CARBON-BASED HYBRID SUPERCAPACITORS FOR HIGH POWER PHOTOVOLTAIC IRRIGATION

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ABSTRACT: A photovoltaic pumping system comprises the following components: a solar photovoltaic (PV) installation, a variable frequency converter, a motor-pump, and a water source. The application combines solar PV technology, hydraulic engineering, and high-efficiency water management techniques to optimize irrigated farming. In the last decades, a growing trend has been observed in the application of renewable energies, which depend on the weather and daily conditions. In the case of cloud passing periods, the generation of energy by the photovoltaic system is drastically reduced, which will affect the overall general operation of the system. To better account for the considered operating parameters of a high-power PV pumping system, dedicated control algorithms have been developed in recent years [1], with the aim of mitigating solar power intermittency. One of the options that can be considered to avoid the sudden change in power generated by the solar PV system is to integrate an energy storage system that could accommodate those changes. In this way, carbon-based hybrid supercapacitors (HSupercap) represent the opportunity to solve this issue with a cost effective and long-lasting energy storage system, controlling PV power ramp rate, improving its overall lifetime. The HSupercap [2] was installed, configured, and tested to characterize it and assess this integration possibility. The tested system presented overall performance characteristics suitable for its application in high power photovoltaic pumping or irrigation.

Keywords: Pumping System, Solar Photovoltaic, Energy Storage, Hybrid Supercapacitors, Solar Power Intermittency

1 INTRODUCTION

In recent years, irrigators have been using high power photovoltaic pumping to replace currently used fossil fuel-based energy sources such as diesel generators or electricity from the grid, reducing the overall carbon emissions associated with water pumping. However, there is one problem they face daily: the intermittency of solar resource. This problem ends up seriously affecting the pumping system, as it ends up damaging some of the components of the operating system.

To solve this problem, algorithms have been developed in recent years as part of the SolaQua project [3] to control the passage of clouds impact over the photovoltaic fields [1]. However, there are more factors that need to be controlled other than through algorithms. As a result, research and development has emerged on technologies for energy storage that do not involve conventional batteries, but other technologies that guarantee higher levels of energy density and power.

Supercapacitors represent the opportunity to solve this issue with a cost effective and long-lasting energy storage system, controlling PV power ramp rate and improving its overall lifetime. This work presents the integration, commissioning, and initial test results of a hybrid supercapacitors system in an experimental microgrid of the Renewable Energies Chair of the University of Évora [4] (CERUÉ). The experimental tests and results of the supercapacitors within this microgrid intend to further study the implementation and results of a power management strategy to control PV power ramp rates and to improve the efficiency of high-power pumping irrigation.

2 CURRENT CONTEXT OF ELECTROCHEMICAL ENERGY STORAGE

2.1 Overview

The efficient storage of energy is a fundamental pillar of the energy transition, as it makes the production and consumption of renewable energy more flexible and guarantees its integration into the energy sector [5]. Electrochemical storage covers a wide range of technologies, including batteries, redox flow systems, fuel cells and electrochemical supercapacitors. All of these technologies are currently available on the market, although at different stages of maturity and with different acquisition prices [6].

In recent years, lithium-ion (li-ion) batteries have been widely applied and considered as a crucial energy storage solution, given their increasing competitiveness compared to other electricity storage technologies. Notwithstanding, upfront energy storage costs still stand for a disadvantage [5].

Since energy storage installations are growing exponentially, as presented in Figure 1, a reduction in the upfront cost of batteries is expected along the coming decade [7].

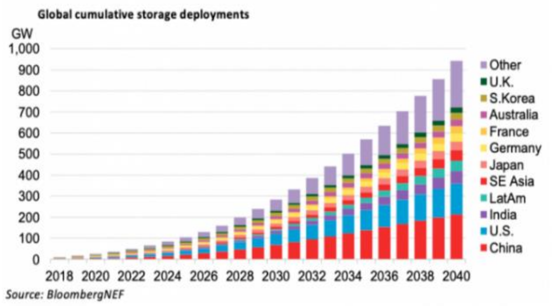

Figure 1: Cumulative increase in energy storage installations worldwide. Adapted from *[13]*.

Whereas li-ion batteries present a high energy density as a technical advantage over other electrochemical storage technologies, as shown in Figure 2, other technologies technical features such as response time and power density, might present themselves as competitive for some applications.

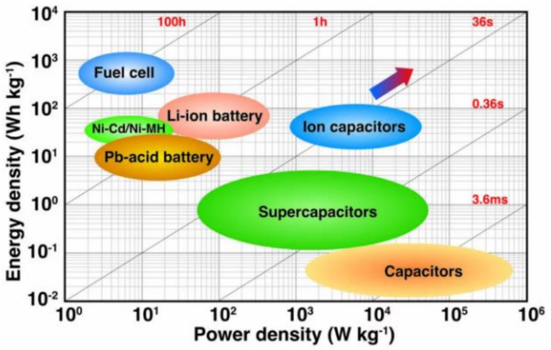

Figure 2: Different types of energy storage technologies according to their energy density and power density. Adapted from *[12]*.

2.2 Supercapacitors

Energy storage in the general variety of supercapacitors occurs due to the accumulation of charged species that are present in an electrolyte, typically activated carbon. There is also another type of supercapacitor that combines an electrode present in conventional batteries (lead or lithium) with a carbon electrode, making it a promising technology due to the combination of these two technologies, which makes its energy storage classified as being electrochemical [6]. The growing interest in this technology is mainly due to the power management that can be achieved by using the grid to reduce the "peak shaving". The supercapacitor that was installed in CERUÉ microgrid is a hybrid supercapacitor (HSupercap) that results from combining the technology of a traditional supercapacitor with a lithium-ion battery.

This technology was acquired from the company Kurt Energy [2] with the purpose of studying the application of this technology in photovoltaic irrigation, to evaluate its response to the intermittency of PV power due to the passage of clouds over the PV plant.

Figure 3: HSupercap installed at CERUÉ's from manufacturer Kurt Energy *[2]*.

The following table shows some of the main performance characteristics of these supercapacitors.

Table I: Main characteristics of the hybrid supercapacitor.

Parameter	Supercapacitor
Nominal Capacity ($\boldsymbol{Ah}$) @1C	45,0 ($\pm$5%)
Nominal Energy ($\boldsymbol{kWh}$)	2,61
Nominal Voltage ($\boldsymbol{V}$)	55,0
Discharge cut-off voltage **(V)**	39,6
Max. charge voltage **(V)**	57,2
Power Density ($\boldsymbol{W/kg}$)	1500
Dimensions (length $\times$ width $\times$ height) ($\boldsymbol{mm}$)	500 $\times$ 350 $\times$ 180
Cycles life at $\boldsymbol{25^{\circ}C}$	> 20 000
Volume Powerpack ($\boldsymbol{dm^3}$)	31,5
Weight of Powerpack ($\boldsymbol{kg}$)	57,36
Operation Temperature (º$\boldsymbol{C}$)	-40 to 80

3 METHODOLGY

The HSupercap was installed in CERUÉ's three-phase microgrid: the high voltages and currents to which this technology is subjected would render difficult to guarantee safety with a single-phase system. The supercapacitor was coupled with three inverters (one per AC phase) from the same model/brand – Inverter Quattro 48/10000/140-100 model from Victron Energy [10]. Dedicated AC and DC protection devices were acquired and installed, following the manufacturer safety guidelines. Precision monitoring devices were also installed to better control the overall system's operation.

The HSupercap was subjected to characterization tests to understand its performance and behaviour, under manufacturer general operating conditions. All the tests followed a protocol specifically designed for the operation of the HSupercap, through the development of LabVIEW programming dedicated to the real-time control of the technology.

The supercapacitor is fully charged and discharged through the consumption and injection of energy into CERUÉ's three-phase grid within controlled power limits that have been set to evaluate its response under typically specified operating conditions. Since it is charged and discharged via energy exchange with the electric grid, it has been assumed that the signal convention used would be positive when charging and negative when discharging.

A control unit, the Cerbo GX, supplied by Victron Energy [8], is responsible for the communication in real time with the inverters to obtain current, voltage, state of charge, temperature, and power data on both the inverter AC and DC sides. The results obtained are analysed and energy efficiencies are calculated. The analysis of this data is relevant to the state of the art of hybrid supercapacitors since it is a pioneering technology in the current energy storage market.

3.1 Test Conditions

3.1.1 Levels of charge and discharge

It is expected that the performance and lifespan of this technology could be affected in the long term by the high charging and discharging rate conditions to which they are subjected. In addition, temperature also turns out to be a crucial factor throughout its operation as any overheating of surfaces can lead to energy losses, reducing performance.

3.1.2 C-Rates

The C-Rates are limits that are imposed by the power electronics when charging/discharging tests are to be carried out to make comparisons between different curves of different energy storage technologies [9].

In the battery sector, the E-rate is equivalent to the C-rate, being the first expressed in power (watts) [9]. In the absence of a current control device to ensure that the current is at a constant value at any given time, a power control was developed to operate the battery within the defined state of charge range. In view of this control strategy, a difference in test results, from those provided by the manufacturer using C-rates, is expected.

In the absence of standards enabling the evaluation of C-rates for HSupercap, E-rates end up being similar to C-rates, reflecting the real operating conditions of this supercapacitor. In the analysis of the C-Rates to our HSupercap, the curve 1C represents a current of 45A, 2C represents 90A and the curve 8C represents 360A.

3.1.3 Reference test conditions

The reference conditions used are the typical real operating conditions in which these systems might operate [9]. The inverters that are connected to the HSupercap have an AC maximum power limit on their maximum charging and discharging power, which in this case is 30kVA. Regarding the ambient temperature, these tests were carried out with a temperature range between 20ºC and 40ºC, controlled by an air conditioning unit.

The tests were carried out for a voltage range of 45V – 56V (being the manufacturer specifications: discharge cut-off voltage of 39.6V and maximum charge voltage of 57.2V).

3.2 LabVIEW programming control

A control program was developed to communicate with the inverters control unit (Cerbo GX). This communication is carried out using the Modbus TCP/IP protocol, and all the programming was developed using LabVIEW [9].

The duration of the control cycles was defined as being two seconds, including sending requests to carry out intermediate measurements, receiving responses from the Cerbo GX and the inverters, wattmeters and datalogger. The precision wattmeters measure several AC energy parameters such as voltage, current, harmonics, etc.

3.3 Inverter efficiencies

Some of the tests were carried out to analyse the efficiency of the inverters and assess their influence on the overall system.

The inverter AC-DC (HSupercap operation in the state of charge) and DC-AC (HSupercap operation in the state of discharge) average efficiencies were calculated, for charge and discharge states, respectively.

DC-AC and AC-DC conversion efficiency considers energy conversion losses from DC to AC energy and from AC to DC energy, respectively, which are presented in Equations (1) and (2).

$$\eta_{Discharge(DC-AC)} = \frac{E_{AC}}{E_{DC}} \qquad (1)$$

$$\eta_{Charge(AC-DC)} = \frac{E_{DC}}{E_{AC}} \qquad (2)$$

where E_{AC} is the AC energy and E_{DC} is the DC energy.

The inverters operate according to an efficiency profile directly related to the power level set and not always at its maximum efficiency. The inverter efficiencies used in this work are calculated through Eq. (1) and Eq. (2), considering the different power levels [9].

In this context, a LabVIEW program was developed to operate the inverter at different power levels, considering a certain percentage of the system's nominal power to calculate the efficiency profile and evaluate its performance. Five tests were conducted for each power level and operation mode: charge and discharge.

3.4 HSupercap efficiency calculation

Technical and economic performance indicators are required to evaluate energy storage. The combination of economic indicators such as CAPEX (capital expenditure) and OPEX (operational expenditure) with technical and energy performance indicators such as energy efficiency and charge and discharge energy capacities (Wh), [9] enable this technical-economic assessment.

The HSupercap performance is characterized by executing charge-discharge cycles within the defined range of the state of charge or voltage operation limits. The operating limits of the HSupercap to perform these tests were chosen regarding the safety margins associated with the recommendations of the manufacturer, considering the HSupercap characteristics.

The energy efficiency is the ratio of electrical energy during the discharge to that during the charge. It is calculated using the following expression (Eq. (3)):

$$\theta_E = \frac{U_{discharge} \times q_{discharge}}{U_{charge} \times q_{charge}} \qquad (3)$$

Where U is the voltage of charge or discharge; q_{charge} is the energy capacity (sum of the energy used to charge the HSupercap); $q_{discharge}$ is the useful energy capacity (sum of the discharged energy drawn) [9].

Six round trip tests with the same power settings were conducted to calculate this average efficiency.

4. RESULTS

4.1 HSupercap performance efficiency

The Table II shows the average energy efficiency, as well as the standard deviation and variance. These parameters result from the average of the data obtained, shown in the Figures 4-7, below. Also, the Table III shows the average calculation of the HSupercap charge and discharge capacity, as well as the standard deviation associated with this calculation.

Table II: HSupercap average energy efficiency.

	Average Efficiency	Standard Deviation	Variance
Energy Efficiency	0,978	0,368	0,145

Table III: HSupercap charge and discharge energy capacities.

C-rate	$\overline{C_C}$ (Wh)	Standard Deviation $\overline{C_C}$	$\overline{C_D}$ (Wh)	Standard Deviation $\overline{C_D}$
2C	1021	98	740	169
3C	499	121	453	83
4C	457	82	404	80
5C	352	69	339	37
6C	218	50	210	42
7C	141	19	137	17
8C	118	9	115	6

Legend: $\overline{C_C}$ – charge energy capacity; $\overline{C_D}$ – discharge energy capacity.
Note: the average charge and discharge capacity values have been obtained from the average of the six tests for each of these curves.

In the following Figures 4-7 a representation example of the charge and discharge curves obtained, according to the HSupercap DC voltage and DC current operational limits, is presented.

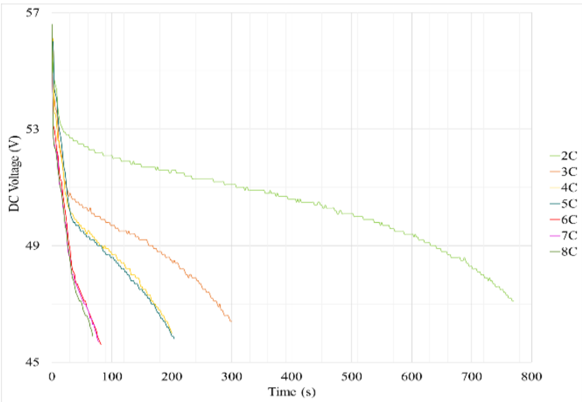

Figure 4: DC Voltage-Time curve for the HSupercap in discharging state.

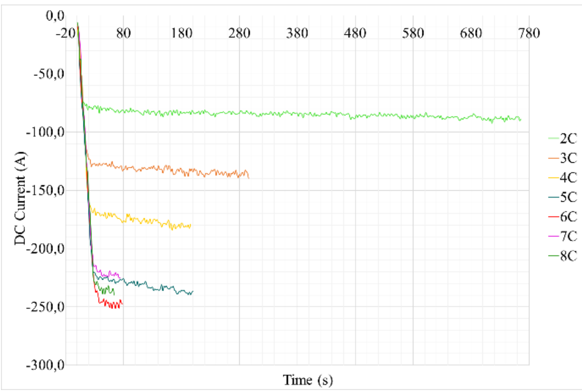

Figure 5: DC Current-Time curve for the HSupercap in discharging state.

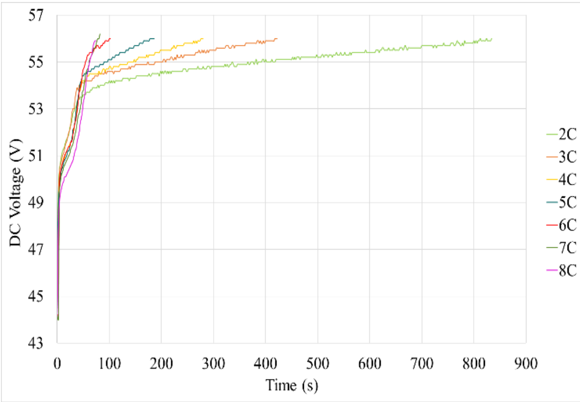

Figure 6: DC Voltage-Time curve for the HSupercap in charging state.

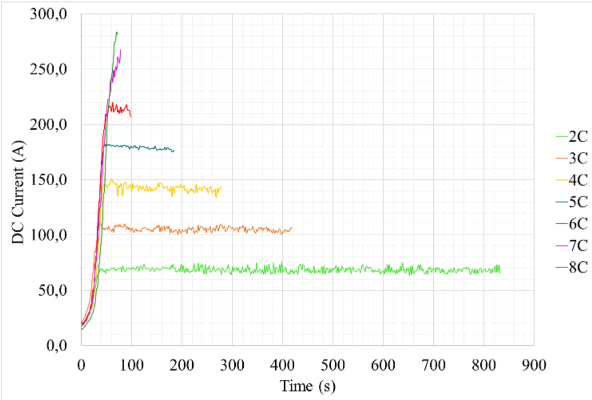

Figure 7: DC Current-Time curve for the HSupercap in charging state.

4.2 Inverter efficiency results

The following charging and discharging efficiency curves were plotted using the data from the charging and discharging tests obtained through the programming developed in LabVIEW, as shown in the Figure 8 and Figure 9.

These efficiencies result from the average of the five tests carried out for each of the selected powers, with these powers representing a certain percentage of the system's nominal power. The following table shows the correspondences for the different powers used in the tests in terms of percentage in relation to the nominal power of the system.

Table IV: Power levels used in the inverter efficiency determination tests.

Nominal Power Percentage (%)	Nominal Power (W)
5	1500
10	3000
20	6000
30	9000
50	15000

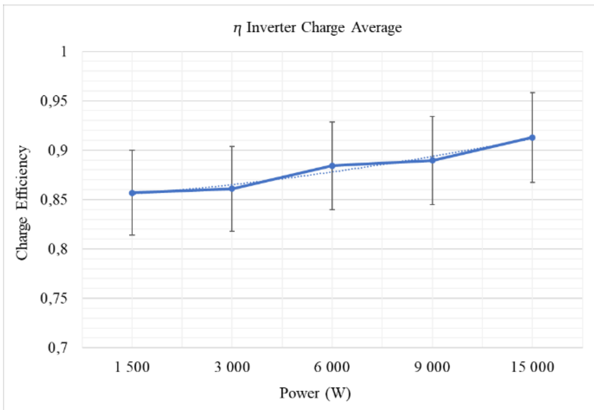

Figure 8: Inverter average charge efficiency at different operating power levels.

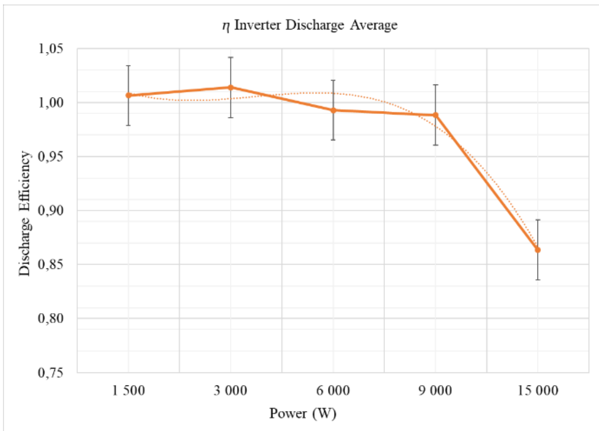

Figure 9: Inverter average discharge efficiency at different operating power levels.

5. RESULTS DISCUSSION

The hybrid powercapacitor technology was successfully integrated into the University of Évora's microgrid, where the control with the power conditioning units was effectively achieved, allowing to proceed with the supercapacitor and inverters characterization testing and operation evaluation.

For the HSupercap average roundtrip energy efficiency a value of 97.8% (±3,7%) was obtained.

Regarding energy capacity, an average value of 1021Wh @2C was calculated for charge and an average of 740 Wh for discharge. Given the voltage range used in the tests, lower energy capacity values than nominal were expected. Similarly, to other energy storage technologies, the useful energy capacity is lower than nominal capacity stated by the manufacturer. In the engineering phase of real application projects, careful sizing of the HSupercaps and inverters should be done. As expected, demanding higher currents of charge/discharge decreases the energy capacity stored.

In Figure 4 and Figure 5, which refer to the discharge state for the HSupercap and relate the DC voltage and DC current as a function of time, respectively, we can observe a decrease in the DC voltage as well as the DC current, as would be expected given that this is a discharge. Initially, the discharge DC current shows an almost linear decrease, eventually becoming almost constant over time.

In Figure 6 and Figure 7, which refer to the HSupercap state of charge and relate the same quantities as those described above, the exact opposite is seen, since this is a state of charge. In the state of charge, there is always an increase in DC voltage and current over time, although the latter eventually becomes almost constant after a certain point. From the well-known expression, $P = VI$, and considering the fact that the DC current becomes constant from a certain point in time for both a charging and discharging state, this means that the HSupercap keeps its voltage constant from a certain point in time, as well as its power, making this current constant over time.

In relation to the Figure 8 and Figure 9, which refer to the charge and discharge efficiencies, respectively, the inverters presented high conversion at different power levels. Average efficiency above 1 was obtained, nevertheless well within the error interval calculated for the tests sample.

Current operational limits for the used inverters model limited the tests at higher power/current levels, being the maximum power reached of 19.8 kW. Future inverters sizing should address this design limitation, enabling to reach the HSupercaps full potential, exceeding 8C rates.

6. RELATIONSHIP WITH HIGH POWER PHOTOVOLTAIC IRRIGATION

The photovoltaic high power irrigation systems are subjected to power fluctuations that occur when clouds pass over the photovoltaic plant. Power storage technologies can address this issue and provide a solution to stabilize these high-power ramp rates. The Figure 10 below presents a typical response of a high-power PV pumping system for a cloud passing event. A decrease of about 80% of global solar radiation was measured, occurring in a 20s interval. Intelligent algorithm control can provide a suitable solution for a large number of these cloud passing events, as well as a power storage technology, capable of delivering a fast response time with high power density and lifetime.

The hybrid powercapacitor module tested provides a response time of <200ms (for a 3600A pulse discharge), and a maximum sustained power capability of 29.7 kW.

In standby mode, the system can achieve a response time <2s (for a low latency network). Given a typical cloud passing as shown Figure 10, with 20s duration, this system proves to have a response time suitable to control the PV power ramp rate.

The tested module has a maximum sustained power capability of 29,7 kW (manufacturer specifications), providing a power density of 1000W/dm^3.

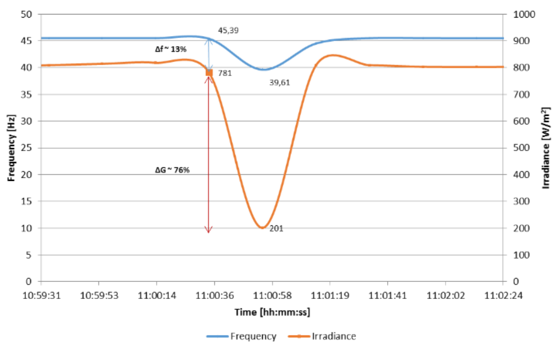

Figure 10: Example of a typical influence of a cloud passage on irradiance and operating frequency of frequency converter. Adapted from [11].

Additional optimization work should be carried to achieve lower control runtime of the LabVIEW software, reaching an overall <1s system response time.

6. CONCLUSIONS

Cloud passing over the PV plant of a high-power PV irrigation system causes extreme power fluctuation (power ramp rate), potentially inducing the sudden stop of the variable frequency converter and, in consequence, of the motor pump. This stopping causes water hammer effects on the hydraulic system, greatly reducing its reliability and lifetime.

The HSupercap technology tested can provide a solution for the control of power ramp rates. A real HSupercap module was installed, commissioned and tested in the CERUE experimental grid. The inverters presented high average efficiency values, for charge and discharge modes. The HSupercap tested presented an average roundtrip energy efficiency of 97.8%. The tested system was not able to achieve higher power than 20 kW due to current operational limits of the inverters. The proper sizing of the inverters and cabling proves to be key to unlock the HSupercap full power capabilities.

This hybrid powercapacitor module provides a response time of <200ms (for a 3600A pulse discharge), and a maximum sustained power capability of 29.7 kW. In standby mode, the system was able to achieve a response time <2s. Given a typical cloud passing event as shown, with 20s duration, this system proves to have suitable characteristics and performance, such as response time, energy capacity and lifetime, suitable to control the occurring PV power ramps.

Additional optimization work should be carried to achieve lower control runtime, reaching an overall <1s response time. Additional tests should be carried out, integrating this HSupercap with a real size PV pumping test rig, to reach a full experimental validation for this application type.

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