Energy-efficient thyristor frequency converter with relay-frequency energy regulation for induction furnace

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Abstract. Here we investigate induction furnace electrical parameters with lump loading changeable liquid melt level in the melting pot, and frequency converter with advanced energy data, with hybrid control of electrical reset mode with frequency controlling and frequency converter reconfiguration in conditions of profoundly changing loads.

1. Introduction

Metals and alloys induction melting is widely used in different branches of industry, because induction furnaces are highly efficient, due to electro thermal conversion right in the melted metal. Induction furnaces are divided into melting furnaces and mixers used for overheating and soaking of the molten metal.

For high-quality steel melting open and vacuum induction crucible furnaces (ICF) are used. They have cubic content up to 2.5 tons, energy capacity up to 2.5 MGWatt. Depending on the cubic content ICF operate in the frequency range from 0.15 up to 10 kHz. ICFs successfully combine factors which favour controlling high precision loading processes. To increase efficiency coefficient and productivity, steel melting ICFs are powered with converters of average (increased) and high frequency, that allows increasing installation specific capacitance comparing with industrial frequency installations.

To power high capacity inductive installations (more than 250 kWt) thyristor frequency converters (TFC) with a three-phase rectifier and an inverter are widely used. To monitor a converter it is energetically efficient to control inverter power supply.

If the load changes dramatically, inventor out-put characteristics control due to supply variation results in TFC energy performance decrease, applied thyristors power-to-size ratio increase due to increased current operation with the same out-put capacity.

During quantified loading (QL) heating and melting, as well as liquid melt change in the melting pot furnace electrical parameters (active and reactive resistance) change significantly, that claims competent furnace and power source control to safe power and speed-up all technological process. It is important to match the parameters of the power source with loading parameters in order to operate in the name plate power mode. It is especially important to determine electrical parameters change dependencies of the system “inducer - load” during ferrous-magnetic QL heating and metal tapping from inductive crucible mixer (ICM), when these parameters change dramatically.
ICF and ICM system “inductor-load” electrical and power parameters change because: load materi-
al electro-physical properties change ($\rho$, $\mu$); liquid melt level change; load grain –size composition
change; melt surface shape changes; crucible erosion during operation.

2. Load parameters change investigation

With the experimental installation, whose construction is shown in fig. 1, ICF electrical parameters
dependences on QL heating temperatures are investigated. To simulate QL steel rods of 25 mm in
length of three diameters (1.1; 2.9 и 6.7 mm) were used. Influencing factors variation ranges were tak-
en: magnetic field strength $H = 6 \div 16.2$ kA/m, temperature $T = 40 \div 1000^\circ$C, inducer current frequen-
cy $f = 17.5$ kHz. ICF is powered with a transistor successive inventor with maximal dependable capacity of 2.5 KW and frequency 16 – 21 kHz.

To determine a function and its coefficients, ICF scale modeling has been carried out. This model is shown in picture 1, where $I$ is the inducer; 2 is QL; 3 is a thermal insulator; 4 is a refractory cruci-
ble. Model installation parameters are the following: $d_{1m} = 94$ mm, $d_{2m} = 67$ mm, $l_{1m} = 76$ mm, $l_{2m} = 113$ mm, inducer coils number $w = 6$.

With the current sensor CS1 and voltage sensor VS 1 actual power, consumed by the installation, was measured. Sensors CS2 and VS2 determine inductor current $I$ and voltage $U$ corre-
spondingly.

Fig. 2 shows the results of ICF model electrical parameters measuring. They are shown as dependencies families of active resistance $R$ and induction coefficient $L$ on temperature at different magnetic field strength on the inductor inner surface and QL rods diameters.

Using an inductively connected contours method the electrical parameters dependencies $R$ and $L$
(fig. 3) on the crucible filling coefficient with molten metal were calculated on the example of ICM - 4 in two cases: the first is when two inducer sections are used and coils take the whole crucible height, the second is when one section takes half of the crucible height. Mixer ICM – 4 technical parameters are: frequency $f = 50$ Hz, nominal capacity $P = 1000$ kW, one inducer section height $h_s = 520$ mm, inducer internal diameter $D = 1030$ mm, crucible diameter $d = 830$ mm.
Figure 3. ICM - 4 electrical parameters change depending on crucible filling coefficient with molten metal for two- (in blue) and single-section (in brown).

Furnace electrical parameters changes to a great extend \((R\) three times, \(L\) two times) forces to look for special ways of frequency converter controlling in order to achieve high energy efficiency of electro technological installation ETI [1].

3. Frequency converter with hybrid control implementation

Work [2] gives a detailed TFC scheme for matching with significantly changing load. Works [3-6] give examples of converter hybrid control systems for enhancing energy efficiency.

Figure 4. TFC functional scheme and the relay-frequency control system (1..6 – three-phase rectifier, 7, 8 – smoothing reactor, 9..21 – power rectifiers and loading contour elements, 22-voltage sensing device, 23-current sensor, 24 – a multiplier, 25 – a setpoint, 26 – three step controller, 27 – amplitude limiting multiplier, 28 – frequency sensor, 29 – phase control sensor, 30 – demultiplexer).

The suggested TFC with hybrid control (fig. 4) has broad options on out-put data control thanks to its reconfigurations; each of these configurations differs by the loading contour capacitors battery re-
active power. This way of matching with load is used in [7, 8]. Inventor faucets fastening angulations is possible in every configuration in limited conditions. It is caused by the following:

1. Voltage rise at thyristors of the current inventor bridge when angle of extinction increases;
2. Peak limiting in thyristors voltage discharge, power control intensity along the angle of extinction can be insignificant for load matching in the whole parameters variation range.

This TFC has three configurations. An alternative way of the reconfigured TFC parameters regulation is a relay three position control. A certain connection layout has a position at regulation (scheme 1 – thyristors 9, 10, 11, 12; scheme 2 – thyristors 9, 10, 17, 18; scheme 3 – thyristors 11, 12, 19, 20).

Hybrid control uses a relay-frequency controller. A relay part consists of the three-position controller. They provide high quality regulation for fast-response inertia objects, such as ICF with QL or ICM.

TFC parameters regulation is done according to actual power consumed by the frequency converter. So, the reconfigured TFC with three position control will switch over scheme 1 or scheme 2, or between scheme 2 and scheme 3. Every configuration has frequency regulation in rather small ranges. Mean value of the furnace active power will correspond to the relay-frequency set point regulator capacity.

With voltage sensor VS2 the control system determines frequency and magnitude TFC voltage output to control operational modes and acts as a feedback unit to keep the required angle of thyristors extinction in TFC.

Control in every scheme of the reconfigured TFC is done by self-starting principle, which provides voltage regulation characteristics stiffness and small output voltage dependence on the load parameters. There is no basic frequency generator in these control systems and voltage is fed into the drive circuit from the inventor AC circuit through the phase control device [9, 10]. This control system model is shown in fig.5a.
**Figure 5.** Self-starting TFC model with the relay-frequency control done in *Simulink*.

After TFC starts load power hybrid control system, whose model is represented in fig. 5b, functions in this way. Error signal goes from power set point to two non-linear links, in the form of two-position relays with hysteresis effect Relay1 and Relay2, one of them has operation and release thresholds in the range of positive errors, the other one – in the range of negative ones. Inventor circuit select input control the switches work (*Switch*), through which the control signals goes to the corresponding thyristors couples.

Figure 6а and 6b show time graphs of average power changes at control systems works of stepped variation of active resistance $R$ in the range $7.5 \div 30$ Mohm at $L = 25$ $\mu$H.

**Figure 6.** Power control diagrams step load resistance change: а – at decreasing resistance; б – at increasing resistance.

Diagrams in pic. 6 evidence that, control static accuracy makes at least $\pm 5\%$ at load parameters change ($R = 7.5 \div 30$ Mohm and $L = 20 \div 40$ $\mu$H). Three step controller parameters: energy set point is
500 kW, gap width $DB = 10$ kW, switching threshold $Relay1$ and $Relay2$ are 5 kW, hysteresis $h = 1$ kW, static coefficient of the chain transfer feedback $k = 1$, feedback RC constant is $T = 0.2$ s.

According to the investigations TFC control system model reconfigured in Simulink, control accuracy is at least $\pm 5\%$ in the wide range of the load changes at parameters given above control systems.

Average power deviations at furnace active resistance decrease by 2 times make not more than 20%.

4. **Conclusion**

The article presents mode control methods of ICF and ICM by its power source energy saving and melting process acceleration. Issues of electric power supply parameter with load parameters matching in order to provide inventor operation in nominal capacity mode.

The main results are as follows:

1. Experimental research of electrical and power characteristics of ICP with QL and ICM, which give dependencies of system electrical parameters to the system parameters “inducer–load” on environmental factors (temperature, magnetic field force, load lump size);
2. Adjustment method of ICP with QL or ICM source parameters with the reduced losses in the converter has been suggested;
3. ETI control system has been fulfilled to stabilize released load power and its characteristics are investigated.
4. High-efficient power source has been developed – thyristor inverter with the account of ICP parameters significant changes during melting and its components parameters have been determined.
5. ETI with ICP control system at ferromagnetic QL heating has been developed and its characteristics are investigated in Simulink.
6. TFC frequency control improves output power accuracy control at profoundly altering load.
7. Switching frequency between configurations declines, that complicates flicker filtration in the consumed circuit.
8. Sub harmonic components peak value declines by narrowing ambiguity area in the output TFC capacity characteristics.
9. Implementation of relay-frequency control is not more difficult than relay control.
10. Frequency control worsens TFC energy parameters on power wastes in converter switches.

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