Power Control System Design in Induction Heating with Resonant Voltage Inverter

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***Abstract*—This paper is concerned with the design of the power control system for a single-phase voltage source inverter feeding a parallel resonant induction heating load. The control of the inverter output current, meaning the active component of the current through the induction coil when the control frequency is equal or slightly exceeds the resonant frequency, is achieved by a Proportional-Integral-Derivative controller tuned in accordance with the Modulus Optimum criterion in Kessler variant. The response of the current loop for different work pipes and set currents has been tested by simulation under the Matlab-Simulink environment and illustrates a very good behavior of the control system.**

***Index Terms*—induction heating, resonant voltage inverter, power control, controller tuning, Modulus Optimum criterion**

I. Introduction

The voltage source inverters with resonant parallel load are used successfully in medium and high frequency induction heating systems [1]-[5].

The replacement of the current source inverters has been facilitated by both the existence on the market of the high power insulated-gate bipolar transistors (IGBTs) and the advantages of voltage source inverters [3], [5], [6]. These consist primarily in simple limiting the switching overvoltage and simplest achievement of switching at zero current.

Last but not least, the use of parallel resonance allows for high load current with a small current through the inverter (only the active component). As the control system handles the operation of the induction coil in parallel with a compensation capacitor at the desired resonant frequency, the current through the induction coil is forced to be sinusoidal.

In practice, the parallel resonant circuit is damped when the work piece is inserted into the induction coil by introducing additional losses into the system and increasing the current drawn from the inverter [1], [3], [5], [7].

This paper is focused on the tuning the control loop of the power transferred to a work pipe in the induction heating process through a voltage source resonant inverter. Starting from the block diagram based on transfer functions, the Modulus Optimum (MO) criterion is successfully applied.

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II. Control System Structure and Block Diagram

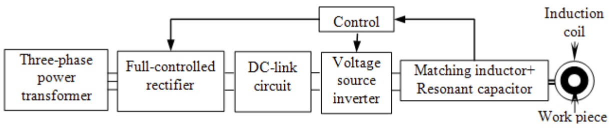

Figure 1. Schematic diagram of the induction heating system

In the adopted structure of the induction heating system (Fig. 1), a three-phase full-controlled bridge rectifier supplies the IGBTs-based single-phase full-bridge voltage source inverter. In order to ensure zero-current switching, the operating frequency of the square-wave inverter, which is provided by an auto-adaptive loop, is imposed to be slightly higher than the resonant frequency of the equivalent circuit consisting of induction coil-work piece in parallel with the resonant capacitor.

The control of the current through the induction coil can be performed by controlling its active component, which means the control of the inverter output current. As regards the required value of the induction coil current, there are two possible approaches:

- The work pipe moves through the inductor at a preset speed and the preset current depends on the required temperature gradient;
- The maximum rated current of the voltage inverter is preset and the work pipe speed is adjusted as a function of the required temperature gradient. This is the option that allows for maximum productivity in terms of the inverter.

The block diagram in Fig. 2 illustrates the transfer functions of inverter current control loop [8].

Starting from the equivalent forward transfer function, a Proportional-Integral-Derivative (PID) controller is adopted in order to remove the dominant time constants (the constants of the DC-link circuit). The following specific constants are used:

K_p, K_R and K_{Ti} – the proportional constants of the controller, rectifier and current transducer, respectively;

T_i and T_d – integral and derivative controllers' time constants;

T_μ - the rectifier's integral time constant which corresponds to the average dead-time associated to the firing circuit;

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$T_{ed} = R_d \cdot C_d$ and $T_{emd} = L_d / R_d$ - the electric and electromagnetic time constants of the DC-link circuit;

$T_{ema} = L_a / R_a$ - the electromagnetic time constant of the matching inductor;

$T_{eb} = R_b \cdot C$ and $T_{emb} = L_b / R_b$ - the electric and electromagnetic time constants of the parallel resonant circuit.

Note that L_b and R_b are associated to the equivalent inductance and resistance of the induction coil and heated piece and C is the capacitance of the resonant capacitor.

The transducer was taken into consideration as proportional element.

The transfer function of the equivalent matching and resonant circuit shown in Fig. 2 can be written in following form:

$$G_{MR}(s) = \frac{I_i(s)}{U_i(s)} = \\ = \frac{1/R_a \cdot \left(1 + T_{eb} s + T_{eb} T_{emb} s^2\right)}{R_b/R_a \cdot (1 + T_{emb} s) + (1 + T_{ema} s) \cdot \left(1 + T_{eb} s + T_{eb} T_{emb} s^2\right)}. \quad (1)$$

where $I_i(s)$ and $U_i(s)$ are the inverter output current and voltage in the Laplace domain. Since $T_{eb} T_{emb} \ll T_{eb}$ and $R_b / R_a \ll 1$, expression (1) becomes:

$$G_{MR}(s) \approx (1/R_a)/(1 + T_{ema} s). \quad (2)$$

III. TUNING THE CURRENT CONTROLLER

The current controller design is based on Modulus Optimum criterion in Kessler variant, which is dedicated to the rapid systems [9].

To reach the square modulus of the closed-loop unity feedback transfer function, the open-loop transfer function is expressed first as:

$$G_{di}(s) = G_{Ri}(s) \cdot G_R(s) \cdot G_{DC}(s) \cdot G_{inv}(s) \cdot \\ \cdot G_{MR}(s) \cdot K_{Ti}. \quad (3)$$

By using the transfer functions shown in Fig. 2 and expression (2), the following expression is obtained:

$$G_{di}(s) = \frac{1 + K_p T_i s + T_i T_d s^2}{s T_i} \cdot \\ \cdot \frac{K_R \cdot (2/\pi) \cdot K_{Ti} \cdot (1/R_a)}{(1 + sT_\mu) \cdot (1 + sT_{ema}) \cdot \left(1 + T_{ed} s + T_{emd} T_{ed} s^2\right)}. \quad (4)$$

To remove the dominant time constants of the DC-link circuit, in accordance with MO criterion, two conditions are imposed in (4):

$$K_p T_i = T_{ed}; \quad T_i T_d = T_{emd} T_{ed}. \quad (5)$$

Thus, expression (4) becomes:

$$G_{di}(s) = \frac{K_I}{sT_i \cdot (1 + sT_\mu) \cdot (1 + sT_{ema})}, \quad (6)$$

where

$$K_I = K_R \cdot (2/\pi) \cdot K_{Ti} \cdot (1/R_a). \quad (7)$$

Next, based on (6), the transfer function of the closed-loop unity feedback system is written as:

$$G_i(s) = \frac{1}{1 + (1/G_{di}(s))} = \\ = \frac{1}{1 + \left[sT_i \cdot (1 + sT_\mu) \cdot (1 + sT_{ema}) / K_I\right]}, \quad (8)$$

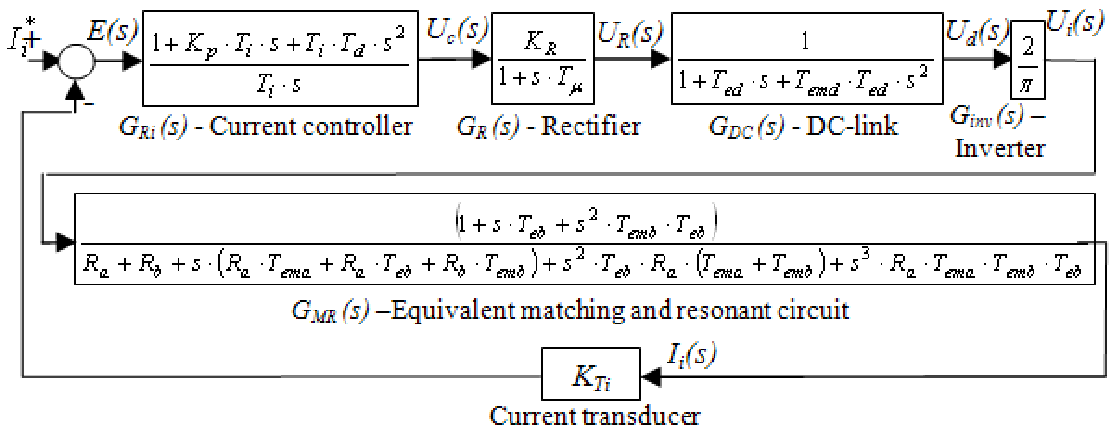

Figure 2. Block diagram of the closed loop control system.

and, after some processing, the square of its modulus can be expressed as:

$$|G(j\omega)|^2 = \frac{1}{1 + K_2 \cdot \omega^2 + K_4 \cdot \omega^4 + K_6 \cdot \omega^6}, \quad (9)$$

where:

$$K_2 = \frac{T_i}{K_I}\left[\frac{T_i}{K_I} - 2(T_\mu + T_{ema})\right]; \quad (10)$$

$$K_4 = \frac{T_i^2}{K_I^2}\left(T_{ema}^2 + T_\mu^2\right); \quad (11)$$

$$K_6 = \frac{T_i^2}{K_I^2} T_{ema}^2 T_\mu^2 . \qquad (12)$$

Canceling the denominator term K_2 which contains a difference in (9), the expression of the integral time constant of the current controller is provided:

$$T_i = 2 \cdot K_I \cdot \left(T_\mu + T_{ema}\right). \qquad (13)$$

When used together with (5), condition (13) gives also the expressions of the proportional and derivative constants of the PID controller:

$$K_p = T_{ed} / \left[2K_I \cdot \left(T_\mu + T_{ema}\right)\right]; \qquad (14)$$

$$T_d = T_{ed} \cdot T_{emd} / \left[2K_I \cdot \left(T_\mu + T_{ema}\right)\right]. \qquad (15)$$

From (13) to (15), it is found that the controller's parameters are independent of load parameters, which is an important advantage.

For instance, for an induction heating system with the DC-link circuit of C_d=2000 μF, L_d=0.1mH and R_d=0.1Ω and the matching inductor of L_a=45 μH and R_a=0.1Ω, the resulting controller parameters are: T_i = 0.3388 s; T_d = 5.9 $\cdot 10^{-7}$ s; K_p=5.9 $\cdot 10^{-4}$.

IV. Control System Performance

To test the performances of the control system, the block diagram in Fig. 2 has been implemented under Matlab-Simulink environment (Fig. 3).

The control system response, in terms of the rms fundamental current at the inverter output for three types of heated pipes, when a prescribed step current is applied, is shown in Fig. 4 and Fig. 5. The induction coil and heated pipes parameters corresponds to real pieces from a leading Romanian manufacturer which produces seamless pipes for industrial applications. The equivalent parameters are given in Table I.

As it can be seen in Fig. 4a, by setting the rms current of 800 A to heat a pipe with a diameter of 210 mm and wall thickness of 10 mm (Φ210/10), the overshoot is of about 5 % and the transient regime ends in about 0.02 seconds. When the set value is reduced two times (400 A instead of 800 A), the response is improved, as there is no overshoot (Fig. 4b).

As shown in Fig. 5a, the set current of 800 A for the pipe Φ210/20 leads to similar performances of the control system compared with the case of the previous pipe (both the overshoot and the settling time are comparable).

In the case of the pipe Φ80/5, the performance is significantly better (Fig. 5b), meaning that practically no overshoot exists and the settling time is reduced to 0.014 seconds (over 25% less).

TABLE I. Equivalent Parameters of the Resonant Load

Φ210/10			Φ210/20			Φ80/5		
Rb (mΩ)	Lb (mH)	C (μF)	Rb (mΩ)	Lb (mH)	C (μF)	Rb (mΩ)	Lb (mH)	C (μF)
13.93	0.0148	198	6.55	0.0170	3000	26.8	0.0177	150

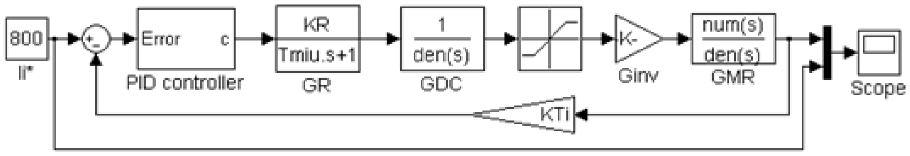

Figure 3. Simulink model of the closed loop control system.

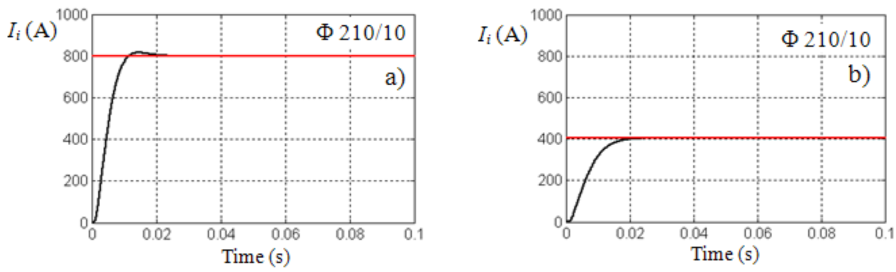

Figure 4. System step response for the pipe Φ 210/10: a) I_i^*=800 A; b) I_i^*=400 A.

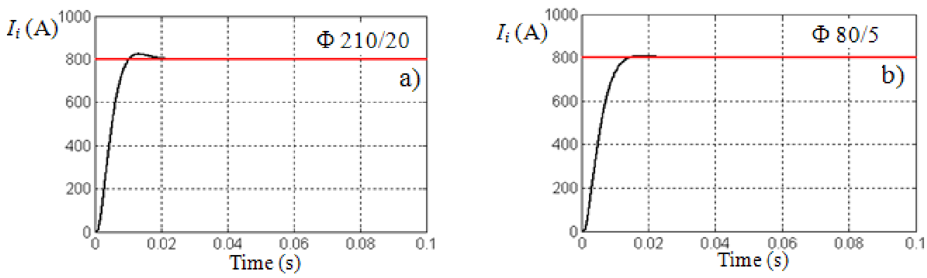

Figure 5. Step response for other heated pipes: a) Φ210/20; b) Φ80/5.

V. CONCLUSIONS

After designing the inverter current control loop followed by the performance testing through simulation, some concluding remarks can be drawn.

- The current controller of PID type was successfully tuned based on Modulus Optimum criterion in Kessler variant.
- The determination of the controller's parameters is unique and leads to the elimination of inertia introduced by the DC-link circuit.
- The tuned current controller leads to a very good performance of the current loop (the overshoot is missing or is below 5%) and the maximum duration of transient is 0.02 seconds).

Therefore, all prerequisites are created to achieve a high performance control system through the implementation in the experimental setup.

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