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Energy management of Photovoltaic System with Battery Storage

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*Abstract*ð **This paper presents a supervisor control for a photovoltaic system that comprises photovoltaic panel, a battery bank and a DC load. The objectives of the energy management algorithm are, primarily, to satisfy the load power demand and, second, to considering the safety and to extend the life of the batteries. For these purposes, the supervisor controller determines the operation mode by controlling the switching unit which links the system components. A simulation study is presented under variable weather conditions and the results show the good energy management of the photovoltaic system.**

Keywords- **PV system, Maximum power point tracker, Battery, Energy management.**

I. Introduction

Photovoltaic source is becoming more and more used as a renewable source since it offers several advantages such as incurring no fuel, not being polluting and no emitting noise. PV modules still have relatively low conversion efficiency; therefore, controlling maximum power point tracking (MPPT) is essential in a PV system. Many methods have been developed to determine the maximum power point [ref]. Most control schemes use the P&O technique because it is easy to implement but the oscillation problem is unavoidable [1-5]. Other intelligent based control schemes MPPT have been developed such as fuzzy logic [4,5]. The fuzzy logic controllers (FLC) are used very successfully in the implementation for MPP searching [ref]. This controller is suitable for any DC/DC topology and gives robust performances under variations in environmental operating conditions and load [5]. The performance of the method is tested using the studied PV system.

The capability of the photovoltaic system to satisfy the power demand depends on the atmospheric conditions. Due to the fluctuation nature of photovoltaic energy source, batteries are added in order to ensure continuous power-flow. The role of the battery bank (either storing or supplying energy) will define different operation modes of the system. Basically, these operation modes are determined by the energy balance between the energy generation and the load demand [6-8]. This paper proposes an energy management strategy to improve the performances of the photovoltaic system.

The performance of the proposed energy management strategy is tested using stand-alone PV system for various operational conditions, such as changing solar radiance and power load. The paper is organized as follows. In Section 2, we present the stand-alone photovoltaic system with battery storage studied. Mathematical relations between the essential variables of a PV system are presented in Section 3. These relations are necessary for simulating its operation. Due to the fluctuation nature of photovoltaic energy source, batteries are added in order to ensure continuous power-flow. The storage battery model used in this paper traduces the correct operating behaviour of the battery. In order to track the MPP of a PV system, an MPPT method, which is based on a fuzzy controller, is developed. The Operating mode of the system and the Energy management algorithm are presented in Section 4, while in Section 5, the obtained simulation results, using the MATLAB®-SIMULINK® are given and interpreted. Finally, Section 6 concludes the work.

II. System description

Fig.1 shows the standalone photovoltaic system used in this paper. It includes photovoltaic panel with DC/DC converter, batteries and variable load. These components are linked with three relays (R_1, R_2 and R3). The system aims are to ensure a maximum operating of the photovoltaic array and to make a decision on switching between different components (PV/Battery/Load) with correct operating of the battery to protect it against overcharge and deep of discharge.

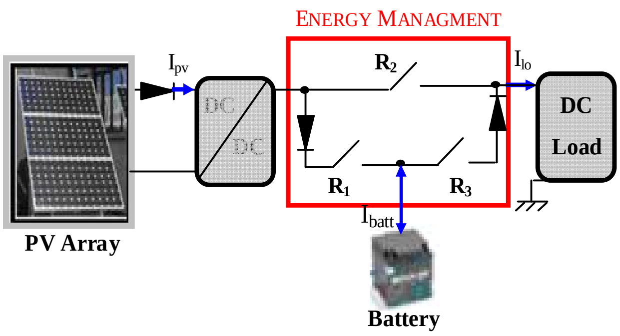

Fig.1 Structure of a stand-alone PV system.

III. MODELING OF THE PROPOSED SYSTEM

A. *Modeling of PV Array*

Various mathematical models of photovoltaic generators were developed to represent their very strongly nonlinear behavior which results from the semiconductors junctions which are at the base of their realization. In our work, we chose the following model [5]:

The PV array equivalent circuit current I_{pv} can be expressed as a function of the PV array voltage V_{pv}

$$I_{pv} = I_{sc}.\{1 - C_1[exp(C_2 V_{pv}^m) - 1]\} \quad (1)$$

Where, C_1= 0.01175 is determined experimentally and the coefficients C_2, C_3 and m are defined as:

$$C_2 = \frac{C_4}{V_{oc}^m} \quad (2)$$

$$C_3 = ln\left[\frac{I_{sc}(1+C_1) - I_{mpp}}{C_1 I_{sc}}\right] \quad (3)$$

$$C_4 = ln\left[\frac{1+C_1}{C_1}\right] \quad (4)$$

$$m = \left[\frac{C_3}{C_4}\right] \Big/ ln\left[\frac{V_{mpp}}{V_{oc}}\right] \quad (5)$$

With V_{mpp} voltage at maximum power point; V_{oc} open circuit voltage; I_{mpp} current at maximum power point; I_{sc} short circuit current. The parameters determination is achieved with the standard test conditions (STC).

Equation (1) is only applicable at one particular irradiance level G and cell temperature T, at (STC) (G_{ref}=1000 W/m^2, T_{ref}=25 °C). When irradiance and temperature vary, the parameters change according to the following equations, where α_{sc} is the current temperature coefficient and β_{oc} the voltage temperature coefficient, R_s is the cell resistance and (ΔT=T-T_{ref})

$$\Delta I_{pv} = \alpha_{sc}\left(\frac{G}{G_{stc}}\right)\Delta T_c + \left(\frac{G}{G_{stc}} - 1\right) I_{sc,stc} \quad (6)$$

$$\Delta V_{pv} = -\beta_{oc}\Delta T_c - R_s \Delta I_{pv} \quad (7)$$

Table.1 shows PV panel's data for a SIEMENS SM 110-24 which was used for in simulations.

The new values of the photovoltaic voltage and current are given by:

$$V_{pv,new} = V_{pv} + \Delta V_{pv} \quad (8)$$

$$I_{pv,new} = I_{pv} + \Delta I_{pv} \quad (9)$$

The experimental curves power-voltage-current (Fig 2) of the photovoltaic panel, are carried out by varying the load's resistance for three levels of irradiance and temperature (G=530W/m², T_c=28.9°C; G=628W/m², T_c=33°C; G=753W/m², T_c=35.7°C).

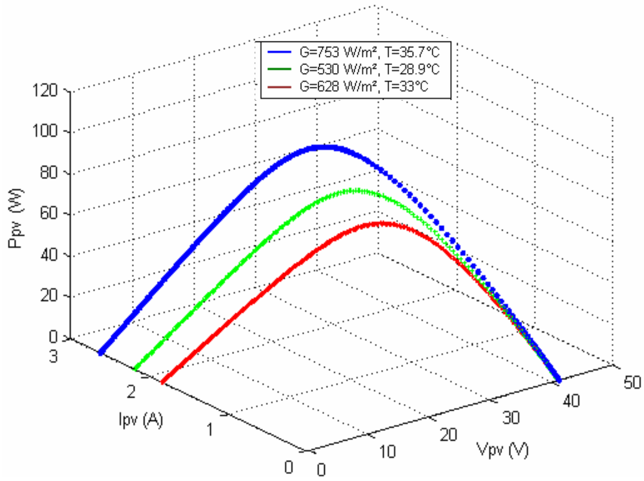

Fig. 2 Experimental PV panel I_{pv}-V_{pv}-P_{pv} 3-D characteristic curves

From these characteristics the non-linear nature of the PV array is apparent. Therefore, an MPPT algorithm must be incorporated to force the system to always operate at the maximum power point (MPP). We introduce a fuzzy logic controller to determine the operating point.

TABLE.I

Parameter of the PV panel SIEMENS SM 110-24.

P_{PV}	110W
I_{mpp}	3.15A
V_{mpp}	35V
I_{sc}	3.45A
V_{oc}	43.5V
α_{sc}	1.4mA/°C
β_{oc}	-152mV/°C
P_{mpp}	110W

B. *Fuzzy MPPT controller*

The proposed FLC measures the PV array characteristics, and then perturbs the operating voltage by an optimal increment ($\Delta V_{pv,ref}$) and the resulting PV power change. The power variation (ΔP_{pv}) is either in the positive direction or in the negative one. The value of (ΔP_{pv}) can also be small or large. From these judgments, the reference photovoltaic voltage variation ($\Delta V_{pv,ref}$) is increased or decreased in a small or respectively large way in the direction which makes it possible to increase the power P_{pv}. The fuzzy logic controller structure can be shown in [5,9].

C. Electrical model of Battery

The lead acid battery model used is given by [10]. It is modelled by putting in series an electromotive force corresponding to the open circuit voltage when it is charged E_b, a capacity indicating the internal capacity of a battery (C_b) and an internal resistance R_b, Fig.3 gives the equivalent circuit. The terminal voltage of the battery is given by:

$$V_{batt} = E_b - R_b.I_{batt} - V_{cb} \qquad (10)$$

The state of charge (SOC) of the battery, which is the amount of electricity stored during the charge, is given equation (11) where Q_d is the ampere-hours stored in the battery during a time t with a charging current I_{batt} and C_{batt} the battery nominal capacity.

$$SOC = 1 - \frac{Q_d}{C_{batt}} = \frac{1 - I_{batt}.t}{C_{batt}} \qquad (11)$$

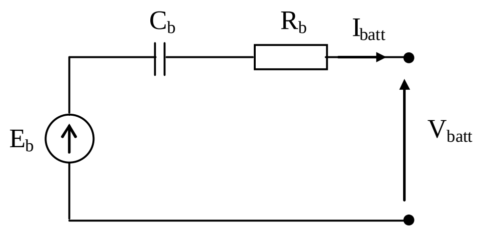

Fig.3 Electrical model of lead acid battery.

IV. OPERATING MODE OF THE SYSTEM

Itôs important to supervise in optimal way the energy between different components of the system with the use of the three relays (R_1, R_2, R_3). The energy management system controls the energy produced by the photovoltaic array and the battery storage (charge/discharge) in function on the consumer demand [6,7].

A. Operating Mode

The proposed standalone PV system operates in one of the following five operation modes, this modes are summarized in Table.II.

- **Mode1 (M1)**: Batteries Charge: in this mode the PV arrays generate sufficient energy to feed the load and charge battery.
- **Mode2 (M2)**: Power compensation: In this mode the energy available in PV array is not sufficient to supply the load, the battery bank supplements the energy required by the load.
- **Mode3 (M3)**: Battery discharge, itôs a particular operation of mode2, itôs occurs when there is no available energy at PV array. In this case, the battery bank supplies full load energy.
- **Mode4 (M4)**: In this mode the PV array generate sufficient energy to feed the load without the intervention of battery.
- **Mode5 (M5)**: in this mode, no PV energy production and battery are completely discharged, then the consumer is disconnected.

TABLE.II
Operating mode in function of the three relays.

Switch / Mode	R1	R2	R3
M1	On	On	Off
M2	Off	On	On
M3	Off	Off	On
M4	Off	On	Off
M5	Off	Off	Off

To protect the batteries against the excessive use, the batteries are connected or disconnected following two limits:

- $\mathbf{V_{HVD}}$: High Voltage Disconnect: correspond to the superior limit when the batteries are fully charged, the batteries charge must be stopped, in our case V_{HVD}=51.6V.
- $\mathbf{V_{LVD}}$**:** Low Voltage Disconnect: when the batteries voltage correspond to the lower limit, then the batteries are considered completely discharged, it must be disconnected to the load, in our case V_{LVD}=44V.

B. Energy management algorithm

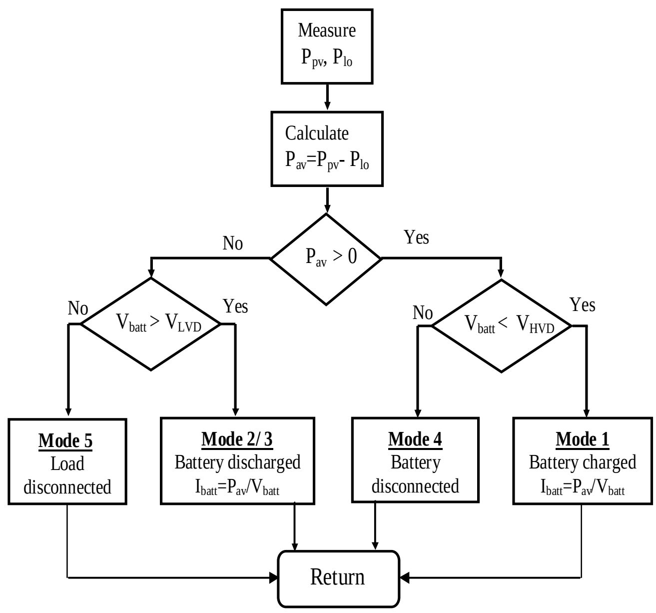

Fig.4 Energy management algorithm.

For batteries charge, the available power P_{av} is function on the photovoltaic power P_{pv} and the load power P_{lo} needed by the consumer, it can be calculated by the following equation:

$$P_{av} = P_{pv} - P_{lo}$$

The energy management system can be represented by the diagram of figure.4.

V. Numerical simulation

From the power required by the load (fig.5), a dimensioning is made to determine the size of PV panel and batteries of the standalone PV system. It is composed of (10) photovoltaic panel of 110W and (04) lead acid batteries of 12V, 260Ah connected in series. The load represent the equipment of a typical family house situated in Bejaia (36Ŭ43_N 5Ŭ04_E 2 m), which is a coastal city of North East of Algeria, with a day consumption of 3500Wh/day. The various parts of the system (photovoltaic panel, DC/DC boost converter, battery and load) are modelled by separate blocks and related in a coherent way. The MPPT is controlled by using fuzzy logic controller (FLC).

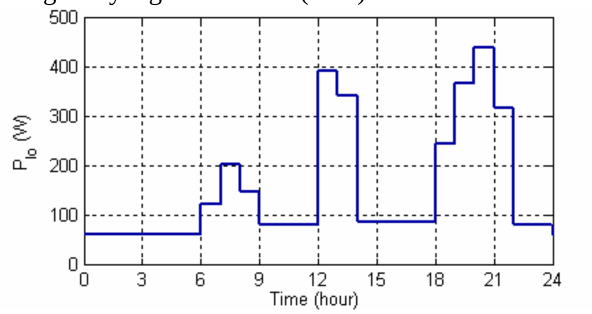

Fig.5 The estimated load power during a day.

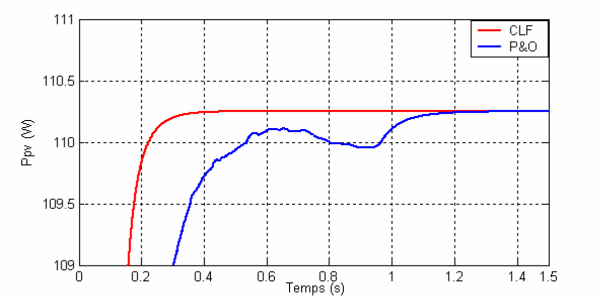

Fig.6 (a) Transitional state of PV power.

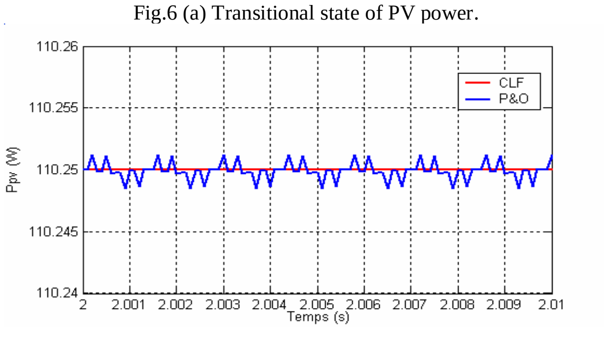

Fig.6(b) Waveform in steady state of PV power.

In order to test the robustness of the MPPT algorithm, simulation results were carried out using the conventional (P&O) method under the same operating conditions. Figs.6 (a,b) present panel power (P_{pv}) waveforms for the two MPPT controllers (P&O and FLC). The fuzzy logic controller (FLC) gives us a fast response compared to perturbation and observation P&O method which requires much time to track the MPP and presents oscillations around the operating point at a steady state. From the simulation result in STC conditions, it is clear that the operating point of this system operate closer to a maximum power as it is shown in fig.7

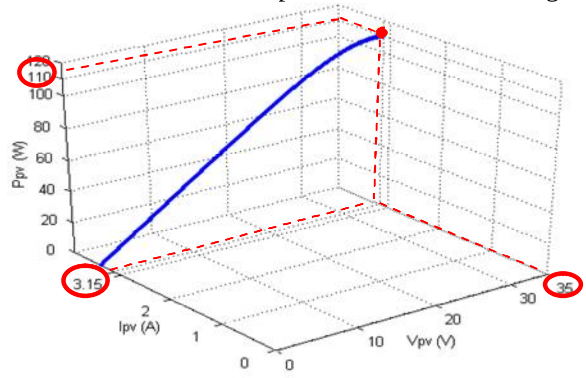

Fig.7 PV panel I_{pv}-V_{pv}-P_{pv} 3-D characteristic curves in STC conditions.

Computer simulations have been conducted for two days to assess the performance of the energy management control. The modes of operation strategy are examined through this simulation which combines periods of sufficient and insufficient generation. In Fig.9, the load power demand and the maximum power tracked from the PV array are represented, In the morning, the load is supplied by PV generator (mode1) or both the PV generator and the battery, by the switching on of R_1 and R_2. At night only R_3 is switched on (mode 3). It can be observed in these figures that the generated power tracks the total power demand, except during periods of insufficient generation (mode 2/3). It is during those periods that the battery bank post pones its recharge cycle and supplements the generation. Figure.10 shows the battery power charged and delivered to the load. The wave forms of photovoltaic current, batteries and load current are shown in fig.11. In figure 12 we can observe that the range of battery voltage variation is comprise between 47.7V and 51.6. The V_{HVD} is reached at t=35.8 hour and the corresponding state of charge is 95% indicated that the batteries are full charged, the batteries will be disconnected (Mode 4). Initially the batteries are charged at 50% and the evolution of battery SOC is shown in fig.13, it is well conserved up to 30% and below 95% to guaranteeing the safety and to extending the life of the batteries. The supervisor control determines the operation modes of the photovoltaic system (fig.14) by controlling the switching unit (R_1, R_2, R_3) which links the system components. Only the (Mode1, 2, 3, 4) are obtained in this example, the (Mode 5) is not appearing. In a winter day for example, the period of night is very long, then the batteries will be much discharged, we can observe the Mode5.

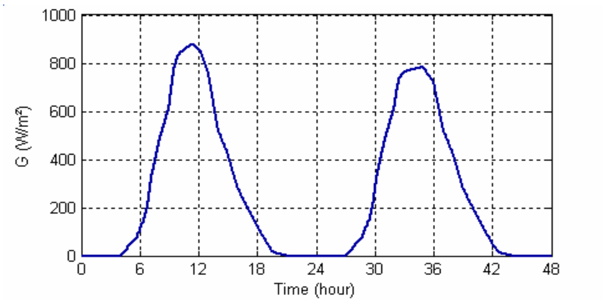

Fig.8 Irradiance (G)

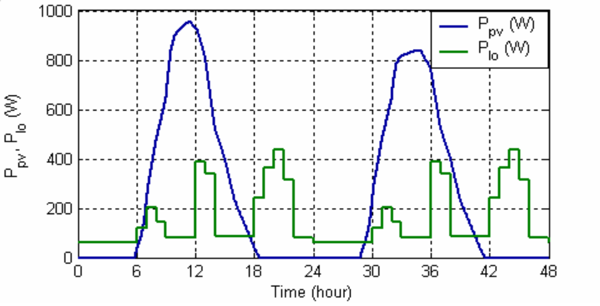

Fig.9 Photovoltaic and load power.

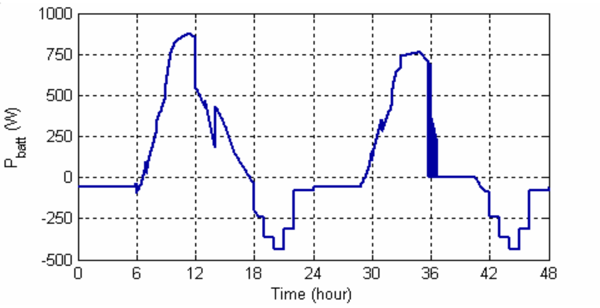

Fig.10 Batteries power.

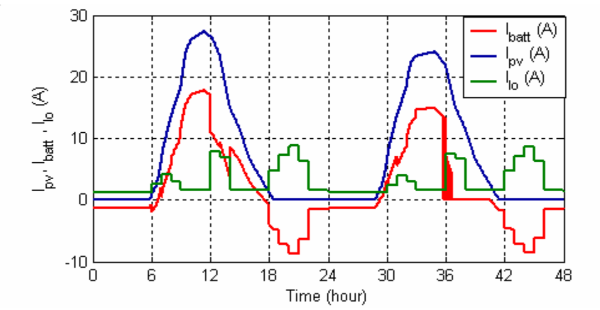

Fig.11 Photovoltaic, batteries and load current.

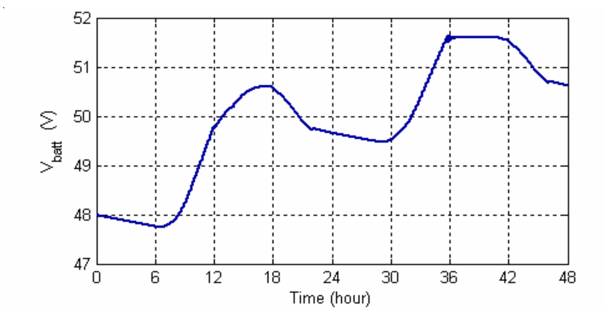

Fig.12 Batteries voltage.

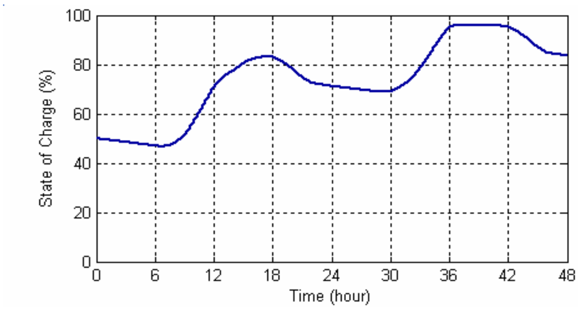

Fig.12 Batteries state of charge (SOC).

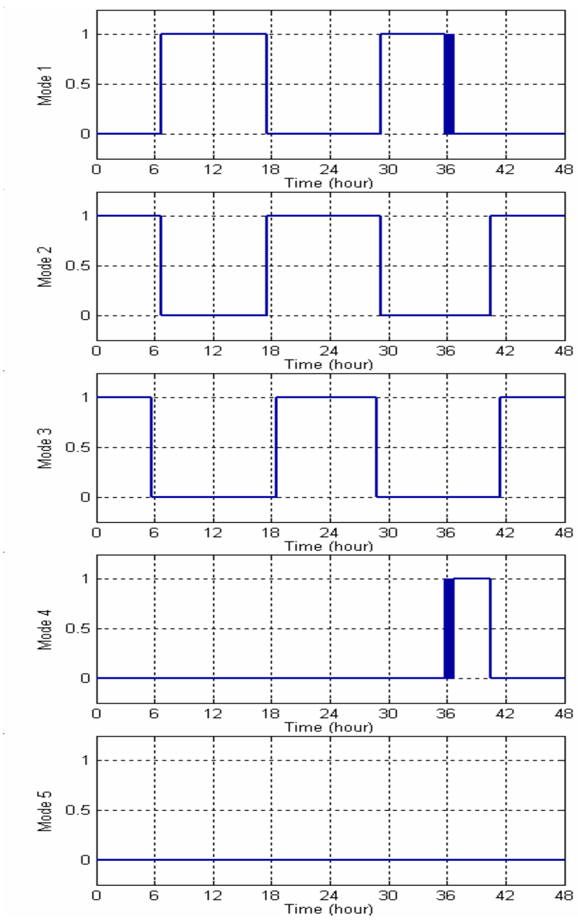

Fig.14 Mode of operation.

VI. C ONCLUSION

The energy management algorithm developed in this paper proved to be highly capable to manage and coordinate the operation mode of the subsystems that constitute the stand alone photovoltaic system. The maximum operating of the system is achieved with a fuzzy logic controller FLC. The simulation results show the robustness of the supervisor to make a decision on switching between different components (PV/Battery/Load) and a correct operating of the battery and protect it against overcharge and deep of discharge. The proposed algorithm provides an adaptable decision structure work to determine the operation mode of each electrical subsystem.

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