A Combinatorial Approach for Addressing Intermittency and Providing Inertial Response in a Grid-connected Photovoltaic System

Arash Anzalchi, *Student Member, IEEE,* Maneli Malek Pour, *Student Member, IEEE,*
and Arif Sarwat, *Member, IEEE*

***Abstract*—The operation of a photovoltaic (PV) generating system under intermittent solar radiation is a challenging task. Furthermore, with high penetration levels of photovoltaic energy sources being integrated into the current electric power grid, the performance of the conventional synchronous generators is being changed and grid inertial response is deteriorating. This paper proposes a combined virtual inertia emulator (VIE) and a hybrid battery-supercapacitor-based energy storage system for enhancing the stability of the Microgrids and smoothing the short-term power fluctuations simultaneously. Not only could the suggested system overcome the slow response of battery system (including dynamics of battery, controller, and converter operation) by redirecting the power surges to the supercapacitor system, but also enhance the inertial response by emulating the kinetic inertia of synchronous generator. Control systems for the VIE and battery-supercapacitor storage system are presented in this paper. Correspondingly simulation results are discussed to validate the effectiveness of the proposed scheme. In this paper, Matlab Simulink software has been considered to develop control designs of VIE and Hybrid Energy Storage System (HESS). Through these studies, it will be demonstrated that the recommended method is capable of achieving voltage and frequency regulation and effective management of the hybrid storage system. Since the suggested technique focuses on short-term fluctuations and includes no long-term power regulation, it needs no mass storage device. Thus, the method is economical. The other concerns raised by renewables (e.g., forecast accuracy, low voltage ride-through, etc.) have not been addressed within this study.**

Keywords*—Virtual Inertia Emulator (VIE), Hybrid Energy Storage System (HESS), Battery Energy Storage System (BESS), Supercapacitor, photovoltaic, Microgrid, Stability, Intermittency.

I. Introduction

As an environmentally friendly and renewable energy source, solar generation has recently observed accelerated proliferation throughout the world [1] [2]. However, as a result of the stochastic nature of solar irradiation, the subsequent fluctuations in solar energy substantially handicap large-scale integration of PV into regional power grids. Another technical challenge of adding high levels of PV generation in the electric grid is the decline of inertial response which is a consequence of incompatibilities amongst the power demand and generation in the (micro) grid [3]. Subject to increasing the instantaneous power or loads with large startup current, energy management and power control of a system with low rotational inertia is a vital concern. Such a high current in a short time not only requires the greater rating of the power apparatuses but also can possibly cause the system voltage and frequency to drop in the entire (micro) grid [4].A possible solution for regulating the natural fluctuating output power of a PV plant is to integrate a hybrid energy storage system (HESS) that has both high energy density storage battery and high power density storage supercapacitor.

More than that, delivering high power in a short period of time is destructive to batteries in a Battery Energy Storage System (BESS), but it is the challenge that supercapacitor can best mitigate. In peak power situations, the supercapacitor is capable of delivering or receiving energy, therefore, it can act as a load-flattening device for the battery. If this is done, the battery output power would become closer to the average load demand, hence decreasing its RMS and peak currents [5].

Additionally, a big change in load within a low inertia Microgrid could cause a transient stability problem when it is islanded, and the same disturbance might pose a small-signal stability problem when it is grid connected [6]. In recent years, the concept of Virtual Synchronous Generators (VSG) has emerged as an effective method for adding virtual inertia to the power system through the control of power electronic converters [7].

Finally, to the best of our knowledge, we make the first attempt in approaching the mixed hybrid battery-supercapacitor energy storage system and virtual inertia emulator to mitigate the challenges of PV intermittency (in generation side) and stability (due to interruptions and the initial current of big loads). Moreover, when the HESS and VIE are implemented together, there is no need for two sets of energy storage systems for each of them and just one HESS can store energy for both of them without any size increase. For this purpose, it is assumed that pulse load and high rates of change of solar irradiation are not happening at the same time. In this work two systems are working independently.

The paper is organized as follows: in section II, the description of the system is presented. In section III, the operation and modeling of the hybrid supercapacitor/battery storage systems is explained. In section IV, the control of the Virtual Inertia Emulator is explained. In section V, the simulation results are

This material is based on work supported by the National Science Foundation under Grant No. 1441223. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

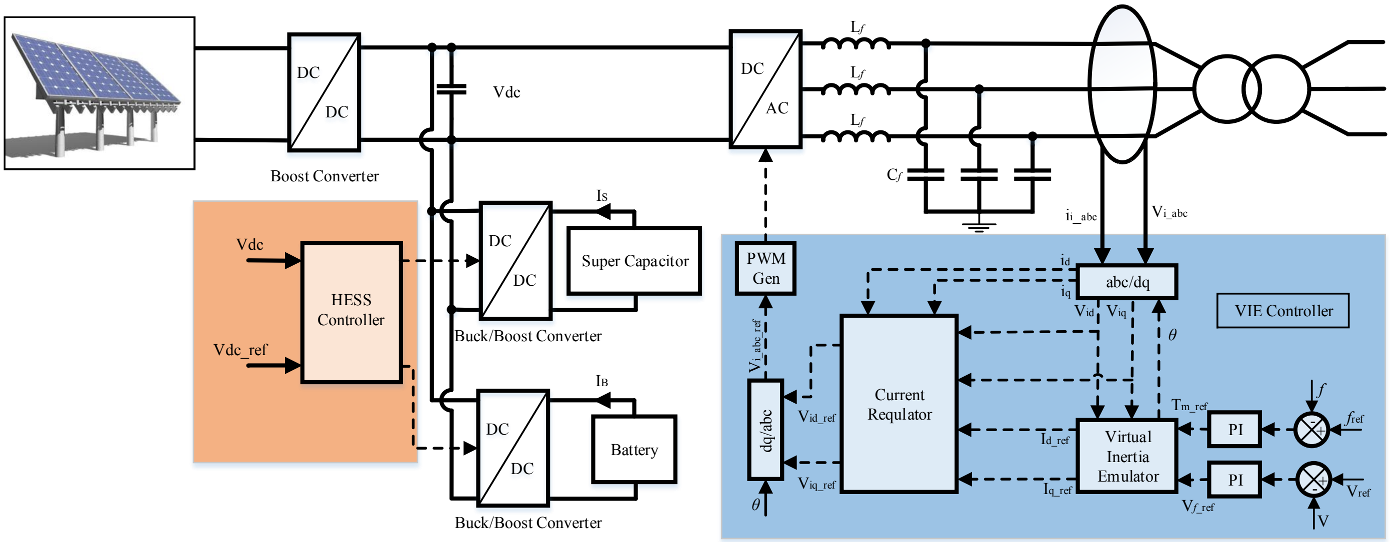

Fig. 1. An overview of the proposed system a)Hybrid Energy Storage Controller b)Virtual Energy Inertia Controller

TABLE I. PARAMETERS USED FOR SIMULATIONS

Elements	Parameters
Rating of PV	10 kW
Rating of battery storage	75 Ah
Rating of supercapacitor	100 F
Rating of constant load	8kW
Rating of pulsed load	80kW
Rated dc link voltage	480V
Battery storage system voltage	450V
Supercapacitor maximum voltage	480
Rated load side voltage	120 V
Load side operating frequency	60 Hz

presented and discussed. Finally, in section VI he conclusions hat can be drawn out of this paper is presented.

II. SYSTEM DESCRIPTION

A grid-connected PV system consisting of PV panel, battery, and supercapacitor arrangement with a virtual inertia emulator and their related controllers is shown in Fig. 1. The PV panel is connected to the dc bus using a boost converter. Here, the boost converter is used to extract the maximum power from PV panel by using maximum power point tracking (MPPT) algorithm. The HESS is connected to the dc bus using bidirectional dc/dc converter. The HESS is used to maintain the constant dc bus voltage (V_{dc}) due to the intermittency of solar irradiance. The parameters that used for simulation are presented in Table I.

The grid-interfaced inverter is controlled to convert the dc to alternating current and regulates the real and reactive powers flowing into the grid instantaneously and autonomously. The inverter controller can be designed to simulate traditional generators, as is the case to be presented in this paper.

III. CONTROLLER DESIGN OF HESS

In the renewable energy systems with battery alone as energy storage, the PV power produced continuously changes in relation to the changes of temperature and irradiance. When this highly fluctuating and intermittent imbalance power is given to the battery, the battery experiences repeated charging and discharging operations. It increases stress on the battery and it may have a harmful effect on the lifetime and performance of the battery. To prevent this, additional energy storage element, supercapacitor, is connected to the grid using bi-directional buck/boost converter. Since the supercapacitor can react faster to quick fluctuations, the stress on the battery can be reduced [8]. Supercapacitor offers a viable solution for power quality upgrading and energy sustainability, as an energy storage device with low power loss, long cyclic life, and high energy density. The HESS charges and discharges according to the PV power generation to keep the dc grid voltage constant.

The PI controller creates the total current required (I_{tot_ref}) from HESS. This I_{tot_ref} is divided into low-frequency (I_{LFC_ref}) and high-frequency (I_{HFC_ref}) components. The low-frequency section is given as:

$$I_{LFC\_ref} = f_{LPF}(I_{tot\_ref}) \tag{1}$$

where, f_{LPF} is the function of low-pass filter. The low-frequency part is given to the rate limiter which controls the charge/discharge patterns of the battery current, i.e., which gives the reference current to battery as given

$$I_{B\_ref} = f_{RL}(I_{LFC\_ref}) \tag{2}$$

where f_{RL} is the function of rate limiter. I_{B_ref} is compared with the actual battery current (I_B), and the error (I_{B_err}) is given to the PI controller. The PI controller generates the duty ratio, which is given to the pulse width modulation (PWM) generator to generate switching pulses corresponding to the battery switches.

On the other hand, the error of I_{HFC_ref} and actual current of the supercapacitor is given to a PI controller which makes the duty ratio of supercapacitor DC/DC Buck/Boost converter.

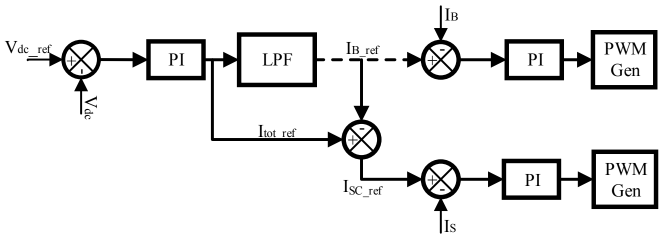

Fig. 2. Control system designed for a HESS.

The block diagram of control strategy of the hybrid battery-supercapacitor is shown in Fig. 2. The basic idea of this control strategy is that the battery supports slow transients, whereas supercapacitor supports fast transients. Therefore, the average dc link voltage (V_{dc}) is compared with a reference voltage (V_{ref}) and passed through compensator. The compensator gives the total current that is to be supplied from the HESS. This total current ($I_{tot-ref}$) is divided into average power component and dynamic power component using low-pass filter as shown in Fig. 2. The average power component is given as reference (I_{B-ref}) to the battery current control loop, whereas dynamic power component is given as reference (I_{S-ref}) to supercapacitor current control loop.

IV. Implementation of Virtual Inertia Emulator

As illustrated in Fig. 1, to allow the frequency control function of the PV/HESS system an HESS is added to the grid-tied inverter. The inverter is controlled to imitate a synchronous generator in its ability to deliver inertia to the electric power grid. This form of inverter control is also known as VIE [9]. In this paper, the topology of a VIE principally contains a three-phase inverter and the output LC filter, as shown in the dotted box in Fig. 1. In the VIE, the stator terminal voltage of the virtual synchronous generator, $v = [v_a, v_b, v_c]^T$, are represented by the voltages across the filter capacitors. The inductance of the filter,L_f, has been involved in the internal impedance of the stator windings of the simulated synchronous generator by the inverter. The induced e.m.f. by the rotating rotor flux is denoted by the vector, $e = [e_a, e_b, e_c]^T$. Note that e is the fundamental frequency component of the generated voltage by the inverter.

In a synchronous machine, the electromagnetic quantities consist of the three-phase currents, voltages, and flux linkages in the abc stationary frameare converted to the dq rotational frame. From the machine theory, the electrical model of the synchronous generator can be represented by the equations (3) in [9].

The generated real power *P* and reactive power *Q* (as seen from the inverter legs) can be defined as

$$\begin{cases} T_e = \frac{3}{2}(\lambda_d i_q + \lambda_q i_d) \\ P = \frac{3}{2}(v_d i_d + v_q i_q) \\ Q = \frac{3}{2}(v_q i_d - v_d i_q) \end{cases} \tag{3}$$

Where v_d and v_q are the VIE terminal voltages, i_d and i_d represents the VIE terminal currents, and λ_d and λ_q are

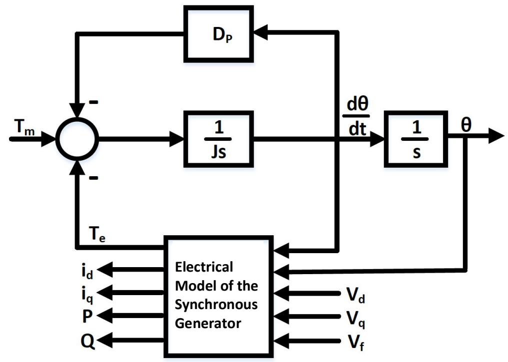

Fig. 3. Schematic diagram of the VIE model.

the stator flux-linkages reflected all in the *dq* frame. Since a balanced system has been considered in this study, the statements describing the zero-sequence winding circuit are not involved in the electrical model equations. Also, T_e is the electromagnetic torque; P and Q are the real and reactive powers.

By including the swing equation of the synchronous generator (6), the general outline of the VIE can be modeled as illustrated in Fig. 3.

$$\begin{cases} T_m - T_e - D_p.\frac{d\theta}{dt} = J.\frac{d\theta}{dt}\omega_m \\ \omega_m = \frac{d\theta}{dt} \end{cases} \tag{4}$$

where T_m is the mechanical torque which can be fixed as a constant value or be ordered to follow a real power demand. In this study, the second case is implemented for the purpose of the frequency control ; D_p is the damping coefficient; and *J* is the moment of inertia required to imitate the rotational mass of a virtual rotor which is investigated through the integration of the HESS.

Based on the virtual inertia emulator a control system for the system is designed and presented in Fig. 1. In this control system, the frequency, f, and voltage magnitude, V_i, are measured at the point of integration (POI) and compared to their reference values, f_{ref} and V_{i-ref}, respectively. The variances are fed into the PI controllers to set the supposed mechanical torque and exciter voltage, T_{m-ref} and V_{f-ref}, within the virtual inertia emulator. The above-designed control system is operated in the following way. When a disturbance occurs in the system, such as a generator trip or big load change, the POI frequency deviates from its nominal value, f_{ref}. To compensate for the frequency deviation, the PI controller functions to regulate the power from the PV/HESS generation system. In this study, the control system of the HESS is designed to regulate the DC- ink voltage as constant, thus the power injected to the POI is balanced with that from the PV/HESS system, ignoring the power losses within the system. In the proposed controller θ is the rotor angle of the VIE.

V. Simulation Results

To confirm the usefulness of the proposed control configurations, a grid-connected PV system with VIE and HESS controller was modeled in Matlab Simulink.

In the first part of simulation, the load was considered an active constant 8kW. In this part, the mitigation of the solar intermittency is the purpose of the study. The battery and supercapacitor charges and discharges according to the intermittency to keep the dc grid voltage. The terminal voltage of the battery and supercapacitor will fluctuate depends on the PV output power imbalance nature.

In the second part, the dc voltage is considered as constant and the effect of a big load connecting into the grid is analyzed. In this simulation, the incremental load change occurs at t=1sec and its value changes from 1 pu to 8 pu.

For this study, we assume that the moment of inertia (J) has five values (from 29.4 kg.m^2 to 400 $\times$ 29.4 kg.m^2) and the load change incident is induced with all values of J, at t = 2sec.

A. Battery and supercapacitor

In order to evaluate the performance of the developed control system for the HESS, its operation is compared with Battery Energy Storage System (BESS). When the rate of change of the solar power is more than 300 w/sec (or less than -300w/sec), power is redirected to the supercapacitor.

A 95-second window of solar irradiation data has been generated based on high ramping rates in order to trigger all the operation modes with a good resolution (Fig. 4). Additionally, the SOC of the HESS has particularly initialized at 0.5 p.u. for the battery and 0.3 p.u. for the SC.

Fig. 5 compares the battery power output of the BESS and the HESS. The results show that not only the number of charges and discharges decreased significantly in Fig 5 (b) but also the battery operates more smoothly and with reduced ramp rates. This will result in less stress on the batteries and the greater longevity of them.

The operation and the power command of the supercapacitor are illustrated in Fig 6. In Fig 7 power output and the required power of the HESS is shown. It can be seen that adding the battery power output in Fig 5(a) and the supercapacitor power output in Fig 6 will satisfy the HESS in Figs 7 (a) and (b).

Fig. 8 shows the simulation results of dc link voltage in the BESS and the HESS. The first steady state voltage (for BESS) has a peak of 488V at t=4.523s, and two peaks at t=64.16 sec and t=72.37 sec, but when the HESS is implemented the voltage fluctuations decreases a lot and a smoother voltage is obtained. As it can be observed from Fig. 10, the DC bus voltage has been significantly smoothed by the proposed system.

B. VIE

As shown in Fig. 9, the existence of the big load switch in event can be absorbed successfully as expected during a high inertia situations (J $\geq$ 100 $\times$ 29.4 kg.m^2). However, the same fault event becomes critical during a low inertia situation (J = 29.4 kg.m^2) since the system frequency goes above 61.2 Hz before the nominal primary frequency control fully kicks in (around 1 second after the load switch in).

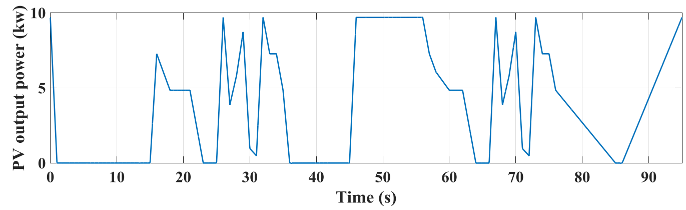

Fig. 4. Photovoltaic power output.

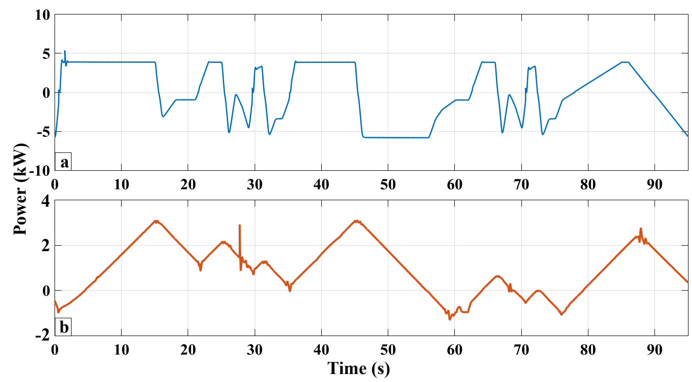

Fig. 5. (a) The battery power output in the BESS (b) The battery power output in the HESS.

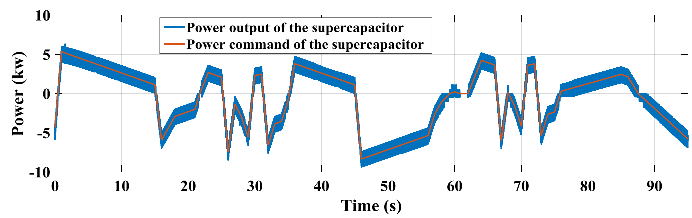

Fig. 6. The power output (blue line) and the power command (red line) of the supercapacitor.

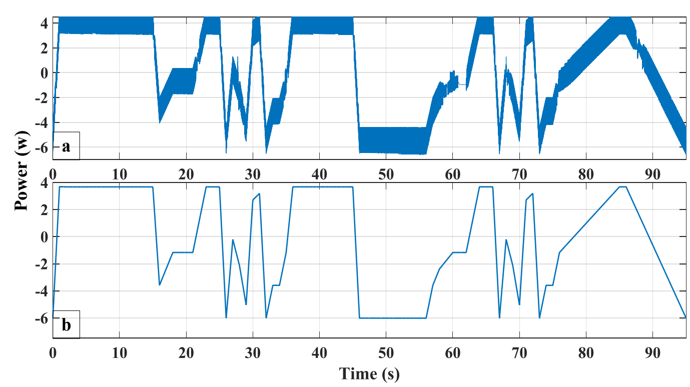

Fig. 7. (a) The HESS power output (b) Required HSSS power.

At t=2 sec the speed of VIE fluctuate quickly when the amount of inertia is small (J = 29.4 kg.m^2). As shown in Fig.

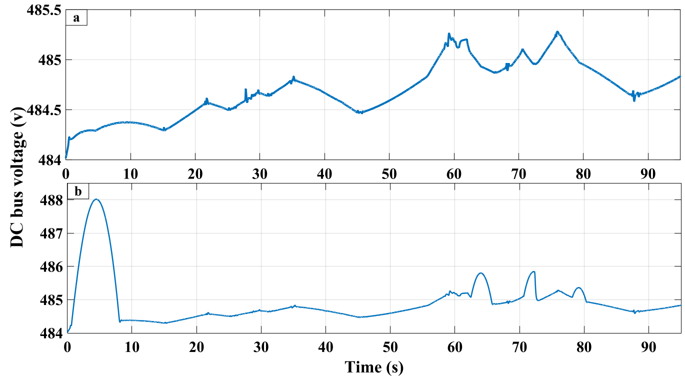

Fig. 8. dc bus voltage for (a) The HESS (b)The BESS.

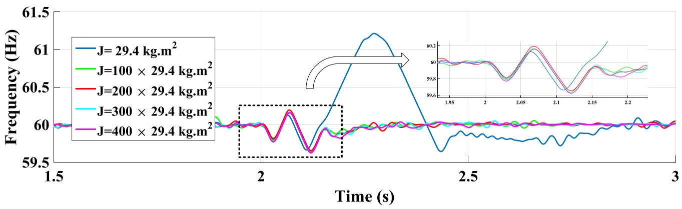

Fig. 9. Dynamic frequency response to a big load switch in at t=2 sec.

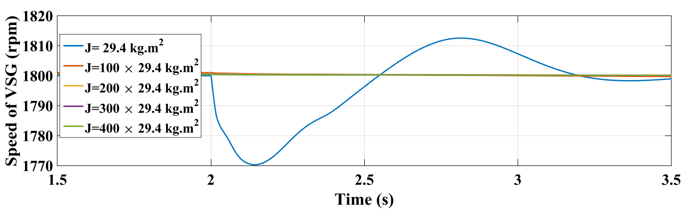

Fig. 10. Speed of the virtual inertia emulator (VIE).

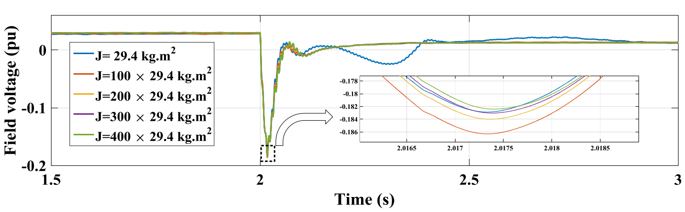

Fig. 11. Field voltage of virtual inertia emulator (VIE).

10, speed of virtual rotor starts fluctuating immediately after the big load switch in, but the turbine goes back to its normal operation about 1.5 s after the initiation of the pulse load. During a high inertia situations, virtual rotor speed does not fluctuate very much.

As shown in Fig. 11, the command of field voltage of the VIE responds quickly to the step change in real power demand at t = 2 sec , and it settled down in less than 18 cycles at high inertia. However, the transient situation continues for about 60 cycles when low inertia is applied

VI. Conclusion

A hybrid energy storage system (HESS) including a battery energy storage system (BESS) and a super-capacitor is assessed in this study. This system is designed to accommodate fast solar power fluctuations because of the intermittent nature of irradiance situations. Also, the storage system will provide the virtual inertia by the VIE. Additionally, as conventional generators are replaced by high-penetration levels of renewable energies (mostly PV generation), the existing rotating kinetic energy in the power system will be notably reduced, causing in a loss of system inertia. A VIE equipped with an HESS connected to a grid-connected PV system was investigated in this paper to help improve system inertial response.

Control systems for the VIE and DC-DC converters of the HESS are designed which have the following advantages: 1) fast voltage regulation; 2) smoothing the dc link voltage 3) lowering charge/discharge rates of battery; 4) reducing stress levels on battery; 5) improving life span of battery, and 6) enhancing system inertial response.

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