A group work of semiconductor resonant inverters of magnetically coupled induction systems

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Abstract. The paper presents the advantages of modular induction heating systems in the problems of group heating with individual power supply stations. When they are close to each other, a magnetic bond may occur between them. The paper shows the non-operability of power sources of magnetically coupled inductors. General principles of construction of noise-resistant magnetically coupled induction heating systems with individual power supply stations are given. A comparison and analysis of the stability of the power sources based on the current inverter and the voltage inverter has been carried out.

1. Introduction
In the metallurgical industry the induction heating devices have a power level up to several hundreds of kilowatts or megawatts. The frequency range of used power sources is from tens of Hz to MHz.

Modular systems are often used to implement induction heating of large parts [1], [2]. In which each of the modules is a complete induction system operating autonomously. Each of the modules provides the task of heating its individual zone [3], [4].

The use of modular structure of induction heaters has significant advantages in induction heating technology, since it allows optimizing the operation modes of equipment in relation to: energy consumption; the homogeneity of the heating [4-5], [5-6]. Therefore, the number of defects of the finished product can be minimized [7, 11], [1, 8].

However, such an architecture is not always realizable in practice due to the significant influence of closely located inductors of the modular induction system on each other [9]. The effect is the constantly changing nature of the response of the load circuit connected to the source. At the same time, the source impact parameters are stationary. As it known, for a certain type of inverter, on the basis of which the power source is built, a certain type of reaction is obligatory. And the work of the inverter with an unusual detuning is emergency.

2. Group work of static frequency converters
In the presence of a magnetic coupling between the inductors, instability in the operation of their power sources may be observed [10].

Figure 1 shows graphs of the output parameters of a semiconductor resonant inverter operating in the presence of a magnetic coupling between two inductors, with the simultaneous operation of their power supplies. In view of the fact that the current and voltage inverter are dual, the forms of their actions and reactions are proportional to each other. In figure 1 X1(t) is the reaction of the resonance circuit, i.e., the voltage across the loop while the inverter current is applied to the circuit, or the current...
of the resonant circuit when the voltage inverter is applied to the circuit. \( Y(t) \) is the effect on the resonant contour in the form of a meander whose shape is valid for both the inventor current (i.e., then \( Y(t) \) is the output current of the inverter current) and for the voltage inverter (i.e., then \( Y(t) \) is the output voltage of the voltage inverter). The abscissa represents the time in increments in relative periods, which is inversely proportional to the frequency of the output effect of the inverter that is under consideration. The absolute value for time \( t \) is defined as the ratio \( n/f_1 \), where \( n \) is a natural number that determines a period number, and \( f_1 \) is the frequency of operation of the inverter that is under consideration. The value along the ordinate axis of the graph \( X_{11}(t): \pm X_{1m} \) is the response amplitude of the load circuit generated by the considered inverter; \( \pm X_{1m} \) is the total amplitude of the reaction, the value of which depends on several parameters considered below. The ordinate value of the graph \( Y(t): \pm Y_m \) is the amplitude of the effect of the full spectrum of the inverter, regardless of the type, on the resonance load circuit.

The figure 1 shows that the loop response is significantly different from the regular one [12], since the operating circuit is influenced (in one way or another) by two inverters with different operating parameters. The first inverter directly affects the load circuit, and the second through the magnetic coupling of the inductors. Consequently, the final reaction, which is obtained by adding the two described effects to the circuit, changes with time, both in amplitude and in nature. It can be seen that in the time interval \( 3/f_1-7/f_1 \), the resultant response of the contour \( X_1(t) \) outruns the action of \( Y(t) \), i.e., for the inverter, the voltage response will be capacitive, and for the inverter current it will be inductive. On the time interval \( 7/f_1-9/f_1 \), \( X_1(t) \) has a purely active character and is perceived by both types of inverters as a resistance, just as in this time interval the amplitude \( X_{1m} \) is maximal. At the interval \( 9 f_1-12/f_1 \) \( X_1(t) \) falls behind \( X_2(t) \), that is, for the voltage inverter the reaction is inductive, and for the inverter current it is capacitive. In sections \( 2/f_1-3/f_1 \) and \( 12/f_1-13/f_1 \), the reaction is also active, but its amplitude practically equals zero.

Figure 2 shows a vector diagram, which illustrates such a significant change of the resonance circuit reaction (Figure 1). For simplicity, the action on the loading contour \( Y \) is directed along the real axis of coordinates. It can be seen that the resultant \( X_1 \) reaction circumscribes a circle around the end of the reaction vector generated by the inverter under consideration, \( X_{11} \), and, as a result, both its amplitude and its nature time change. The vector \( X_1 \) is the sum of the vectors \( X_{11} \) (reaction to the effect of directly connected inverter) and \( X_{12} \) (the reaction of the circuit to the induced EMF from the magnetically coupled inductor) [10]. Since the frequency of the inverter of a magnetically connected inductor is different from the frequency of operation of the considered inverter, then with each time interval equal to \( 1/f_1 \) the position \( X_{12} \), with respect to \( X_{11} \) will differ from the previous one, as a result \( X_1 \) varies in amplitude and character with respect to \( Y \). The frequency of rotation \( \omega_1 \) of the \( X_1 \) vector around \( X_{11} \) is equal to the difference between the frequencies of \( X_{12} \) and \( X_{11} \), while if the rotational speed of \( X_{12} \) (\( \omega_2 \)) is greater than the frequency of \( X_{11} \) (\( \omega_1 \)), then the resulting vector rotates counterclockwise, and if less, then vice versa.
3. **Basic principles for achieving stable operation of power supplies of magnetically coupled inductors**

In the presence of a magnetic coupling between the inductors, instability in the operation of their power sources may be observed. According to this construction, such induction systems are unique technological complexes [11]. However, the method described in the work allows us to solve the problem of constructing magnetically coupled induction systems with individual power supply stations without the use of complex circuit solutions.

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**Figure 1.** Graphs of the output parameters of a semiconductor resonant inverter in relative units of the operating period of the inverter: a - without applying measures to reduce mutual influence; b - with application of measures to reduce mutual influence.

**Figure 2.** Vector diagram with equality of the amplitudes of the effects on the load circuit of the 2 inverters.
The Figure 3 presents the scheme, allowing to determine the amount of induced interference on a magnetically coupled circuit. At the same time, the contour from the side of which the review takes place is designated as “countour 1”, and magnetically connected with it, as “countour 2”. According to the principle of superposition, to determine the reaction induced on a magnetically coupled circuit, it suffices to conduct consideration from only one source. Figure 4 shows the induced reaction on the adjacent contour in conventional units of frequency, where f1, f2 are the resonant frequencies of the magnetically coupled circuits, the frequency f1 is the resonant frequency of the load circuit, and f2 is the magnetically coupled circuit. It can be seen that X12(f) has two local maximums: at the resonance frequency of the intrinsic circuit and at a frequency close to the resonance frequency of the neighbouring contour. Also, there are the modules of the imaginary and real parts of the response of the loading circuit in the graph. Therefore, it can be seen that with a deviation from the frequency of the resonance, the amplitude of the induced interference sharply decreases, and the active component of the reaction also decreases, but the reactive component increases (within certain limits). Also, with the inequality of the resonant frequencies of the magnetically coupled circuits, the guidance on the magnetically coupled is limited due to the fact that the magnetically coupled circuit has a significantly reactive resistance at the operating frequency of the considered one. The maximum is observed due to the fact that at the resonance frequency of the circuit under consideration, the amplitude of its response is maximum - hence, the maximum magnetically coupled one is maximum. At the resonance frequency of a magnetically coupled loop, the noise on it from the circuit under consideration also has a maximum due to the fact that at this frequency the magnetically coupled circuit is most susceptible to the effect of the source of the circuit in question.

Figure 3. Circuit for the study of guided serial and parallel magnetically coupled circuits.

Figure 4. The dependence of the reaction on the frequency without magneting coupling and dependence of the modulus of the induced reaction on the frequency.

Figure 5 depicts hodograph of the reaction on parallel counter with stabilizing of the active component of full power and the active component of the reaction equal to 1. When you leave the resonance frequency of the parallel oscillatory circuit, the consumption power starts growing substantially.

However, due to the current of the solutions used in the inverter, the active power can be stabilized upon leaving the resonance frequency. Therefore, the reactive component of the reaction grows and practically becomes modulo the same as at the resonance frequency.

Figure 6 depicts the hodograph of the reaction of a sequential circuit with a maximum of the active component of the reaction equal to 1, and the vector of action for simplification is directed along the real axis of the coordinate. When a deviation from the resonance frequency of the parallel oscillatory circuit takes place, just like in the previous case, the amplitude of the induced interference decreases.
However, the maximum of the reactive component remains at the level of 0.5 versus 0.83 for the parallel inverter. In addition, at 0.5:0.5 (figure 6), the output power of the inverter is reduced exactly by 2 times, because the amplitude of the reaction decreases by 1.41 times. The reactive component of the inverter current response is bigger since they usually have the possibility of stabilizing the output power, depending on the frequency. The stabilization power is implemented due to the fact that active components, such as a chopper or a rectifier that allows reducing the supply voltage of the inverter, are adopted in the resonant inverter current. However, the currents of the inverter are substantially increased. Thus, the semiconductor switches must be selected with a reserve current, for the possibility of transferring all the power (active and reactive) to the load, since the presented method requires significant inverter power to circulate through the inverter [12].

On Figure 7 the output parameters of a semiconductor resonant inverter in relative units of the inverter operating period is shown. It can be seen that with the implementation of measures to reduce mutual influence reaction has a purely active character:
- deviation of operating frequencies from resonance frequency
- the separation of the resonant frequencies of the circuits.

**Figure 5.** Hodograph of the reaction of a parallel circuit with the active component of the power stabilized on it. **Figure 6.** Hodograph of the series resonant circuit.
Figure 7. Graphs of output parameters of a semiconductor resonant inverter in relative units of the period of operation of the inverter when performing measures to reduce the mutual influence.

4. Conclusions

It is shown that, due to the magnetic coupling, the resultant reaction of the load circuit varies with the invariance of the operating parameters of the inverters, both in nature and in amplitude. This is dangerous because transistor inverters of both types do not work optimally for capacitive detuning of the load circuit there is also a risk of exceeding the nominal parameters of the semiconductor switches of the inverters (voltage for the inverter current and current for the voltage inverter) [13], [14]. For thyristor converters, such a change in the reaction has an even greater effect, since the thyristor inverter loses control when it goes into inductive detuning. That is, this mode of operation for all listed types of converters is emergency and not valid [15].

Constantly changing at each period of the output frequency of the nature of the reaction is associated with the addition of several different-frequency oscillations in consequence of which there is a negative effect described in the work. The method consists in the following: differential resonant frequencies of the circuits of magnetically coupled inductors, which reduce the mutual induced reactions of the circuits of the inductors to an acceptable level; the location of the vector reaction to the impact of the connected source must be such that the vector of the final reaction is always located in the same fourth vector diagram.

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