



Power Tracking of Resonant Inverter with Soft-Switching Over Full Load Range for Induction Heating Applications

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ABSTRACT: Induction heating (IH) is nowadays widely used in domestic, industrial and even medical applications because of its advantages such as cleanliness, direct and fast heating, better efficiency etc. Advances are taking place rapidly in the technologies mainly in the power electronics section and the control used in IH. This paper analyses a voltage fed inverter with the power control strategy that allows the inverter switches to operate at zero voltage switching at a load range from 0-100%. The frequency is maintained constant and thus the switching losses are minimized. The soft-switching achieved over the entire load range improves the overall efficiency and the results are analyzed using MATLAB/Simulink.

KEYWORDS: Induction heating, Power tracking, Full-bridge inverter, Zero-Voltage Switching (ZVS)

I. INTRODUCTION

Nowadays, induction heating (IH) is a form of electrical heating which has been widely used in industrial, medical and domestic applications. The concept of induction heating came into existence when Michael Faraday introduced the electromagnetic induction principle in 1831. IH has many dominant advantages over the other heating techniques which includes faster heating, increased efficiency, consistency improved process quality, and most importantly its cleanliness and safety [2], [5]. Advances in induction heating has been taking place with the introduction of different topologies in resonant converters and also with various tank (inductors (L) and capacitors (C)) resonant coil like series and parallel and also LCL or CCL resonance coupling circuit [3]. The power electronics parts include the electromagnetic compatibility filter, an ac-dc converter, an inverter and a resonant load. Depending on the applications, each of the above mentioned components are improving day by day.

At present, researchers are investigating on how to develop a compact-sized, efficient inverter system using either new semiconductor devices or a new circuit topology with the simple control technique or vice-versa [10]. On the basis of number of switching devices, the inverter topologies can be commonly classified full-bridge, half-bridge and single switch resonant inverters. Among these the full-bridge inverter has been widely used in all areas as its range can be extended to even very high power levels.

Modulation and control algorithms have to accurately control the power converter to obtain the desired performance. More specifically, accurate output power within the temperature limit and current control are required. To obtain an appropriate output power control, different modulation techniques have been successfully used for single phase systems; commonly square wave, asymmetrical control [3], [6], frequency modulation [8] pulse amplitude modulation (PAM), etc. All these modulation and control algorithms have been implemented either using analog [5] or digital techniques. Nowadays, digital signal processors (DSPs) or field-programmable gate arrays (FPGAs) [2] are commonly used for digital implementation.

Thus different components for induction heating systems are selected depending on the applications and in each case the priority factors are varied. Here a full-bridge high frequency series resonant inverter (SRI) is analysed using a full load range zero voltage switching modulation technique [4]. The advantage of using full-bridge inverter is that its

output power can be increased even beyond 5 kHz and it is the standard choice for the industrial applications. Compared to half-bridge inverter which is commonly used for domestic applications, the output power can be increased by four times using the full-bridge inverter. For half-bridge inverter, a three-wire dc supply is required which becomes difficult during hardware implementation. This can be overcome by the use of full-bridge inverter [1].

Using the above mentioned control scheme, the ZVS condition is maintained for the entire load range and the switching losses can be minimized, thus improving the efficiency. Here the switching frequency is maintained constant. The paper is organized as follows. In Section II the principle of induction heating, its working and factors affecting the same are presented. Section III gives an explanation of the inverter circuit along with the modes of operation and the working principle. The control used for the inverter is briefed in section IV. Consequently, in Section V the design of the inverter and the resonant tank is done. This analysis is validated using the simulation results in section VI. Finally, conclusions obtained are presented in Section VII.

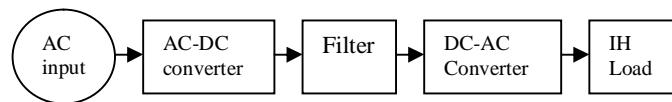


Fig. 1. Power conversion flow in IH

II. PRINCIPLE OF INDUCTION HEATING

IH is the process of heating the material using three principles: electromagnetic induction, the skin effect, and heat transfer. In induction cooking, the heating coil is excited and a current is induced into the load [13]. Heat is generated at the bottom layer of the pan due to the eddy current combined with the hysteresis losses from the magnetic material of the pan. By increasing the magnetic field, the part of the metal placed near to it will be heated by induction without any direct contact. But the ac input has a frequency of 50 Hz which is to be increased in order to create a sufficiently strong magnetic field for heating. For this a high frequency circuit is to be employed. For the same purpose, a three stage power conversion is used [14].

In IH, the rectifier first converts AC current from the power source into DC. Passing this through a smoothing stage, its output is connected to a high frequency switching circuit and thus a high frequency current is administered to the heating coil as shown in fig 1. According to Ampere's Law a high frequency magnetic field will be created around the heated coil. By placing a conductive object inside this magnetic field an induced voltage and an eddy current will be generated on the skin depth of the heating object. For domestic applications this heat energy will be utilized for cooking.

Most of the heat generated by the eddy current is concentrated on the periphery of the work piece and this is given by

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad (1)$$

where f is the switching frequency, δ is the thickness at periphery, μ and ρ are the magnetic permeability and electrical resistivity of the work-piece. The amount of heat generated depends on different factors, mainly: the material and number of turns of the heating coil, the magnetic permeability of the work-piece and the frequency [11].

III. POWER CONVERTER DESCRIPTION

i. Analysis of Power Converter

This paper presents a soft-switched high frequency full-bridge SRI. A diode bridge rectifier is used to convert the single phase AC input of 50 Hz into DC. A dc link capacitor is used to filter the ripple content. The filtered dc is given into the full-bridge inverter and a high frequency AC current is attained which is applied to the load i.e. the induction coil.

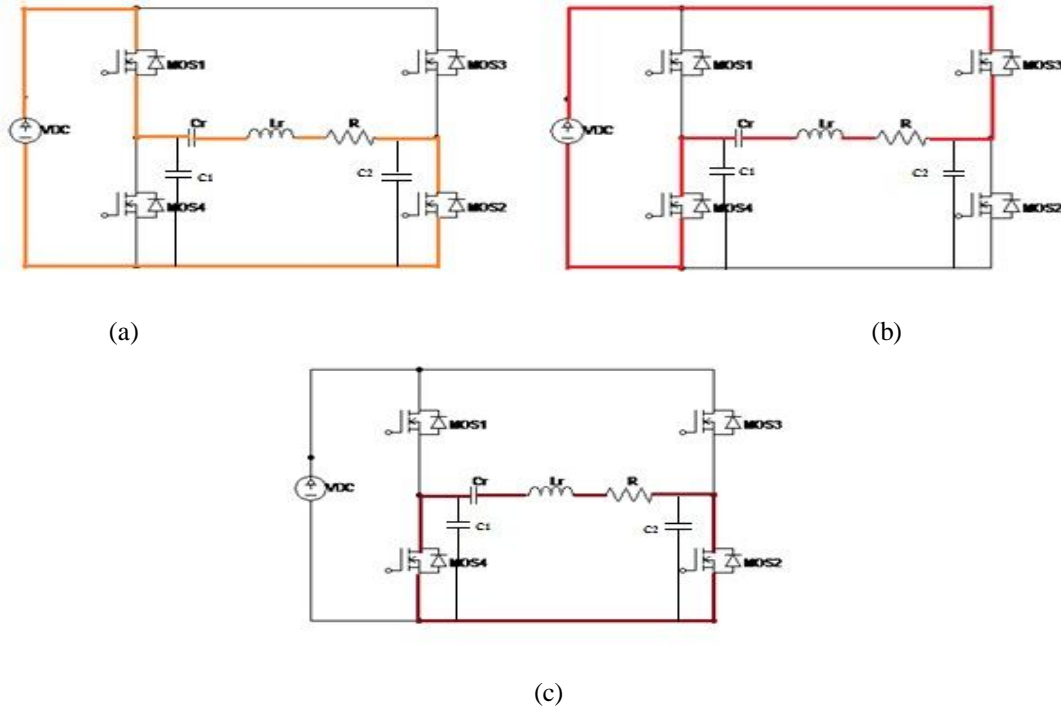


Fig. 2. Modes of operation(a) Mode I. (b) Mode II. (c) Mode III

The four switches Q_1 , Q_2 , Q_3 and Q_4 of the full-bridge inverter are bidirectional type MOSFETs with anti-parallel diodes. C_r is engaged in series with R and L_r to create resonance[7]. Two edge resonant snubber capacitors C_1 and C_2 are connected parallel to the switches Q_4 and Q_2 . C_1 creates the zero voltage soft-switching condition of Q_1 and Q_4 and the same is provided by C_2 for Q_3 and Q_4 . The snubber capacitors function during the dead time and reduce the turn off losses. Switches Q_1 and Q_2 turn on initially and after an interval of 180° the rest switches are turned on.

ii. Operating principle

Fig. 2 shows the switching modes of an equivalent circuit of the voltage source series resonant full range zero voltage switching inverter. A conventional voltage source SRI takes alternate mode I and II in Fig. 2 (a) and (b) to produce a square-wave ac voltage state. In addition to modes I and II, the full range ZVS inverter introduces mode III to produce a zero voltage state at its output terminals as show in Fig. 2 (c). During mode III, a gate turn-on signal is provided to either lower or upper leg IGBT's respectively. As a result, both, one IGBT and a diode connected in anti-parallel to the other IGBT, remain turned on.

IV. CONTROL CIRCUIT

Fig 3 shows the block diagram for the control strategy used in this induction heating circuit. For any IH process, first the input voltage is checked to determine whether its value is within the limits, if this condition is satisfied the main relay is closed. Next the pan detection occurs. . If the pan is detected the control will move to the next step. Then a pulse density sweep will be performed. Upon starting, a pulse density will be applied and the relative power delivered to the load will be calculated. From this point the initial pulse density will be increased or decreased in order to generate a table where the pulse densities are associated with their corresponding power levels.

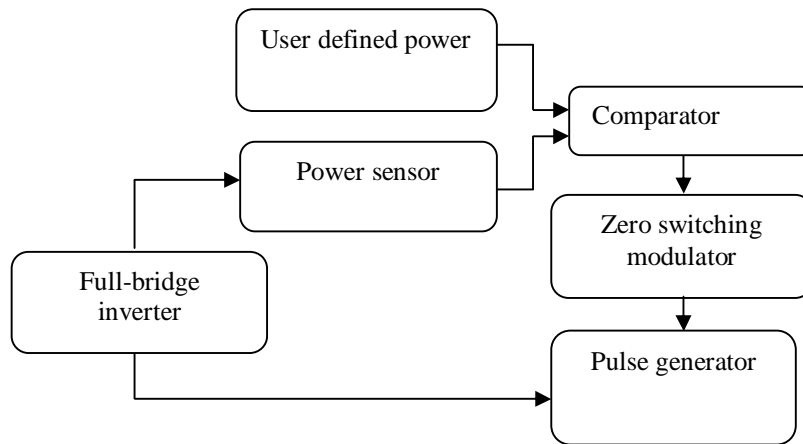


Fig. 3. Block diagram for the control strategy

Then the user request will be processed, selecting a pulse density from the afore mentioned table and a comparison between the power requested and the power delivered will be performed within a certain time interval in order to deliver the requested power[9]. If the power exceeds the request, the pulse density will be increased, otherwise it remains constant. In case the actual power is less than the request vice-verse takes place. In parallel with this process all the protections will be functional.

Using the control scheme used in fig 4, the pulses for the inverter can be generated. The significance of using this is that, the output power is regulated by varying the duration in which the inverter injects high frequency current into the coil. The ZVS condition is maintained for the entire load range and thus the switching loss is minimized maintaining the switching frequency constant [8]. Here the high frequency pulses are compared with the low. In order to avoid acoustic noises, the low frequency pulses are usually taken less than 20 Hz. Pulses for all the switches are generated when the low frequency signal goes high. When the low frequency pulse goes low, the switches do not receive the gate pulses and they remain off. Here the high frequency signals are represented using triangular wave with the switching frequency.

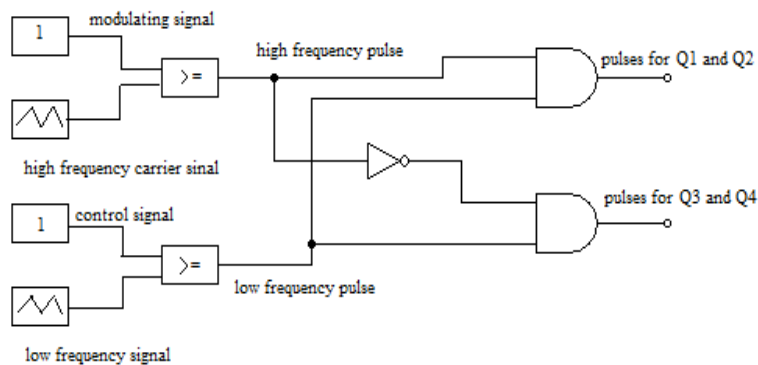


Fig. 4. Pulse generation technique

V. DESIGN

During analysis, the following assumptions have been considered: 1) the switches are ideal, so no switching losses are taken into account; 2) the current through the load is sinusoidal as its loaded quality factor (Q) is sufficiently high. For the proper damp operation of the circuit, $4L_0 > R_0^2 C_r$ condition is to be maintained. Since the IH load branch is in resonance, the flowing current is resistive current as the resistance alone resists the flowing current in the pure series

resonant tank [15]. The analysis of the simple R –L₀ –C_r series resonant tank is carried out and the total impedance of the tank is

$$Z_r = \sqrt{R_0^2 + \left(\omega_s L_0 - \frac{1}{\omega_s C_r}\right)^2} \tan^{-1} \frac{\left(\omega_s L_0 - \frac{1}{\omega_s C_r}\right)}{R_0}$$

$$= R_0 \sqrt{1 + Q^2 \left(u - \frac{1}{u}\right)^2} \tan^{-1} Q \left(u - \frac{1}{u}\right) \quad (2)$$

where Q is the loaded quality, and the normalized frequency is $u = f_s / f_r$. For ZVS operation, it is defined as $u > 1$. The quality factor Q measures the “goodness” or the quality of the circuit. This can be defined as the ratio between the power stored in the inductor and the power dissipated in the resistance of the resonant circuit

$$Q = \frac{\omega_r \times L_r}{R} = \frac{1}{\omega_r \times C_r \times R} = \frac{Z_r}{R} \quad (3)$$

$$Q = \frac{1}{R} \times \sqrt{\frac{L_r}{C_r}}$$

The output power for the resonant tank only is obtained as

$$P_o = \frac{2V_s^2 \cos(\tan^{-1} Q(u - 1/u))}{\pi R_0 \sqrt{1 + Q^2(u - 1/u)^2}} \quad (4)$$

VI. ANALYSIS AND RESULTS

Simulation of full-bridge inverter using the full load range soft-switching control has been done using the MATLAB/Simulink model for the following input and output data specifications given in table I. The inverter is designed for output power of 4000W with input voltage 220V and switching frequency of 25 kHz. Simulation is done for different power levels and the voltage and current for each switch is obtained.

TABLE 1 Specification of parameters

Parameters	Values
DC input voltage, V _s	220V
Switching frequency, f _s	25kHz
Load resistance, R	150Ω
Load inductance, L ₀	146μH
Resonant capacitor, C _r	0.3μF
Snubber capacitor, C ₁ , C ₂	1*10 ⁻¹⁰ F

Fig 5 shows the voltage and current for the power of 4000W done using pulse density modulation. The red waveform indicates the voltage and the current is shown in blue. The zoomed view of these voltages and currents are shown in fig 6. During the dead time snubber capacitor C₁ and C₂ charges and discharges; therefore, the load voltage gradually increases in both polarities. The current waveform is shown in fig 7. The load current waveform is completely sinusoidal and does not have any distortion during dead time.

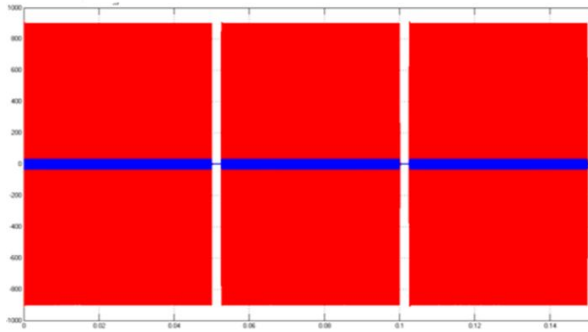


Fig. 5. pulse density modulated output voltage and current for 4000W

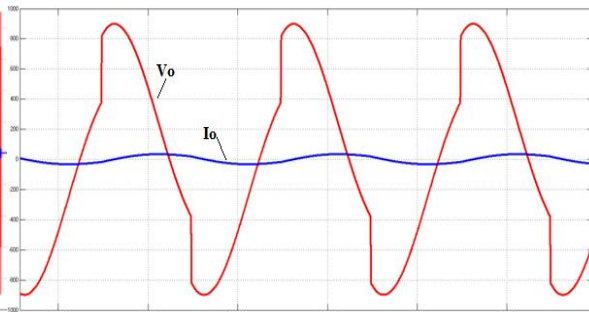


Fig. 6. Zoomed view of voltage and current

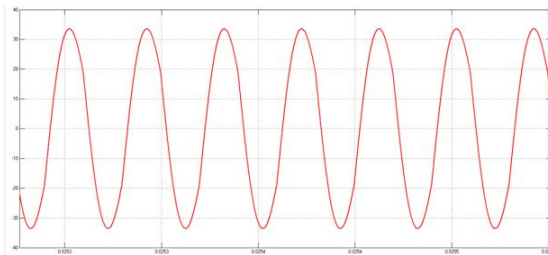


Fig. 7. Current through the load

The voltage and current through the switches Q_1 and Q_2 and for Q_3 and Q_4 are described through the waveform in fig 8 and 9. Here it is clear that the soft-switching takes place for all the switches. This property is shown for the switches for the entire load range i.e., the soft-switching can be observed at any condition for the load is change from 0-100%. Fig 10 shows the zoomed view of one of the switch voltage and current showing soft-switching in the switch.

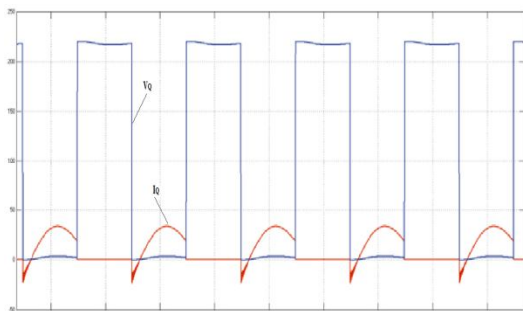


Fig. 8. Switching of Q_1 and Q_2 at 4000W

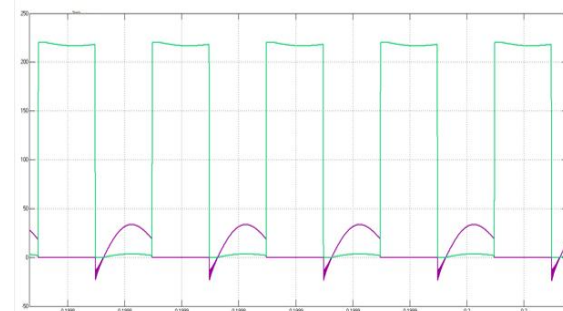


Fig. 9. Switching of Q_3 and Q_4 at 4000W

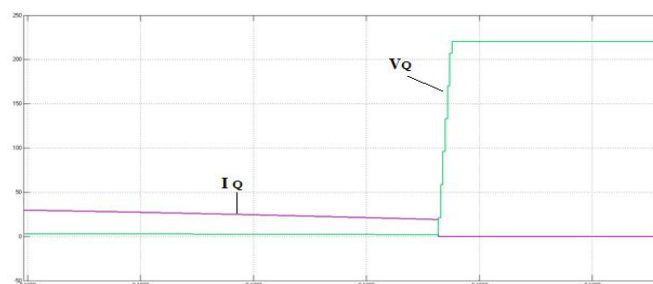


Fig. 10. Zoomed view showing soft-switching

The charging and discharging of the capacitor voltage is shown in fig 11. The voltage and current for the power of 1000W is shown in fig 12. Here the voltage and current values remain the same. It is only the density of these parameters which gets altered. The density here implies that the number of cycles of these voltages and currents increased or decreased according to the power levels. In this manner, the power can be varied to any level up to 4000W maintaining the soft-switching conditions for the entire range.

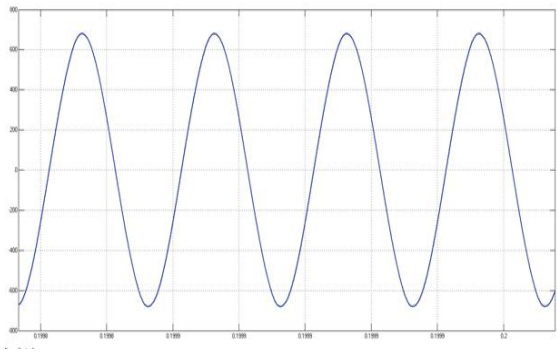


Fig. 11. Resonant capacitor voltage

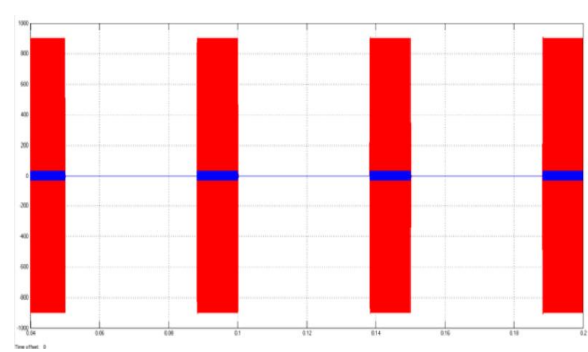


Fig. 12. Pulse density modulated voltage and current at 1000W

Fig 13 depicts the zoomed view of voltage and current at 1000W which resembles the waveform in fig 6. This proves that the magnitudes of both the parameters are not altered but the power is varied by modifying its pulse density.

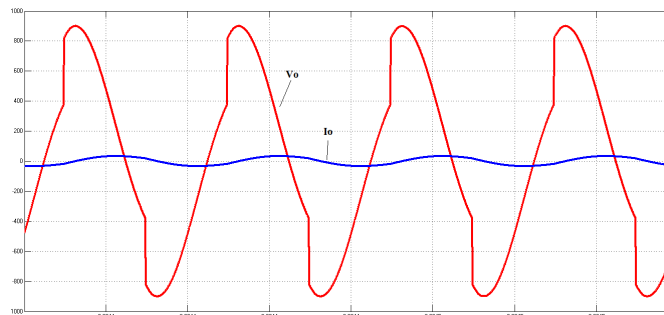


Fig. 13. Zoomed view of voltage and current

Fig 14 and fig 15 shows the switching for the respective switches. Here the soft switching is observed across all the switches. Hence it can be proved that soft switching is obtained over the full load range.

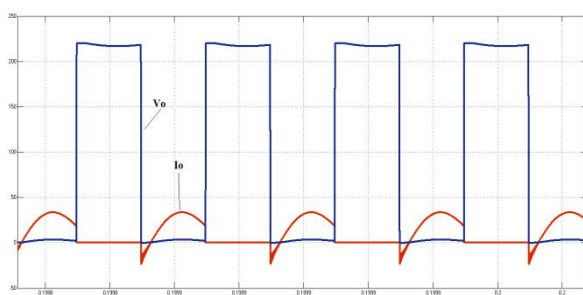


Fig. 14. Switching of Q₁ and Q₂ at 1000W

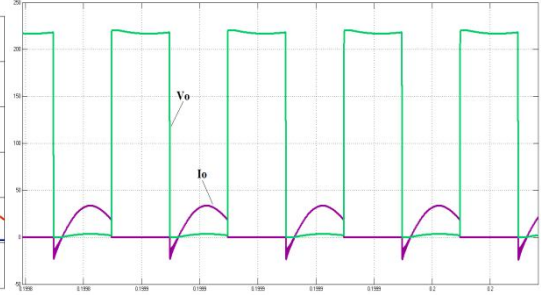


Fig. 15. Switching of Q₃ and Q₄ at 1000W

VII.CONCLUSION

This paper presents the full-bridge series resonant high frequency inverter with full load range zero switching modulation technique. Here the power of the inverter is varied by changing the density so that the output voltage and



current remains the same. The ZVS condition was attained for 0-100% load range thus minimizing the switching losses. As the switching frequency is also maintained constant throughout the operation, the overall performance of the inverter is improved. The output load current attained is sinusoidal, which implies minimum distortion. The ZVS condition for each switches are validated for different load ranges using MATLAB/Simulink.

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