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Wang, Xiongfei; Pang, Ying; Loh, Poh Chiang; Blaabjerg, Frede

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A Series- LC -Filtered Active Damper with Grid Disturbance Rejection for AC Power-Electronics-Based Power Systems

Xiongfei Wang, *Member IEEE*, Ying Pang, Poh Chiang Loh, and Frede Blaabjerg, *Fellow IEEE*

Abstract—This letter proposes an active damper with a series LC -filter for suppressing resonances in an ac power-electronics-based power system. The added series filter capacitor helps to withstand most of the system voltage, hence allowing a lower rated converter to be used for implementing the active damper. Unlike an active power filter for mitigating low-frequency harmonics, the proposed damper dampens resonances at higher frequencies, whose values are dependent on interactions among multiple grid-connected converters and reactive elements of the system. Its control requirements are therefore different, particularly in the low-frequency range, where the series LC -filter is predominantly capacitive, rather than the usual inductive characteristics that exist between voltage-source converters and the grid (or load). This low-frequency challenge can fortunately be resolved by the proposed fourth-order resonant controller, in addition to the second-order resonant controller used for resonance damping. Experimental results obtained have confirmed the effectiveness of these controllers, and hence the feasibility of the active damper.

Index Terms—Active damper, resonances, stabilization, series LC -filter, converters, disturbance rejection.

I. INTRODUCTION

AC power-electronics-based power systems are evolving, mainly driven by the increasing use of power electronic converters with renewable energy sources and energy-efficient loads [1]. The resulting converter-interfaced sources and loads are more controllable and efficient, but they also generate more harmonics into power systems [2], [3]. The harmonics may, in turn, trigger resonances introduced by inductive and capacitive elements residing in the systems [4], [5]. Such resonances may further interact with control loops of the converters, leading to instability problems over a wide frequency range [5]-[7]. It is thus necessary to develop effective measures for preserving stability and power quality of the ac power grids.

One possibility is to re-shape the dynamic properties of the converters by adding control loops or digital filters [7]-[9].

Although lossless damping of resonances can be achieved by these control additions, their effectiveness is usually influenced by the variations of the system conditions [7]. Alternatively, additional passive or active devices can be used as dampers for stabilizing the systems [10]-[14]. Passive dampers are, in general, robust, but they incur additional power losses [10], [11]. Lower-loss active dampers are therefore preferred, which however require the use of the high-bandwidth converters for suppressing those high-frequency resonances burdening the power systems [12]-[14].

In terms of convenience, the active dampers are generally added in parallel like in [12], where an active damper has been added to the Point of Common Coupling (PCC), together with other paralleled grid converters. By dynamically shaping the equivalent grid impedance at the PCC, the active damper in [12] dampens resonances effectively, thus maintaining stability of the considered system. Moreover, since the damper in [12] focuses only on high-frequency resonances from 800 Hz to 2 kHz, its power rating is not high. It however requires switching at frequency, preferably, higher than a normal source or load converter, in order to provide the necessary control bandwidth for damping. This requirement can be costly for the damper in [12] because of its higher voltage rating, as compared to the source and load converters. Higher voltage rating of the damper is mainly contributed by its series ac L -filter, whose voltage drop is higher than in a traditional shunt Active Power Filter (APF) due to its higher-frequency current flow. Consequently, a higher dc-link voltage is needed, which is not attractive [13].

To effectively reduce its voltage rating, a series- LC -filtered active damper is proposed in this letter. The filter has an extra capacitor connected in series for withstanding most of the system voltage. The damping converter can then be realized with a lower voltage rating and a smaller filter inductor. The resulting damper is similar to the series- LC -APF proposed in [15]. However, their control requirements and challenges encountered are different with the active damper concentrating on the higher-frequency resonances damping, rather than the low-frequency harmonics compensation targeted by the APF. On the other hand, the capacitive filter characteristic in the low-frequency range challenges the stability of grid current controller for the damper. A fourth-order resonant controller is developed for the damper to reject common grid disturbances. Experimental results showing the damper ability to stabilize a grid converter have been obtained for verification.

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X. Wang, P. C. Loh, and F. Blaabjerg are with the Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: xwa@et.aau.dk, pcl@et.aau.dk, fbl@et.aau.dk).

Y. Pang is with KK Wind Solution A/S, 7430 Ikast, Denmark (e-mail: yipang@kkwindsolutions.com).

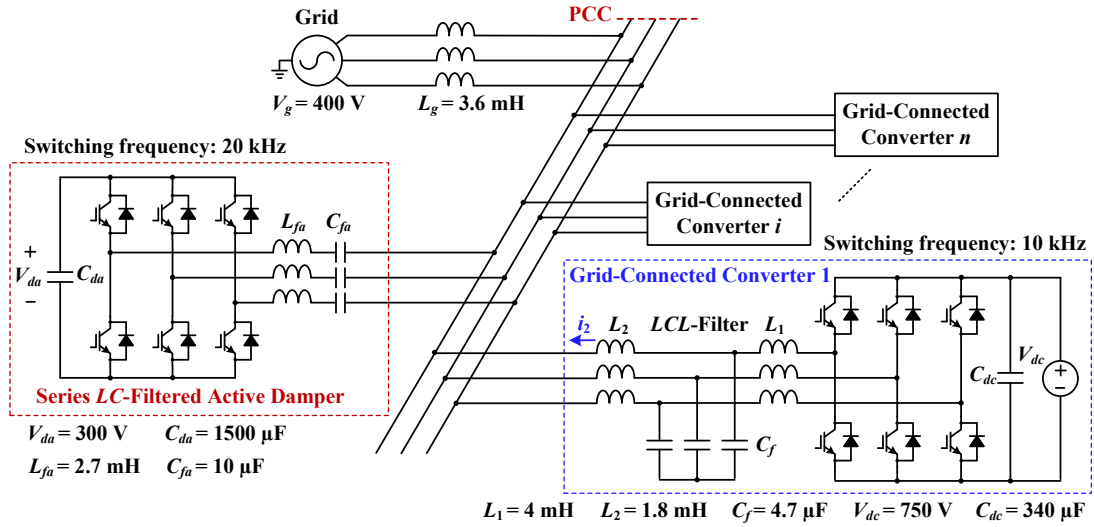


Fig. 1. An example power system showing the series-LC-filtered active damper and multiple paralleled LCL-filtered grid converters.

II. OPERATIONAL PRINCIPLE

Fig. 1 shows an example power system with the proposed series-LC-damper added to the PCC, together with other LCL-filtered grid converters. Like in [15] for a series-LC-APF, the added filter capacitor C_{fa} is used for withstanding most of the PCC voltage, allowing a lower rated converter and a smaller filter inductor L_{fa} to be used, in turn. However, as an APF, the topology is mainly designed for mitigating dominant low-frequency harmonics, whose bandwidth and other control demands are therefore less stringent. The LC-filter resonance frequency of the APF is also usually tuned close to the low-frequency harmonics, which is different from an active damper.

Filter resonance frequency formed by C_{fa} and L_{fa} of the active damper should in fact be slightly lower than the smallest system resonance frequency¹. An immediate compromise will then be the tougher rejection of the common 5th and 7th grid voltage harmonics. The predominantly capacitive filter characteristic at those frequencies (instead of the usual inductive characteristic demanded between a voltage-source converter and the grid or load) challenges the use of usual harmonic current controllers. It is therefore nontrivial to design the damper control scheme, whose general representation is provided in Fig. 2 for realizing three capabilities to be described next.

A. DC-Link Voltage Regulation

DC-link voltage regulation of the damper involves both the DC Voltage Control and AC Current Control blocks shown in Fig. 2. Their purpose is to keep voltage V_{da} across the dc-link capacitor C_{da} constant. Detailed diagram of the DC Voltage Control is given in Fig. 3(a), where a proportional-integral (PI) controller has been included for enforcing zero dc voltage error in the steady state. The PI controller output is an active current command i_{Lq}^* that the damper draws for compensating losses. Reactive current command i_{Ld}^* is included too, but is set to zero

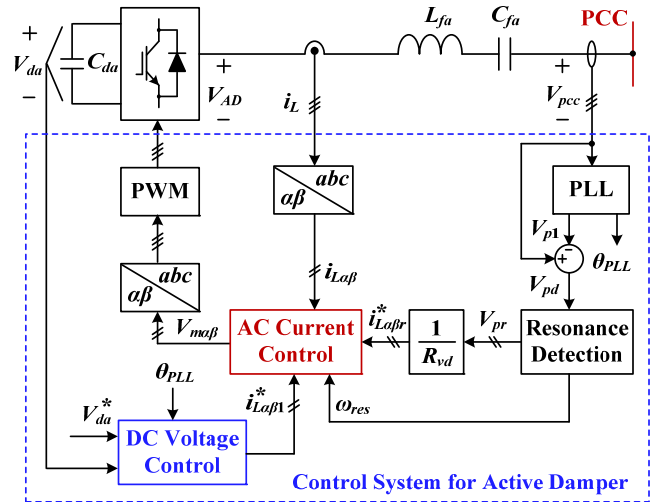
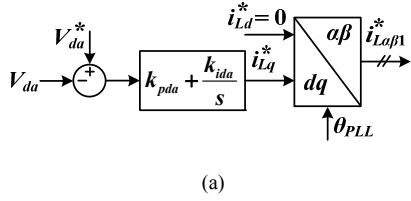


Fig. 2. Overall control of the active damper.

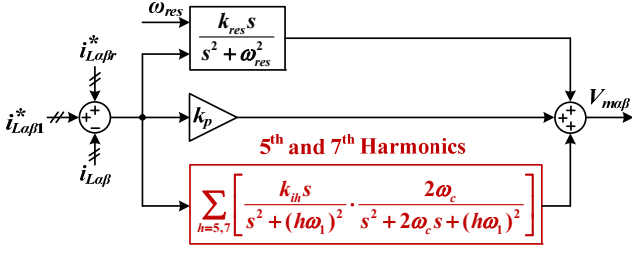
since the damping converter is generally not able to produce a sizable reactive power. Reactive power generation is instead dominated by filter capacitor C_{fa} , whose voltage is higher while carrying the same series current.

The active and reactive current commands can next be brought to the stationary $\alpha\beta$ frame by performing the necessary “dq-to- $\alpha\beta$ ” transformation. A Phase-Locked-Loop (PLL) is needed, as shown in Fig. 2, for generating the phase angle θ_{PLL} synchronized to the PCC voltage [15]. The PCC voltage, as mentioned earlier, is mostly across filter capacitor C_{fa} , meaning its voltage is approximately in phase with the PCC voltage. Current through it and the damping converter in series will hence be approximately orthogonal to the PCC voltage. In other words, if the PCC voltage is aligned along the d -axis in the synchronous frame, the damper active current command must be aligned along the orthogonal q -axis. This is why the active and reactive current commands in Fig. 3(a) have been notated with subscripts q and d , respectively, instead of the reverse. The

¹ Filter resonance relates to C_{fa} and L_{fa} of the active damper only, while system resonance relates to all reactive elements and converter impedances found in the system.



(a)



(b)

Fig. 3. Illustration of the (a) DC Voltage Control and (b) AC Current Control blocks of the active damper.

same explanation has been mentioned in [15] for a series-*LC*-APF, but because of its simpler single-loop implementation, an important stability concern has not been clarified.

This related concern can be explained by referring to Fig. 4 (a), where the assumption made for performing “*dq*-to- $\alpha\beta$ ” transformation has been illustrated pictorially. It clearly shows that with the voltage across capacitor C_{fa} assumed in phase with the PCC voltage, the resulting sum of voltages across C_{fa} , L_{fa} and the damping converter does not lead to the PCC voltage. It is thus not realizable in practice, but merely an approximation made for simplifying analysis. The more likely phasor diagram is shown in Fig. 4(b), where it can be seen that the actual active current flowing through the series filter and damping converter cannot be exactly along the q -axis. It is therefore not possible for the actual active current to track its command earlier placed along the q -axis. Common practice of adding a controller for enforcing zero steady-state current tracking error must thus not be applied to avoid destabilizing the system. Hence, only a proportional gain k_p is used with the ac current controller for the dc-link voltage regulation, as shown in Fig. 3 (b). Besides the proportional current controller, the AC Current Control block also comprises a second-order resonant controller for system stabilization and a fourth-order resonant controller proposed for grid disturbance rejection. They are explained in the following.

B. Resonance Detection and Damping

This second function of the active damper is realized by the Resonance Detection and AC Current Control blocks shown in Fig. 5 and Fig. 3(b). A Frequency-Locked Loop (FLL) based on a Pre-filtered Adaptive Notch Filter (P-ANF) is used to detect the resonance component from the PCC voltage [13]. The basic principle underlying this detection scheme is the Least Mean Square (LMS) adaptation algorithm [18]. Differently from the Second-Order Generalized Integrator (SOGI)-based FLL used for grid synchronization [19], the GI with a sixth-order Taylor series approximation is applied to the ANF for a more accurate estimation of the high-frequency resonance component [20]. To

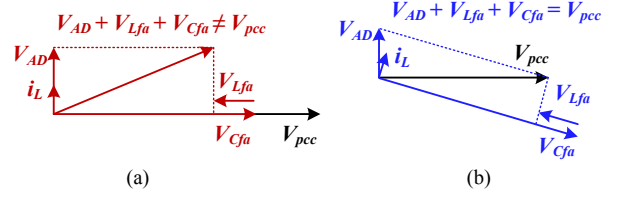


Fig. 4. (a) Assumed and (b) actual phasor orientations of the active damper.

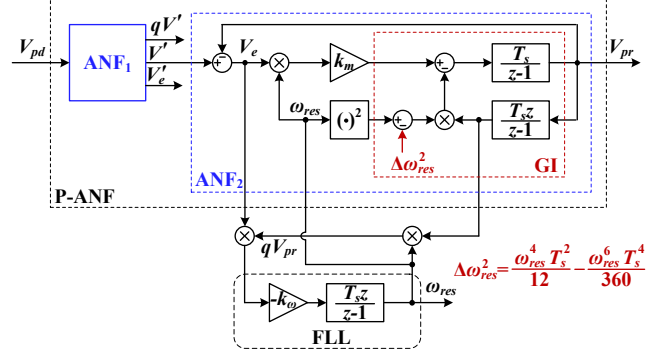


Fig. 5. Block diagram of Resonance Detection of the active damper.

further remove the low-frequency disturbances, two ANFs are cascaded to form a pre-filtered structure.

The resonance component of the PCC voltage is then divided by a chosen virtual resistance R_{vd} for the damping purpose, as shown in Fig. 2. In this way, the active damper behaves like a resistance, which adaptively reshapes the grid impedance at the resonance frequency in order to stabilize the system [12]. The resulting current command i_{afbr}^* is fed to the AC Current Control block for tracking, which in the stationary frame, is performed by the second-order resonant controller shown in Fig. 3(b) with its gain and resonance frequency notated as k_{res} and ω_{res} .

C. Grid Disturbance Rejection

It is common for the grid voltage to be disturbed by the 5th and 7th harmonics, located lower than most system resonances. Rejection of these grid voltage harmonics is not trivial for the proposed active damper, owing to its predominantly capacitive filter characteristic at those frequencies. Usual synchronous integral and stationary resonant controllers will therefore not work. Instead, a fourth-order resonant controller is proposed and shown in Fig. 3(b), where ω_1 is the fundamental frequency, ω_c is the cutoff frequency, and k_{gh} is the controller gain. The purpose of this controller is to re-shape the predominantly capacitive “control plant”, which in the worst case, can be represented by an equivalent capacitance C_{eq} .

For illustrating the intended re-shaping, the forward transfer function of grid disturbance rejection path is written as:

$$\begin{aligned}
 G_R(s) \cdot G_{re-p}(s) &= \sum_{h=5,7} \left\{ \frac{k_{gh} s}{s^2 + (h\omega_1)^2} \cdot \frac{2\omega_c}{s^2 + 2\omega_c s + (h\omega_1)^2} \right\} \cdot sC_{eq} \\
 &= \sum_{h=5,7} \left\{ \left[\frac{k_{gh} s}{s^2 + (h\omega_1)^2} \right] \cdot \left[\frac{2\omega_c s}{s^2 + 2\omega_c s + (h\omega_1)^2} \cdot C_{eq} \right] \right\}
 \end{aligned} \tag{1}$$

where $G_R(s)$ is the usual resonant controllers placed at the 5th and 7th harmonic frequencies, and $G_{re-P}(s)$ is the re-shaped “plant”. The re-shaped “plant” becomes a band-pass filter with a common gain of C_{eq} placed at the 5th and 7th harmonic frequencies. In other words, the re-shaped plant behaves like a resistor at those considered frequencies, hence allowing $G_R(s)$ to perform the necessary control without being burdened by stability and dynamic concerns.

III. EXPERIMENTAL RESULTS

For verification, the three-phase experimental system shown in Fig. 1 has been built, but with only one LCL -filtered grid converter. Table I lists the controller parameters used for the active damper. The control scheme of the grid converter and current controller parameters are shown in Fig. 6. Stability of Fig. 6, with its grid current i_2 regulated by a Proportional Resonant (PR) controller in the stationary $\alpha\beta$ -frame, is however greatly influenced by time delays inherited from its digital implementation [16] and variation of the grid impedance [17]. The active damper is thus added for stabilizing the system by performing the necessary resonance damping.

Fig. 7 shows the measured grid current i_2 of the LCL -filtered grid converter without and with the active damper. The grid inductance is switched between 3.6 mH and 7.2 mH, which results in two different resonance frequencies at 1.3 kHz (26th harmonic) and 1.25 kHz (25th harmonic), respectively, as shown in Fig. 7 (a) and (b). Fig. 7 (c) shows the measured result after enabling the active damper, where it is clear that the system is stabilized by the active damper in both cases.

Fig. 8 next shows the measured dc-link voltage and output current of the active damper. At the instant of enabling the active damper, the dc-link voltage rapidly falls from its pre-charged value (through anti-parallel diodes of the damping converter) to the regulated value of 300 V. Compared with the dc voltage of 750 V needed by the grid converter, dc-link voltage of the damper is clearly reduced by the added series filter capacitor. This reduction can further be increased by using higher rated filter capacitor depending on requirements.

Fig. 9 shows the ac current flowing through the damper without and with using the grid disturbance rejection control described in Subsection II (C). Without the grid disturbance control, the presence of 7th grid voltage harmonic influences the damper control, resulting in 7th harmonic current seen from Fig. 9 (a). This harmonic current is promptly removed in Fig. 9 (b) by the fourth-order resonant controller developed in this letter.

TABLE I

CONTROLLER PARAMETERS OF ACTIVE DAMPER

Symbol	Meaning	Value
T_{s_AD}	Sampling period of active damper	50 μ s
k_{pda}	Proportional gain of dc-link voltage controller	0.5
k_{ida}	Integral gain of dc-link voltage controller	0.01
R_{vd}	Virtual damping resistance	0.2 Ω
k_p	Proportional current controller	15
k_{res}	Resonance damping controller	600
k_{ih}	Proposed resonant controller gain	$4 \cdot 10^5$
ω_c	Proposed resonant controller cut-off frequency	250 rad/s

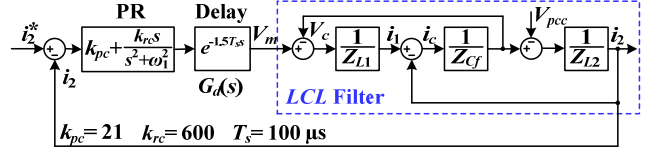


Fig. 6. Grid current control loop for the LCL -filtered grid converter.

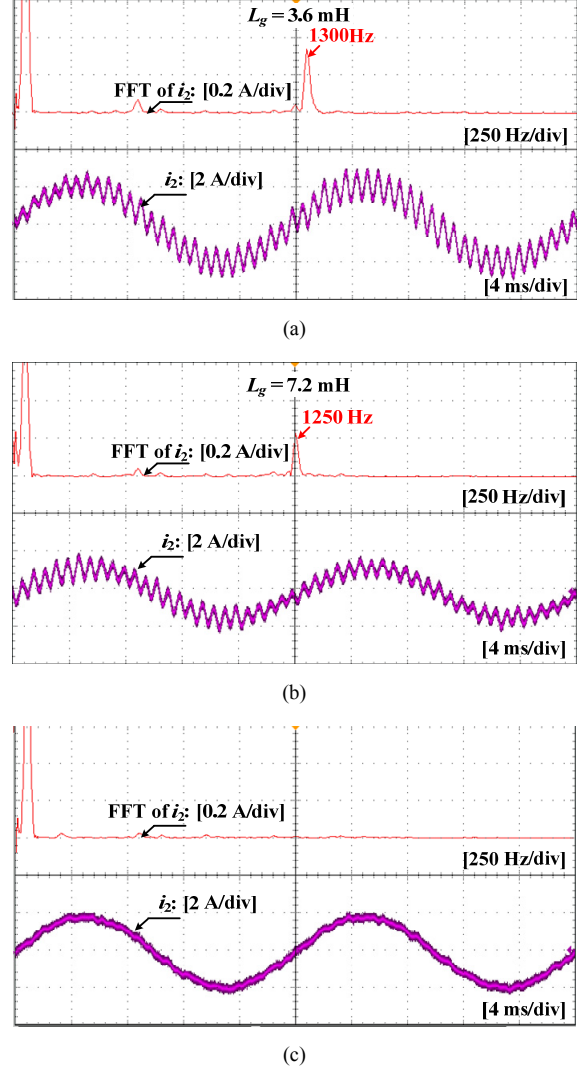


Fig. 7. Measured grid current i_2 of the LCL -filtered grid converter and its harmonic spectrum. (a) Without active damper ($L_g = 3.6$ mH). (b) Without active damper ($L_g = 7.2$ mH). (c) With active damper.

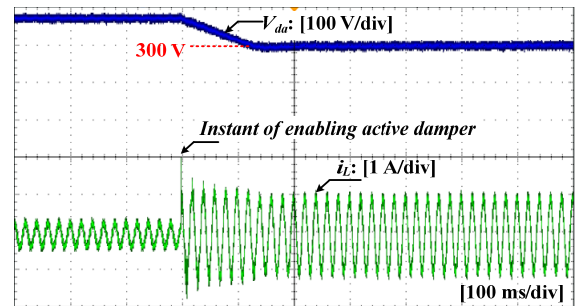


Fig. 8. Measured dc-link voltage and ac current of the active damper.

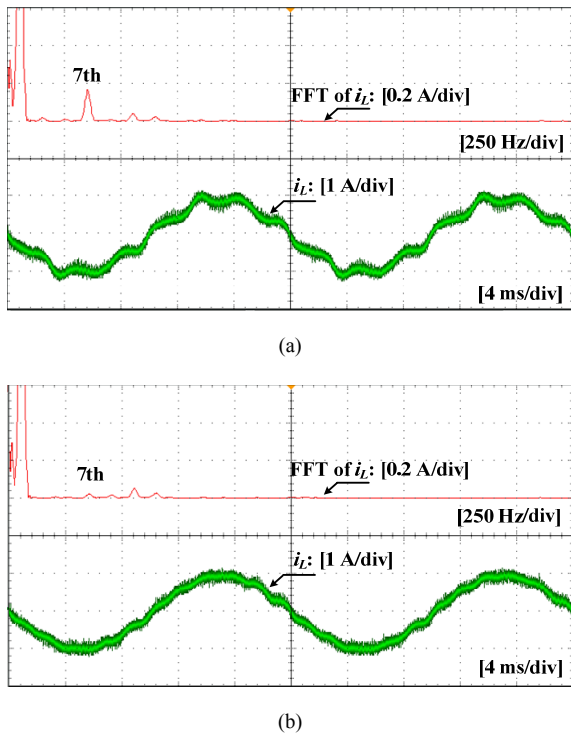


Fig. 9. Measured output current of the active damper and its spectrum. (a) Without grid disturbance rejection. (b) With grid disturbance rejection.

IV. CONCLUSIONS

This letter presents a series- LC -filtered active damper for stabilizing ac power-electronics-based power systems. Performance of the damper has been verified in experiment with the series filter capacitor demonstrated to withstand most of the system voltage. The damping converter can then be rated low in voltage, allowing for a faster switching operation. Stability of the proposed damper has been analyzed over a wide frequency range with appropriate controllers recommended for each requirement, including the fourth-order resonant controller developed for grid disturbance rejection. With its low- and high- frequency control coordinated, the proposed active damper is thus a promising solution for addressing multiple concerns faced by the newer power systems.

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