Effects of Irradiance Patterns on Efficiency of a Photovoltaic System Controlled by the Perturbation and Observation Method

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***Abstract* - This paper presents an investigation on effects of different irradiance patterns on efficiencies of photovoltaic (PV) systems controlled by the well-known conventional maximum power point tracking (MPPT) method, the Perturbation and Observation (P&O). In this work, performances of three insolation scenarios demonstrating ambient conditions are assessed in the MATLAB/Simulink environment. The results indicate that even a minor change in the insolation level illuminating the PV module can influence the efficiency. In addition, the number of duty cycle provided by MPPT-based control system is increased. Therefore, the perception of low efficiency of the P&O or similar conventional methods is challenged specially for a PV module under uniform shaded conditions (USCs). It is argued that real-world environmental data is needed to verify efficiency and effectiveness of an MPPT approach. These results indicate that using P&O can be the best candidate for a PV system including a PV module comparing to a costly and more complex MPPT control system utilizing sophisticated algorithms.**

Keywords – photovoltaic systems; PV; MPPT; P&O; efficiency; uniform shaded conditions

I. INTRODUCTION

Nowadays, photovoltaic systems are broadly used to deliver electricity to the power grid. They are environmental-friendly and sustainable renewable energy resources requiring little maintenance [1, 2]. However, the high installation cost and the low energy conversion efficiency (about 9-17%) [3], particularly under variable climate conditions, impede the extensive application of PV systems in power networks. In order to overcome low efficiency related to power conversion, maximum powers need to be harvested from PV systems. This objective can be accomplished by MPPT methods allowing a PV system to perform in its optimal operation. Systematically, MPPT techniques are clustered into two major groups: soft computing MPPT and conventional techniques [4].

Soft computing methods can detect global maxima in PV arrays where several local maximum points and one global maxima exist due to partial shading conditions (PSCs).Two major streams in this field can be categorized into: I) the artificial intelligence (AI) including the artificial neural network (ANN) and the fuzzy logic (FL), and II) meta-heuristic optimization techniques [5]. Although dealing with nonlinearity and PSCs are the advantages of these intelligent techniques [5], a few drawbacks affect utilizing them. The ANN requires a comprehensive training process demanding more advanced microcontroller with higher cost [6], and the FL-based MPPT controller is extremely dependent on the designer knowledge and experience about the PV system [6, 7]. In addition, complexity of algorithms and cost associated with controlling systems are their major obstacles. On the other hand, there are meta-heuristic MPPT algorithms which can deal with nonlinearity and PSCs related to PV systems. The dominant methods and most practiced ones can be named as genetic algorithm, cuckoo search (CS), particle swarm optimization (PSO), and ant colony optimization (ACO) [8, 9]. Regardless of undeniable merits provided by these techniques, their algorithms require sophisticated and costly control systems. Therefore, mobile applications and PV systems operating in remote areas will be affected by the extra cost and equipment needed for the control systems.

In contrast, conventional MPPT methods offer convenience and simplicity [10]. However, they may be trapped in local points and detect one of the local points as the MPP for the system consisting of several PVs performing under PSCs. In most cases when a PV module involved in the system, these methods capable of tracking MPP even in varying ambient conditions. The P&O is the well-known conventional MPPT technique broadly used commercially for many years [11, 12]. This method provides a convenience control system with minimum complexity and acceptable efficiency that can rapidly trace the MPP under USCs. In the current work, efficiencies of three different insolation are calculated for the PV system experiencing various irradiance. Moreover, it is argued that the low efficiency associated with the P&O method, comparing to soft computing methods, can be challenged. In many simulations role of the irradiance pattern and its volatility are not investigated. Bases on the presented results, it is shown that even a minor change in the irradiance shape will result variation in efficiency.

The paper is structured as follows: major attributes of eminent conventional MPPT methods are presented in section II. A PV cell model, I-V and the P-V characteristics of a PV system, as well as uniform and PSCs are described in section III. Section IV illustrates the shading patterns used for the simulation running the P&O. In section V, the output results and analysis are provided; finally, it is followed by the conclusion and discussion in section VI.

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TABLE I. MERITS AND DEMERITS OF EMINENT CONVENTIONAL MPPT METHODS

MPPT Method	Reference	PV dependent	Complexity	speed	Cost	Efficiency
P&O [13-15]	[16-18]	No	Low	Fast	Low	High
IC [13, 14, 19, 20]	[16, 17, 21]	No	Medium	Varies	Depends	High
HC [13, 14, 19]	[18]	No	Low	Varies	Low	High
Fractional-SCC [22]	[11, 21]	Yes	Medium	Medium	Low	Low
Fractional-OCV [22, 23]	[11, 21]	Yes	Low	Medium	Low	Low
RC Control [24]	[11, 18]	No	Complex	Fast	High	High
3 point weighted avg. [25]	[18]	No	Medium	Varies	Low	High
ES Control [26]	[11, 21]	No	Medium	Fast	Low	High
Sliding mode control [27]	[17, 18]	No	Medium	Fast	Medium	High
Load C/V max. [28]	[17]	Yes	High	Fast	High	High
Bisection search [29]	[17]	No	Low	Varies	Low	Low
β-method [30]	[17, 18]	No	Moderate	Fast	Medium	High

II. EMINENT CONVENTIONAL MPPT METHODS

Conventional MPPT methods are recognized due to their fast convergence time considering their simplicities and online responses [11, 12, 16, 17, 21, 31, 32]. Major conventional methods are known as: P&O, Incremental Conductance (IC), hill climbing (HC), fractional short-circuit current, fractional open-circuit voltage, ripple correlation control, three point weighted average, extremum seeking (ES) control, sliding mode control, load current/voltage maximization, bisection search and β-method. Table (I) shows some merits and demerits of the conventional MPPT techniques. Describing applications of these methods are not the purpose of this paper, in fact, the presented Table (1) depicts major attributes of the methods.

Table (1) also demonstrates the overall benefits of the P&O compare to the other methods. Although there exist other approaches representing slightly better performance, the popularity of the P&O method among PV system designers is undeniable. It is widely used for stand-alone and grid-connected applications and can be implemented in analog circuits or cheaper digital elements [11]. Its acceptable high efficiency, more than 93% in most cases [11, 16], and simple implementation of the algorithm have been convinced PV system designers to employ this MPPT method more than any other approaches. This advantage is a great favor of using PVs in mobile applications and/or remote locations. Fig. 1 shows flowchart of the P&O method. PV units performing in remote areas demand simplicity with regards to their MPPT-based control systems.

III. CHARACTERISTICS OF A PV SYSTEM

A. A PV Cell Model

The most important element of a PV system is a PV cell. An accurate PV model defines major attributes including efficiency of the PV system, the MPP, and the interaction between the power converter and the PV panel [33-35]. The equivalent circuit of a solar panel, consisted of photovoltaic cells, can be represented as a single diode model shown in Fig. 2 [5]. Eq. (1) describes the *I-V* relationship in the PV cell.

$$I = I_{PV} - I_0\left[\exp\left(\frac{V+R_S I}{aV_t}\right) - 1\right] - \frac{V+R_S I}{R_P} \quad (1)$$

where I_{PV} is the PV current and has a direct relationship with sun intensity and varies with temperature variations.

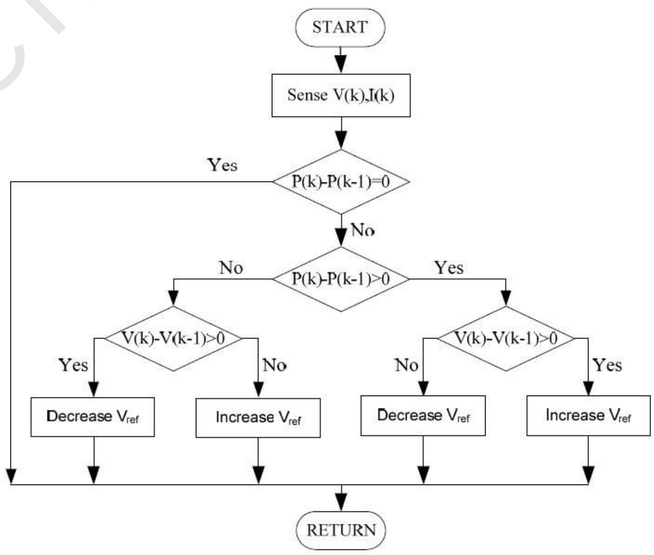

Fig. 1. Flowchart of the P&O algorithm

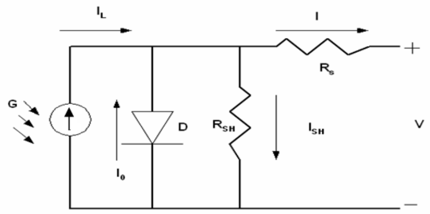

Fig. 2. Equivalent circuit of a PV cell

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I_0 is the saturated revers current also depends on temperature differences; a is a constant known as the diode ideality factor, $V_t = {N_S KT}/{q}$ is the thermal voltage associated with the cell, N_S is the number of cells connected in series, q is the charge of the electron, K is the Boltzmann constant, T is the absolute temperature of the p-n junction, and R_S and R_P are the series and parallel equivalent resistances of the solar panel, respectively. Manufacturers provide Standard Test Conditions (STC) datasheets reflecting condition of 1000 (W/m²) with 1.5 air mass spectral distribution at temperature 25°C contributed by a solar simulator called Flash Tester [36]. Some of them even provide the tabulated variables including Open Circuit Voltage (V_{OC}), Short Circuit Current (I_{SC}), MPP Current (I_{MPP}), Voltage (V_{MPP}), and Power (P_{MPP}) that are different from the circuit parameters in the model such as photo-current (I_{PV}), saturation current (I_0), diode ideality factors (a), series and shunt resistances (R_s , R_P). Precise estimation of the PV parameters of its electrical circuit model enable system designers to predict variations of *I-V* and *P-V* curves and efficiency in various ambient conditions. The followings explain *I-V* and *P-V* characteristics of a PV module operating under different shading conditions.

B. Uniform and Partial Shading Conditions

PSCs are occurred due to irregularity in environmental factors and ambient conditions such as clouds, snow, dust, and nearby buildings and trees, while uniform shading conditions indicate uniformity in iraddiance applied to the PV module.

STC datasheets provide values of PV modules operating under different USCs, usually sun insolation 1000 (W/m²) and at temperature 25°C. Fig. 3 shows the *I-V* and *P-V* curves when a PV module operating at 25°C under varying irradiance. Fig. 4 illustrates the curves at different temperatures and the irradiance1000 (W/m²).

To generate a desired voltage and current, PV modules are assembled in different series and parallel configurations. The total power in an array is less than the sum of the individual rated power of each module in the case of PSCs. The impacts depend on module type, fill factor, bypass diode placement, severity of shade and string configuration [37]. The P&O algorithm might be trapped in one of the local points and unable to find the global maximum. Therefore, soft computing methods are implemented to solve this problem. In fact, fluctuation of shadings and the speed of the changes can affect P&O performances.

IV. Shading Patterns and the Implementations of the P&O Method

An avaiable MATLAB/Simulink model running the P&O algorithm is tested for three different irradiance scenarios [38]. The simulation includes a grid-connected PV module in conjunction to a DC-DC buck converter controlled by P&O-based MPPT and a DC-AC inverter, Fig. 5. To be able to improve the efficiency of the overall PV system in different irradiance, the controller provides appropriate duty cycles to the DC-DC buck converter. In fact, the P&O algorithm modulate the duty cycle for the converter and enables PV system to perform in its maximum efficiency.

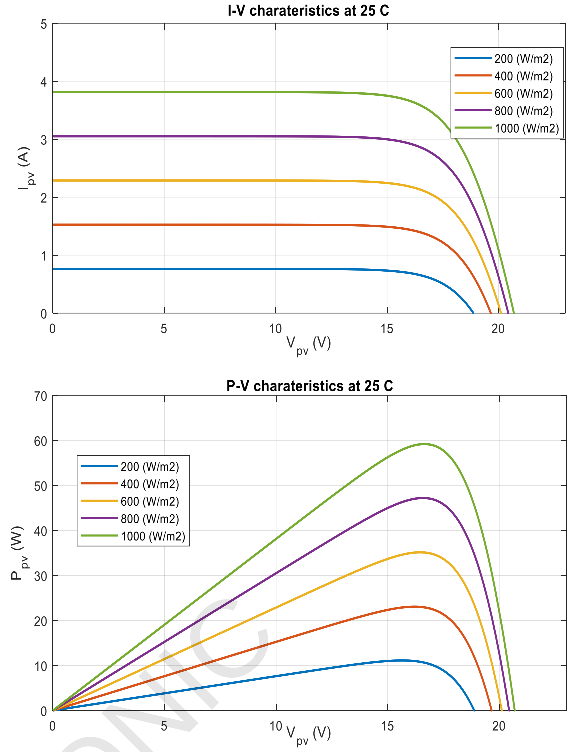

Fig. 3. *I-V* and *P-V* curves of a PV at 25 °C under various insolations

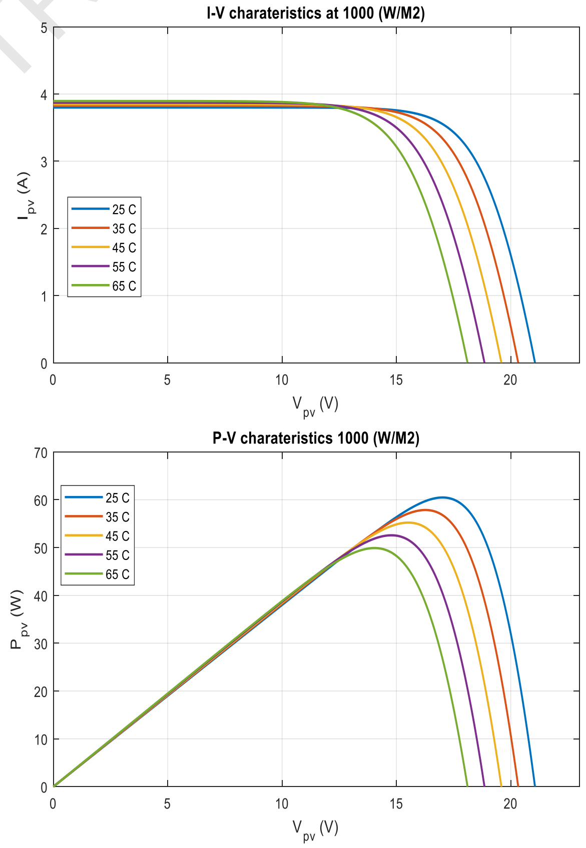

Fig. 4. *I-V* and *P-V* curves of a PV at 1000 (W/m²) under various

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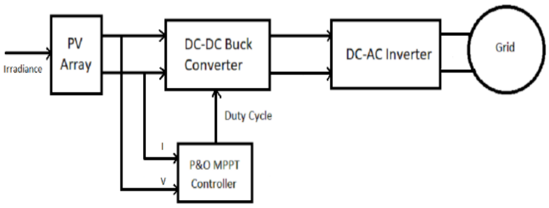

Fig. 5. The block diagram of the MATLAB/Simulate model tested

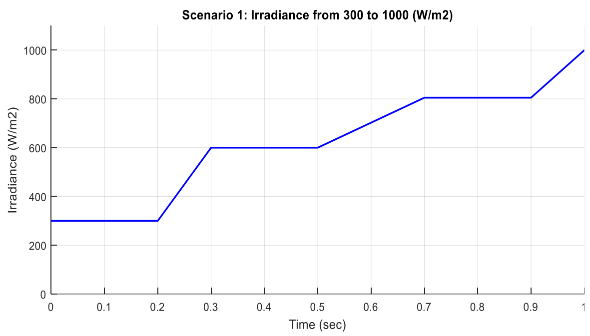

Fig. 6. (a) Scenario 1: irradiance from 300 (W/m^2) to 1000 (W/m^2)

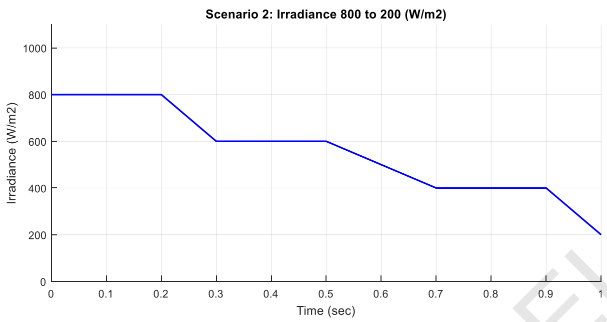

Fig. 6. (b) Scenario 2: irradiance from 800 (W/m^2) to 200 (W/m^2)

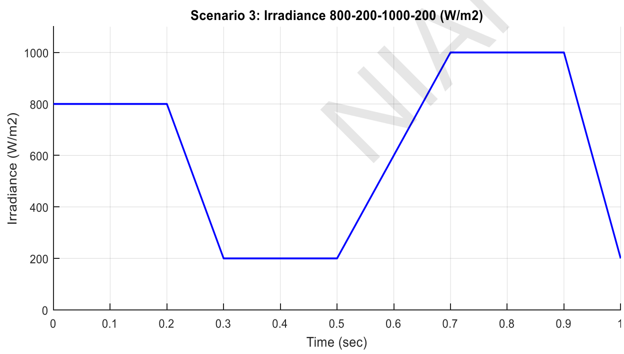

Fig. 6. (c) Scenario 3: irradiance from 800 (W/m^2) to 200 (W/m^2)

The three scenarios, shown in Figs. 6 (a), (b), and (c), demonstrate irradiance patterns illuminating the PV module in one second. Scenario 1 illustrates irradiance increasing from 300 (W/m^2) to 1000 (W/m^2), while scenario 2 shows 600 (W/m^2) declining from 800 (W/m^2) to 200 (W/m^2). In both patterns, the point of changes is similar. Scenario 3 depicts a more rapid shape of variations starting with 800 (W/m^2) to 200 (W/m^2) then to 1000 (W/m^2), and finally back to 200 (W/m^2). The MPP is tracked by increasing or decreasing a step size to the voltage reference, then the appropriate duty cycle is applied to the DC-DC converter.

V. SIMULATION RESULTS AND ANALYSIS

To verify the efficiencies of the three patterns, the three scenarios are applied to the simulink. The results are shown in Fig. 7, Fig. 8, and Fig. 9. Comparing output voltages (V) of the PV and the converter in scenarios 1 and 2 presents the vulnerability of the method even with a slight difference at 0.2 (s): 300 (W/m^2) increase in scenario 1 versus 200 (W/m^2) decrease in scenario 2.

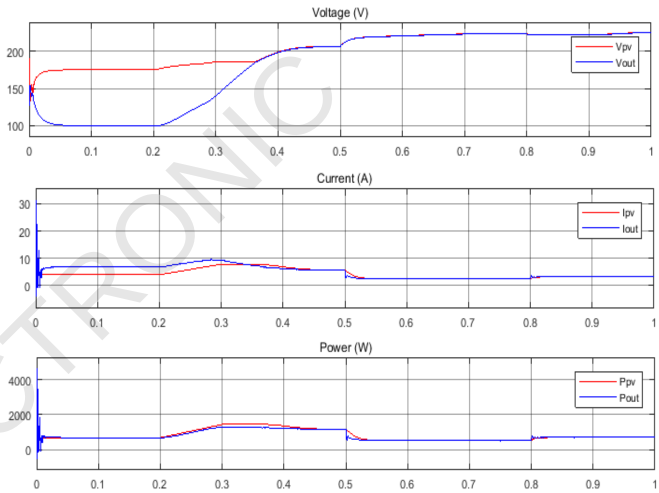

Fig. 7. Scenario 1

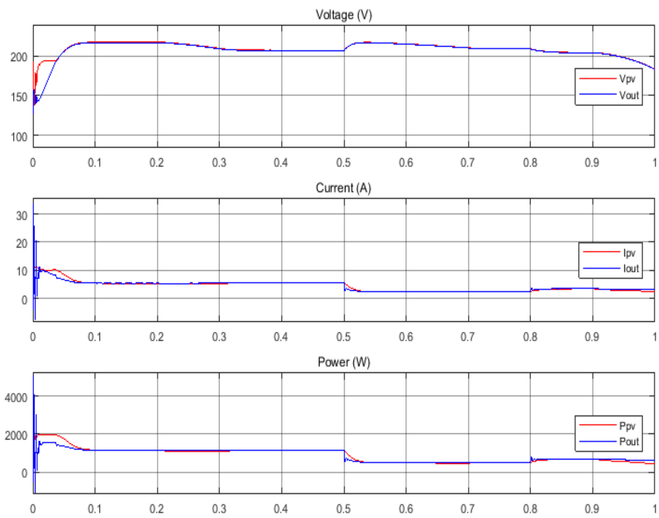

Fig. 8. Scenario 2

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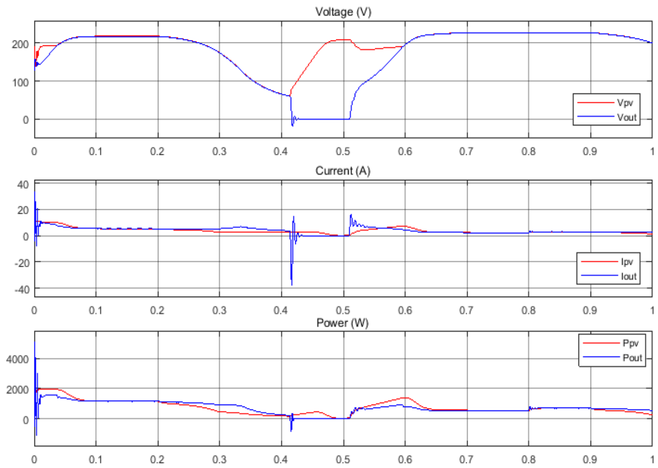

Fig. 9. Scenario 3

The rest of the irradiance patterns and the point of variations are similar in these situations. Although the differences of the current and power outputs of the PV and DC-DC converter are not as significant as the voltages in scenario 1 and 2, there exist slight deficiencies in both parameters. In scenario 3, the volatility of the illumination from 0.3 (s) to 0.7 (s) is dropped from 800 (W/m^2) to 200 (W/m^2), and then it rises to 1000 (W/m^2). Expectedly, the alterations of the converter current after 0.4 (s) and the curve variations of the voltage, the current and the power are much more substantial than the previous patterns. In addition, because of the major irradiance shortage at the end of the pattern, currents and powers of the PV and converter also experience small differences. Investigating the output power the DC-DC converter in the simulation's workspace indicates that the number of iterations for scenario 3 are higher than patterns in situations 1 and 2. This number, in fact, indicates the number of duty cycles that are generated by the MPPT controller in period of the execution time.

Eq. (2) [21] is used to calculate efficiency for each situation. Output powers of the PV and the converter are available in the workspace of the MATLAB/simulation.

$$\eta_T = \frac{1}{n}\sum_{i=0}^{n}\frac{P_i}{P_{max,i}} \qquad (2)$$

where, P_i is the PV power (W), $P_{max,i}$ is the maximum power produced (converter output), and n is the number of samples, respectively. The efficiencies and the number of samples in each scenario are presented in Table II. As expected, substantial alterations in an irradiance pattern marks in lower efficiency with a greater number for the iteration number (n).

TABLE II. RESULTS

scenario	n	Efficiency
1	11372	95.3318 %
2	11366	97.4 %
3	11702	95.536 %

VI. Conclusion and Discussion

Obtaining maximum efficiency is the most important aspect of power conversion in PV systems. Although a few papers argue this issue, to the best of our knowledge, the effect of irradiance patterns on efficiency has not been investigated yet. The results of this work indicate that to define efficiency for an MPPT method, the simulation must be implemented experiencing several irradiance shapes. In addition, as it is observed in scenario 3, an unrealistic irradiance patterns establishes unrealistic efficiency result. In this regard, the reliability and accuracy of simulations presenting poor efficiency for the P&O method can be challenged. The fact that there are no standard irradiance patterns to evaluate accuracy of a simulation, the accuracy and reliability of the MPPT methods and their efficiencies are questionable. Testing multiple conditions and considering local irradiance data can assist system designers to pick optimum MPPT method required for the PV system. Moreover, the simulated irradiance patterns and their volatility should reflect real shading conditions based on the local climate data. In addition, a simple MPPT control system associated with the P&O algorithm can be used for PV applications demanding minimum equipment and devices.

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