POWER SYSTEM DESIGN ISSUES FOR SMART MATERIALS

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ABSTRACT

The effect of bidirectional power flow on the power distribution system of an aircraft is addressed in this paper. The active vibration control problem of the tail surface of an aircraft using piezoelectric actuators is chosen to motivate the study presented. A simple dynamic model of the tail surface is developed. A current controlled switched-mode power amplifier is used to drive the actuators. The integration of the “amplifier-actuator” into the power distribution system of the aircraft is studied in detail. The effect of circulating energy between the actuators and the DC bus on the voltage on the bus is explained. Solutions to avoid instability and undesirable distortion in the DC bus voltage are proposed.

1. INTRODUCTION

The drive amplifiers for piezoelectric and electrostrictor actuators have received some attention lately [2-9]. The design of these amplifiers must take into account the reactive (capacitive) nature of the smart actuators. These reactive loads require a significant amount of electrical energy to be cycled between the actuator and amplifier. The amplifier must not only deliver power but it must be able to accept regenerative power from the actuator. Switching amplifiers offer attractive alternatives for these actuators when efficiency is required. They also appear to be naturally suited for integration into the next generation power distribution systems on aircraft. Switching amplifiers achieve their efficiency by essentially connecting the actuator directly to the power bus. This topology allows the energy to be circulated between the actuator and the power bus. Most power distribution systems are not configured to accept this regenerative power flow, however. For smart structures with many actuators, this regenerative power flow can lead to voltage spikes of unacceptable magnitude and possible loss of stability of the power distribution system. Hence, the regenerative power flow from the smart actuators must be taken into consideration in the design of the power distribution system.

Piezoelectric actuators have been widely used for active vibration control of structures. One important application of this technology is the use of piezoelectric actuators for alleviating the “tail buffeting” problem in a twin tail aircraft [1]. The buffet loads acting on the tail surface cause excessive wear and tear that significantly reduce the lifetime of the aircraft and increase repair and maintenance costs. Piezoelectric actuators mounted at the root of the tail and on the surface are controlled to actively suppress the effect of the buffet loads on the tail surface. The drive amplifier for the piezoelectric actuators proposed in this paper is a current controlled switch mode converter. A dynamic model for the actively controlled tail structure has been developed. This model is then integrated into a power distribution system and its interaction with the DC power bus is studied.

2. MODELING

A simplified schematic of the actively controlled tail surface is shown in Figure 1. The one-dimensional linear coupled electromechanical constitutive relations between the strain ε_1, stress σ_1, electric field E_3, and electric displacement D_3, are given below:

$$D_3 = K_{33}^{\sigma} E_3 + d_{31}\sigma_1 \quad \text{….. (1.a)}$$

$$\varepsilon_1 = d_{31} E_3 + s_{11}^{E}\sigma_1 \quad \text{….. (1.b)}$$

where, K_{33} and s_{11} are the permittivity and compliance (reciprocal of the Young’s modulus) respectively and d_{31} is the transverse piezoelectric charge constant. The first index in the subscripts indicates the direction of the electrical component and the second index indicates the mechanical direction. Equation 1.a. states that the electric displacement is the superposition of the direct piezoelectric effect and the applied field times the permittivity. Equation 1.b. states that the strain is the superposition of Hooke’s law and the indirect effect where a mechanical deformation is caused due to the application of an electric field.

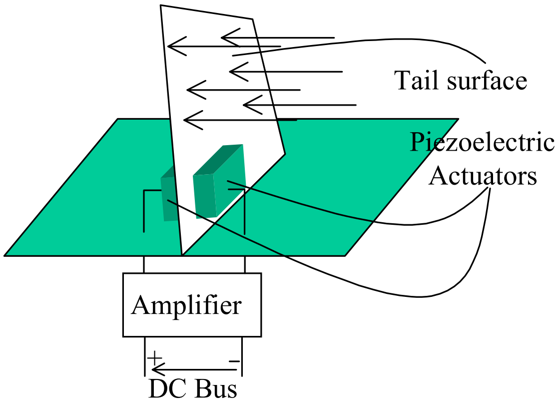


Figure 1. Actively controlled tail surface with piezoelectric actuators and amplifier

The piezoelectric actuator essentially behaves like a capacitor whose voltage is the sum of two components:

1. The direct capacitive effect where $v = \frac{1}{C}\int_0^t i.dt$ and
2. A contribution from the mechanical stress.

Figure 2 illustrates the voltage contribution from the direct capacitive effect.

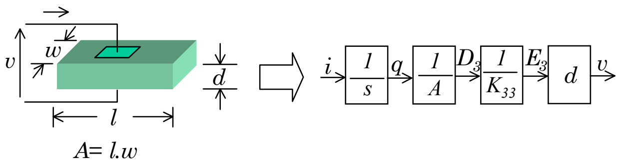


Figure 2. Voltage due to direct capacitive effect

The contribution from the mechanical component is derived as follows. Figure 3 shows a schematic of a bending motor.

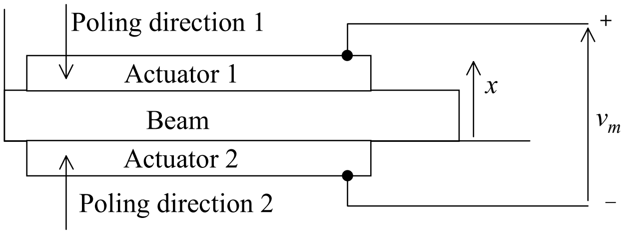


Figure 3. Bending Motor

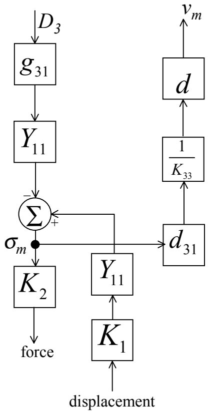
A bending motor is formed by bonding two piezoelectric actuators on either side of the substructure. An electric field applied opposite to the poling direction of the top actuator and along that of the bottom actuator will cause the top material to expand laterally and the bottom material to laterally contract thereby inducing bending of the surface. The total moment at the cross section of the surface is the sum of the moment M_S caused by the bending of the surface and the moment M_A caused by the bending of the actuator mounted on the surface. This sum is equal to the bending moment M_Λ induced in the structure by the actuators due to the applied electric field as shown in Equation 2.

$$M_S + M_A = M_\Lambda \qquad \text{..... (2)}$$

The net mechanical stress σ_m, in the piezoelectric actuators is then given by the difference between the stress induced by the electric field and the stress caused by the bending in the surface. Using Equation 1, the voltage contribution from the mechanical component can then be given by:

$$V_m = \frac{d_{31}}{K_{33}^{\sigma}} d\sigma_m \qquad \text{..... (3)}$$

The mechanical model of the actuator is shown in Figure 4.



d = Thickness of Actuator
K_{33} = Permittivity of actuator material
d_{31} = Transverse piezoelectric charge constant
g_{31} = Transverse piezoelectric voltage constant
Y_{11} = *Young's modulus*
K_1 = displacement to strain
K_2 = stress to force

Figure 4. Mechanical Model of Actuator-Tail Structure

The constants K_1 and K_2 in Figure 4 relate the tip displacement of the tail surface to the strain of the actuators and the net mechanical stress σ_m to the generalized force f acting on the tail surface respectively. The modal equations are represented by n-uncoupled single degree of freedom systems each with a structural damping and resonant frequency. With reference to Figure 1, we assume that the tail surface can be modeled as a single degree of freedom system with a given structural damping and resonant frequency driven by an equivalent generalized force f and the buffet load f_{ext}. The dynamic equations are then given by:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = f + f_{ext} \qquad \text{….. (4)}$$

The complete electromechanical model of the actuator-tail structure is then shown in Figure 5. An important feature of this particular model is that explicitly identifies both the forward and reverse power flow through the piezoelectric actuator.

The objective of the active vibration control problem is to minimize the effect of the net force f_{ext} on the acceleration a, of the tip of the tail (Figure 1). Thus, a closed loop system is required that will effectively minimize the transfer function between the external force and the tip acceleration.

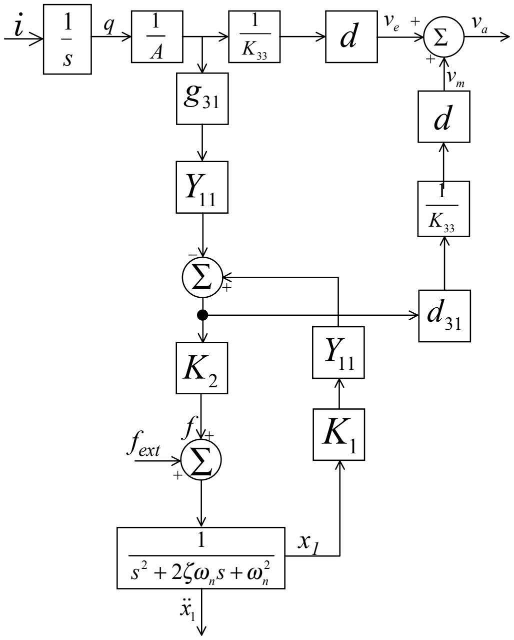


Figure 5. Electromechanical Model of Actuator-Tail Structure

The mechanical dynamics of the tail surface, represented by the transfer function in Figure 5, can be equivalently represented by the block diagram shown in Figure 6.

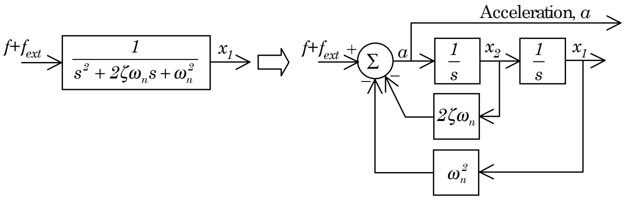


Figure 6. Equivalent representation of the mechanical dynamics

The closed loop system will involve a switched mode power amplifier that will drive the piezoelectric actuator such that an equivalent compensating force is applied to the tail to minimize the tip acceleration and hence reduce wear and tear. The power amplifier will be current controlled with the reference current provided by an outer tip-acceleration feedback loop.

3. DRIVE AMPLIFIER

The power amplifier used to provide the required drive current to the piezoelectric actuator is a single–phase DC-AC inverter that feeds off a *270V DC* bus. A schematic of the amplifier is shown in Figure 7.

The amplifier supplies a sinusoidally pulse width modulated voltage whose fundamental component is at the required magnitude and frequency.

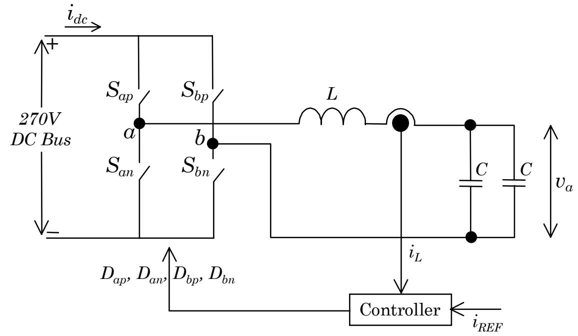


Figure 7. Schematic of Drive Amplifier

The average voltage applied between *a* and *b* can be written in terms of the DC bus voltage and the duty cycles of the switches S_{ap} and S_{bp} as follows:

$$v_{ab} = \left(d_{ap} - d_{bp}\right)V_{dc} = d_{ab}V_{dc} \qquad \text{..... (5)}$$

The controller provides the duty cycles to the inverter in response to a reference current command to be driven into the actuator. The two capacitors in parallel shown in Figure 7 represent the two piezoelectric actuators on either side of the beam in the bending motor configuration (Figure 3). The poling directions of the two actuators are opposite to one another to induce bending in the beam. But their electrical characteristics as capacitive elements do not depend on their poling directions. Hence, if the contribution to the voltage across the actuators is neglected the two actuators simply appear as two capacitors in parallel loading the amplifier. The state equations for the amplifier model shown in Figure 7 are given below:

$$\begin{aligned} \frac{di_L}{dt} &= \frac{1}{L}\left(d_{ab}\cdot V_g - v_a\right) \\ \frac{dv_a}{dt} &= \frac{1}{2C}i_L \end{aligned} \qquad \text{..... (6)}$$

Control Design

The controller for the amplifier-actuator system consists of a two-loop compensator with an inner current loop and an outer acceleration loop.

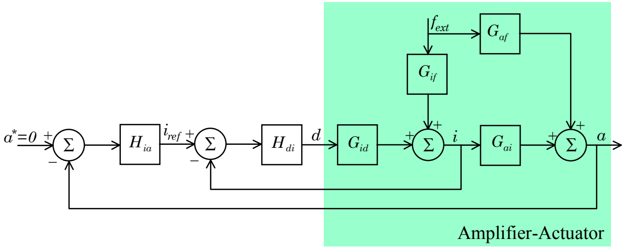


Figure 8. Control Block Diagram of the Amplifier-Actuator System

The current loop generates the duty cycle command for the drive amplifier so that inductor current follows the reference current provided by the acceleration loop. The block diagram of the closed loop control system is shown in Figure 8. The open-loop and closed loop transfer functions between f_{ext} and a are shown in Figure 9.

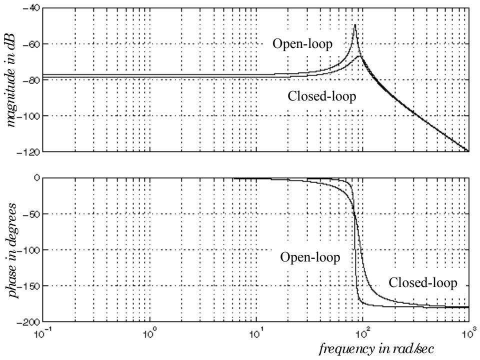


Figure 9. Open-loop and Closed-loop Transfer Functions between f_{ext} and a.

4. INTERACTION WITH DC BUS

The block diagram of the baseline power system architecture is shown in Figure 10. The baseline power system consists of a three phase AC generator represented by an ideal three phase sinusoidal voltage source, a three phase to DC rectifier [10] feeding the DC distribution bus, the piezoelectric actuator system and other constant current i_o, constant power Z, and resistive R, loads .

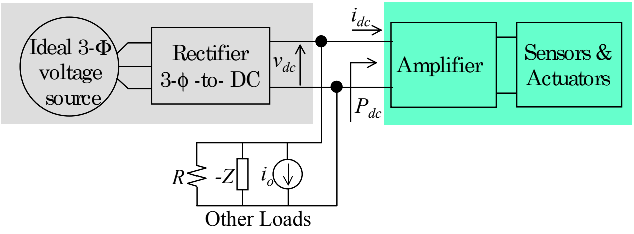


Figure 10. Baseline Power System Architecture with Piezoelectric Actuator

The power distribution system model shown in Figure 10 is based on the next generation power distribution system currently under development for the F-22.

The piezoelectric actuator appears as a reactive load to the amplifier. Consequently, a considerable amount of power circulates between the DC bus and the "amplifier-actuator" subsystem. One of the main concerns in the design of the power distribution system is the development of methods to handle this bidirectional flow of power between the source and the load. The signals i_{dc} and P_{dc} respectively represent the current and power flowing into and out of the "amplifier-actuator" subsystem shown in Figure 10. Positive values of represent the flow of power from the DC bus to the amplifier and negative values represent the regenerated energy flowing back into the bus. The circulating power between the DC bus and the amplifier appears as a pulsating load current to the three-phase rectifier feeding the DC bus. This pulsating current can lead to undesirable distortion in the DC bus voltage. The magnitude and nature of the distortion in the voltage depends on the parameters of the rectifier and other loads feeding off the bus. Simulation results that illustrate the effect a pulsating load current can have on the DC bus are shown in Figure 11.

The response of the DC bus voltage to a pulsating load current depends upon the impedance Z_o, looking into the output terminals of the rectifier. The output impedance Z_o depends critically on the regulation bandwidth ω_p, of the rectifier, the DC bus capacitor at the output of the rectifier and the other loads connected to the DC bus. Since the three-phase rectifier is essentially a nonlinear system, the output impedance and regulation bandwidth are determined after linearizing the system around a steady state operating point. The other loads on the system are assumed to be constant in this study. The variation of the output impedance Z_o of the rectifier as a function of the regulation bandwidth and output capacitor value is shown in Figures 12 and 13.

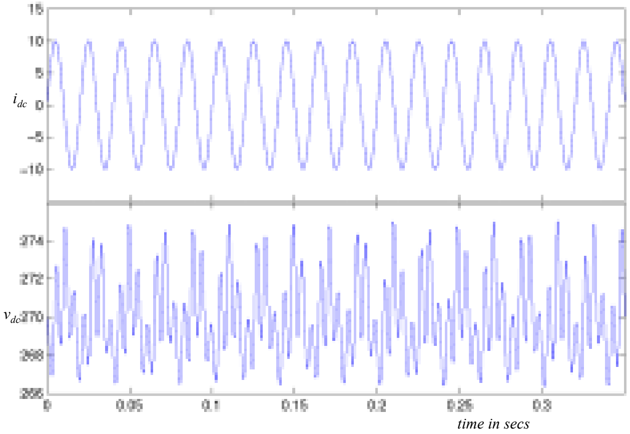


Figure 11. Effect of Pulsating Load Current on DC Bus Voltage

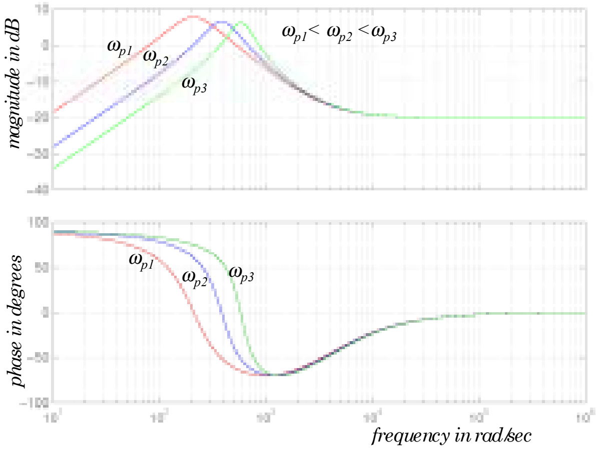


Figure 12. Variation of Z_o as a Function of Regulation Bandwidth of Rectifier

It can be observed that the output impedance reduces as the regulation bandwidth increases. Hence, an increase in regulation bandwidth can be expected to result in lesser distortion of the DC bus voltage. However, increase in bandwidth is accompanied by the risk of instability. This effect is illustrated in Figure 14 where the phase margin of the rectifier is shown as a function of the regulation bandwidth. As the value of the DC bus capacitor is increased, the output impedance falls. But a large DC bus capacitance allows a very narrow regulation bandwidth resulting in a very sluggish response of the DC bus voltage to disturbances. Thus, a trade-off between bandwidth and bus capacitor value has to be achieved while maintaining stability and satisfactory speed of response.

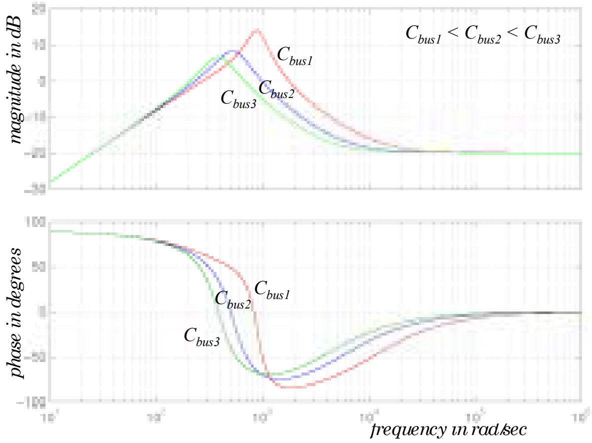


Figure 13. Variation of Z_o as a Function of Bus Capacitor

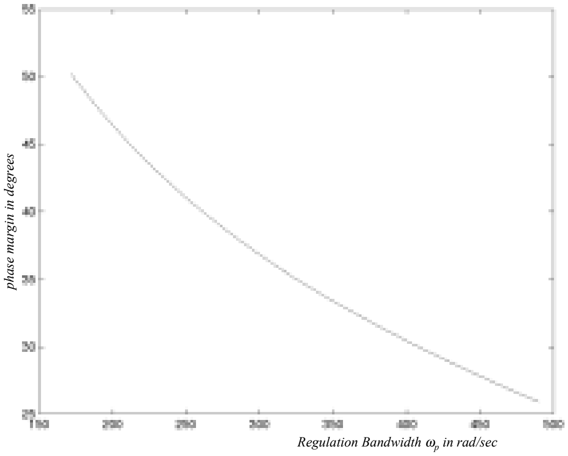


Figure 14. Phase Margin of Three-Phase Rectifier as a function of ω_p.

Bus Conditioners

Another way to handle the bidirectional power flow from the actuators is to use a bus conditioner to cancel the pulsating current of the actuator. [11]. Bus Conditioners are controlled power electronic converters that are connected to the DC bus of a distributed power system to alleviate disturbances arising due to pulsating or harmonic loads, system transients such as load switching etc. The simplified schematic shown in Figure 15 explains the concept of the active bus conditioners.

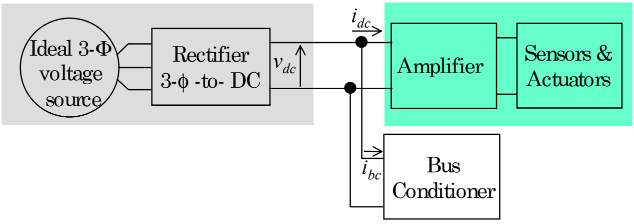


Figure 15. The concept of a bus conditioner

The control of a bus conditioner is different from that of a conventional regulated power converter. On sensing harmonic or pulsating power required by loads from the DC bus, the bus conditioner provides these loads with the required power thus helping maintain the stability of the DC bus. The bus conditioner hence, essentially serves as an actively controlled storage device that can source and sink energy to and from the DC bus. The circuit schematic of the bus conditioner is shown in Figure 16.

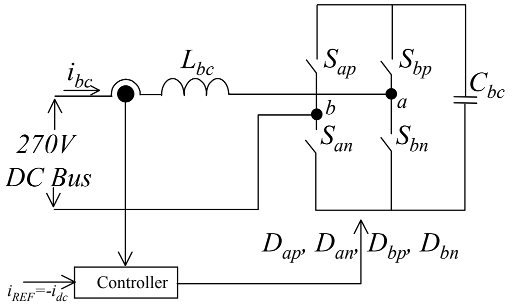


Figure 16. Schematic of Active Bus Conditioner

The controller for the bus conditioner consists of a high bandwidth current loop that drives the current flowing in and out of the bus conditioner to follow a reference. The reference current is tailored to cancel out the unwanted disturbance loads on the DC bus.

Since, a capacitive storage mechanism is usually preferred, a very slow voltage loop is closed around the current loop to ensure adequate energy on the capacitor during periods of inactivity on the bus.

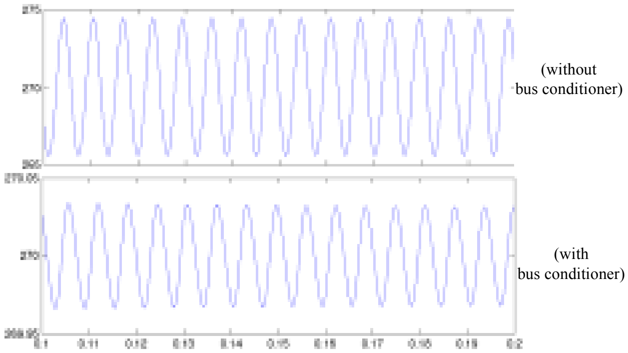


Figure 17. Effect of Bus Conditioner of Response of DC Bus Voltage

Figure 17 shows the response of the DC bus voltage when loaded by a pulsating current with and without a DC bus conditioner. The other loads in the system are assumed to be zero for the results shown in Figure 17. It can be seen that bus conditioner reduces the amplitude of the oscillations in the bus voltage considerably. The disadvantage of using a bus conditioner is the need for an additional converter and its associated control circuitry.

CONCLUSIONS

The problem of bidirectional power flow from piezoelectric actuators has been addressed in this paper. A simple dynamic model of an actively controlled tail surface of an aircraft was developed. A current controlled switched mode converter is used as the drive amplifier for the piezoelectric actuators driving the tail surface. The actively controlled actuator system was then integrated into the baseline power distribution system to study the effects of the regenerative power flow on the DC bus voltage. The effect of the regulation bandwidth and bus capacitor value on the DC bus voltage response was presented. The use of an actively controlled bus conditioner was also proposed to counter the pulsating current from the actuator system to mitigate the oscillations in the DC bus voltage.

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