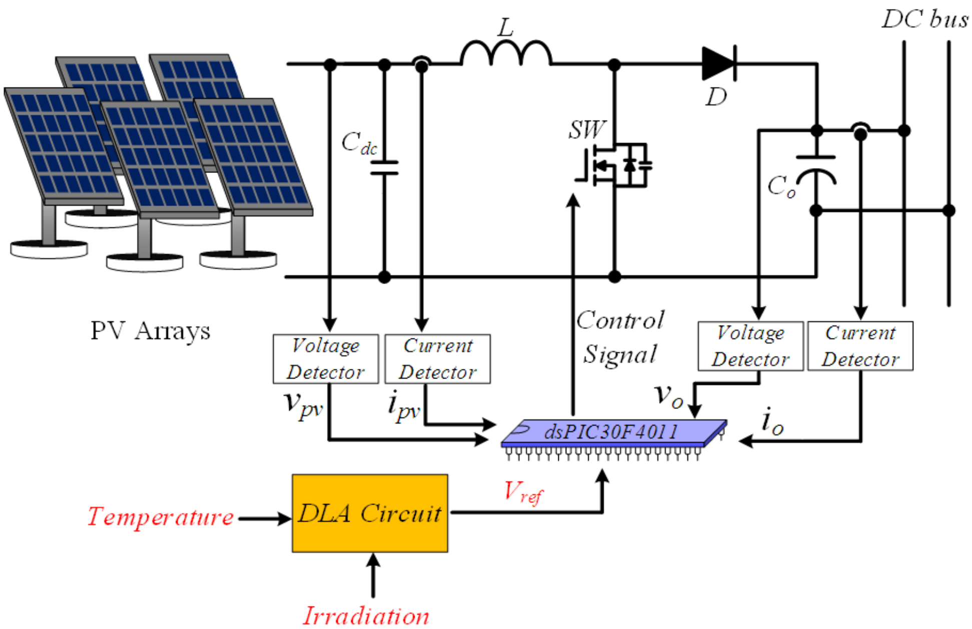

Figure 9. The configuration of the dc/dc converter system with the propsed DLA circuit for verification

4. **Simulations and Experimental Results.** To verify the theoretical analysis and validate the proposed DLA, a 1.1 kW converter system to deal with PV power is implemented, of which schematics is shown in Figure 9. The system contains a boost dc/dc converter, a DLA circuit, a system controller, two voltage detectors, two current sensors, and PV arrays. The key parameters of the system are summarized as follows:

PV arrays: AJP-M660-215B (5 pieces in series),
Active power switch: IXFH26N50Q,
Diode: BYV42,
$C_{dc} = 10\ \mu$F, $C_o = 220\ \mu$F, and $L = 234\ \mu$H.

In Figure 9, the input of the system consists of 5 pieces of solar modules in series. The microprocessor, dsPIC30f4011, is in charge of system controller to determine control signals. After sensing temperature and irradiation, the DLA circuit will forward a reference voltage to the controller instantaneously. Then, the boost converter will regulate the output voltage of PV arrays to the reference voltage to attract maximum PV power.

Tracked by the proposed DLA circuit, Figure 10 shows the simulated MPPT trajectories under fixed irradiation, whereas Figure 11 illustrates the PV curve under fixed temperature. In Figures 10 and 11, all the maximum power points at different temperature and irradiation conditions are denoted as color dots. It is obvious that the DLA circuit tracks the maximum PV power correctly. Figure 12 shows the MPPT trajectory under the condition that irradiation and temperature vary simultaneously.

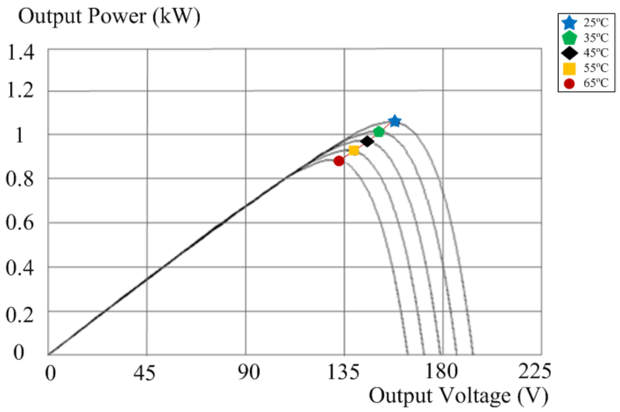

FIGURE 10. The MPPT trajectory tracked by the DLA circuit under fixed irradiation

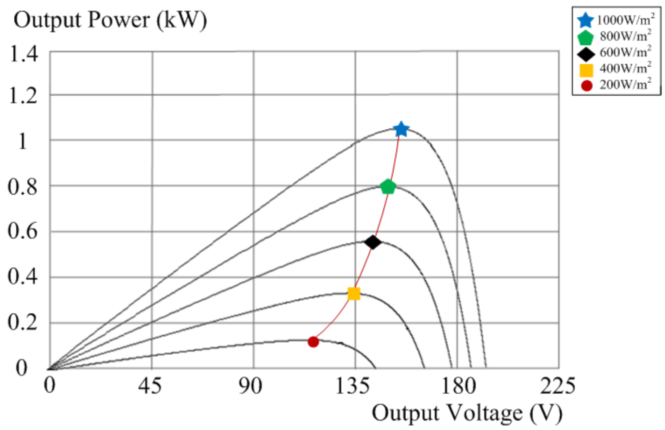

FIGURE 11. The MPPT trajectory tracked by the DLA circuit under fixed temperature

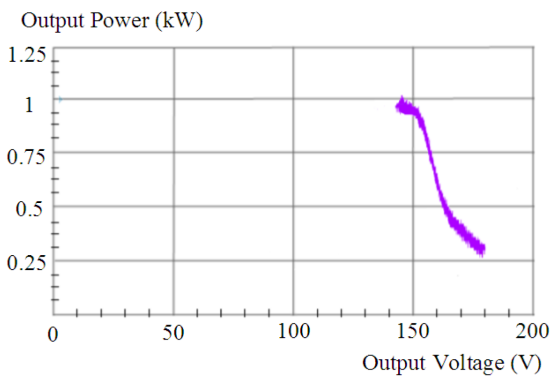

FIGURE 12. MPPT trajectory tracked by the proposed DLA circuit under the condition that irradiation and temperature increase simultaneously

5. **Conclusions.** In this paper, a simple DLA analog circuit is proposed, which has the minimum component count, as compared with other DLA circuits. The circuit has the advantages of low cost, high reliability, being easy to implement, and prompt response. Once the DLA circuit determines a maximum power point, a dc/dc converter can accordingly control the terminal voltage of PV arrays for MPPT achievement. The boost converter system with the analog circuit is set up in this study for demonstration. Simulated results and practical measurements have proven the correctness and effectiveness of the proposed circuit. If considering the aging effect of discrete devices and PV module, a compensator to modify the double linearity can be a major future research.

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