A THREE-PHASE ACTIVE POWER FILTER OPERATING WITH FIXED SWITCHING FREQUENCY FOR REACTIVE POWER AND CURRENT HARMONIC COMPENSATION

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ABSTRACT: The performance and dynamic characteristics of a three phase active power filter operating with fixed switching frequency is presented and analyzed in this paper. The proposed scheme employs a PWM voltage-source inverter and has two important characteristics. First, it operates with fixed switching frequency, and second, it can compensate the reactive power and the current harmonic components of nonlinear loads. Reactive power compensation is achieved without sensing and computing the reactive component of the load current, thus simplifying the control system. Current harmonic compensation is done in time domain.

The principles of operation of the proposed active power filter along with the design criteria of the power and control circuit components are discussed in detail. Finally, experimental results obtained from a 5 kVA prototype confirm the feasibility and the features of the proposed system.

I.- INTRODUCTION

The proliferation of nonlinear loads such as static power converters and arc furnaces results in a variety of undesirable phenomena in the operation of power systems. The most important among these are harmonic contamination, increased reactive power demand and power system voltage fluctuations. Harmonic contamination has become a major concern for power system specialists due to its effects on sensitive loads and on the power distribution system. Harmonic current components increase power system losses, cause excessive heating in rotating machinery, can create significant interference with communication circuits that shared common right-of-ways with ac power lines, and can generate noise on regulating and control circuits causing erroneous operation of such equipment.

Conventionally, passive LC filters have been used to eliminate line current harmonics and to increase the load power factor. However, in practical applications these passive second order filters present the following disadvantages:

i) The source impedance strongly affects filtering characteristics.
ii) As both the harmonic and the fundamental current components flow into the filter, the capacity of the filter must be rated by taking into account both currents.
iii) When the harmonic current components increase, the filter can be overloaded.
iv) Parallel resonance between the power system and the passive filter causes amplification of harmonic currents on the source side at a specific frequency.
v) The passive filter may fall into series resonance with the power system, so that voltage distortion produces excessive harmonic currents flowing into the passive filter.

In order to overcome these problems, active power filter have been researched and developed [1]. In recent years, various active power filter configurations with their respective control strategies have been proposed, and gradually being recognized as a viable solution to the problems created by high power nonlinear loads [2] - [6].

The topology of the three-phase active power filter presented in this paper is shown in Fig. 1. The proposed configuration is based on a force-commutated pulse-width modulated voltage-source inverter (PWM-VSI) connected to a dc capacitor. Although there are a number of articles which deal with the analysis of active power filter using force-commutated voltage-source inverters [4] - [6], the three-phase active power filter presented in this paper differs from previously discussed approaches in the following ways:

i) Reactive power compensation is achieved without sensing and computing the reactive current component of the load, thus simplifying the control circuit.
ii) Current control is achieved with constant switching frequency producing a better switching pattern than hysteresis current control [7]. This results in a reduction of inverter output high frequency current harmonics and lower stresses on the semiconductor devices.
iii) Current compensation is done in time domain allowing fast time response.
iv) In order to improve the active power filter performance a dc voltage control loop is implemented. The dc voltage control loop keeps the voltage across the dc capacitor constant increasing the inverter voltage gain and reducing the amplitude of high frequency ac current harmonics.
v) The voltage and current control loops are simple and easy to implement.

The treatment presented in this paper includes a comprehensive steady-state and transient analysis of the active power filter. Also, the design criteria of the power and the control circuit are reported. Finally, all the predicted results are experimentally verified on a 5 kVA laboratory prototype.

II.- PRINCIPLES OF OPERATION

The main section of the active power filter shown in Fig. 1 is a force-commutated voltage-source inverter connected to a dc capacitor. Current harmonic compensation is achieved by injecting equal, but opposite current harmonic components at the point of connection, thereby cancelling the original distortion and improving the power quality on the connected power system [2], [3].

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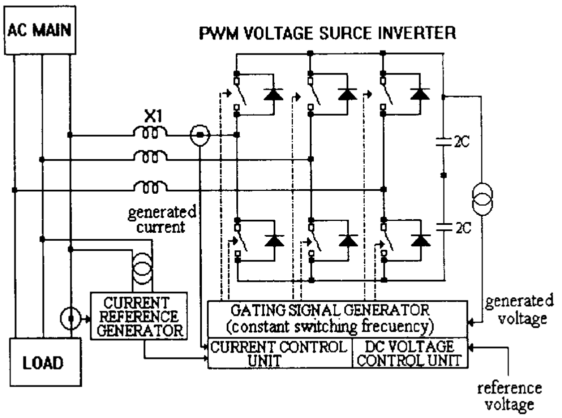


Fig. 1. The active power filter configuration.

The block diagram of the active filter control system is shown in Fig. 2. It consists of a current control unit, a dc voltage control unit, a current reference generator and a gating signals generator.

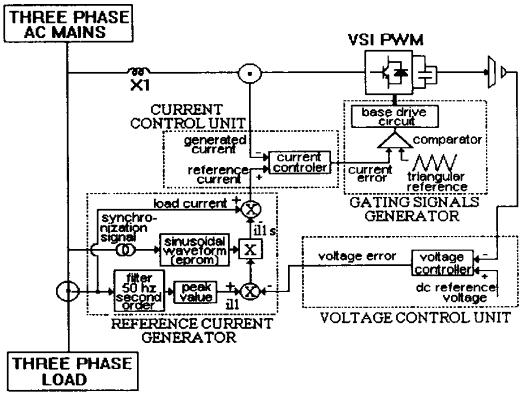
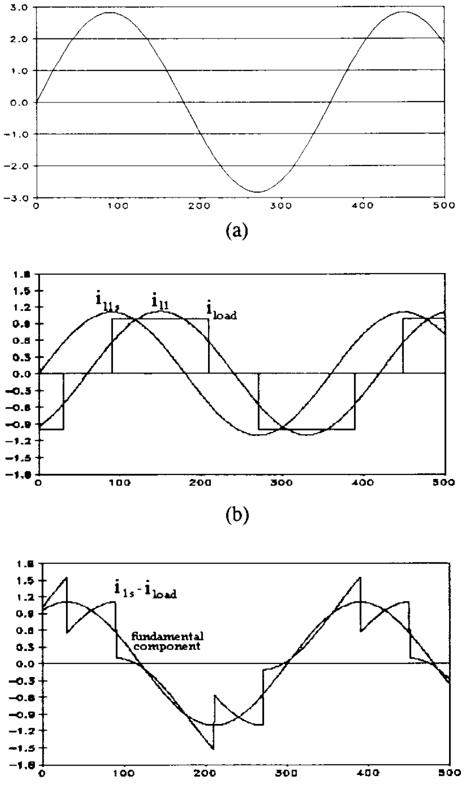


Fig. 2. Block diagram of the active power filter control system.

The ac current generated by the inverter is forced to follow the reference signal obtained from the current reference generator. In this circuit, the distorted load current is filtered extracting the fundamental component, i_{load1}. The filter is tuned at the fundamental frequency (50 or 60 Hz), so that the phase shift angle and the gain attenuation introduced in the filter output signal are zero. Thus, the filter output current is exactly equal to the fundamental component of the load current. If the load current is subtracted from the fundamental current component obtained from the second order filter, the reference current waveform required to compensate only harmonic distortion is obtained. In order to provide the reactive power required by the load, the current signal obtained from the filter is synchronized with the respective phase to neutral source voltage (Fig. 3), so that the inverter ac output current is forced to lead the respective inverter output voltage, thereby generating the required reactive power and absorbing the real power necessary to maintain the dc voltage constant and to supply the switching losses. The real power absorbed by the inverter is controlled by adjusting the amplitude of the current reference waveform obtained from the passive filter (Fig. 2). The amplitude of this sinusoidal waveform is equal to the amplitude of the fundamental component of the load current minus the error signal obtained from the dc voltage control unit. In this way, the current signal allows the inverter to supply the current harmonic components, the reactive power required by the load, and to absorb the small amount of active power necessary to cover the switching losses and to keep the dc voltage constant. By keeping the dc voltage constant, the inverter voltage gain is increased and the amplitude of the high frequency inverter current harmonic component are reduced.



(a)

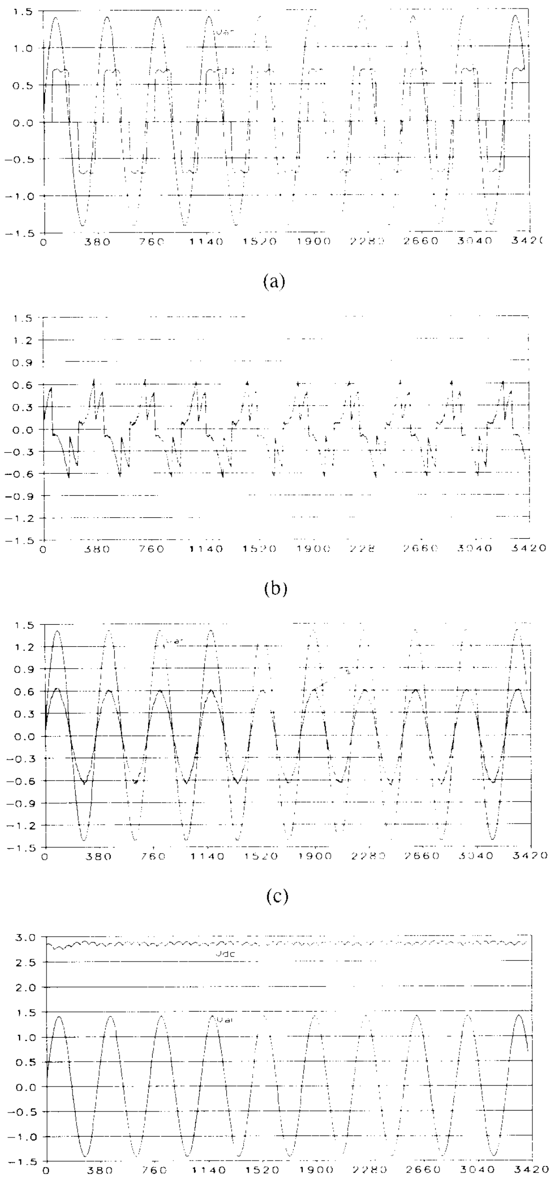
(b)

(c)

Fig. 3. The procedure for the generation of the current reference waveform. (a) The phase to neutral source voltage, v_{an}. (b) The load current, i_{load}, its fundamental component, i_{l1}, and the fundamental current component synchronized with the source voltage, i_{l1s}. (c) The synchronized fundamental current signal minus the load current, i_{l1s}-i_{load}, and its fundamental component.

A constant switching frequency is achieved by comparing the current error signal with a triangular reference waveform. This method can be explained by considering the bang-bang hysteresis technique plus the addition of a fixed frequency triangular waveform inside the imaginary hysteresis window [8]. The purpose of introducing the triangular waveform is to stabilize the converter switching frequency by forcing it to be constant and equal to the frequency of the triangular reference signal.

Figures 4 and 5 show simulated current and voltage waveforms for steady state and transient operating conditions. In both cases the active power filter is compensating a six pulse controlled rectifier. Figure 4 proves that the active power filter compensates harmonic component and the reactive power effectively. Also, this figure illustrates how the inverter gain voltage is improved with the addition of the dc voltage control loop (Gain = 0.85, Fig. 4(d)).



(a)

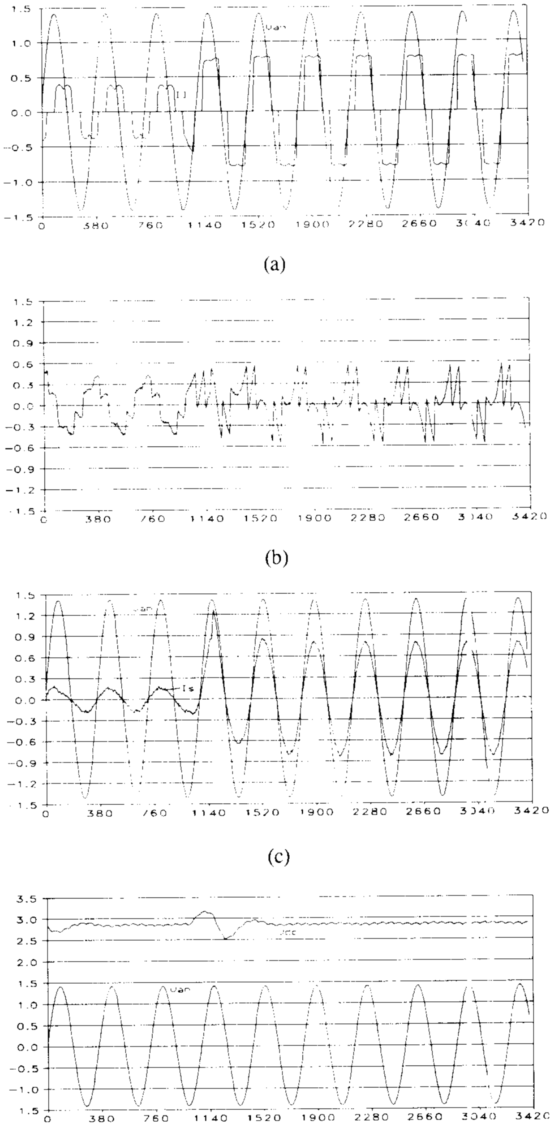
(b)

(c)

(d)

Fig. 4. Simulated results for steady state operating conditions. (a) Phase to neutral source voltage, V_{an}, and respective load current, I_l. (b) Inverter ac output current. (c) Phase to neutral source voltage, V_{an}, and the respective ac mains line current, I_S. (d) The voltage across the dc capacitor, V_{dc}, and the phase to neutral ac mains voltage, V_{an}.

In Fig. 5, a step change in the load power factor and current amplitude is simulated. The amplitude of the load current is changed from 0.4 to 0.8 in p.u. while the phase shift angle, α, decreases from 45° to 15°. These figures show that the active power filter is fast enough to respond to this severe change in the load operating condition, keeping the source line current in phase with the respective phase to neutral voltage and with a low harmonic distortion.



(a)

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Fig. 5. Simulated results for transient operating conditions. (a) The phase to neutral source voltage, V_{an}, and the respective load current, I_l. (b) Inverter ac output current. (c) Phase to neutral source voltage, V_{an}, and the respective ac mains line current I_S. (d) The voltage across the dc capacitor, V_{dc}, and the phase to neutral source voltage, V_{an}.

III.- POWER CIRCUIT DESIGN

The selection of the ac link reactor and the dc capacitor values affects directly the performance of the active power filter. Static var compensators implemented with voltage-source inverters present the same power circuit topology, but for this type of application, the criteria used to select the values of L and C are different. For reactive power compensation, the design of the synchronous link inductor, L, and the dc capacitor, C, is performed based on harmonic distortion constraint. That is, L must reduced the amplitude of the current harmonics generated by the inverter while C must keep the dc voltage ripple factor below a given value [8]. This design criteria cannot be applied in the active power filter since it must be able to generate distorted current waveforms. However, L must be specified so that it keeps the high frequency ripple of the inverter ac output current smaller than a defined value.

3.1 Design of the Synchronous Link Reactor

The design of the synchronous link reactor is performed with the constraint that for a given switching frequency the minimum slope of the inductor current is smaller than the slope of the triangular waveform that defines the switching frequency (Fig. 2). In this way, the intersection between the current error signal and the triangular waveform will always exist.

The slope of the triangular waveform is defined by:

$$\lambda = 4\,\xi\, f_t \qquad (1)$$

where ξ is the amplitude of the triangular waveform, which has to be equal to the maximum permitted amount of ripple current, and ft is the frequency of the triangular waveform (i.e. the inverter switching frequency). The maximum slope of the inductor current is equal to:

$$\frac{di_L}{dt} = \frac{V_{an} + 0.5V_{dc}}{L} \qquad (2)$$

Since the slope of the inductor current has to be smaller than the slope of the triangular waveform, and the ripple current is known, from (1) and (2):

$$L = \frac{V_{an} + 0.5V_{dc}}{4\xi f_t} \qquad (3)$$

3.2 Design of the Dc Capacitor

Transient changes in the instantaneous power absorbed to the load generate voltage fluctuations across the dc capacitor (Fig. 5(d)). The amplitude of these voltage fluctuations can be controlled effectively with an appropriate dc capacitor value. It must be noticed that the dc voltage control loop stabilizes the capacitor voltage after few cycles, but is not fast enough to limit the first voltage variations. The capacitor value obtained with this criteria is bigger than the value obtained based on maximum dc voltage ripple constraint. For this reason, the voltage across the dc capacitor presents a small harmonic distortion factor.

The maximum overvoltage generated across the dc capacitor is given by:

$$V_{cmax} = \frac{1}{C}\int_{\frac{\theta_1}{\omega}}^{\frac{\theta_2}{\omega}} i_c(t)dt + V_{dc} \qquad (4)$$

where Vcmax is the maximum voltage across the dc capacitor,
Vdc is the steady state dc voltage,
ic(t) is the instantaneous dc bus current.

From (4)

$$C = \frac{1}{\Delta V}\int_{\frac{\theta_1}{\omega}}^{\frac{\theta_2}{\omega}} ic(t)dt \qquad (5)$$

Equation (5) gives the value of the dc capacitor, C, that will maintain the dc voltage fluctuation below ΔV p.u.. The instantaneous value of the dc current is defined by the product of the inverter line currents with the respective switching functions. The mean value of the dc current that generates the maximum overvoltage can be estimated by:

$$\int_{\frac{\theta_1}{\omega}}^{\frac{\theta_2}{\omega}} i_c(t)dt = I_{inv}\int_{\frac{\theta_1}{\omega}}^{\frac{\theta_2}{\omega}}[\sin(\omega t) + \sin(\omega t + 120^{o})dt] \qquad (6)$$

In this expression the inverter ac current is assumed to be sinusoidal. This operating conditions represents the worst case.

IV.- CONTROL CIRCUIT DESIGN

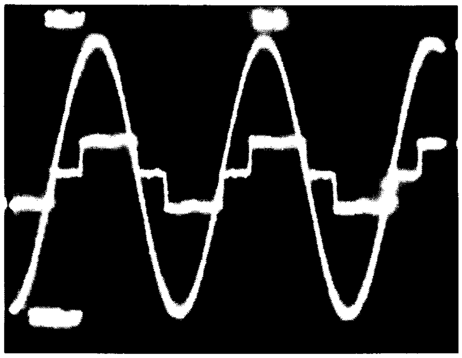
The design procedure for the current and voltage loops is based on the respective time response requirements. Since the transient response of the active power filter is determined by the current control loop, its time response has to be fast be fast enough to follow the current reference waveform closely. On the other hand, the time response of the dc voltage control need not be fast and is selected to be at least 10 times slower than the current loop time response. Thus, these units can be designed as two independent systems.

A PI controller are selected for the current and the voltage control loops since it contributes to zero steady state error in tracking the reference current and voltage signals respectively. Simulated results have shown that the active filter transient response is improved by adjusting the gain of the proportional part of the PI current control to be equal to one and the gain of the integrator equal to the frequency of the triangular waveform.

V.- EXPERIMENTAL RESULTS

A 5 kVA laboratory prototype using IGBT switches was implemented and successfully tested in compensating a six pulses controlled rectifier. The inverter was operated at 1.5 KHz switching frequency. Steady-state and transient results obtained with this bread board unit are depicted in Figs. 6 and 7.

Steady-state experimental results for a nonlinear compensation are illustrate in Fig. 6. Figure 6(a) shows the line to neutral ac mains voltage with the respective load current (three-phase controlled rectifier). In Fig. 6(b), the phase to neutral source voltage with the respective source line current are illustrated. This figure shows that the active power filter eliminates low frequency harmonic components effectively and is able to compensate the reactive power required by the load (phase shift angle is almost zero).



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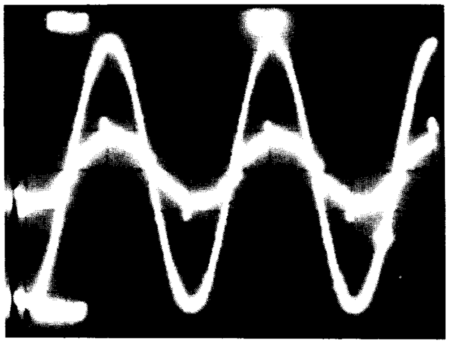
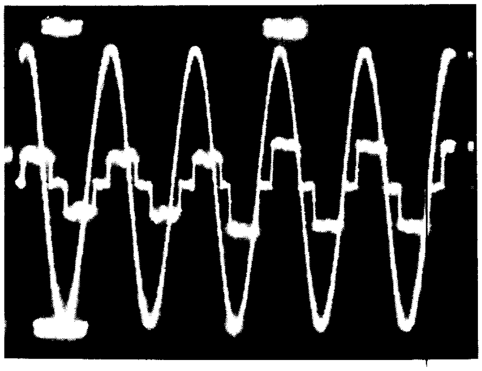


(b)

Fig. 6. Steady-state experimental results. (a) The phase to neutral source voltage, Van, 50 V/div, and the respective load current, 5A/div. (b) The phase to neutral source voltage, Van, 50 V/div, and the respective source current, 5 A/div.

Transient results are shown in Fig. 7. Transient operating condition is obtained by generating a step change in the firing angle (from $\alpha=45^{\circ}$ to $\alpha=15^{\circ}$) of the three-phase controlled rectifier. In particular, Fig. 7(a) shows the transient step change in the load current and in the power factor. In Fig. 7(b) the ac mains phase to neutral source voltage with the respective line current are shown. This figure shows the effectiveness of the active power filter, since it is able to keep the current in phase with the respective phase to neutral voltage, thereby keeping the ac source power factor equal to one, and eliminating low frequency current harmonics. Figure 7(c) shows that the line current reaches staedy-state in almost two cycles. This result proves that time response of the current loop control is fast. Finally, Fig. 7(d) shows the respective inverter output current.

Comparison with simulated waveforms shown in Figs. 4 and 5 reveals a close agreement between predicted and experimental waveforms. Moreover, agreement in waveforms validates the analysis presented.



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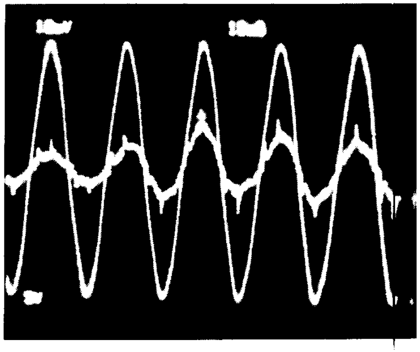

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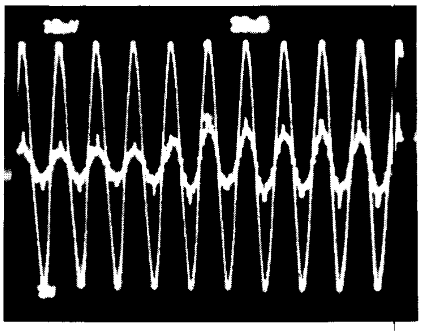

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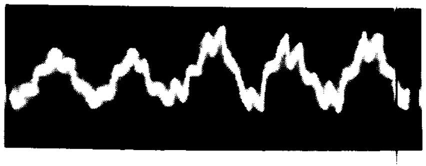

(d)

Fig. 7. Transient experimental results. (a) Phase to neutral voltage, 50 V/div, and load current, 5 A/div. (b) Phase to neutral voltage, 50 V/div, and the source line current, 5 A/div. (c) Phase to neutral source voltage, 50 V/div, and the source current, 5 A/div. (d) The inverter output current, 5 A/div.

VI.- CONCLUSION

In this paper an active power filter that operates with fixed switching frequency has been presented and analyzed. The proposed active power filter acn compensate current harmonic components and the reactive power required by the load. Reactive power compensation is achieved without sensing and computing the associated reactive power component, thus simplifying circuit topology. The performance of the active power filter has been improved by including a dc voltage control loop that maintain the voltage across the dc capacitor constant. In this way, the inverter voltage gain is increased and the high frequency ripple current is reduced. The close agreement between the analytical and the experimental results proves the validity of the analysis and the feasibility of the proposed system.

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