Control of Induction Heating Power Converter for Ferromagnetic Materials Melting

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Abstract – **The paper discusses the electronic control of Induction heater power converter for ferromagnetic materials melting working in independent excitation. The system of power electronic converters is composed by a controlled three-phase rectifier and parallel current source inverter. Analysis of regime with fixed current from the DC supply source has been made. This guarantees working with maximum power and respectively short meting process time.**

Keywords – **Frequency converters, Current source inverter Simulation, Controllers, Induction melting, Robust control, Power Electronics.**

I. Introduction

The control of electronic converters for supplying power for induction heating is important part of the technological process in the electrothermical devices. It is expected to provide normal operation of the converters, keeping the electrical regime of the electronic devices optimal and achieve best electrical properties [1-4, 6, 7, 9].

On the other side for the normal operation of the system of power electronic energy converters in the devices for induction heating it is necessary to achieve the following conditions [1, 4, 6, 7]:

• The consumed current from the supply unit I_d must not exceed the boundary value $I_{d\ adm}$;

• The inverted voltage and also the voltage over all circuit's elements must not exceed their maximum ratings;

• When using thyristor circuits (common practice in the ferromagnetic materials melting), the commutated turn-off time t_{qc} must be greater than the datasheet specified t_q for the elements.

For the utilization of such systems two methods of automated regulation of the electrical regime are possible for the converters [1, 7]:

• Stabilization of the inverted voltage U_T. This regime finds application in the devices for surface metal hardening and heaters with methodical operation, where it is necessary repetitiveness of the process of heating in periodical change of the molds;

• Stabilization of the consumed current I_d of fixed value. This is used in the devices for melting, because it guarantees working with maximum active power and respectively fastest melting of the metal.

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In the operation of the induction heating system in each of these regimes, it is observed change in the equivalent resistance of the load [1, 6, 7]. Because of that during the technological process it is possible disruption of the normal operation of the electronic converters.

The emphasis of the work is the control of a thyristor frequency converter, composed of three-phase rectifier and parallel current source inverter with active-inductive load.

II. Converter Model

The schematic of a parallel current source thyristor inverter is shown on Fig. 1. By the synthesis of the mathematical model are made the following assumptions:

• The pulsations from the DC source are not considered;

• The thyristors are simulated as ideal switches, the capacitors and inductors have no losses;

• The magnetic components are linear;

• The current commutation between the thyristor pairs is instantaneous.

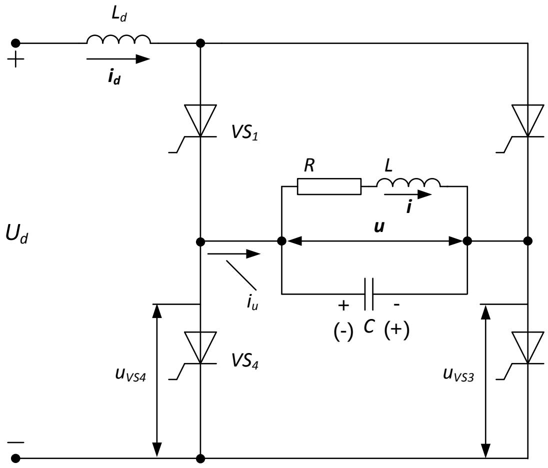

Fig. 1. Full Bridge parallel current source thyristor inverter with active-inductive load circuit.

The workings of the power circuit is discussed in [1, 7, 9]. In the mathematical representation of the inverter can be distinguished two structures [13]:

The first is when thyristors VS_1 and VS_3 are conducting and is assumed that this is through the positive half-waves of the inverted current n = 1, 3, 5... (n is the number of the half-wave);

and the second – when VS_2 and VS_4 are conducting through the negative half-waves n = 2, 4, 6... In order to illustrate these commutations a coefficient is defined:

$$k = \begin{cases} 1, & npu\ i + C\dfrac{du}{dt} > 0 \\ -1, & npu\ i + C\dfrac{du}{dt} < 0 \end{cases} \tag{1}$$

This approach allows unifying the differential equation system describing the two half-waves. A state vector is defined as:

$$x = \begin{vmatrix} u \\ i_d \\ i \end{vmatrix},$$

where:
u - the voltage of the capacitor;
i_d - input current;
i - load current.

If for the examined circuit is applied first and second Kirchhoff's laws and write down:

$$\dot{x} = Ax + bU_d, \tag{2}$$

where:
U_d - supply voltage and A and b matrices are:

$$A = \begin{vmatrix} 0 & \dfrac{k}{C} & -\dfrac{1}{C} \\ -\dfrac{k}{L_d} & 0 & 0 \\ \dfrac{1}{L} & 0 & -\dfrac{R}{L} \end{vmatrix} \qquad b = \begin{vmatrix} 0 \\ \dfrac{1}{Ld} \\ 0 \end{vmatrix} \tag{3}$$

The shown model is realized in Matlab software environment. When the DC–AC converter is working in melting regime, the changes of the load must be considered, which are described in detail in [1, 16] and shown on Fig. 2.

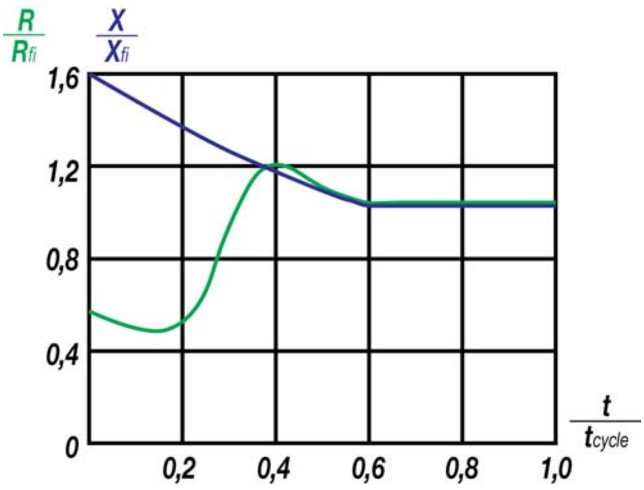

Fig. 2. Change of load paramaters during the melting

When melting ferromagnetic materials the technological process sets the following restrictions:

• input current - $I_D \le I_{Dmax}$; (4)
• output voltage of the converter - $U \le U_{max}$; (5)
• recovery time of the thyristors - $t_{qcmin} \le t_{qc} \le t_{qcmax}$; (6)
• minimum operating frequency in order the converter to work above resonance. (7)

The task is to operate the input current of the converter in the different regimes – warming (from cold) and melting (from hot). The control is done through varying the converter operating frequency

III. Control Algorithm

The control algorithm must allow effective operation at start-up of the system, working in warming regime, melting and processing disturbances in the input supply voltage channel.

Developing the control algorithm requires the following:

• Considering the restrictions (4) to (7);
• Comply with the settled current values, which are different for warming, transition and melting (Fig. 2)
• Choosing and setting up a regulator, that is robust in relation to changes of circuit's parameters.

The arrangement shown on Fig. 5 consists from four intervals:

• for the interval $t \in [0;0.1]$ the current is rising linear for a soft start;
• for the interval $t \in [0.1;0.6]$ has constant value 80 A, according to the warm-up regime;
• for the interval $t \in [0.6;1]$ is arranged linear change of load parameters with respect for transition from warm-up to melting regime;
• for the interval $t \in [1.0;1.6]$ the current is constant at 200 A according to the melting regime.

In the moment $t = 1.2$ the supply voltage is lowered with 20% (Fig. 7).

The block diagram of the controller is shown on Fig. 3 [12]. This structure provides saturation of the integrator output (anti-windup) and saturation of the regulator output. This allows for restriction of the input current (4). The other restrictions (5) to (7) are satisfied with a rational arrangement of the inverter circuit's elements [6, 7].

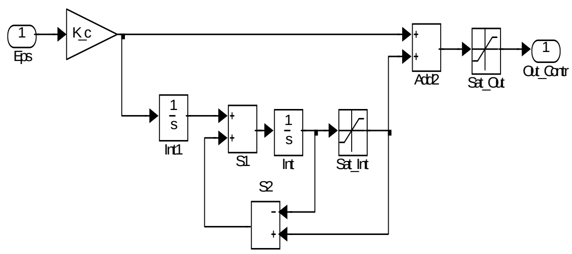

Fig. 3. Block diagram of the controller

IV. Modeling Results

The model block diagram is shown on Fig. 4. It is composed of the following elements – reference block (Reference), controller (Controller), converter controller to frequency (Converter contr to frequency), current FET converter (Current FET Converter), block supply voltage reference (Ref U), reference block loading coil (Ref L) and block assignment active resistance (Ref R).

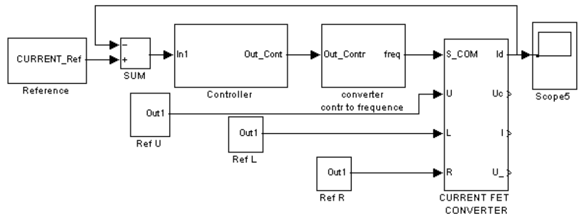

Fig. 4. Model block diagram of the technological device for metal melting

A current-source parallel inverter is designed according to [7, 8] with the following parameters in melting regime:

- active output power $P_T = 100$ kW;
- working frequency at the end of the process – $f = 2.4$ kHz;
- Power factor in the load $\cos(\varphi_T) = 0.1$;
- Output voltage in the load $U_T = 700$ VAC;
- Input voltage $U_d = 500$ VDC;

In warm-up regime is referenced input current $I_d = 80$ A, and in melting regime $I_d = 200$ A (Fig. 5).

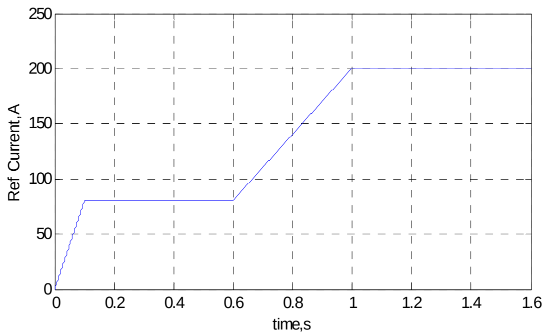

Fig. 5. Current reference

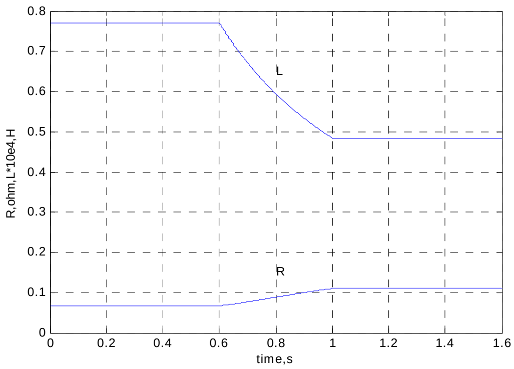

Fig. 6. Change of load parameters

The controller reference data must be set so, that the load parameters *R* and *L* (Fig. 6) doesn't affect the stability and quality of the processes in the technological device, that is to guarantee robust stability and quality [12] of the processes in the melting system.

Because of the thermal time constants are much greater from the electrical time constants in the inverter the main requirement is bound with the stability of the system, without having requirements to the transient processes in the converter. In the case it's inappropriate to use differential component mainly because of the presence of higher frequencies in the output (current) of the inverter. The control has significant reserve with respect to the rate of change of the load parameters *R* and *L*. In this paper is the entire time for the changing values of *R* and *L* is considered 0.4 seconds. In reality this time is several magnitudes higher.

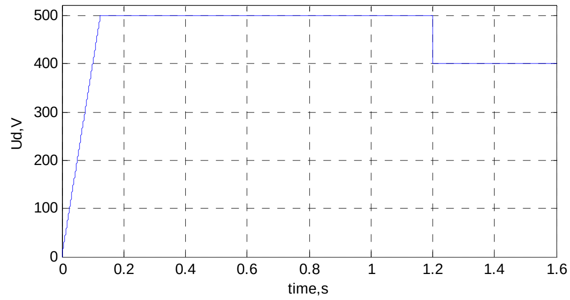

Fig. 7. Supply voltage change

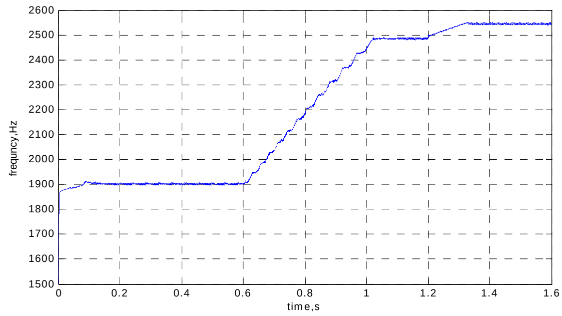

Fig. 8. Inverter operating frequency change

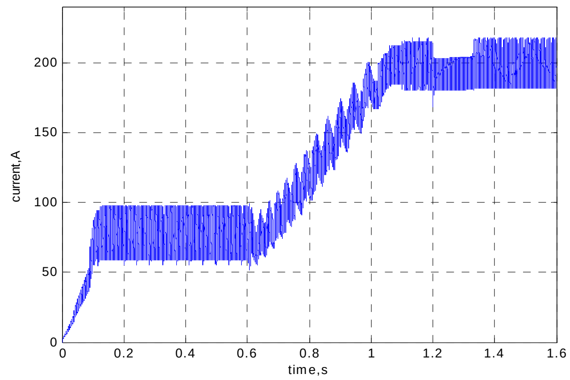

Fig. 9. Input current

In spite of the significant change in the resonant frequency of the parallel load circuit at the change of load parameters, the operating frequency (Fig. 8) is changing in the settled boundaries. This allows the operation of the system at high energy efficiency. At all regimes the inverter frequency is greater than the minimum allowed 1816 Hz.

From Fig. 7 and Fig. 9 is visible that the processing of a disturbance at the input supply voltage with the chosen controller is effective and with enough speed performance.

When comparing the results shown on (Fig. 5) and (Fig. 9) is determined that the processing of the parameters in all regimes is with enough accuracy.

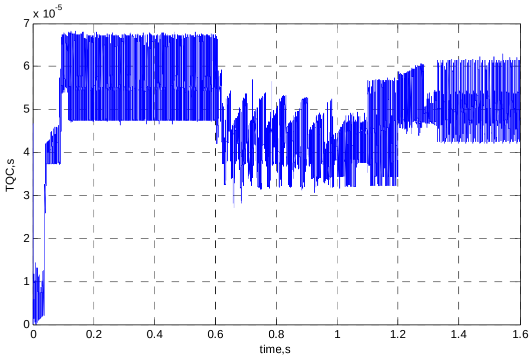

Fig. 10. Circuit's commutated turn-off time of the thyristors

V. CONCLUSION

As a result to the laid out above is determined that the system is designed correctly and is appropriate with the requirements of the technological process. A good control with guaranteed quality and high energy efficiencies is achieved.

The performance of the converter is proven to the changing parameters of the parallel load circuit with respect of the restrictions, set by the switching elements, at working frequencies maximum close to the resonant.

The realized method for control allows for the process to be controlled without regulation of the supply voltage. This rises the power factor and lowers the consumption of reactive power.

The system is with reserve for robustness, because the change of the parameters in the real process are significantly slower than these assumed in our research.

The use of classical tools for control simplifies the technological realization and rises the safety of the system.

From another point of view the system is unsusceptible to great changes in the supply voltage (up to 20%) which is the main disturbance at the work of these types of thermical devices in real production conditions.

The analysis of (Fig. 10) shows that the commutated turn-off time is in the boundaries defined by the data sheets. It is found out also that independently of the change of the supply voltage and the current reference to the controller, in the initial moment the circuit's commutated turn-off time for the thyristors is insufficient for the safe operation of the device. In this relation it is necessary to correct the control system with emphasis on eliminating this flaw or usage of another starting procedure [1, 7].

A future research on the system operation including the effect of the non-linearity of the inductive elements is considered useful alongside the expansion for other technological objects like the induction heating, welding and rectifier converters and others.

At higher quality requirements and speed performance at fixed robustness is possible and effective use of advanced control methods, in particular the model predictive control [15, 16].

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