Using Smart Devices To Provide Distributed Reactive Power Support

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***Abstract*—Smart devices are becoming more common. Many of them already possess the hardware and software capabilities to implement the reactive power injection control as discussed in this paper. In the near future, such devices would be dispersed over a large portion of the electric distribution network, thus making distributed reactive voltage support feasible. This paper presents network-level benefits of such a scheme using a PowerWorld simulation. Applications are discussed, a proposed control framework is simulated in Simulink for a single smart device and future work is outlined.**

***Index Terms*—Smart devices, voltage control, reactive power resources, distributed control.**

I. Introduction

There has been an increasing mention of smart devices being utilized for active demand-side management. This covers a variety of strategies such as active response of home appliances, HVAC systems, hybrid electric vehicles (HEVs), uninterrupted power supplies (UPSs) and even solar arrays. A smart device is a device that has the ability to communicate with the smart grid. The presence of digital processors and sensors provide them the ability to move beyond localized control schemes and respond to system-wide objectives through remote communication and algorithms. This paper outlines part of the ongoing research to provide an authenticated framework for mobilizing distribution level devices to provide reactive power support. More specifically, it discusses the facilitation of reactive power injection control at the residential level.

While the advantages of distributed voltage support have been shown for decades, the use of power electronics in the power systems industry is more modern, becoming prominent in the 21st century. Traditionally reactive power support was implemented by switching large banks of capacitors. SVC's have been used since the 70's, but it wasn't until the late 90's that power electronics started to gain traction for active switching applications. In 1997 the acronym FACTS was added to the IEEE dictionary and the first STATCOM was installed in 1999 [1]. The most effective solution for a load that is consuming reactive power is power factor correction or compensation at the source. The Smart Grid opens up opportunity for a level of distributed voltage support that has not been used in the past.

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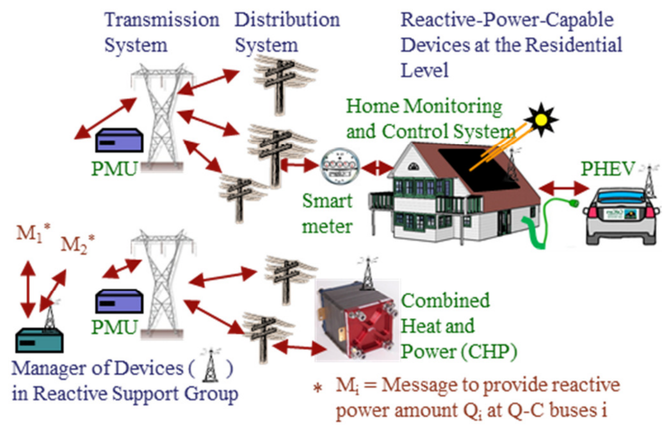

Figure 1. Constituents of a reactive support group

Fig. 1 shows possible constituents of a reactive support group [2]. As seen in the diagram, the Plug-in HEV (PHEV) is a smart device which can be remotely controlled by a manager higher up in the hierarchy of the distribution/transmission network. These devices would be scattered over a large area and require substation level co-ordinated aggregate control to meet multiple objectives such as voltage set points, minimization in transmission line loading or minimization of network losses. At present, such devices are not common and remote control network algorithms are still a major research area. In theory such control schemes can be implemented with concurrent development of secure communication and smart device technology.

The remainder of this paper is organized as follows. Section II presents examples to motivate the idea of reactive power based voltage regulation in a distribution network. Section III discusses areas of possible application. Section IV presents a simple simulation of a proposed control scheme of a smart device. Section V addresses challenges and the scope of future work. Finally, conclusions are presented in Section VI.

II. Reactive Power Voltage Support

A. *Traditional Use Of Shunt Capacitor Banks*

Fig. 2 shows a one-line diagram of a primary feeder supplying power to a load at the end of the feeder [3]. The load bus has a shunt of –j2.10 p.u. which can be switched in or out. The sending end voltage, V_S, is maintained at 1.05 p.u. Summary of calculation for the cases when the shunt is disconnected and when connected is shown in Table I.

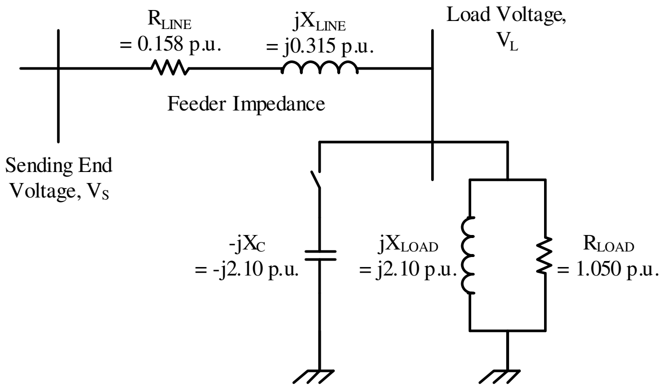

Figure 2. Shunt capacitor (switched out) at the end of a primary feeder ($S_{base3\phi}$ = 10 MVA & V_{baseLL} = 13.8 kV)

TABLE I. SUMMARY OF CALCULATIONS

	Shunt Disconnected	Shunt Connected
Line Current, $\lvert I_{LINE}\rvert$ (p.u.)	0.8473	0.8414
Load Voltage, $\lvert V_L\rvert$ (p.u.)	0.7957	0.8833
Real Power Loss, P_{LOSS} (p.u.)	0.1131	0.1115

Since the transmission of reactive power over long distances (from power plants to loads) is not economically feasible, shunt capacitors are widely used in distribution systems. The example in Fig. 2 shows the benefit of having reactive power injection closer to the load bus. When the shunt capacitor bank is connected, $\lvert I_{LINE}\rvert$, decreases, $\lvert V_L\rvert$ increases and $\lvert P_{LOSS}\rvert$ decreases (Table I). All of the above are desirable effects which can be achieved by power factor correction at the load bus instead of reactive power being supplied from the distribution substation.

Although the above example results in unity power factor at the load bus, similar effects can be achieved through real-time control of smart devices which help push the power factor closer to unity. Unlike the shunt capacitor bank, these smart devices will be able to inject reactive power in a more distributed way. This will be particularly helpful in residential distribution networks which are typically radial and are prone to under-voltage conditions.

B. Proposed Use Of Smart Devices As Variable Reactive Power Sources

In order to demonstrate the feasibility of distributed smart devices to provide reactive power, the modified 44-bus (originally 37-bus [4]) power system illustrated in Fig. 3 is simulated using PowerWorld. It has been adapted to include load buses in a radial configuration at the bus named WOLEN69. In essence, this reflects additional detail in the network topology as shown in Fig. 4. Usually, such detail is ignored for large system studies. However, studying this extended network helps enforce the idea of distributed reactive voltage support.

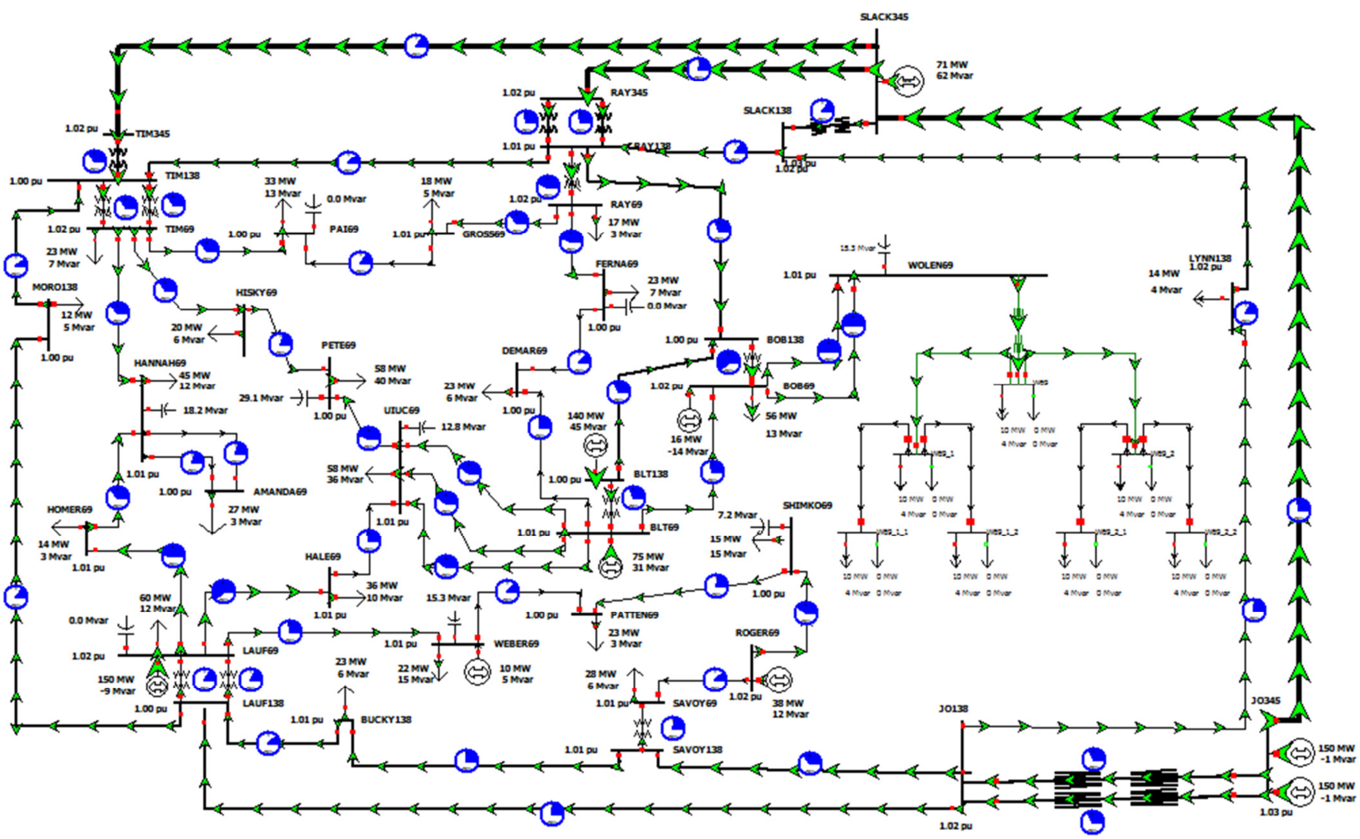

Figure 3. Modified 44-bus network (originally 37-bus)

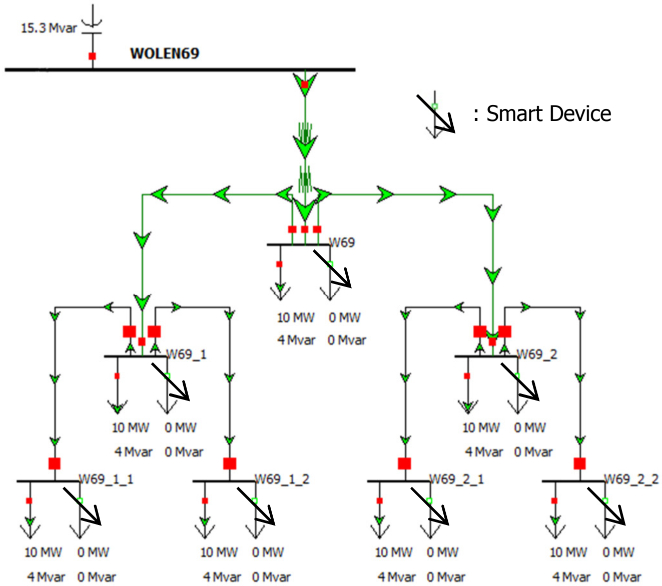

Figure 4. 13.8kV Sub-network of WOLEN69
(Shunt capacitor is connected and smart devices are disconnected)

TABLE II. BUS VOLTAGE MAGNITUDES FOR WOLEN69 SUB-NETWORK

Bus Voltages (p.u.)	Only shunt capacitor is connected at WOLEN 69	Only distributed “smart devices are connected
WOLEN69	1.0063	1.0063
W69	0.9632	0.9822
W69_1	0.9580	0.9783
W69_1_1	0.9563	0.9771

Distributed devices make it possible to inject reactive power more evenly along the radial load buses. These distributed injections ensure a better power factor at each load bus; ultimately resulting in a more even voltage profile throughout the radial network. Widespread presence of such smart devices would reduce the demand for reactive power, allowing generators to operate within the same ratings while increasing real power production. Such benefits make distributed reactive voltage support appealing.

III. APPLICATIONS

With the advent of the Smart Grid to the average household, comes opportunity to improve the nation’s grid on many different levels. The impact of EV and PHEV’s on the grid is an active area of research. Typically, a vehicle can be charged overnight when the demand for electricity is low. To improve the overall efficiency of transmission, the power factor at which the vehicle is charged can be controlled. Furthermore, it can be used to provide reactive voltage support when it is at full charge and even the option of real power support in the case of a critical need or to provide backup power during an outage. There is a multitude of other devices that can be used as well. The research presented in this paper focuses on EV/PHEVs, PV systems and UPS devices. The motivation lies in the improvements that can be made to the nation’s grid through the use of existing products.

The advantages of injecting reactive power locally are clear from the discussion in Section II. By improving the power factor, the line current is reduced, hence reducing the line losses. However, the benefits need to be weighed against the drawbacks. The maximum charge current typically depends on the charging method available. The assumption for this research is based on a consumer grade system from [5], so Level 1 and 2 charging as shown in Table III are considered. By charging at a non-unity power factor the charge time will be extended. Furthermore, the losses in the charging system will increase and the stress on the electrical components will be slightly higher. Ultimately the decision to choose should be left to the consumer based on the incentives. That being said, the focus of this research does not include power system economics, pricing or the communication framework required. Agent based technologies could be a good choice as presented in [6] and [7]. Further research is being conducted on the effects of malicious attacks relating to the distributed injection of reactive power.

Another point to consider is the availability of these devices since the peak-load occurs during the day. Solar panels or UPS systems are stationary, but PHEV's may be out on the road, at home or at work. It is reasonable to assume that the number of cars in an area will have a correlation with the number of people and ultimately the load in that area. If charge stations are made available in the future, PHEVs can have a greater impact by participating in these areas that are expected to have a higher load.

The modes of operation of interest (1, 2 and 3) are labeled in Fig. 5; consuming reactive power is not being considered. Option 1 is the base scenario; charging at a unity power factor with no reactive power injection. Option 2 shows charging at a leading power factor. Both the current magnitude and current angle can be adjusted. A slow charge is recommended when time is not critical, such as overnight charging. Since the magnitude of current is smaller, the stress on the batteries/system as well as conduction losses are reduced. Option 3 is used to solely inject reactive power while the loss in the system is to be compensated by the grid.

Although the supply of real power is a possibility, it is assumed to be undesirable and such modes of operation will not be used [8], [9]. The objective is to supply reactive power strictly from the available capacitance (i.e. stored charge), without affecting battery life. As such, the chemistry of the cells is not critical, but proper battery management systems must be used to protect against improper use. For initial experiments, $LiFePO_4$ batteries have been selected based on considerations such as safety and power density. The dc bus voltage is application specific; for this project it was selected to be 330V based on the inverter used [10]. As always, there is a tradeoff in using a higher voltage to achieve less conduction losses versus increased switching losses.

TABLE III. Charging level specifications

	Voltage (V)	Phase	Peak Current (A)
AC Level 1	120	Single Phase	16
AC Level 2	240	Split Phase	32

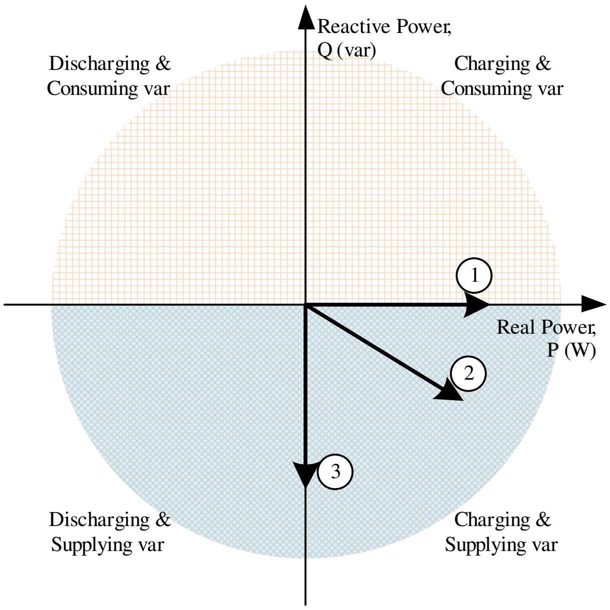

Figure 5: Modes of operation (load notation: $P_L + jQ_L$)

IV. Battery-Inverter Device Simulation

This section presents a method of controlling a single smart device purely for the intended purpose of reactive power injection. The presence of suitable power electronics, sensors and a digital processor in many modern devices make them suitable for similar purposes. For example, the reader can imagine a PHEV set up to inject reactive power. To show the basic scheme, a simple battery-inverter device is simulated in Simulink.

A. *Simulation Set Up*

Fig. 6 shows the Simulink block diagram. The model for the battery type is Li-ion with parameters similar to that of approximately 100 series-connected $LiFePO_4$ batteries. Such batteries are being used in energy storage systems and HEVs [11]. As seen in Fig. 6, the battery (330 V) is connected in parallel with a dc bus capacitor and to an H-bridge. The bridge is operated as an inverter and the output of the H-bridge is connected to a 120 V ac wall outlet.

The remaining blocks form a current controlled hysteresis loop. This requires a voltage sensor to detect the wall outlet voltage phase and a current sensor to monitor the injected current. In the simulation, the commanded current is set to 10 A ac. The simulation shows that such a setup is able to track the voltage and inject a current which is almost $\frac{\pi}{2}$ rad out of phase. This translates to an injection of reactive power except for the system's real power losses being compensated from the grid. In this case, the power factor of this device would be approaching 0 leading with respect to the grid.

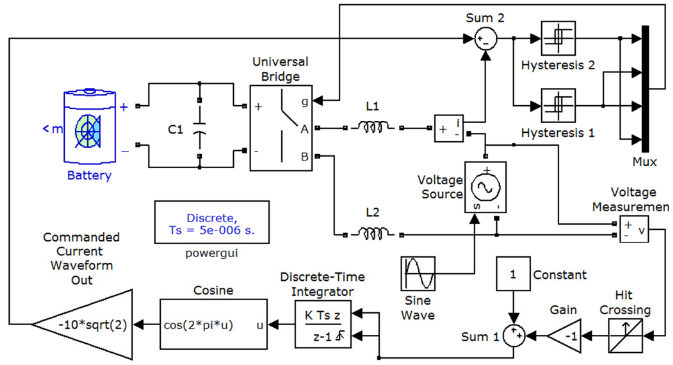

Figure 6. Simulink block diagram of the battery-inverter device

In Fig. 6, parameters such as battery characteristics and value of C_1 have been adjusted to be as close of a match to the actual hardware which will be used to implement this scheme. The hysteresis bounds and values of L_1 and L_2 have also been tweaked to ensure that the switching frequency remains within the capability of the hardware.

B. *Results*

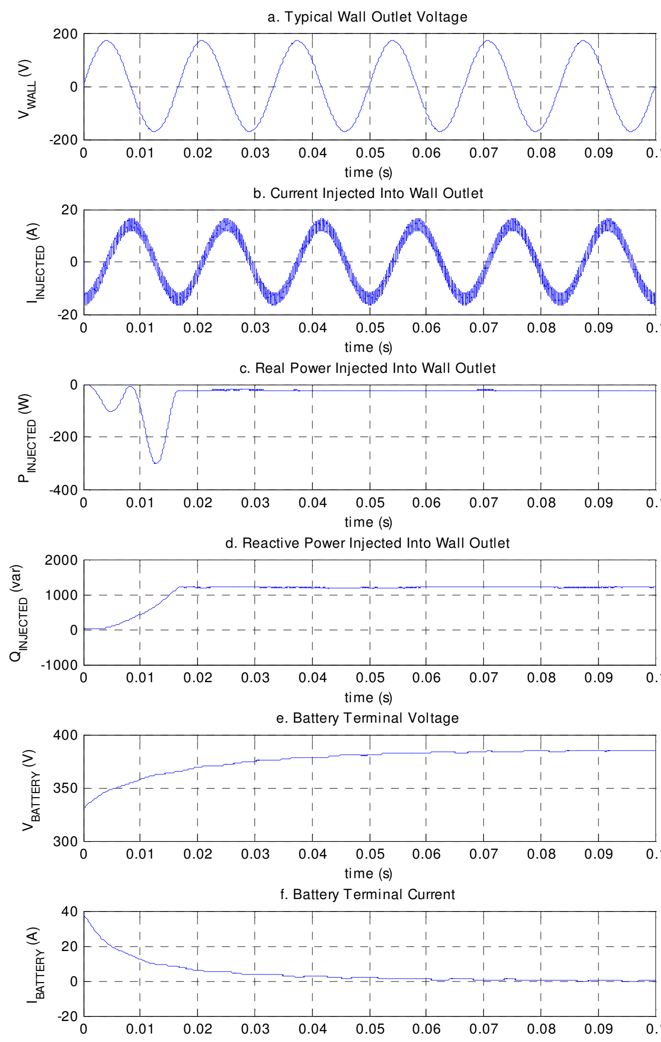

Figure 7: Battery-inverter device simulation results (injected notation)

The simulation shows that this control scheme is able to detect the zero-crossing of the wall voltage, V_{WALL} (Fig. 7a) and command an injected current which is $\frac{\pi}{2}$ rad lagging (equivalent to commanding a drawn current which is $\frac{\pi}{2}$ rad leading) with respect to V_{WALL}. The hysteresis loop is able to track the commanded current and ensure that the injected current, $I_{INJECTED}$, stays within limits of the hysteresis loop. As seen in Fig. 7b, $I_{INJECTED}$ has significant harmonic content and would not be recommended for grid interfacing. This will be addressed during hardware implementation and is discussed in Section V.

At t = 0 s (Fig. 7), a command is issued to inject 10 A ac. The assumption is that the dc link capacitor, C_1, is fully charged before t = 0 s. Fig. 7c shows that the battery-inverter device initially draws real power as the value of $P_{INJECTED}$ reaches approximately -300 W. After approximately one cycle, it reaches a steady-state value of -23 W, corresponding to system losses. Since the simulation model has bidirectional current flow capability, the battery remains fully charged throughout. This is a desirable scheme, which can be incorporated into a charger of a PHEV [8]. The injected reactive power, $Q_{INJECTED}$, increases to its steady-state value of about 1.2 kvar in the same duration.

C. *Discussion*

Fig. 7e and 7f show the voltage, $V_{BATTERY}$, and current drawn, $I_{BATTERY}$, at the battery terminals. Studying these signals is necessary to understand what kind of voltage and current waveforms the battery will be exposed to. As shown in Fig. 7e, the bidirectional nature of the simulation allows the battery to charge up to its maximum rating of about 384 V. In the simulation, this maximum bound is set in the parameters. However, a battery management system would be required to ensure charge and other battery limits in a real hardware implementation. Research on bidirectional supplies such as [8], demonstrate the modes of interest without any adverse effects on the battery.

In the event that regulations might disallow the bidirectional flow of current, the battery will be unable to be charged simultaneously. As the battery discharges, its use will be time-limited. This will be further studied with an experimental set-up in the future.

The quick response of the battery-inverter device makes it an attractive candidate for responding to emergency conditions in the electric grid. It is representative of increasing types of upcoming devices. With a proper control framework, such devices can collectively provide voltage support rather than just burdening the grid.

V. Future Work

A hardware implementation of the battery-inverter device is in progress. The value of 1.2 kvar was an arbitrary choice of a relatively small value which could be tested in a laboratory setting. Actual capacity would be device dependent and is still a work in progress for this research project.

As discussed, $I_{INJECTED}$ shown in Fig. 7b has harmonic content. Work is in progress to implement a layer of PWM control [12] in addition to the current control scheme presented in this paper. Research is planned to develop an optimization algorithm which could be implemented via remote control to manage aggregate groups of smart devices.

VI. Conclusion

This paper has discussed the use of smart devices for distributed reactive voltage support. The sensing and processing required is within the capability of target systems and in many cases, devices could continue operating normally without inconveniencing the user. This presents new possibilities to supply reactive power, both during active and standby modes. Although several control schemes can be remotely implemented, communication, security and consumer confidence still remain a challenge. Cost and robustness of such energy storage and auxiliary technologies would be a major driver in the consumer's willingness to opt in or out of such schemes. Distributed voltage support has the potential to transform the electric grid, empowering the industry to expand its capability of emergency response measures for maintaining stability.

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