

# Power supplies for dual-frequency induction melting of metals

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**Abstract.** The article discusses the benefits of multi frequency induction melting in the production of synthetic cast iron, structural (electric circuit) principles of dual frequency Power supplies of melting systems. The ways of electric power regulation of low frequency and high frequency components of the current in the inductor sections of furnace are demonstrated, namely power rescheduling at the metal melting stage, alloying stage and decarburizing of synthetic cast iron.

## 1. Introduction

Induction melting of metals in strong electromagnetic fields is widely used to obtain complex high homogenized alloys of ferrous and non-ferrous metals in modern foundry production of parts with high mechanical and physical characteristics. Undoubted advantages of medium frequency induction furnaces are: low energy consumption per ton of produced metal; batch regime of periodic melting (without "heel"); the high intensity of melting at high specific power of the electric power supplied to the metal; high performance of a metal production with a relatively low cost of induction furnace equipment.

Improving the performance of induction furnaces is provided by the increase of specific power at a higher current frequency in the furnace inductor [1]. However, both the power action of high frequency electromagnetic field to the molten metal, and the intensity of the magnetohydrodynamic (MHD) processes of metal mixing are decreased. To obtain a homogeneous alloy with high accuracy of temperature distribution in the molten bath, power supply of furnace is produced by high and low frequencies currents at different stages of melting [2].

## 2. Dual-frequency induction melting

In the existing induction melting systems multi-frequency power inductor furnace are implemented [3]. The main mode of heating and melting of the batch mixture is carried out when induction furnace is supplied by the high frequency currents close to the resonant frequency of the load circuit. To supply inductor furnace by low frequency currents it is necessary to reduce the resonance frequency of the load circuit, for example, by switching of series-connected blocks of compensating capacitors in parallel circuit connection to the inductor.

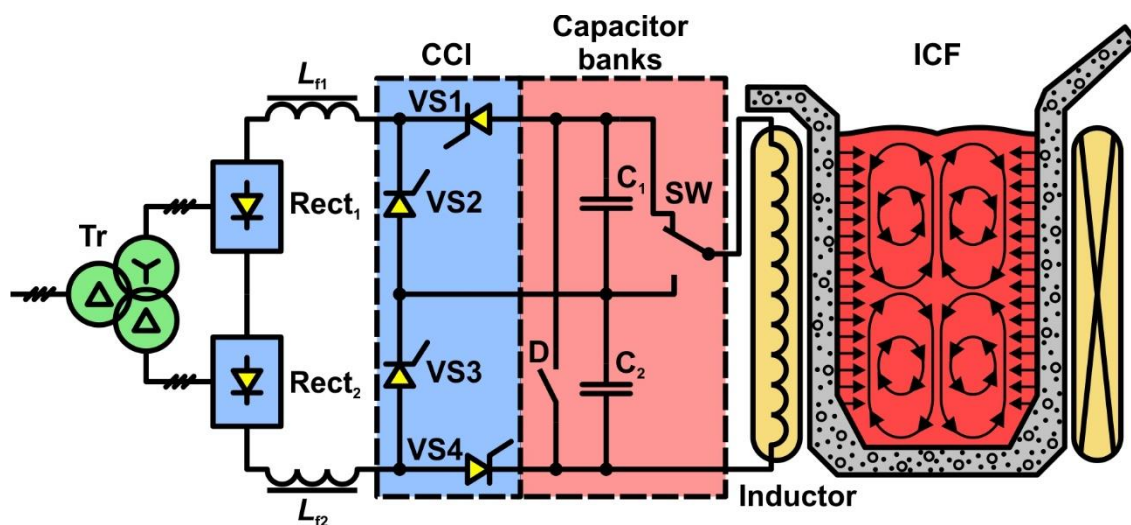
The Otto Junker Co. (Germany) offered the "Multi-Frequenz" technology, which was tested at the MAN Diesel foundry of grey iron in Denmark. Decarburization of metal was made by changing power supply mode of inductor furnace from 250Hz to 125Hz. Studies have shown that the duration of the



decarburization process was reduced to 1.5-2 times by increasing the metal speed of movement, thus energy consumption and the cost of production of synthetic cast iron were significantly reduced.

### 2.1. Changing power supply mode of furnace

Similar multi-frequency induction melting system was developed in the Ural Federal University and the Research and Production "RELTEC" Co. (Russia, Ekaterinburg) whose electric circuit is shown in figure 1 [4]. In this circuit, cascade current inverter (CCI) assembled on thyristors VS1, VS2 and VS3, VS4 is applied, which operates in synchronous mode of switching on the switch of the first and second cascade to the load circuit formed by series-connected capacitor banks (C1, C2) and furnace inductors (I).



**Figure 1.** Electrical circuit of the frequency converter with power mode switching of the furnace.

When operating at high frequency, voltage on the inductor is twice higher compared to the bridge circuit of the current inverter, which allows to reduce the level of the inductor current and reduce the active losses in the load circuit proportional to the square of the current. After melting the metal at the stage of technological alloying and decarburizing operations, the switching mode of the inductor's power supply is produced at low frequency by parallel switching of the compensating capacitor blocks by a disconnector (D) and connecting the inductor of the furnace with a switch (SW) to the diagonal of the alternating current of the inverter bridge VS1 ÷ VS4. Thus, the resonant frequency of the load circuit is halved and the voltage on it is also reduced by a factor of two by switching the current inverter circuit from cascade to bridge circuit, which in turn gives an opportunity to interface the load and the frequency converter parameters.

In this power supply system of induction crucible furnace power switch devices (D and SW) must be rated for full current of the inductor, which significantly complicates and increases the cost of the equipment.

Frequency change of inductor current increases the action on the molten metal and the metal speed of movement, but does not change the process of metal circulation in the two toroidal circuits, heat and mass transfer between them is negligible.

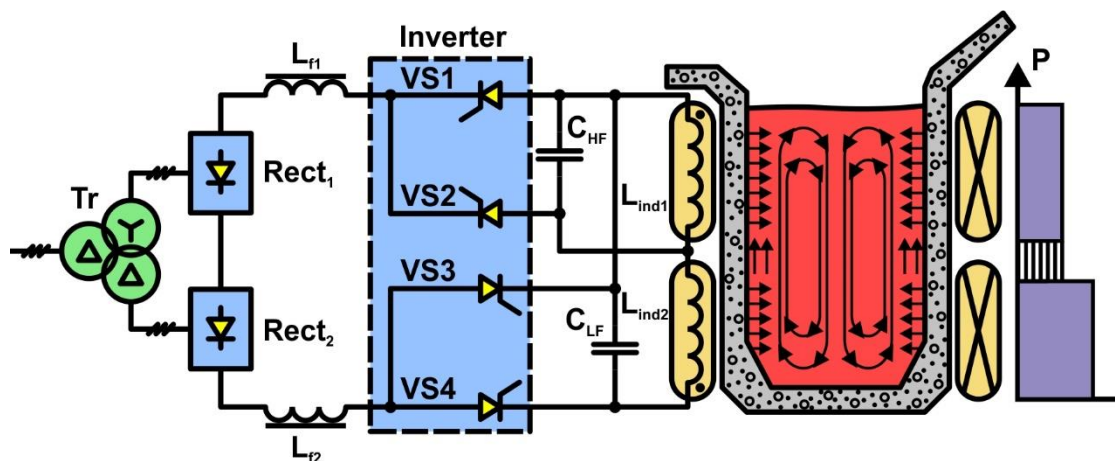
### 2.2. Dual-frequency power supply

To improve the efficiency of metal movement control the furnace inductor is expediently performed as a sectionalized and each section is better to be powered simultaneously with high and low frequency

currents, and at different stages of melting it is necessary to be able to change the ratio of high and low frequency currents as well as phase shift.

Power supply of the furnace inductor sections by low frequency currents allows increasing the electromagnetic pressure on the molten bath and the metal speed of movement, and by changing the ratio of the low-frequency current in the inductor sections and their phase shift, control of the direction of metal movement is achieved, which contributes to the expansion of technological capabilities and induction melting efficiency in obtaining exact alloys.

Thus, the simultaneous power supply of the crucible furnace with high and low frequency currents makes it possible to increase the efficiency of induction medium-frequency melting of metals and to expand the technological capabilities of the furnace by controlling the movement of the metal under the action of low-frequency currents. Figure 2 indicates the electric circuit diagram of a dual-frequency converter and induction crucible furnace, in which the inductor consists of two coaxially placed sections having right and left winding of turns in each section. Compensation of the reactive power of the furnace is carried out by high-frequency capacitors ( $C_{HF}$ ) connected in parallel with the upper section of the inductor, and low-frequency capacitors ( $C_{LF}$ ) cover both inductively connected sections of the inductor.



**Figure 2.** Schematic circuit of a dual-frequency converter and an induction crucible furnace with a diagram of the electromagnetic pressure.

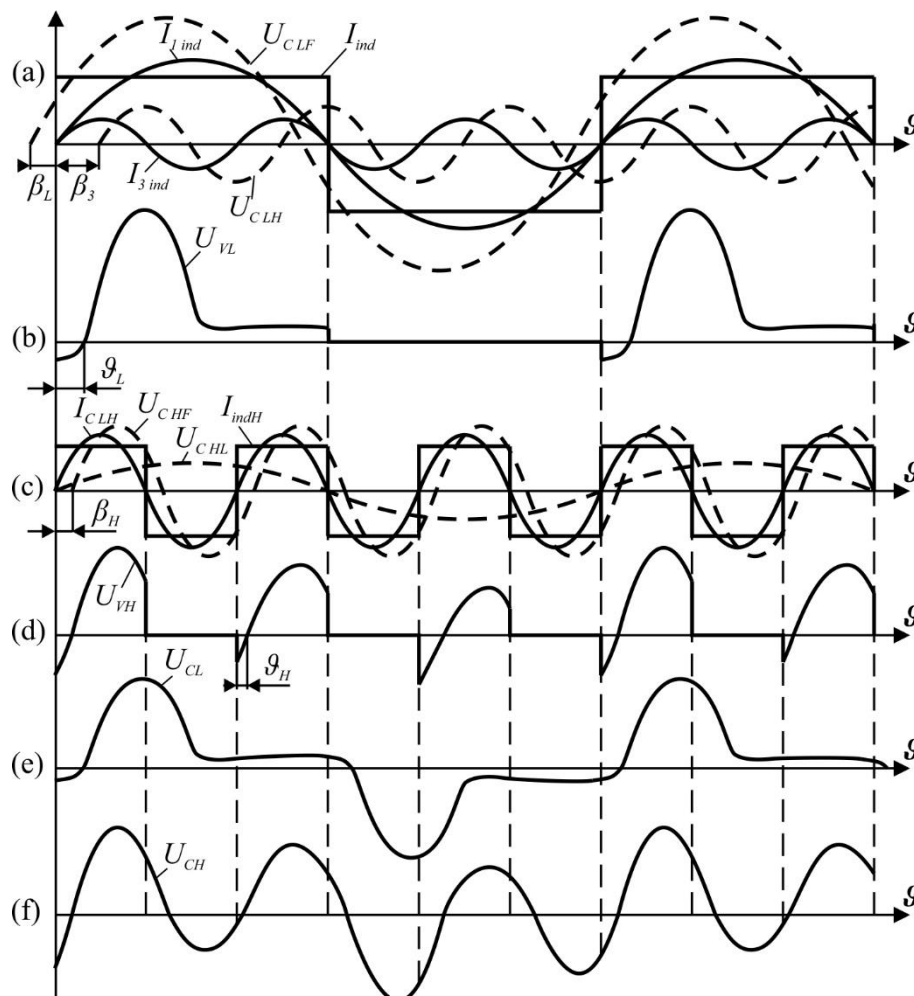
Two-circuit current inverter is connected by means of its output to a low-frequency and high-frequency capacitor. The high-frequency cascade of the inverter (VS1, VS2) operates at higher frequency in relation to normal frequency of the high-frequency load loop formed by the parallel sections of the inductor ( $L_{ind1}$ ,  $L_{ind2}$ ) through a low-frequency capacitor ( $C_{LF}$ ) and a high-frequency capacitor ( $C_{HF}$ ), therefore it allows commutating thyristors of this cascade.

Low frequency cascade inverter (VS3, VS4) operates synchronously with high frequency cascade at frequency which is in three times lower. In this case the normal frequency of the low frequency load circuit, formed by series connected sections of the inductor ( $L_{ind1}$ ,  $L_{ind2}$ ) and the capacitor low frequency ( $C_{LF}$ ), is to be slightly higher than the frequency of the low frequency of the cascade, and the conditions of switching of its thyristors are provided by a high-frequency component of the voltage on the capacitor low frequency ( $C_{LF}$ ).

Figure 3 demonstrates diagram of two-circuit current inverter operation. Low frequency cascade forms output current of the low frequency  $I_{ind}$  with rectangular shape (see figure 3(a)), which consists of main  $I_{1ind}$  and third harmonics  $I_{3ind}$ . Low frequency  $U_{CLF}$  and triple frequency  $U_{CLH}$  voltages are formed on the capacitor  $C_{LF}$ . They are shifted relative to the harmonic components of output current ( $\beta_L$  and  $\beta_3$ ). The total voltage  $U_{CL}$  on low frequency capacitor (see figure 3(e)) determines the voltage

at the thyristors of the low-frequency cascade  $U_{VL}$ , the diagram of which is shown in figure 3(b). Switching conditions of thyristors are provided by the presence of reverse voltage at the switching time of inverter  $\vartheta_L$ , the value of which is determined by the mode of high frequency cascade operation.

High frequency cascade forms the triple frequency output current with rectangular shape  $I_{indH}$  (figure 3). Main harmonic of that current  $I_{1indH}$  and voltage  $U_{CHF}$  (shifted in phase by the angle  $\beta_H$ ) at the high-frequency capacitor, determine the power of a high frequency cascade. Low-frequency current branches off high frequency capacitor. Branched current determines the low-frequency component of voltage  $U_{CHL}$ . High and low frequency total current at high frequency capacitor (see figure 3(f)) determines the voltage at the thyristors of the high-frequency cascade  $U_{VH}$ . Diagram of  $U_{VH}$  is shown in figure 3(d).



**Figure 3.** Diagram of two-circuit current inverter operation.

Thyristor switching conditions of high-frequency cascade are due to the presence of reverse voltage at the time of switching and due to recovery angle of thyristors  $\vartheta_H$ . Value of  $\vartheta_H$  is determined by the ratio of high and low frequency voltages.

Thus, the high-frequency cascade is leading at the inverter operation, and the low-frequency cascade is the trailing. When the control frequency of the high-frequency cascade increases, the degree of the operating frequency offset from the resonant frequency of the high-frequency load circuit increases, and the operating frequency of the low-frequency cascade, on the contrary, is close to the

resonant frequency of the low-frequency load circuit. As a result of control frequency regulating of the leading cascade, the ratio of the low and high frequency current components changes in the inductor sections, and consequently the required levels of the high-frequency and low-frequency current components in the inductor at different stages of the metal melting process can be established. At the stage of heating and melting of the batch mixture, a maximum level of high-frequency current is required, at which the most intense heat release in the metal occurs.

After melting and forming a liquid metal bath, it is advisable to carry out intensive movement and mixing of the metal under the power action of the low-frequency component of the current in the inductor, the value of which should be maximum, during the process of alloying, homogenizing and melt temperature balancing. Figure 2 shows a diagram of the electromagnetic pressure distribution over the height of a metal bath under the influence of low-frequency current components in the inductor sections. The electromagnetic normal pressure exerted by the upper section is slightly lower than that created by the lower section, because the upper section of the inductor is shunted by a high-frequency capacitor ( $C_{HF}$ ) and the level of low-frequency current in it is lower. In addition, the low-frequency current of the upper section is slightly behind the current in the lower section of the inductor, which is responsible for the effect of tangential electromagnetic forces on the molten metal directed upwards in the inter-winding space.

### 3. Control of the power

Analysis of inverter electromagnetic processes is advisable to perform by fundamental harmonic method because furnace power load circuits have high quality factor. Figure 4 shows a simplified equivalent circuit of a two-stage current inverter, working on low frequency circuit which in turn is formed by inductor series connected sections of the  $L_{ind1}$ ,  $L_{ind2}$  and low frequency capacitor  $C_{LF}$  and high frequency circuit which is represented by parallel connection of capacitors  $C_{HF}$ ,  $L_{ind1}$  inductor section and series-connected capacitor  $C_{LF}$  and  $L_{ind2}$  inductor sections.

Inverter low-frequency cascade which forms current rectangular shape  $I_{ind} = 0,5I_d$  can be replaced by a source of sinusoidal current of the fundamental harmonic

$$i_{(1)LF} = 0,45I_d \cdot \sin \omega t, \quad (1)$$

and also by the source of third harmonic component

$$i_{(3)HF} = 0,15I_d \cdot \sin 3\omega t. \quad (2)$$

High frequency inverter cascade works in cophasal mode with third harmonic component of low frequency current and at frequency which is 3 times higher than frequency of low-frequency cascade. High frequency inverter forms rectangular high frequency current  $I_{indH} = 0,5I_d$ . The main harmonic of this current can be defined as

$$i_{(1)HF} = 0,45I_d \cdot \sin 3\omega t. \quad (3)$$

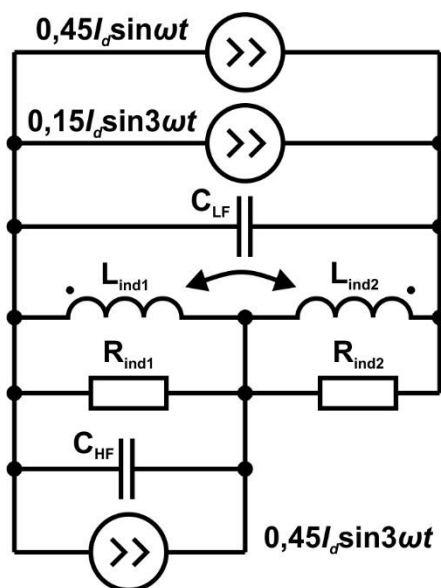
Capacitance of compensating capacitors  $C_{LF}$  и  $C_{HF}$  are selected on the basis of balance between resonant frequency of power circuits  $\omega_{0LF}$  и  $\omega_{0HF}$  and operating frequency of cascade inverter. However, to implement frequency control method of high and low frequency current levels  $K_I = I_{LF}/I_{HF}$  in the furnace inductor sections it is advisable to install the double ratio of natural frequencies oscillating circuits. If double ratio is installed than deep regulation of low and high currents frequency  $K_I = 1 \div 3,5$  is achieved and stabilization of the total power transmitted to load  $P_\Sigma$  is provided at the high and low frequency.

In the proposed circuit of a two-circuit parallel current inverter without switching devices, it is possible to control smoothly the low-frequency component of the current in the inductor sections of the furnace. At the stage of heating and melting the batch mixture, it is necessary to apply high level of the high-frequency component of the current in the inductor sections, at which the melting process is

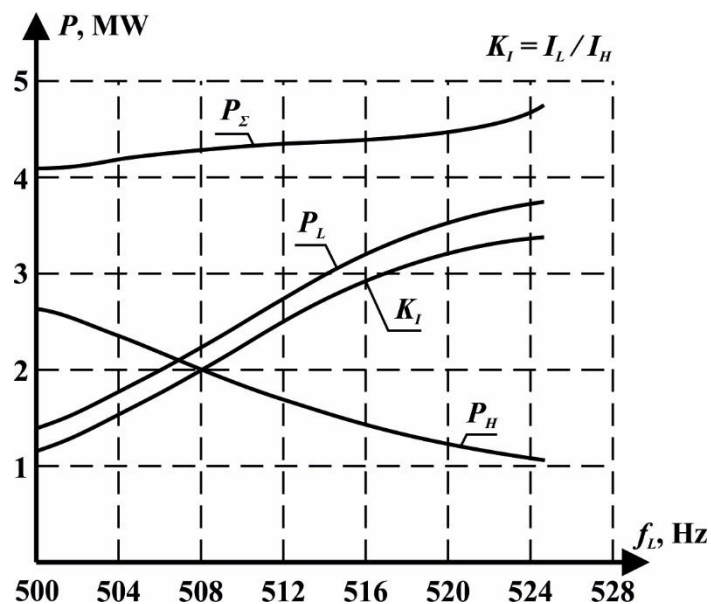


the most effective. At the stage of technological treatment of liquid metal (alloying, decarburization), it is necessary to increase the intensity of mixing by raising the level of the low-frequency component of the current in the inductor sections. In the proposed circuit, a smooth change of the ratio between low and high frequency component  $K_I$  is ensured by the correct choice of the ratio between normal frequencies of the low and high frequency load circuits. Regulation of this ratio is achieved by changing the control frequency of high frequency cascade,  $f_H$  and the frequency control of low frequency cascade should be three times smaller than  $f_L = 1/3 \cdot f_H$ .

Figure 5 demonstrates behaviour of total power transmitted to the load  $P_\Sigma$ , power of low-frequency cascade of  $P_L$ , high-frequency cascade  $P_H$  and the coefficient  $K_I$ . These characteristics are calculated for an 8 tons induction furnace. Characteristics show that stabilization of the total power  $P_\Sigma$  in the regulation of  $f_H$  is achieved by a significant change of  $K_I$  (about 3 times). This ensures electrical load constancy of converter power equipment elements and rate of melting metal. A significant change of low-frequency current component in the furnace inductor sections at the end of melting process allows to change the character of liquid metal movement and to convert it from a two-circuit toroidal motion to single-circuit toroidal motion throughout the bath volume. In addition, under the influence of low frequency currents metal speed of movement significantly increases, which contributes to acceleration of technological processes of alloying, temperature equalization in the molten metal bath, homogenization of alloy. In the production of synthetic cast iron control of the ratio between low and high frequency components of currents allows to reduce the decarburizing time by several times.



**Figure 4.** Equivalent circuit of a two-stage current inverter.



**Figure 5.** Frequency characteristics of the power supply.

#### 4. Conclusion

Studies of double-frequency melting induction systems of metals have shown that using multi-frequency heating makes it possible to realize flexible control of the heating and metal movement in the furnace bath through organization of necessary heat and force action of electromagnetic field. Thus it is possible to create new technologies for the production of high quality metals and alloys for cost-effective foundries.

Particularly, actual application of innovative technologies of metals induction melting becomes at the present stage of foundry factories development, allowing to diversify maximally foundry production at minimum costs.

### References

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