A Fast and Accurate Maximum Power Point Tracker for PV Systems

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***Abstract* -The paper presents a fast and accurate maximum power point tracking (MPPT) algorithm for a photovoltaic (PV) panel that uses the open circuit voltage and the short circuit current of the PV panel. The mathematical equations describing the nonlinear V-I characteristics of the PV panel are used in developing the algorithm. The MPPT algorithm is valid under different insolation, temperature, and level of degradation. The algorithm is verified using MATLAB and it is found that the results obtained using the algorithm are very close to the theoretical values over a wide range of temperature and illumination levels. The maximum deviation in the maximum power is less than 1.5% for the illumination levels and temperatures normally encountered by a commercial PV panel. The complete derivation of this MPPT algorithm is presented. It is seen that the algorithm is faster than other MPPT algorithms like perturbation and observation (P&Q) and more accurate than approximate methods that use the linearity between voltage (current) at maximum power point and open-circuit voltage (short-circuit current). The block diagram of a buck-boost PV battery charger with the proposed maximum power point (MPP) tracker is given.**

I. INTRODUCTION

Photovoltaic (PV) energy is an important energy source since it is abundant, clean, and pollution free. The electrical power supplied by a PV panel depends on many extrinsic factors, such as temperature and illumination level, and the peak value of panel power increases with insolation and decreases with ambient temperature. The complex volt-ampere characteristic of the PV panel requires the use of harvesting techniques which are most often difficult to implement. Several harvesting schemes use microcontrollers or digital signal processors for tracking the maximum power point (MPP) based on a perturbation and observation (P&Q) approach [1]-[2]. These methods are slow, often result in oscillations, and fail to settle in the absolute MPP. These methods are not accurate when there are fast variations in insolation and other atmospheric conditions. To overcome some of the drawbacks, modified versions of the P&Q method are proposed [3]-[5]. Other methods combining one-cycle-control [6] and frequency injection technique [7] have also been proposed. There are also approximate methods that use the linearity between the voltage (current) at MPP and the open-circuit voltage (short-circuit current) of the panel [8]-[10]. These methods are easy to implement and fast in response. However, they are not very accurate since the proportionality constant between the MPP voltage (current) and open-circuit voltage (short-circuit current) is not the same at all insolation and temperature levels.

A fast and accurate technique to track the MPP of the PV panel by sensing the open circuit voltage and the short circuit current is described in this paper. The methodology is based on a maximum power point tracking (MPPT) equation, which is set up in terms of the current at the MPP, the short-circuit current, and open-circuit voltage and there is no need to measure the temperature. Detailed mathematical derivation of the MPPT equation is presented and the control algorithm is proposed. The developed algorithm is first verified using MATLAB and plots are given to show that the proposed algorithm works extremely well over wide temperature and illumination ranges. The MPPT is realized for the case a PV battery charger by sensing the short circuit current and the open circuit voltage and adjusting the duty cycle of a buck-boost converter and hence the converter output current such that the MPPT equation holds. Experimental waveforms are also included. Compared with the previously proposed methods, this method is more cost-effective, accurate, and fast.

II. MATHEMATICAL ANALYSIS

The approximate expression for the output current I_Q of a PV Panel at any operating point Q is given by [1]:

$$I_Q = I_{SC} - I_S \exp(KV_Q) \tag{1}$$

where V_Q is the voltage across the PV panel, I_Q is the output current, I_{SC} is the short-circuit current, I_S is the dark saturation current, and K is a constant that depends on temperature and the arrangement of the cells in the panel. Rewriting equation (1), we get:

$$KV_Q = \ln\left(\frac{I_{SC} - I_Q}{I_S}\right). \tag{2}$$

The power output P_Q (= $V_Q I_Q$) of the PV panel is given by:

$$KP_Q = I_Q \ln\left(\frac{I_{SC} - I_Q}{I_S}\right). \tag{3}$$

For obtaining the coordinates (V_{MP} and I_{MP}) of the MPP, (3) is differentiated with respect to I_Q and equated to zero giving

$$I_{sc} = \left(\frac{1}{KV_{MP}} + 1\right) I_{MP}. \tag{4}$$

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From (1), (2), and (4), I_{MP} is obtained as

$$I_{MP} = (I_{SC} - I_{MP}) ln\left(\frac{I_{SC} - I_{MP}}{I_S}\right). \quad (5)$$

a. Exact Approach

The dark saturation current of the PV Panel in (1) can be expressed as [1]:

$$I_S = I_{or}\left(\frac{T}{T_r}\right)^3 exp\left[\frac{qE_{go}}{Bk}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (6)$$

where I_{or} is the cell's reverse saturation current at a reference temperature T_r (= 298 ^{0} K), T is the cell temperature in ^{0}K, E_{go} is the band gap for Silicon in eV, q is electron charge, B is ideality factor, and k is Boltzmann's constant. Equation (6) can be rewritten as:

$$I_S = I_{or}\left(\frac{T}{T_r}\right)^3 exp\left[K_1 - K_1\frac{T_r}{T}\right] \quad (7)$$

where K_1 is a constant. Using (7) in (5) and simplifying, the final equation can be written as:

$$I_{MP} = (I_{SC} - I_{MP})\left[ln(I_{SC} - I_{MP}) + ln(A) - 3ln(T) + C/T\right] \quad (8)$$

where $A = \dfrac{T_r^3}{I_{or}exp(K_1)}$ and $C = \dfrac{qE_{go}}{Bk}$. The open-circuit voltage $V_{OC}(T)$ at temperature T can be expressed as:

$$V_{OC}(T) = V_{OC}(T_r) + \alpha(T-T_r) \quad (9)$$

where $V_{OC}(T_r)$ is the open-circuit voltage at a reference temperature T_r and α is the temperature coefficient of V_{OC}. Substituting for T from (9) into (8):

$$I_{MP} = (I_{SC} - I_{MP})\left[\begin{array}{l} ln(I_{SC} - I_{MP}) + ln(A) + C\left(\dfrac{\alpha}{V_{OC}(T) - V_{OC}(T_r) + \alpha T_r}\right) \\ -3ln\left(\dfrac{V_{OC}(T) - V_{OC}(T_r)}{\alpha} + T_r\right)\end{array}\right]. \quad (10)$$

Equation (10) gives an exact relationship between I_{MP}, I_{SC}, and V_{OC} which is valid at any T and insolation (I_{SC}).

b. Approximate Approach

To reduce the complexity of implementation of (10), the term $[T/T_r]^3$ in (6) can be approximated to 1 in the practical temperature range of the PV Panel. With the above approximation, the accuracy of tracking the maximum power point will be quite acceptable. The resulting equation is obtained as

$$I_{MP} = (I_{SC} - I_{MP})\left[ln(I_{SC} - I_{MP}) + ln(B') + C\left(\frac{\alpha}{V_{OC}(T) - V_{OC}(T_r) + \alpha T_r}\right)\right]. \quad (11)$$

where B' is a constant and equal to $1/(I_{or}\,exp(K_1))$. Hereafter equation (11) will be called "MPPT-Equation". The performance of the MPPT system implementing (11) should be quite satisfactory.

Equation (4) can be rewritten as:

$$KV_{MP} = \frac{I_{MP}}{I_{SC} - I_{MP}}. \quad (12)$$

Multiplying (12) by I_{MP} and simplifying, the maximum power from the PV panel is given by

$$P_{MP} = \frac{1}{K}\frac{I_{MP}^2}{I_{SC} - I_{MP}}. \quad (13)$$

The value of I_{MP} can be calculated from (10) or (11) for a specific temperature T and illumination level (specific short-circuit current I_{sc}) and the maximum power is calculated from (13).

III. MATLAB SIMULATION

The proposed MPPT algorithm is verified for the PV panel BP SX 120 using MATLAB. For the BP SX 120 PV panel (120W), the value of α is -160mV/^{o}C [11]. Keeping the temperature constant at 308^{0}K, the short circuit current of the panel is varied. The values of the exact P_{MP} as well as the one from the proposed approach (equations 10, 11, and 13) for the PV panel are calculated and plotted in Fig. 1(a). It is seen that the difference between the two maximum powers over a range of short-circuit currents is very small. Fig. 1(b) is the plot of the exact I_{MP} and the I_{MP} calculated from the approximate method. Similar analysis is done for temperature variation. Fig. 2(a) shows the variation of exact and approximate maximum power (P_{MP}) with temperature and Fig. 2(b) shows the variation of exact and approximate I_{MP} with temperature. From Figs. 1 and 2, it is seen that the P_{MP} delivered to the load by the proposed MPP tracker has roughly 1.25% error with respect to the actual P_{MP}.

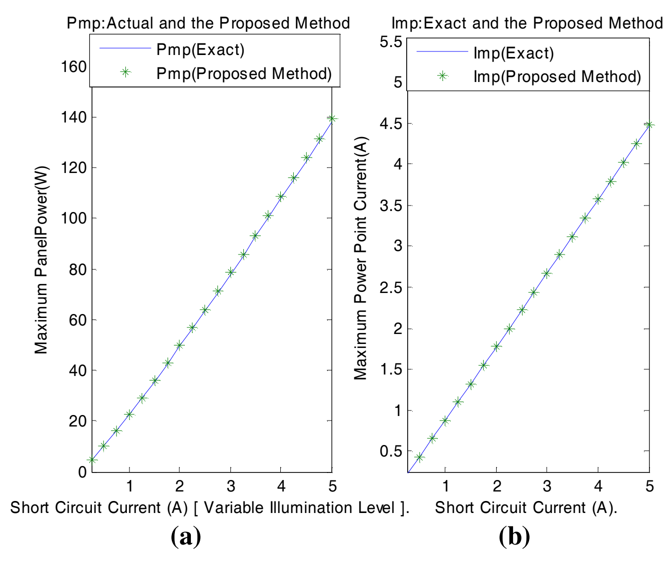

Fig. 1. Comparison of P_{MP} and I_{MP} (a) Exact P_{MP} and the P_{MP} from the approximate approach. (b) Actual I_{MP} and the I_{MP} from the approximate approach. (variation of insolation (I_{SC}))

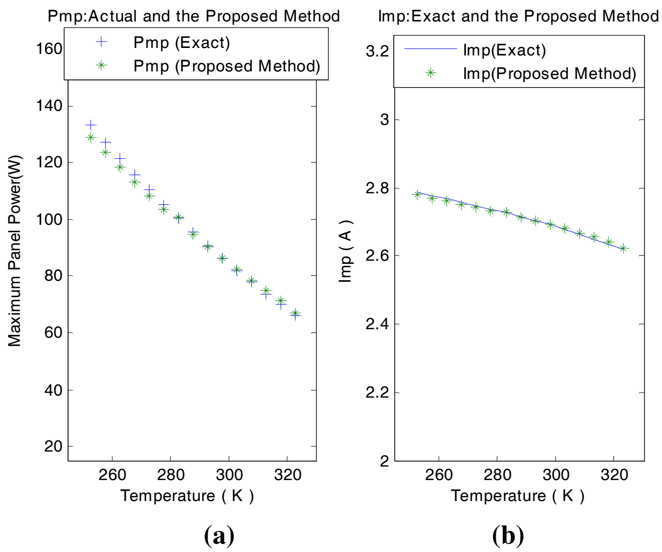

Fig. 2. Comparison of the exact and calculated values a) P_{MP} (b)I_{MP} (Variation of temperature)

IV. Control Circuit

The power circuit and block diagram of the control scheme for a battery charger with the proposed MPPT method are shown in Fig. 3. A buck-boost converter topology is chosen so that the battery can be charged when the output voltage at MPP is lower (low insolation) or higher (high insolation) than the battery voltage. The output voltage of a BP SX 120 panel is applied to the buck-boost converter made up of the MOSFET M1, inductor L1, diode D1, and capacitor C1. The PV panel currents (I_{SC} as well as I_{MP}) are measured as V_1 across R_s and V_{OC} is measured as V_2 using the potential divider with R_1 and R_2. The details of the signal processing circuit that (a) obtains the gate pulse VG for the MOSFET and (b) processes V_1 and V_2 to obtain I_{SC}, I_{MP}, and V_{OC} are shown in Fig. 4. The illustrative waveforms of the PV converter system are shown in Fig. 5. The MPPT is realized by sensing both the open circuit voltage and the short circuit current of the panel and adjusting the duty ratio of the converter such that the MPPT-Equation (11) holds. The LHS and RHS of (11) are applied to a PI controller which decides the duty cycle so the PV panel operates at its MPP.

For implementation purposes, equation (11) is rewritten as

$$I_{MP} = (I_{SC} - I_{MP})\left[\ln(I_{SC} - I_{MP}) + X + \frac{Y}{V_{OC} - Z}\right] \qquad (12)$$

where X, Y, and Z are constants whose values are calculated from the manufacturer's datasheet and fed into the control circuit. It is to be noted that the MPPT scheme proposed for the battery charger does not use any additional switch other than the one used for DC-DC conversion. As seen from Fig. 5, V_{OC} is measured by blocking the gate pulse to M1 for a short time (panel open) and I_{SC} is measured by applying an extended pulse (panel short). These pulses are in addition to the variable duty-cycle pulses that force the converter to satisfy the MPPT equation. When the gate pulse is blocked, the voltage V_2 goes through an initial transient so it is sampled at an appropriate instant to obtain the steady state value. The sampling pulse and the final V_{OC} after hold are shown in Fig. 5.

The short-circuit current I_{SC} is measured by applying an extended pulse to the MOSFET. The voltage V_1 across Rs represents the short-circuit current and it is sampled appropriately to get the steady state value of I_{SC} (Fig. 5). The panel current I_Q which becomes I_{MP} when the MPPT equation is satisfied is obtained by sampling the voltage V_1 at an instant within the normal switching period of the buck-boost converter as shown by the illustrative waveforms of Fig. 5.

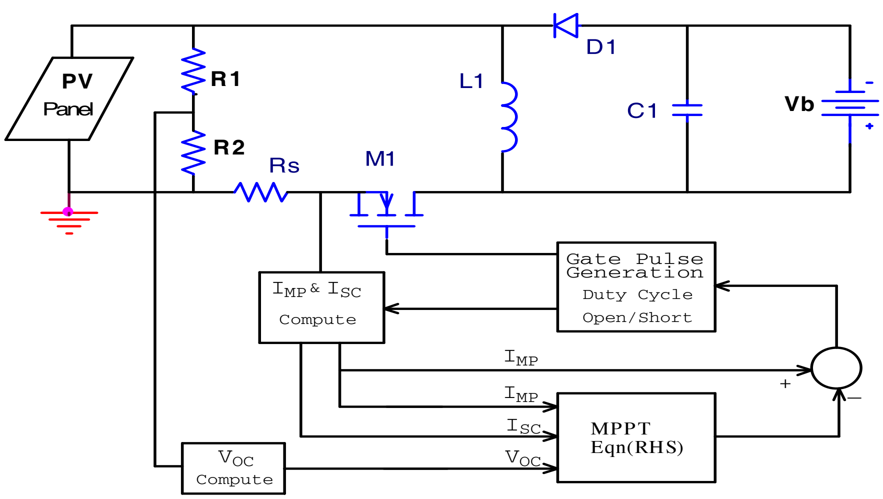

Fig. 3. Power circuit and block diagram of control circuit

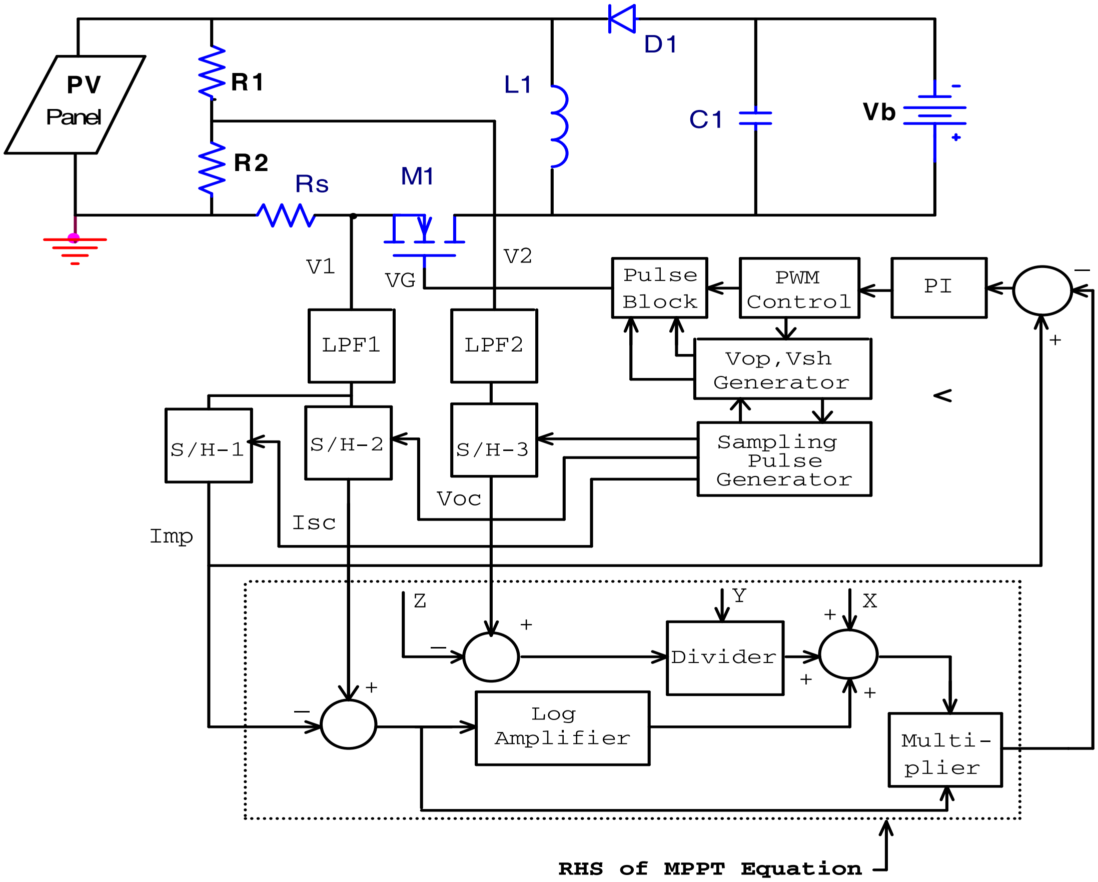

Fig. 4 Details of control circuit

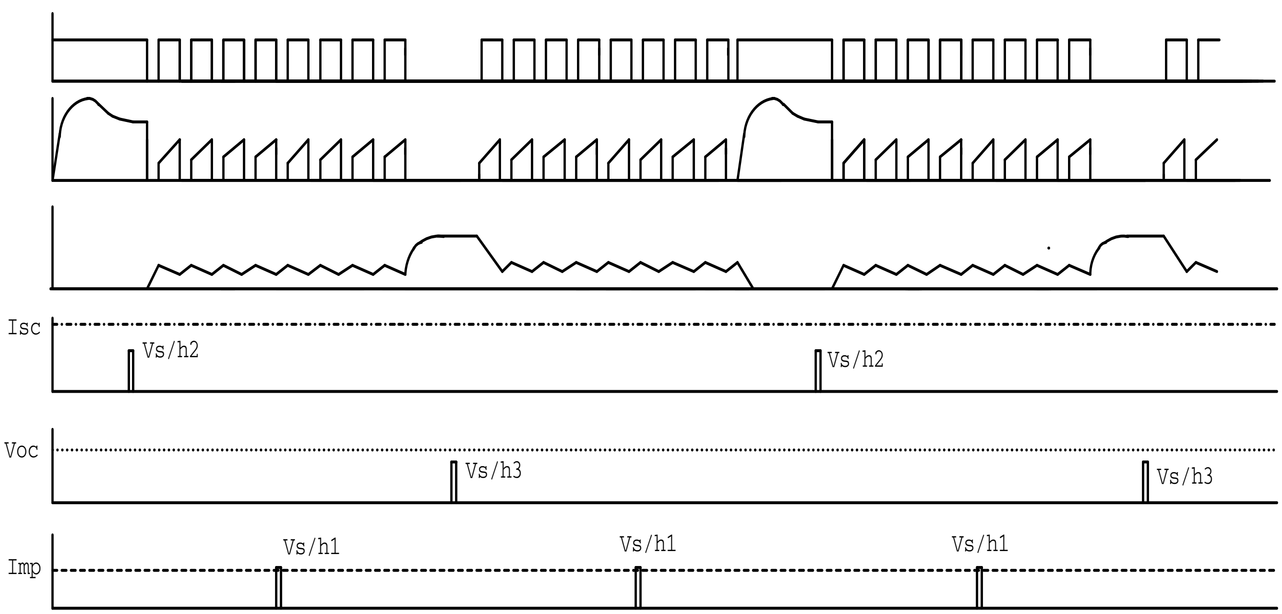

Fig. 5 Illustrative waveforms from control circuit

As shown in Fig. 4, the RHS of equation (12) is computed using the logarithmic, divider, and multiplier blocks. Three sample/hold (S/H) amplifiers are used to obtain I_{SC}, I_{MP}, and V_{OC}. The sampling pulses to the S/H amplifiers are derived from the blocking/shorting pulses using a simple logic circuit whose details are not shown for want of space. The shorting/opening intervals are approximately 2 to 3 times the switching period and they occur once in 40 to 60ms. For a switching frequency of 25kHz, the panel is shorted/opened for approximately 0.2% of the time and hence there is a corresponding loss in the power supplied by the panel. The reduction in power, however, is very small.

V. RESULTS

The complete PV battering charging system was built and tested. A BP SX 120 PV panel with the following (typical) specifications was used in the testing:

Maximum power (P_{max}):	120W
Voltage at Pmax (V_{MP}):	33.7V
Current at Pmax (I_{MP}):	3.56A
Open circuit voltage (V_{oc}):	42.1V
Short-circuit current (I_{sc}):	3.87A
Temperature coefficient of Voc (α):	-160mV/^{o}C

The buck-boost converter was used to charge a 12V battery operating in the buck mode and a 36V battery operating in the boost mode. The waveforms obtained from the section sensing V_{oc} are given in Fig. 6 and those from the section sensing I_{sc} are given in Fig. 7. The maximum output power available from the PV panel varies during the day. Since the battery voltage is fairly constant, the charging current varies with insolation. The output power was measured using a Yokagawa digital power meter.

VI. CONCLUSIONS

An accurate maximum power point tracking algorithm which uses the open-circuit voltage and the short-circuit current of a PV panel is presented. An approximate 'MPPT equation' that includes the effect of temperature variation is derived. The maximum power from a PV panel is calculated using the exact equation and the approximate equation using MATLAB and it is shown that the error is very small. A buck-boost converter is used for charging a battery froma PV panel. The proposed control circuit is simple and derives all the control variables without adding any extra switch to the power circuit. The harvesting scheme proposed can be used for small-scale PV power systems.

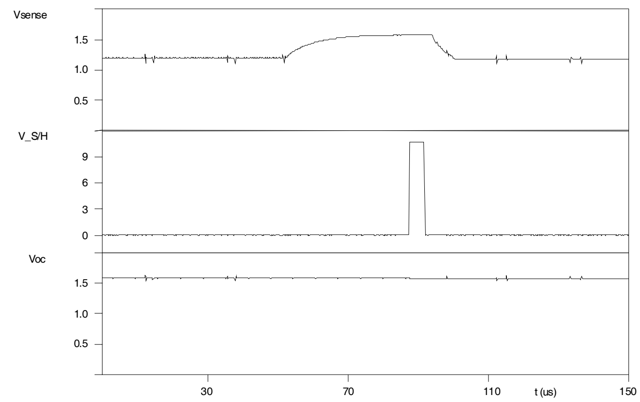

Fig. 6 Experimental waveforms showing V_{oc} Measurement

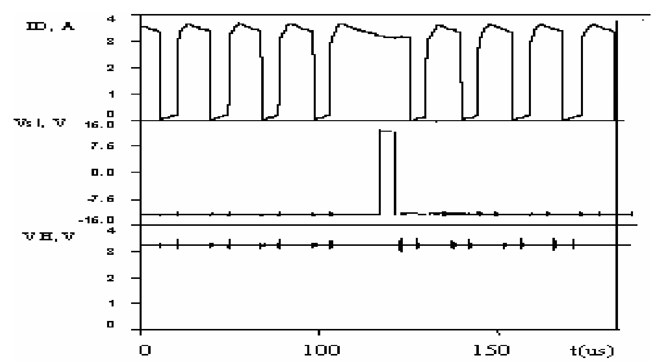

Fig. 7 Experimental waveforms showing I_{sc} measurement

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