A Double-Linear Approximation Algorithm to Achieve Maximum-Power-Point Tracking for PV Arrays

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Abstract -- **In this paper, a double-linear approximation algorithm (DLAA) to achieve maximum-power-point tracking (MPPT) for PV arrays is proposed. The DLAA is based on that the trajectories of maximum power point varying with irradiation and temperature are approximately linear. With the DLAA, a maximum power point can be determined instantaneously. Moreover, complicated calculation and perturbation about an optimal point can be avoided. In the paper a corresponding circuit to complete DLAA is proposed as well, of which configuration is simple. As a result, the proposed circuit is cost-effective and can be embedded into PV arrays easily. An implementation example of PV power system with the proposed MPPT is designed and the DLAA is compared with the perturb-and-observe method. From simulated and experimental results, the proposed MPPT algorithm has been verified and the feasibility of the proposed circuit is also demonstrated.**

Keywords—Maximum power point tracking, PV arrays, and double-linear approximation algorithm.

I. INTRODUCTION

Due to the rapid development of industry, the overuse of fossil fuel results in environment pollution, greenhouse effect and ecological damage. Adopting renewable and clean energy resources to replace fossil fuel is imperative. Among all kinds of renewable-energy resources, solar energy is obtainable readily so that the demand for photovoltaic (PV) panel has been increasing more and more. The output voltage and current of a PV panel vary with irradiation, panel temperature and power loading nonlinearly. There is a maximum power point (MPP) under certain atmospheric condition. To draw maximum power from PV panel, a large number of researchers have proposed maximum power point tracking (MPPT) algorithms. The present MPPT algorithms include voltage feedback method (VFM)[1], power feedback method (PFM)[2]-[4], perturb-and-observe method (PAOM)[5]-[7], incremental conductance method (ICM)[8]-[9], three-point weight comparison method (TPWCM)[10]-[11], and linear approximation method (LAM)[12]. The VFM is the simplest method for MPPT, which regulates PV arrays terminal voltage to a reference, handling the operation point of a PV arrays near the maximum power point. It is only suitable for constant irradiation. In power feedback method, the derivative (dP/dV) is regarded as a control index. While controlled output voltage and power meet the derivative being zero, maximum power point is achieved. However, more parameters and complicated calculations are required, which steps up the difficulty of MPPT. Perturb-and-observe method is widely used in maximum PV power tracking because it is easy to carry out and few measured parameters are required. Even though a maximum PV power point is reached, continued perturbing and observing will oscillate around the point resulting in PV power loss, especially in constant or slowly varying atmospheric condition. To overcome the mentioned drawbacks of the PAOM, the ICM is developed. In the ICM, the output voltage or current of a PV arrays is adjusted until an incremental conductance dI/dV just reaches the ratio of PV output current to voltage. Owing to detection error, hardly is the determined incremental conductance to agree with the value of I/V. In another solution to avoid fluctuation about the maximum power point, the TPWCM is developed, in which three points on PV curve are compared and weighted. While the weighted positively or negatively matches the preset, succeeding comparison step stops. Nevertheless, a complicated procedure is also required, which lowers dynamic response significantly. The LAM tracks maximum power according to a straight line interconnecting all MPPs under different irradiation. It is easy to implement and locates MPP rapidly. However, the influence on temperature is neglected.

In this paper, a double-linear approximation algorithm (DLAA) is proposed, which can track maximum power point instantaneously and can be implemented easily. The DLAA is based on that the trajectories of maximum power point varying with irradiation and temperature are approximately linear. According to the DLAA, MPPT can be achieved without any calculation and perturbation about an optimal point can be avoided. In this paper, a corresponding circuit of the DLAA is developed, which determines a reference voltage in order to draw maximum power from PV arrays. Since the configuration of the circuit is simple, it is cost-effective and can be embedded into PV arrays easily. Comparison between the DLAA and the PAOM is performed. The simulations and practical measurements have verified the advantages of the proposed algorithm and the feasibility of the corresponding MPPT circuit.

II. CHARACTERISTICS OF PV ARRAYS

In general, PV arrays are composed by a number of PV modules, which are connected in series and/or in parallel. A PV module is made of a group of PV cells, which are wired each other and encapsulated in a weather-proof flat container. One side of the module is transparent, allowing sunlight to reach the PV cell. Each PV cell is a *p-n* junction semiconductor converting solar energy into electricity. An equivalent circuit is shown in Fig. 1, in which I_{ph} stands for the cell photocurrent source, D_j represents the p-n junction, R_j, R_{sh} and R_s are the p-n junction nonlinear impedance, intrinsic shunt resistance and intrinsic series resistance, respectively. The series resistance R_s is relatively small and the shunt resistance R_{sh} is relatively large. Therefore, the equivalent circuit can be simplified by neglecting both resistors.

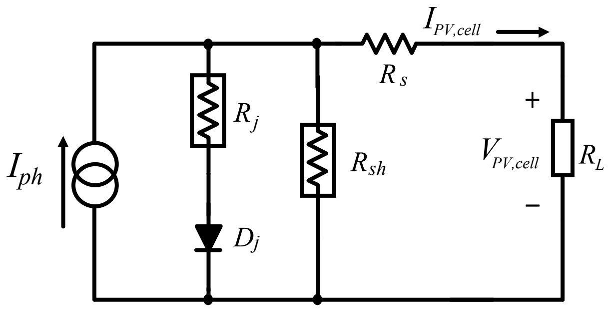

Fig. 1. An equivalent circuit of a PV cell.

From the characteristics of a p-n junction and the equivalent circuit, output current of PV arrays, I_{PV}, can be described as

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

where V_{PV} is output voltage of PV arrays, n_s is the total number of cells in series, n_p stands for the total number of cells in parallel, q denotes the charges of an electron ($1.6\text{x}10^{-19}$ coulomb), k is the Boltzmann's constant ($1.38\text{x}10^{-23}$ J/°K), T is temperature of PV arrays (°K), and A represents ideality factor of the *p-n* junction (between 1 and 5). In addition, I_{sat} is the reversed saturation current of the PV cell, which depends on temperature of PV arrays and it can be expressed by the following equation:

$$I_{sat} = I_{rr}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{q\,E_{gap}}{kA}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right], \tag{2}$$

where T_r is cell reference temperature, I_{rr} is the corresponding reversed saturation current at T_r, and E_{gap} stands for band-gap energy of the semiconductor in the PV cell. In (1), the I_{ph} varies with irradiation S_i and PV array temperature T, which can be represented as

$$I_{ph} = [I_{sso} + k_i(T - T_r)]S_i/100, \tag{3}$$

where I_{sso} is the short-circuit current while reference irradiation is 100 mW/cm^2 and reference temperature is set at T_r, and k_i is the temperature coefficient. Based on (1), output power (P_{PV}) of PV arrays then can be determined as follows:

$$P_{PV} = I_{PV}V_{PV} = n_p I_{ph} V_{PV} - n_p I_{sat} V_{PV}\left[exp\left(\frac{q}{kTA}\frac{V_{PV}}{n_s}\right) - 1\right], \tag{4}$$

which reveals that the amount of generated power P_{PV} varies with irradiation S_i and PV-array temperature T.

The PV arrays used in this paper are SIEMENS SM55, and the electrical characteristics of each module are listed in Table 1. By solving (1)-(4) and with the listed values in Table1, the relationships of I_{PV}-V_{PV} and P_{PV}-V_{PV} can be sketched. With fixed module temperature (25°C), simulated P_{PV}-V_{PV} curves under various irradiations are shown in Fig. 2. In the case of constant irradiation (1000W/m^2), Fig. 3 shows the relationship between P_{PV} and V_{PV} under various module temperatures.

From the above simulations, it is obvious that the two factors, array temperature T and irradiation S_i, will affect the generated PV power significantly. To improve system efficiency, an MPPT algorithm has to be adopted to draw maximum power from PV arrays.

Table 1. Electrical characteristics of the used PV module (SIEMENS SM55).

Model	SM55
Typical peak power (P_P)	55 W
Voltage at peak power (V_{PP})	17.4 V
Current at peak power (I_{PP})	3.15 A
Short-circuit current (I_{SC})	3.45 A
Open-circuit voltage(V_{OC})	21.7V
Temperature coefficient of open-circuit voltage	-0.077V/℃
Temperature coefficient of short-circuit current(K_1)	1.2m A/℃

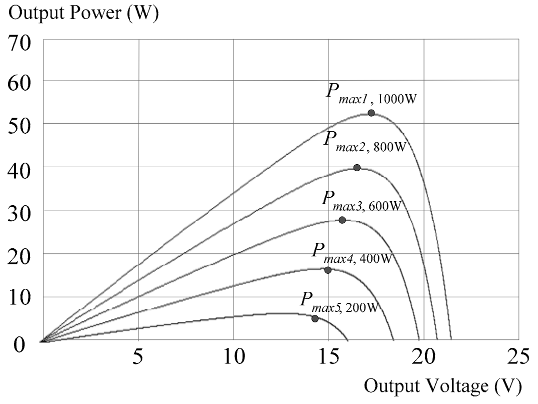

Fig. 2. P-V curve of the PV module with constant temperature (25℃).

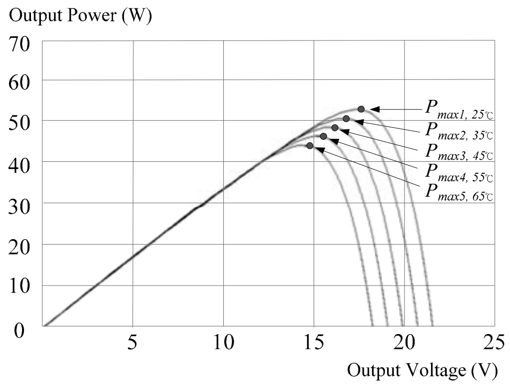

Fig. 3. P-V curve of the PV module with fixed irradiation (1000W/m^2).

III. THE PROPOSED MPPT ALGORITHM

From Figs. 2 and 3, it can be found that a maximum power point occurs when the derivative of PV output power with respect to terminal voltage equals zero. Therefore, from (3) and (4), the optimal PV terminal voltage $V_{ref,\ MPPT}$ in order to draw maximum power from PV arrays can be obtained:

$$V_{ref,MPPT}=\frac{kTA}{q}\ln\left(\frac{kTA[I_{SSO}+k_i(T-T_r)Si-100I_{sat}]}{100I_{sat}[qV_{ref,MPPT}+kTA]}\right). \tag{5}$$

In the derivation, both n_s and n_p have been assumed to be one. Then, by substituting (5) into (4), the maximum power P_{MPPT} is expressed as

$$P_{MPPT}=I_{ph}V_{ref,MPPT}-I_{sat}V_{ref,MPPT}[\exp\frac{q}{kTA}V_{ref,MPPT}-1]. \tag{6}$$

Fig. 4 shows the relationship between P_{MPPT} and $V_{ref,\ MPPT}$ under constant module temperature while irradiation varies from 200 to 1000 W/m^2. In the case of fixed irradiation, the trajectory of P_{MPPT} -$V_{ref,\ MPPT}$ with an increase of temperature from 25 to 65°C is shown in Fig. 5. Fig. 4 and Fig. 5 reveal that P_{MPPT} is linear to $V_{ref,\ MPPT}$ approximately. In addition, based on (4), the curves of $V_{ref,\ MPPT}$ -T and $V_{ref,\ MPPT}$ -S_i are shown in Fig. 6 and Fig. 7, respectively, both of which can be approximated by straight lines. As a result, once a $V_{ref,\ MPPT}$ is obtained, the MPPT is achieved readily. An analog circuit to determine $V_{ref,\ MPPT}$ is designed and shown in Fig. 8.

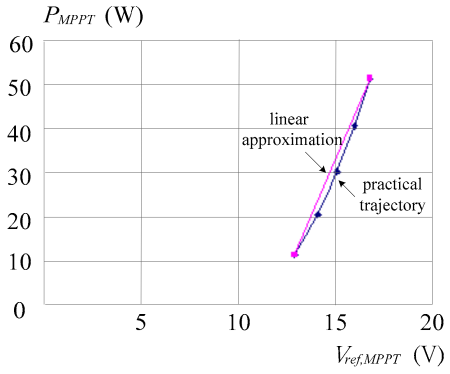

Fig. 4. The relationship between P_{MPPT} and $V_{ref,\ MPPT}$ while irradiation increases from 200 to 1000 W/m^2.

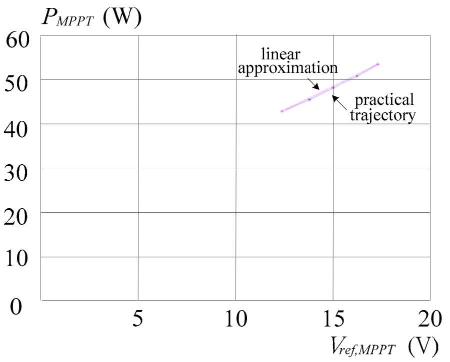

Fig. 5. The relationship between P_{MPPT} and $V_{ref,\ MPPT}$ while module temperature increases from 25 to 65°C.

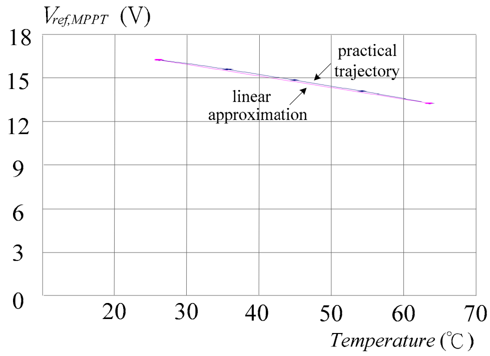

Fig. 6. The trajectory of $V_{ref,\ MPPT}$ versus T.

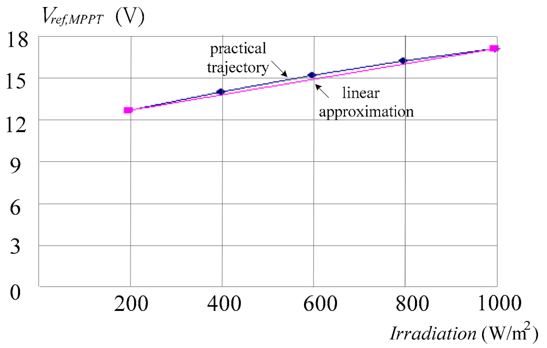

Fig. 7. The trajectory of $V_{ref,\ MPPT}$ versus S_i.

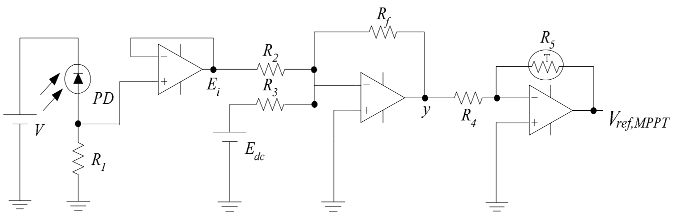

Fig. 8. The proposed DLAA circuit.

IV. AN IMPLEMENTATION EXAMPLE

To verify the proposed MPPT algorithm, a PV dc power supply system is constructed, as shown in Fig. 9, which mainly contains PV arrays, a DLAA circuit, and a dc/dc buck converter. Some important parameters in the system are listed as follows:

PV arrays: SIEMENS SM55 (4 pieces in series), C_i = 100uF, C_o = 100uF, L_f = 2.11mH, active power switch: IRF540N , and ultrafast diode: FR605.

In Fig. 9, the DLAA circuit determines a reference voltage $V_{ref,\ MPPT}$ corresponding to an atmospheric condition. The PV output voltage is sensed and compared with the $V_{ref,\ MPPT}$. Through the simple PI controller an appropriate control signal is generated to regulate the PV output voltage so that the dc/dc converter draws maximum power from PV arrays. Then, the dc/dc converter injects the power into dc bus for dc-distribution application or into utility via a grid-connection dc/ac inverter.

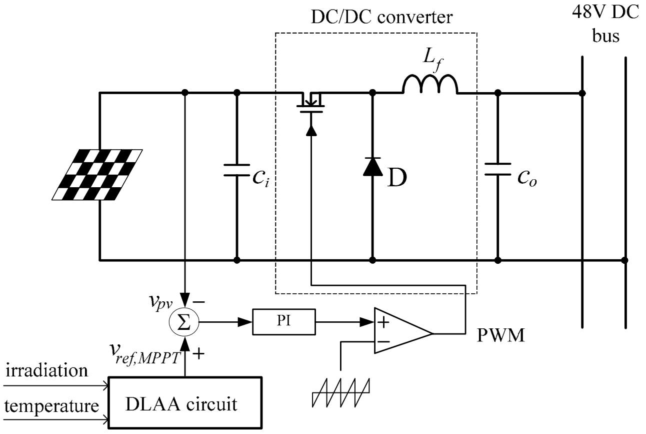

Fig. 9. Illustration of an implementation example.

V. SIMULATED AND EXPERIMENTAL RESULTS

The PV power system mentioned in Section IV is simulated and implemented to demonstrate the effectiveness of the proposed approach. In simulation and implementation, both algorithms of DLAA and PAOM are adopted and embedded into the PV power system to fulfill MPPT. With fixed temperature Fig. 10 and Fig. 11 show the simulated MPPT trajectories by the PAOM and the DLAA, respectively, while Fig. 12 and Fig. 13 show the MPPT results under constant irradiation. As irradiation and module temperature increase, the trajectories of MPPT by the PAOM and the DLAA are shown in Fig. 14 and Fig. 15, in turn. In hardware measurements, Fig. 16 is the practical result of the PV power system with PAOM and Fig. 17 shows MPPT trajectory by the DLAA under the variation of atmospheric condition. From Figs. 10-17, it is illustrated that the DLAA can trace MPP effectively and the proposed corresponding circuit is feasible. In addition, a dc/dc converter with the proposed algorithm can obtain better MPPT performance than that with a PAOM.

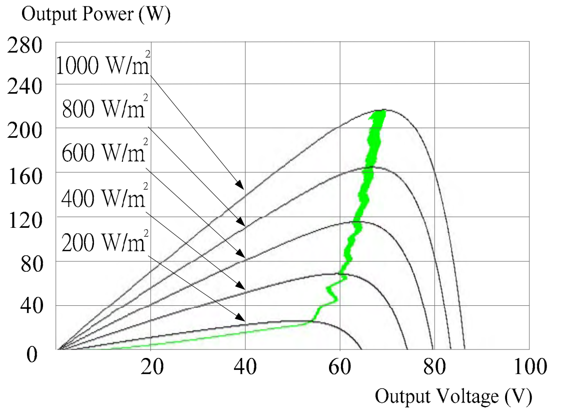

Fig. 10. The MPPT trajectory by the PAOM under fixed temperature.

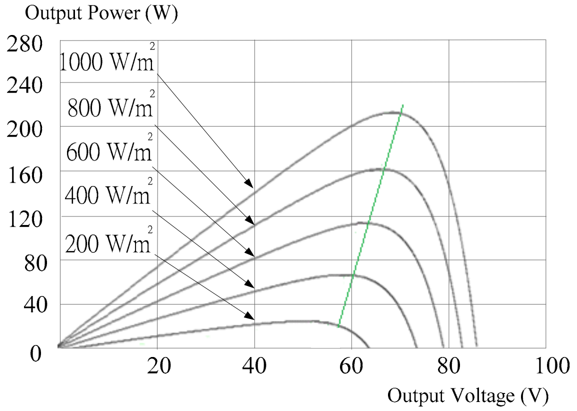

Fig. 11. The MPPT trajectory by the DLAA under fixed temperature.

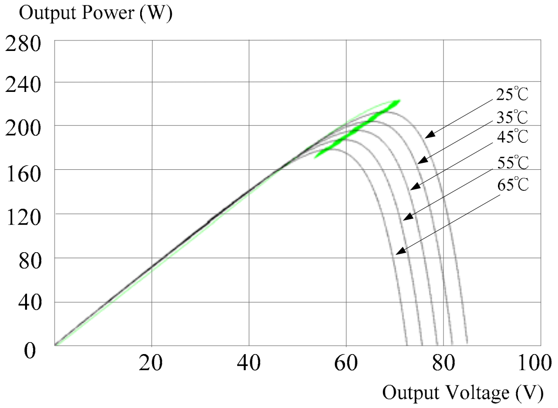

Fig. 12. The MPPT trajectory by the PAOM under constant irradiation.

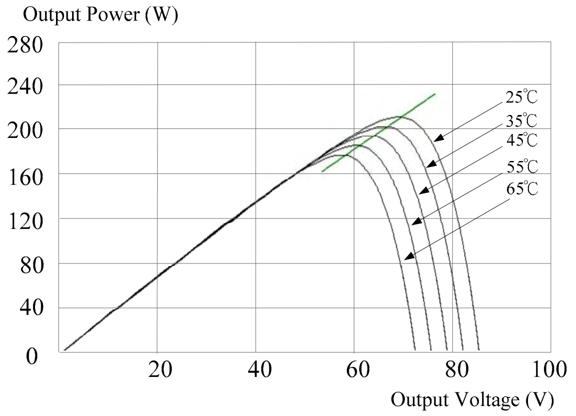

Fig. 13. MPPT trajectory by the DLAA under constant irradiation.

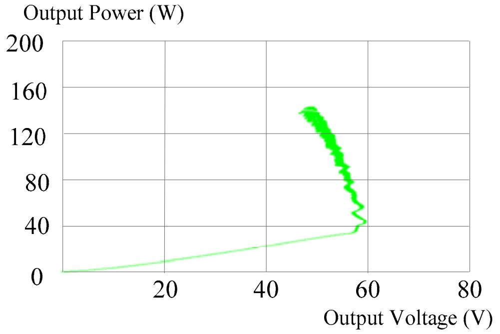

Fig.14. MPPT trajectory by the PAOM while irradiation and temperature increase.

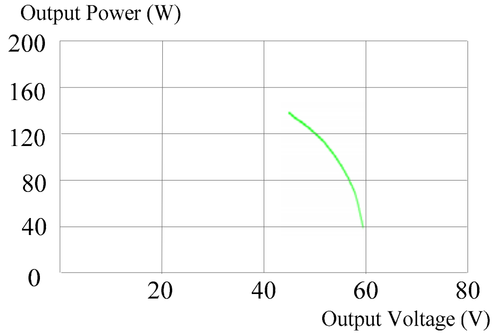

Fig.15. MPPT trajectory by the DALL while irradiation and temperature increase.

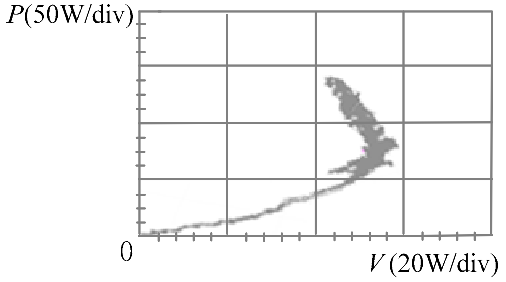

Fig.16. Practical measurement of the PV power system with the PAOM.

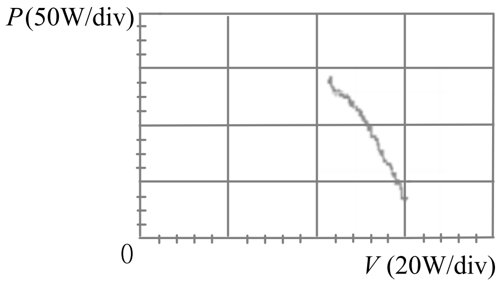

Fig.17. Practical measurement of the PV power system with the DLAA.

VI. CONCLUSIONS

In this paper, a MPPT algorithm is proposed, which is based on the relationship that an MPPT voltage varies with irradiation and temperature linearly. A corresponding analog circuit is also proposed. To verify the proposed algorithm and to illustrate the feasibility of the MPPT circuit, a PV power supply system embedding the MPPT circuit is simulated and implemented. Simulations and practical measurements have demonstrated that the proposed DLAA can trace maximum power point effectively and prevent an operation point from vibrating.

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