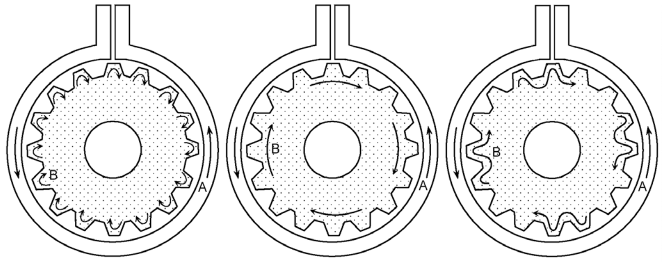
High Power Resonant Inverter with Simultaneous Dual-Frequency Output

V. Esteve, J. Pardo, J. Jordán, E. J. Dede, E. Sanchis-Kilders, E. Maset
Department of Electronic Engineering
ETSE, University of Valencia
Dr. Moliner 50, 46100 Burjassot, Spain
Email: vesteveg@uv.es

Abstract – **Induction surface hardening of parts with non-uniform cylindrical shape requires a multi-frequency process in order to obtain a uniform surface hardened depth. This paper presents an induction heating high power supply constituted of an only inverter circuit and a specially designed output resonant circuit. The whole circuit supplies both medium and high frequency power signals to the heating inductor simultaneously.**

I. INTRODUCTION

Induction hardening is a cost–effective heat treatment used to increase the abrasion resistance and fatigue strength on mobile metallic pieces. The part to be heated is placed in a magnetic field generated by a coil called heating inductor which is fed by using a high current and high frequency power supply. The Foucault or eddy currents induced inside the workpiece originate the heat due to Joule and hysteresis losses. Inductive surface hardening is an attempt to harden only the surface without affecting the inner portion of the workpiece. The depth of the heated zone depends on the current frequency by virtue of the skin effect as well as the heat conduction property.



a) high frequency b) medium frequency c) medium+high frequencies

Fig. 1: Behaviour of inducted currents in a gear hardening process with high frequency a), medium frequency b) and simultaneous dual-frequency c).

Complex-shaped parts used especially in automotive industry, such as splined hubs, sprockets and gears, need a special heat treatment process in order to obtain a uniform hardened contour using circular inductors. The classic induction hardening of these parts without uniform cylindrical shape is carried out with two sequential heating processes. High frequencies (HF) are required to heat the surfaces nearer to the inductor (the tip and flanges of the teeth), and medium frequencies (MF) heat the quasi-cylindrical area near the surface (the root area of the teeth). Fig 1.a and Fig 1.b show how the induced current is distributed in a gear for high and medium working frequencies respectively. This process requires two separate induction coils, a very fast mechanical transport and two separated power supplies [1]. Fig 1.c shows how a current signal which results from a suitable combination of the two frequencies obtains the required heating contour. In this approach, medium and high frequencies are supplied by one generator to one inductor simultaneously and intermediate transport is not necessary [2].

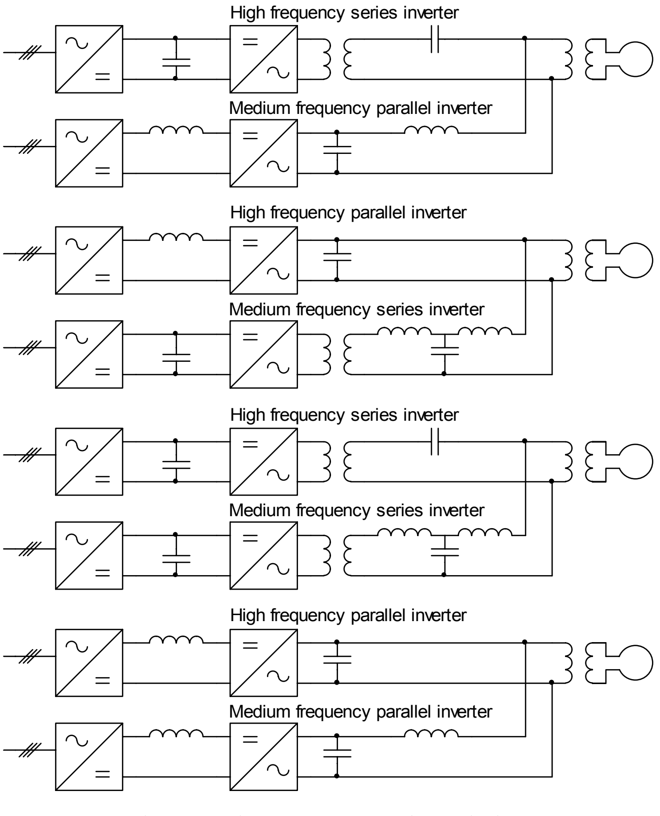


Fig. 2: Two-inverter power supply topologies.

II. POWER SUPPLY TOPOLOGIES

In order to obtain power supplies for this special process of induction hardening, several solutions are possible. Nowadays the solution used consists of one common induction coil supplied with a high frequency inverter and a medium frequency inverter. Since current-fed parallel resonant inverters as well as voltage-fed series resonant inverters are normally used in induction heating, there are only four

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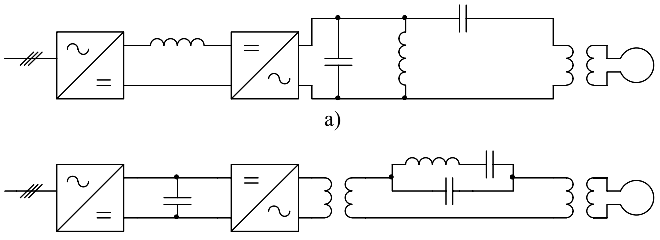
possible topologies of these "two-inverter power supplies". Fig 2 shows these power supplies where HF and MF are generated separately by using series and/or parallel inverters.

The composition of both current signals is carried out by a two frequencies resonant circuit that connects the output of the inverters to the induction coil. Some of these solutions are used nowadays for induction heating manufacturing companies [3][4]. The power regulation of the inductor signal can be made in each inverter individually by means of conventional techniques.

This paper proposes new topologies with an only inverter. In this case the separated frequency components of the inductor current are obtained by means of a medium-frequency PWM modulation of the high frequency signal. Fig 3 shows the two possible one-inverter topologies. The dual-frequency parallel inverter is shown in Fig. 3.a. It is composed by a current-fed parallel inverter and a four-reactive-element load circuit with two different parallel resonant frequencies. The diagram shown in Fig 3.b corresponds to a second topology: the dual-frequency series inverter (DFSI), with a voltage-fed series inverter and a four-reactive-element resonant circuit that will be described in the next paragraph.

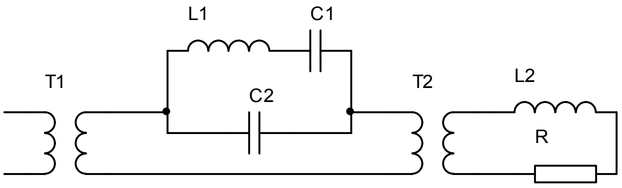

a)

b)

Fig. 3: One-inverter power supply topologies.

III. DESIGN OF THE DUAL-FREQUENCY SERIES INVERTER

Fig 4 shows a practical design of the DFSI output resonant circuit. L2 and R represent the equivalent induction heating coil impedance (including the workpiece equivalent resistance). Transformers T1 and T2 adapt the inverter output current and inductor equivalent impedance respectively. The component values in a possible implementation for 100 kW output power and 10 kHz and 300 kHz working frequencies are also shown in Fig 4.



L1=4 μH, C1=65 μF, C2=3 μF, L2=0.4 μH, R=0.1 Ω, T1=5.5:1, T2=1:2

Fig. 4: Schematic diagram of the DFSI output resonant circuit.

Fig 5 shows the frequency response of the input impedance module of the resonant circuit. S1 and S2 represent the two working series resonances and P represents an additional parallel resonance.

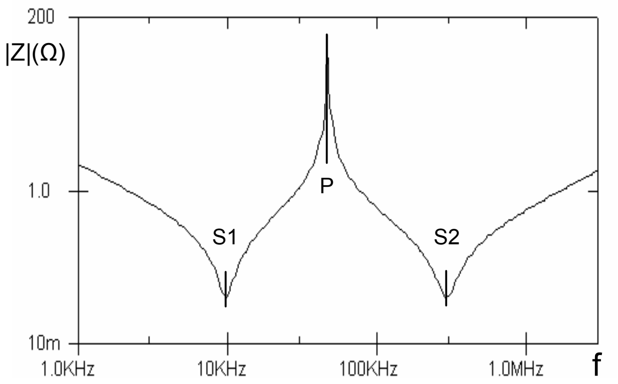


Fig. 5: Input impedance frequency response of the DFSI output resonant circuit.

The simplified equations used to design the reactive components of the circuit are shown in (1) and (2) It is supposed that C2 is significantly smaller than C1.

$$\omega_P = \omega_{22}\sqrt{\beta}\ ;\ \omega_{S1} = \frac{\omega_{11}}{\sqrt{\beta+1}}\ ;\ \omega_{S2} = \omega_{22}\sqrt{\beta+1} \tag{1}$$

where:

$$\beta = \frac{L_2}{L_1};\quad \omega_{11} = \frac{1}{\sqrt{L_1C_1}}\ ;\quad \omega_{22} = \frac{1}{\sqrt{L_2C_2}} \tag{2}$$

Fig. 6 and Fig 7 show the simplified diagram of the DFSI power and control stages and their relevant simulated waveforms. The output power regulation is achieved by changing the amplitude of Va (medium frequency power regulation) and by adjusting the frequency of Vb (high frequency power regulation) continuously and separately.

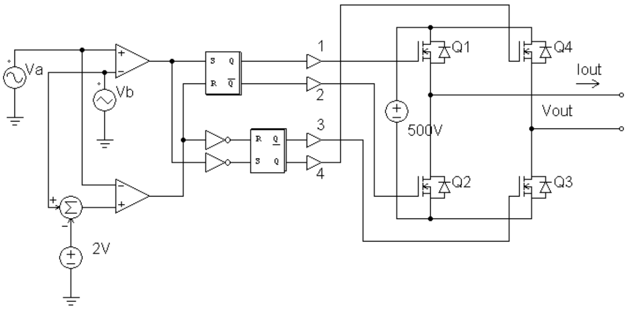


Fig. 6: Simplified diagram of the DFSI power and control stages.

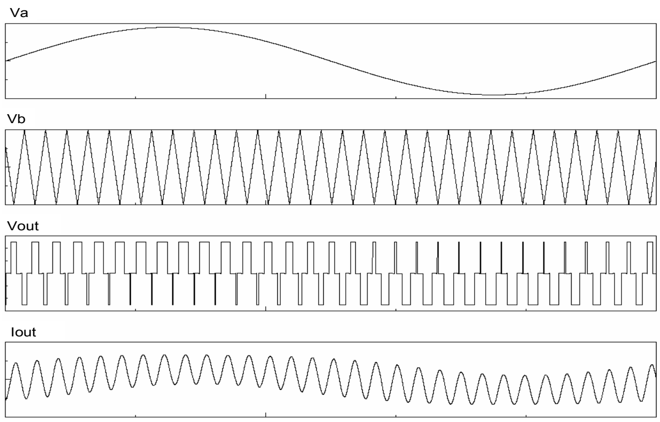


Fig. 7: Simulated waveforms of the DFSI power and control stages. Va 0.5V/div; Vb 1V/div; Vout 200V/div; Iout 500A/div; TB: 20μs/div

Bearing in mind the shape of the current that feeds the heating inductor, labeled in fig 7 as Iout, it can be defined a magnitude called «output current ratio» (OCR) as

$$OCR = \frac{I_{MF}}{I_{HF}} \qquad (3)$$

Where I_{MF} and I_{HF} are the amplitudes of the MF current component and the HF current component respectively. The regulation system presented above allows getting a wide range of OCR values. The ultimate OCR value will be pointed out by the concrete application specifications in order to obtain an optimal hardened contour.

IV. EXPERIMENTAL RESULTS

A 1 kW total output power prototype with 10 kHz and 300 kHz working frequencies was tested satisfactorily. Inverter stage was made by using high voltage power MOSFET transistors with FREDFET intrinsic body diode (IXFN 44N80) fed with a 200 V bus. Moreover, a non-inductive layout was designed so as to prevent switching overvoltages. Fig 8 shows the inverter output waveforms for a value of OCR close to the unity.

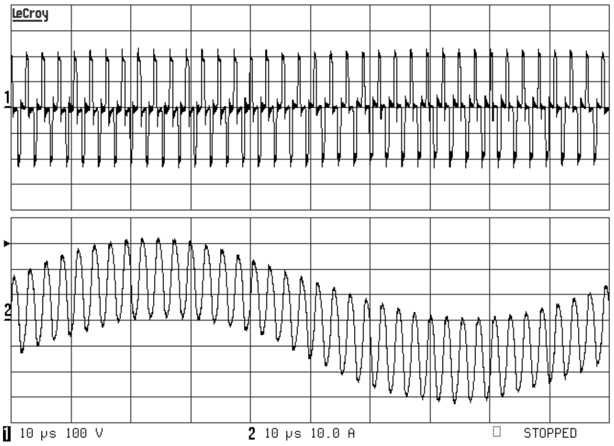


Fig. 8: Experimental output voltage and current waveforms of the DFSI.

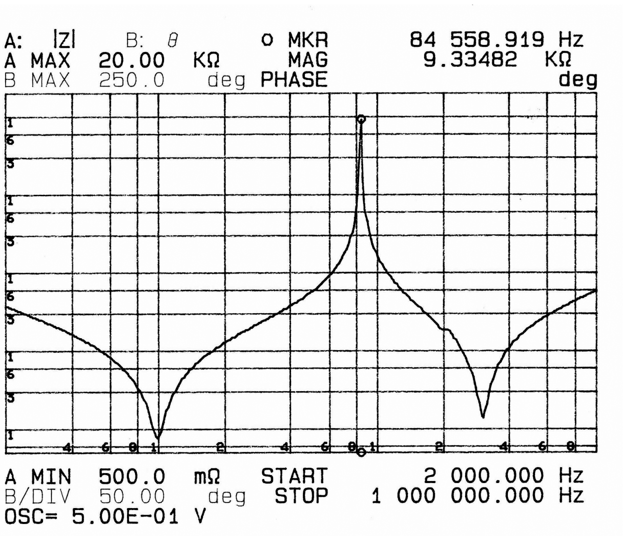


Fig. 9: Impedance frequency response of the DFSI output resonant circuit.

The output resonant circuit for this applications was implemented with L1 = 130 μH, C1 = 2 μF, C2 = 30 nF and L2 = 10 μH. No transformers were used. Fig 9 shows the measured frequency response of the output circuit impedance module.

The DFSI switching conditions depend on the values of the OCR and phase shifting between HF output voltage and current components mainly. Hard commutations can appear under non-zero current or voltage switching conditions. In order to obtain a suitable inverter efficiency analysis, measurements of the switching power losses are required. Fig 10 shows the measured energy involved in turn-on and turn-off switching processes. Fig 11 shows the experimental measurement of the DFSI efficiency which agree with the previous calculations.

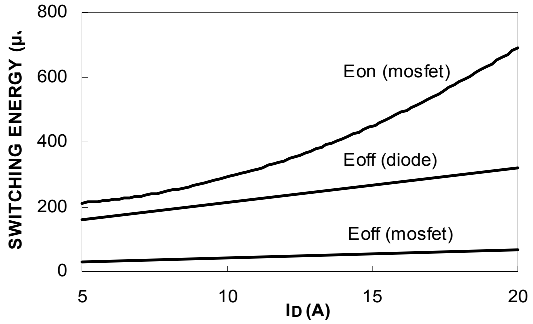


Fig. 10: Experimental measurement of the switching power losses.

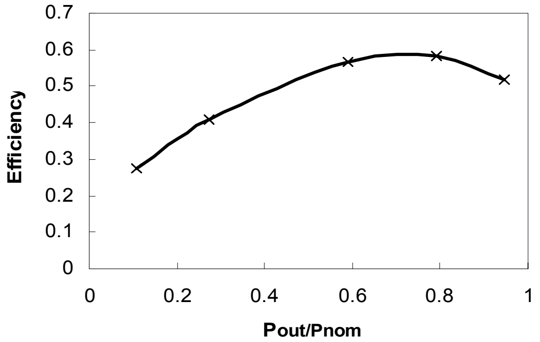


Fig. 11: Experimental measurement of the DFSI efficiency vs. normalized output power.

A new 100 kW prototype is been tested at the moment so as to meet the industrial application requests. Such a prototype is been developed by using anti-parallel discrete diodes with better recovery response. When the body diode is hard commutated off the MOSFET has about 5 times higher turn-on energy than if a discrete fast recovery diode is used according to switching analysis studies [5], therefore an improvement of the inverter efficiency is expected.

V. CONCLUSIONS

Comparing the experimental and simulated results, the validity of the proposed circuit has been demonstrated. The Dual-Frequency Series Inverter is a cost-effective solution for the hardening of parts with non-uniform cylindrical shape that achieves an important reduction of the total heating process time and improvement of the hardening quality.

Additionally, the use of the one-inverter power supply will allow reducing the equipment cost and saving installation space requirement.

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