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Impedance matching in dual-frequency induction heating systems

***Abstract**. The paper discusses the issues of impedance matching occurring between the source and the load in induction heating systems. The problem of impedance matching related to the skin effect that occurs in the systems for dual-frequency heating, especially those fed from a single-inverter topology source, is pointed out. Two new topologies of resonance high-current circuits of dual-frequency induction heating generators were proposed in which it is possible to regulate the ratio of substitute resistances occurring for low and high resonance frequency.*

***Streszczenie.** W pracy omówiono zagadnienia dopasowania impedancyjnego występującego między źródłem a obciążeniem w układach nagrzewania indukcyjnego. Wskazano na problem dopasowania impedancyjnego związany ze zjawiskiem naskórkowości jaki występuje w układach do nagrzewania dwuczęstotliwościowego, szczególnie zasilanych ze źródła o topologii jedno-falownikowej. Zaproponowano dwie nowe topologie rezonansowych obwodów silnoprądowych generatorów do indukcyjnego nagrzewania dwuczęstotliwościowego, w których możliwe jest regulowanie stosunku rezystancji zastępczych występujących dla niskiej i wysokiej częstotliwości rezonansowej. (**Dopasowanie impedancyjne w układach do indukcyjnego nagrzewania dwuczęstotliwościowego**)*

Keywords: induction heating, dual frequency, impedance matching.
Słowa kluczowe: nagrzewanie indukcyjne, dwuczęstotliwościowe, dopasowanie impedancyjne.

Introduction

The intensive development of inductive heating technology led to the creation of many different concepts of power supply generators for induction heating systems (IHS). A variety of solutions concern both the power electronics used, the power circuits, and the control algorithms. The specificity of the realized technology and the object itself (charge) impose specific requirements and poses the task of finding the optimal solution to the constructor. A special case of power sources used for induction heating are dual-frequency generators. Their unique properties allow for independent control of the heating process of the material layers at different depths. This specificity of the operation allows, among other things, the thermal treatment of concave-convex charges with complex shape [1] like, for example, gear wheels [2, 3].

There are several different types of power generators available today, which differently allow for the simultaneous induction of two frequencies current in the load.

One of the more popular ways (which can be called “double- inverter" topology) is to create separate power supplies for high (HF) and medium frequency (MF) and provide separation between converters by using filters [4], Fig.1a.

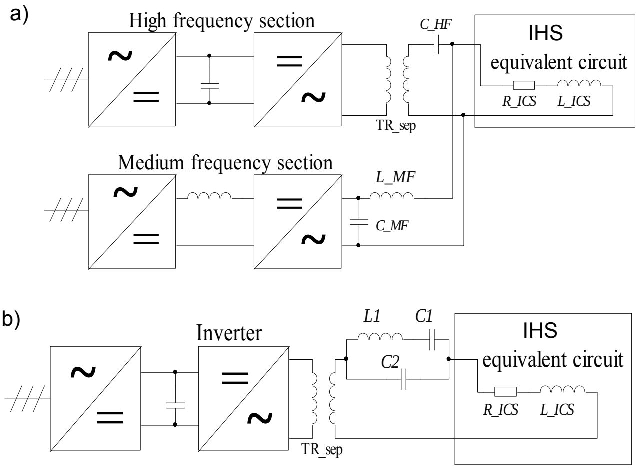


Fig.1. Typical topologies of generators for simultaneous dual-frequency heating: a) "double- inverter " topology, b) "single-inverter" topology

Each converter operates independently, but for one common load (inductor-charge system), and can be implemented as a current or voltage inverter.
The example of simulation results of the current waveforms in the inductor in the case of equal power distribution for both HF and MF frequencies is shown in Fig.2.

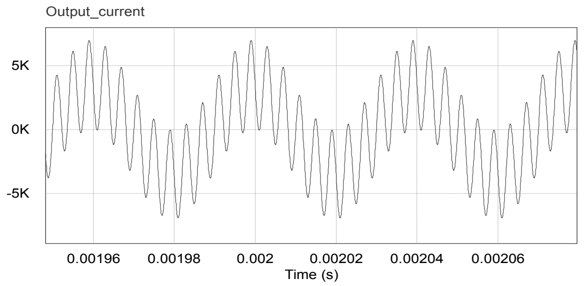


Fig. 2. The simulation results of the inductor current waveform for equal power, in a load with constant resistance, for both HF and MF frequencies.

Another method (which can be called “single-inverter" topology) is to use one converter in the resonance generator, built usually as a full bridge, with higher then two order resonance system [5], in which two components of the current of different frequencies can be simultaneously formed. Such solution, with 3rd order LCC coupling circuit, is shown in Fig.1b.

The values of the inductance and the capacitance of the coupling circuit are so chosen that two predefined serial resonance frequencies occur with the inductance of the IHS. In the first approximation we can say that elements $L1$ and $C1$ create together with the inductance of the induction heating system IHS a lower MF resonance circuit, while the $C2$ capacitance together with the inductance of IHS create a HF resonant circuit. By properly controlling the operation of the inverter using simultaneous overlapping and mutual modulation of the two control signals, an IHS current (current in inductor) is obtained which is the sum of two passes. This gives possibility to received the inductor current waveform similar as that, Fig. 2, received for “double- inverter" topology.

Apart from these two basic structures, there are other, less popular structures used mainly in low-power devices, such as a solution involving a cyclical change of resonant circuit parameters by shorting one of the two LC circuit capacitors [6]. It can be said that it is a dual-frequency pseudo generator, which alternately generates low and high frequency current in the load. This can cause a heating effect similar to that caused by a two-frequency signal generated simultaneous, Fig. 3. The division of the power to two different frequencies is accomplished by adjusting the ratio of the operating time with each of the two frequencies. For both frequencies there is a such value of the inductor current, which results from the resistance of the induction heating system and the voltage supplying the inverter, the same for both frequencies.

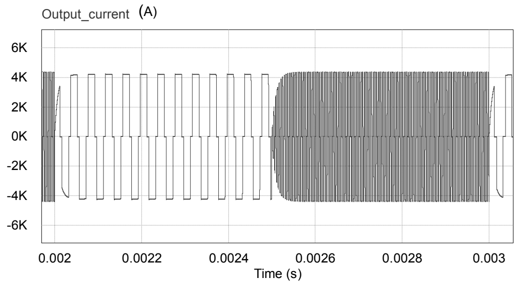


Fig. 3. An example of a current waveform in a dual frequency generator [6] with shorted capacitors.

Each of the solutions of dual-frequency generators, compared to classical solutions with a single resonance frequency, poses significantly higher construction requirements. These requirements are particularly important in processes with high variability of load parameters, of induction heating system. Each of the structures of the dual-frequency generators has different frequency ranges, another sensitivity to the variation of the parameters of the generator circuit and various possibilities of shaping the power division into particular frequencies.

The "single-inverter" topology, as in Fig. 1b, of the dual-frequency generator for induction heating, can be treated as a kind of extension of the generator construction for single-frequency induction heating, which from the commercial side (production plant) facilitates the unification of generator production. For that reason, solutions of this type were mainly analyzed in the further part of the paper.

Impedance matching of resonant inverter and induction heating system

In the induction heating station one can, from an electrical point of view, distinguish two cooperating, basic blocks: power supply and the so-called induction heating system which is an inductor with a charge.

The power source, which is usually a resonant transistor generator, with nominal power P_N, rated U_N voltage and output I_N current has a certain nominal value of the output impedance $Z_N=U_N/I_N$, which for the resonant generator is close to the nominal resistance $R_N = P_N / I_N^2 \approx Z_N$. For efficient transfer of energy from the source to the induction heating system, it is necessary that the source be loaded in a resonance state with a substitute value $R_{eq,ch}$ of load which is approximately equal to R_N. Only in such case it is possible to transfer from the source to the load (induction heating system) the energy at a maximum power similar to the rated power P_N without exceeding the rated current or voltage of the source. The value of the impedance of the source load, changing both in the function of the type of connected inductor-charge system as well as in the function of the charge temperature, makes it difficult or even impossible to obtain the rated load of the source, mainly the nominal power. This requires the use of specialized impedance matching systems for the inverter and induction heating system, Fig. 4, which applies to both single and dual frequency induction heating.

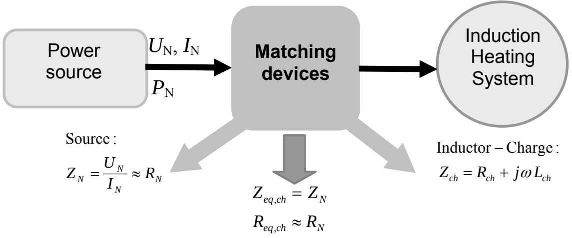


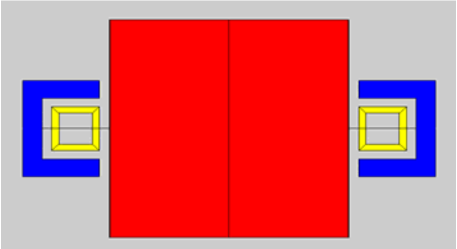
Fig. 4. Basic functional units of the induction heating station.

Its task is to transform the load impedance Z_{ch} so that its substitute value $Z_{eq,ch}$, and especially the resistance R_{ch} during resonance, will be approximately equal to the nominal resistance of the source $R_{eq,ch}=R_N$.

This task, both for single- and dual-frequency heating, is usually carried out by special constructions of matching transformers, serial or parallel connection of inverter modules or use of higher-order passive systems [7]. All of these solutions have the disadvantage because they fulfill only a static matching to one working point (one of the load resistance values), in addition they are not performed automatically by the power system, they require intervention of the station's service. For dual-frequency induction heating, such solutions are not at all the answer to the additional problem of impedance matching resulting from the skin effect.

Impedance matching in dual-frequency induction heating

Consider an example case of induction heating of steel cylindrical charge in a cylindrical inductor, Fig.5. Let's determine how the resistance of inductor-charge system changes when the power frequency changes in this non-linear magnetic system. Let us consider this change for the initial heating state ("cold state") in a situation where, with changing frequency, we want received the same value of power dissipated in the inductor-charge system.



Charge material ST235:

- resistivity: $\rho = 0{,}20 \cdot 10^{-6}(1+6 \cdot 10^{-3} \cdot T)[\Omega \mathrm{m}]$,
- magnetization: saturation: J=2[T], initial relative magnetic permeability μ_{rp}=600.

Fig. 5. An example of the inductor-charge system model.

Numerical analysis of the electromagnetic field was carried out based on the Maxwell equations:

$$\gamma \frac{d\mathbf{A}}{dt} + rot\,(\frac{1}{\mu} rot\,\mathbf{A}) = \mathbf{J} \tag{1}$$

$$\mathbf{H} = \frac{1}{\mu}\, rot\,\mathbf{A} \tag{2}$$

where: A – magnetic vector potential, **J** - current density, **H** - magnetic field strength, μ - magnetic permeability, γ - conductivity.

From the point of view of the efficiency of solving the Maxwell equations, it is advisable to use complex numbers, but this requires the assumption of sinusoidal electric and magnetic field, which leads to the assumption of the linearity of the environment. In the considered case the magnetic non-linear material of charge is used what contradicts this assumption. A certain mitigation of this contradiction may be the use of modified, substitute [8] magnetizing curves $B(H)$ in calculations. On the other hand, we should remember that especially when quality factor of induction heating setup Q>4, the participation of the higher harmonics in the inductor current usually does not exceed a few percent [9].

In this work, such a solution was adopted, deciding to implement field electromagnetic calculations using the commercial Flux® package with API interface [10]. In such case the equation (1) was reduced to the form:

$$j\omega\gamma\,\mathbf{A} + rot\,(\frac{1}{\mu}rot\,\mathbf{A}) = \mathbf{J} \tag{3}$$

where: $\omega = 2\cdot\pi\cdot f$ - pulsation, f - frequency.

The results of the conducted analysis, in the form of frequency characteristics of resistance and inductance of the inductor-charge system from Fig. 5 are shown in Fig.6.

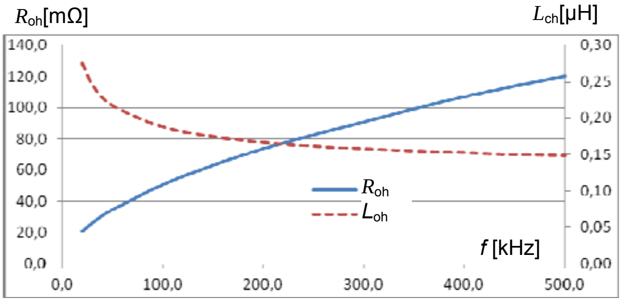


Fig. 6. Dependence of resistance and inductance of the inductor-charge system on frequency.

The value of the frequency has obviously the influence both the value of the calculated resistance and inductance. The determined changes were taken into account in the simulation of the work of the dual-frequency generator for induction heating with "single-inverter" topology, as in Fig. 1b.

The analysis of generator work was carried out as AC (frequency) analysis for the "single-inverter" topology model shown in Fig.7, by using commercial program Portunus.

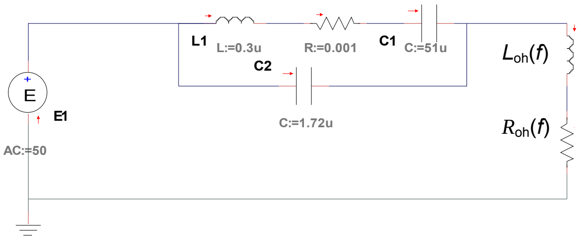


Fig.7. The single inverter topology generator model from Fig.1b.

The circuit method allows for relatively easy and quick analysis of both frequency and time of operation of the generator system for dual frequency heating, if constant values of load parameters are assumed. The problem becomes more complicated (specially in the time analysis) if you want to take into account the phenomenon of skin and approximation effect that change these parameters with frequency.

The AC analyses were made when the amplitude E1 of source was 50V, $C1$= 51μF, $C2$= 1.72μF. Two cases have been considered. First case in which was assumed that R_{ch} and L_{ch} are not change with frequency (it is often assume in circuit analyses) and second when $R_{ch}(f)$ and $L_{ch}(f)$ change as in Fig.6. In first case R_{ch} = 26mΩ, L_{ch} = 0.25μH, so as for f=30kHz in second case.

Figure 8 shows the waveforms of the power generated in the load and the angle of the phase shift between the current and the voltage of the supply source E1, for both considered cases, with constant (Fig. 8a) and varying with frequency (Fig. 8b) the electrical parameters of the load.

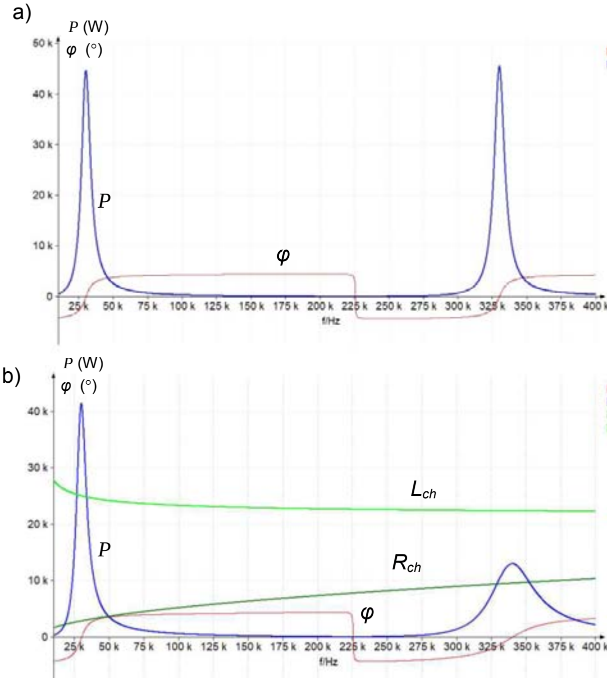


Fig.8. Changing the phase and load power as a function of operating frequency: a) for constant R_{ch}= 26 mΩ and L_{ch}=0.25 μH, b) for $R_{ch}(f)$ and $L_{ch}(f)$ varying as in Fig.6.

As can be noticed in Fig.8 for assumed resonant capacitances $C1$ and $C2$ in the system there are two resonant frequencies which values for constant parameter s of load (Fig.8a) are respectively MF≈30kHz and HF≈330kHz.

We see that the power values that are the same for a constant load resistance value (Fig.8a) vary significantly when considering the actual change in load resistance with frequency (Fig.8b). That show the problem of impedance matching typical for dual frequency induction heating.

In the known solutions of “single-inverter” dual frequency induction heating generators it is not possible to fully use their power for both middle MF and high HF resonance frequency. An impedance matched generator for one frequency can be loaded with a second frequency with a power several times less than the nominal one (without exceeding the permissible current or voltage). This is a serious technical limitation of these constructions. This work considered the possibility of eliminating this limitation.

New topology of generators for dual-frequency induction heating

Taking into account the limitations in the impedance matching of the generator for dual frequency heating, the works aimed at developing a new topology of a single-inverter dual-frequency generator devoid of the above-mentioned disadvantage were taken.

The work was directed towards the solution that gives the possibility of adjusting the proportions of substitute load resistances for HF and MF. At the final stage of the work, two solutions were focused. They are shown schematically in Fig.9.

The overall concept of the solution consisted in using passive systems of a higher order to obtain in the inductor-charge system (R_{ch}, L_{ch}) of resonant currents with different frequencies. In this sense, it is a concept similar to that described in [5], Fig.1b, where the LCC output circuit was used to obtain a series resonance at two different frequency values. In the proposed systems we deal with such a combination of passive elements, which leads to the possibility of occurrence of both series and parallel resonance, which gives much greater regulatory possibilities.

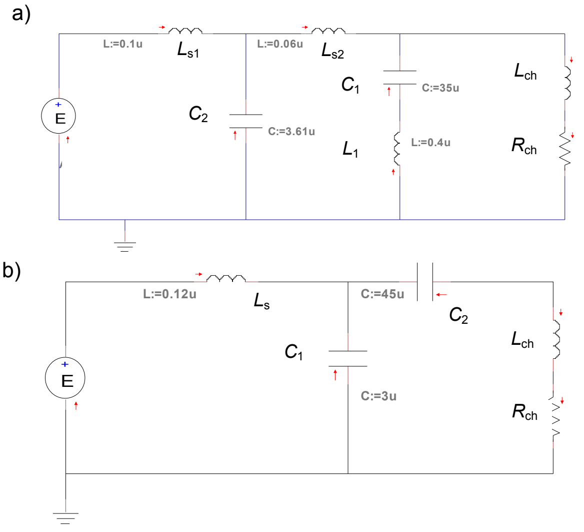


Fig.9. Concepts of high current circuits for dual frequency generators: a) a 5th order system, b) a 4th order system.

For the proposed topology in Fig.10 presents the relation of the power generated in the load (taking into account the change of the load resistance from the frequency) and the angle of the phase shift between the current and the output voltage of the inverter (source E, Fig.9).

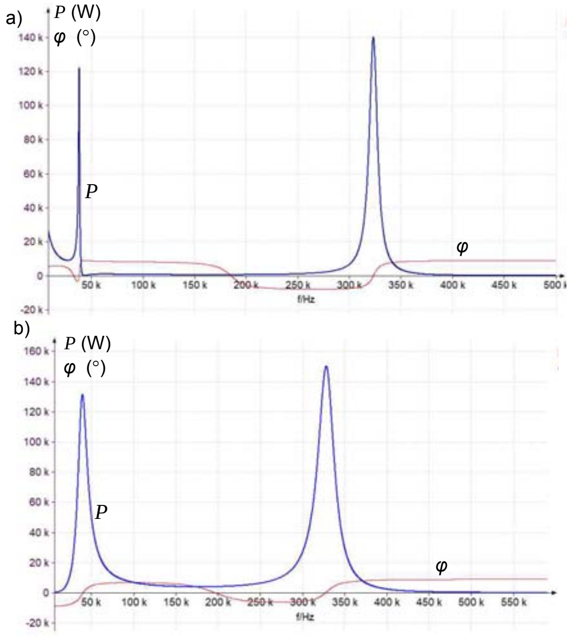


Fig.10. The frequency dependence of the active power in the load and the supply phase shift for the circuits shown respectively: a) in Fig. 9a, b) in Fig.9b.

In the solutions shown in Fig. 9, in addition to the possibility of obtaining two resonant frequencies, it is possible to change the substitute resistance of load. For topology from Fig. 9a, by changing L_{s1} and L_{s2}, it is possible to change the equivalent resistance of the load for the lower and upper resonant frequency, and for the solution from Fig. 9b it is possible mainly for the upper frequency by changing the inductance L_s. The conducted analysis indicated that the system from Fig. 9b shows better utility parameters. Its main advantage (in relation to the system in Fig. 9a) is the lower demand for reactive power, which transfers to smaller capacitor banks, a lower price.

Conclusions

The impedance matching is a significant problem for induction heating, in which we often have the need for heating by a given source the inductor-charge systems with a different impedance value. Also during the heating process itself, especially steel charge, there is a significant change in both the resistance and inductance of the inductor-charge system.

For a dual-frequency heating, the problem deepens due to differences in the charge resistances resulting from the skin effect. This phenomenon is rarely raised when discussing generators for dual frequency heating. The topologies of generator for dual-frequency induction heating based on the 4th and 5th order resonance systems proposed in the paper allow not only to achieve simultaneous impedance matching for both MF and HF, but also have the potential to regulate this degree of fit, depending on the user's needs.

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