Performance Analysis of Control techniques of Full-Bridge Resonant Inverter for Induction Metal Surface Hardening

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Abstract—In this paper, several control techniques for induction metal treating are examined to assess their performances using resonant series inverter. In fact, many types of steel are treated with heat to increase toughness and resistance to wear. Induction heating seems to be appropriate and provides several advantages in comparison with conventional techniques. In this paper, these techniques are evaluated comprehensively, through simulation and experiment, and compared to each other in terms of heating rate and efficiency, using one metal sample hardened to 1mm in depth up to 700°C, with a 400 W power supply. The simulation results obtained are satisfactory, and agree with those of the experiments. Furthermore, the study shows the control strategy based on frequency may not be sufficient, but should be associated with other control techniques in order to address appropriately the hardening process, bearing in mind processing time and efficiency. The strategy with frequency associated with phase shift control appears to fit well metal treating during the hardening, and can be easily tailored to its hardening requirements, compared to the other techniques.

Keywords—Induction metal hardning; Resonant Inverter; Power control

I. INTRODUCTION

Modern induction heating provides reliable, repeatable, non-contact and energy-efficient heat in a minimal amount of time. This kind of heating is increasingly used within the metal hardening industry. The phenomena of induction heating begin by passing an alternating current through a coil in order to generate a magnetic field. Eddy currents are induced in any electrically conductive object, e.g. metal bar, placed inside the coil. The phenomenon of resistance generates heat in the area where the eddy currents are flowing. The eddy currents are most active close to the surface of the object being heated, but weaken considerably in strength towards the center. Their penetration depth changes in relation to various parameters such as heating times, initial material and choice of frequency. In the hardening metal industry, the induction heating treatment is aimed at increasing toughness and resistance to wear. In addition, induction techniques are sought for their fast-hardening cycles, accurate heating pattern and cores that remain relatively cold and stable. Such characteristics minimize distortion and make heating outcomes extremely repeatable. In fact, it fulfills better the hardening process, either through hardening when treating the entire part, or case-hardening which deals only with parts of the surface area and some of the interior area, according to the depth of the hardening requirements for a specific application [1]. The first process is more often defined by the time required to heat the part than by the frequency, whereas in the case treating, the depths may vary according to supply frequency [2]. Moreover, much attention has been focused on the improvement of high frequency resonant inverters capable of supplying high power to induction heating loads [1]. Resonant inverters reduced power device switching losses by means of soft-switching technique (operating with zero voltage or current switching) and attractive possibilities in developing higher frequency of operation, higher efficiency, lightweight and overall system simplicity in terms of inverter control, protection and maintainability [1]-[2]. Moreover, the series and parallel inverter system has revealed that voltage source series resonant inverter offers better overall performance than the parallel resonant counterpart with respect to converter utilization [9]. Owing to its advantages, the series resonant inverter topology has been retained and exploited in this paper. The control techniques, input voltage
control at the rectifier side or at the inverter side using frequency, PWM duty cycle or phase shift may be suited to achieve a reasonable hardening quality according to specific application requirements. However, their use might not be effective when addressing the whole process. In addition, there seems to be limited literature on the subject. In the present paper, the performance of these techniques are examined comprehensively and assessed in terms of efficiency and heating rate using a sample of a commercial metal alloy bar heated up to 1mm in depth, with a temperature increase up to 700°C with an inverter supply power of less than 400W using a series resonant inverter. First, a simulation model, Matlab/Simulink based is presented, through which a theoretical study is conducted. This study is confined only to assessing the electrical characteristics of the system. Then an experimental kit built for the purpose is presented. At last, the obtained results are discussed; with heating aspects being taken into account in order compare the performance of these techniques and to validate the simulation model.

II. PRINCIPLE OF INDUCTION HEATING

The principle of induction heating is shown in Fig1. An electric conductor such as iron or steel placed in the inductor is heated rapidly through induced eddy current caused by electromagnetic induction, and hysteresis heat loss, which is generated by vibration and friction of each molecule in magnetic under AC magnetic flux [2].

Most of the heat generated by eddy currents in the heating load tends to concentrate close to the metal surface; where the peripheral layer of skin depth $\delta$ is given by [3]:

$$\delta = \frac{\rho}{\pi f \mu \mu_r}$$  \hspace{1cm} (1)

Where: 
$\mu_r$: Relative magnetic permeability of the material 
$\rho$: Electrical resistivity of the material 
$f$: Operating frequency

The penetration depth is defined as the thickness of the surface layer where 63% of current and 87% of the generated power flows [3]-[5].

III. SYSTEM MODELING

A. Circuit Description

Fig. 2 shows the overall configuration of induction heating system. The three AC voltage inputs are converted to DC voltage by a three-phase converter. This output is then filtered and fed to a DC/DC converter. The voltage output is converted to a high frequency AC voltage through a full-bridge inverter which consists of high-speed IGBTs (T1, T2, T3, and T4) with fast anti-parallel diodes. The inverter is connected to a series resonant circuit. This consists of an equivalent inductance representing the heating coil and work-piece in series with high-frequency compensating capacitor [3]-[4]-[6].

The heating coil and the load are modelled as a transformer with a single turn secondary winding. The equivalent model for a transformer can be in a simplified form by an equivalent inductor and resistor [5]-[7]-[8]. These load parameters depend on several variables as reported above. The heating coil and the load can be represented by an equivalent series inductor $L_{eq}$ and resistor $R_{eq}$, as represented in Fig. 3.

Nature of the material of heating load, relative position between inductor and work-piece, excitation frequency, and temperature may change the equivalent load parameters [3]. This can be described by its quality factor $Q$, defined by [2]:

$$Q = \frac{L_{eq}}{R_{eq}} = \frac{1}{R_{eq} C_{eq} \omega}$$  \hspace{1cm} (2)
It is common to classify the loads by the quality factor at the resonant frequency $f_{res}$. The resonant frequency is given by:

$$f_{res} = \frac{1}{2\pi \sqrt{L_{eq} C_{res}}}$$  \hspace{1cm} (3)

B. Simulation Results

In order to assess the performances of the system using the series inverter topology, in terms of output power and efficiency with respect to various control strategies, first a model simulation without control was performed. This was followed taking into account control techniques. The electrical parameters values of the components of the proposed system design are summarized in table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load voltage</td>
<td>$V_{load}$</td>
<td>20 V</td>
</tr>
<tr>
<td>Coil voltage</td>
<td>$V_{coil}$</td>
<td>25 A</td>
</tr>
<tr>
<td>Load current</td>
<td>$I_{load}$</td>
<td>25 A</td>
</tr>
<tr>
<td>Output power</td>
<td>$P$</td>
<td></td>
</tr>
<tr>
<td>Quality factor</td>
<td>$Q$</td>
<td>3.315</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>$f_{res}$</td>
<td>16 kHz</td>
</tr>
<tr>
<td>DC-Link voltage</td>
<td>$V_{dc}$</td>
<td>20 V</td>
</tr>
<tr>
<td>Equivalent Inductor</td>
<td>$L_{eq}$</td>
<td>33 uH</td>
</tr>
<tr>
<td>Equivalent Resistor</td>
<td>$R_{eq}$</td>
<td>1 ohm</td>
</tr>
<tr>
<td>Tank capacitor</td>
<td>$C_{res}$</td>
<td>3 µF</td>
</tr>
</tbody>
</table>

We note that the resonance is well established, for an input DC voltage of 20Volts, and a maximum current of 25A. We also note that the maximum power occurs at the resonant frequency, and diminishes as the operating frequency gets away from the resonance mode. These obtained results are satisfactory in way model simulation is able to predict most the characteristics under resonant mode and consolidates the system behavior using the design system parameters. A consistent model validation is carried out with experimental set up described later.

IV. POWER CONTROL STRATEGY

In an induction heating system, and particularly in metal hardening, various temperature profiles and penetration depths are sought. Therefore, power control is applied to meet these profile cycles. Here, various control strategies are exploited and investigated to allow power control. They are described in the following sections. The performances of these techniques are evaluated primarily through simulation, Matlab/Simulink based, and then through experiment. The system is simulated with the diagram blocs featuring all the components of the system and taking into account the control parameter values that are selected later in the experiment. This model simulation and experiment will certainly allow not only a comprehensive assessment of the performances of the techniques and also for a fair comparison between them in terms of efficiency and heating rate.
A. Varying the DC Link Voltage

In this technique the power processed by the series resonant inverter is decreased by reducing the supply voltage to the inverter through a chopper placed at the inverter input. As a result, varying the link voltage allows full control of the heating power. Fig. 8 represents efficiency and output power according to the input voltage variation. It is found that the output power is proportional to the output voltage, and since the system remains under the resonant mode, the performance is optimum.

![Efficiency and output power according to the input voltage](Image)

Fig. 8. Efficiency and output power according to the input voltage

B. Varying the Duty Cycle

The power control is conducted through the variation of the on-time of the switches in the inverter. The power is only sourced to the work-piece at the time the devices are switched on. The load current is then left to freewheel through the diodes during the dead time when both devices are turned off. Therefore, varying the duty cycle of switching the time of the device allows full control of the power from 0% to 100%. Fig. 9 shows efficiency and output power according to the duty cycle variation. We note here that the power control is performed using the duty cycle. The resonance is no longer ensured and therefore system efficiency is decreased.

![Efficiency and output power according to the duty cycle](Image)

Fig. 9. Efficiency and output power according to the duty cycle

C. Varying the Operating Frequency

The power supplied by the inverter to the work coil is reduced by detuning the inverter from the natural resonant frequency of the tank circuit incorporating the work coil. As the operating frequency is moved away from this frequency, there is less resonant rise in the tank circuit, and the current in the work coil diminishes.

![Efficiency and output power according to the frequency](Image)

Fig. 10. Efficiency and output power according to the frequency

D. Varying the Phase-Shift

The power variation is achieved through the control of switching instants of both bridge legs. This is done through the adjustment of the phase-shift between them. As a result, the power can be varied from 0% to 100% when varying the phase shift from 0 to 180°. Fig. 11 represents efficiency and output power according to the phase-shift variation. We found that the power is higher when the phase-shift is low and gradually decreases as it becomes greater.

![Efficiency and output power according to the phase-shift](Image)

Fig. 11. Efficiency and output power according to the phase-shift

V. EXPERIMENTAL SET UP AND RESULTS

An experimental kit of a full-bridge resonant inverter system has been set up using MITSUBISHI IGBT 2MB175UA-120 as the main switching devices, with short-circuit and overcurrent protection logic circuits. Since the heating system is tailored toward surface metal treatment and hardening in the low power range, various control have been designed and implemented to cater for the DC inverter input parameters control and at its high frequency AC output. The coil was designed according to the specification provided. The work-piece consists of metallic bars. The spacing between the work-piece and the heating coil was set to 5mm using thermal insulator. The load system parameters are as follows: \( R_{eq}=1 \Omega, L_{eq}=33 \mu H, C_{res}=3 \mu F \) and the dead-band was adjusted to 1µs. Also, the system was operated at an input DC voltage of 20V, with a maximum input current set to 25A and an
operating frequency of 16 kHz. These operating conditions are found in the experimental stage adequate for our application.

### TABLE II. SPECIFICATION OF COIL AND WORK-PIECE DESIGN

<table>
<thead>
<tr>
<th>Coil parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Length</td>
<td>170 mm</td>
</tr>
<tr>
<td>Internal diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>External diameter</td>
<td>30 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work-piece parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>26 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>5 mm</td>
</tr>
</tbody>
</table>

Figs. 12 and 13 show respectively the working coil with metal inside being tested and the electrical system components of the experimental kit.

### A. Digital Implementation

In order to generate the various control signals for full-bridge inverter control, a TMS320F28027 microcontroller from Texas Instrument has been used. TIMER1 is used for the reading and measuring the control signal period.

The different registers TBPRD, TBPHS and CMPA are used to implement the several control techniques as mentioned above (frequency, input voltage, phase-shift and duty cycle). Microcontroller clock speed equals 60 MHz, allowing for swift information processing, and therefore a real time adaptation.

### B. Experimental Results

The experiment was conducted in a way so that the various control techniques could be applied and comprehensively investigated in terms of heating rate and efficiency of the system. With respect to each technique, the input DC power of inverter, its output power, and temperature increase at the metal surface was recorded for a period of 60 seconds. In addition, the heating power transferred to the working piece was evaluated using the equation below:

$$ P = \frac{mC(T_2-T_1)}{\Delta t} $$

Where:
- $P$: Heating power
- $m$: Mass of the work-piece
- $C$: Specific heat of the material
- $\Delta t$: Heating duration
- $T_1, T_2$: Initial and final temperatures at the surface

The initial operating conditions were set as in the simulation with the system fed with at an input DC voltage of 20V, with a maximum input current set to 25A and an operating frequency of 16 kHz. These conditions correspond to resonant mode where the maximum power is applied. With regards to input voltage variations, three DC voltage values were selected using the chopper control at the inverter input (10, 15 and 20 Volts). As for the frequency control, the operating frequency of 14, 18 and 25 kHz were assessed once again. From the inverter duty cycle control, this was varied from 50% to 10%. As for the phase-shift control, the variation spans from 0° to 180° degrees with increment of 10°. Figs 14 and 15 highlight respectively the variation of control signal/load current, the heating rate and the inverter output voltage when the DC input is at 15V increasing heating rate of about 2.8°C/s. Other variations of the control signal, load current, and heating rate with respect to phase shift, duty cycle and frequency control are respectively shown in Figs. 16, 17, and 18.
C. Discussion of the Experimental Results

It appears, overall, that the various control strategies considered in this paper allow principal full control of the power. However, when compared to each other in terms of heating rate and efficiency, these tend to show differences which can have a great impact on the system. The results show that the voltage control has a higher efficiency (above 80%), as the system runs continuously at the resonant mode. But since its control happens only at the rectifier side, the heating rate is slower than the other techniques with a maximum of 2.8 °C/s. In contrast, the other techniques allow an enhanced heating rate since they have a direct impact on the coil heating power. It appears also from the experimental results that the phase-shift control has better features in terms of efficiency, in comparison to the frequency and duty-cycle control. In summary, and bearing in mind the metal hardening requirements, it seems that the DC link voltage and phase-shift control should be preferred when it comes to precise control of the heating process with respect to hardening depth and temperature rise. Frequency control tuned towards frequency
slightly higher than the resonance frequency appears to lead to a greater heating rate (higher than 4.5 °C/s) with acceptable efficiency. This is due to the ZVC operating mode. As a result, detuning on the high side of the resonant frequency can be favored, as the operating of the inverter in ZVC is ensured contrary to the low side where ZVC is lost.

In addition, and in an attempt to highlight the differences that exist between these techniques, we have reported in Table III a fair comparison between them based on the experimental data obtained in terms of heating rate and efficiency.

<table>
<thead>
<tr>
<th>Control techniques</th>
<th>Heating rate</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage</td>
<td>Slow</td>
<td>high</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>Fairly high</td>
<td>Low</td>
</tr>
<tr>
<td>Phase-shift</td>
<td>High</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Frequency</td>
<td>Very high</td>
<td>low</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

In this paper, several control techniques for induction metal treating are examined to assess their performances using series resonant inverter. The obtained simulation results are satisfactory, and agree well with those of the experiments. Furthermore, the study shows the control strategy based on frequency can be limited and may be confined to metal temperature penetration depth only. This control should be associated with the phase-shift variation at the inverter level, in order to meet temperature profiles according to the metal hardening requirements with less processing time and optimum efficiency.

REFERENCES