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Impedance matching of the inverter for induction heating

***Abstract**. The impedance matching of source and load has influences on the ability to transfer power. In induction heating processes, the electrical parameters of the induction heating system can significantly differ. In the paper the comparison of sensitivity of power sources with different resonant systems on the changing the load impedance are presented. The possibility of increasing the elasticity of the inverter with LLC resonant circuit has been analyzed. The solution combining the controlled LLC circuit with a suitable algorithm has been proposed to automatically correct the substitute impedance of the load by the power source system.*

***Streszczenie.** Dopasowanie impedancyjne źródła i obciążenia decyduje o możliwość przekazywania mocy do obciążenia. Przy nagrzewaniu indukcyjnym parametry elektryczne indukcyjnego układu grzejnego mogą się znacząco różnić. W artykule porównano wrażliwość źródeł zasilania z różnymi układami rezonansowymi na zmianę impedancji obciążenia. Przeanalizowano możliwości zwiększenia elastyczności impedancyjnej źródła z układem rezonansowym LLC poprzez połączenie sterowanego układu LLC z odpowiednim algorytmem pozwalającym na samoczynne korygowanie przez źródło zasilania zastępczej impedancji obciążenia.(**Impedancyjne dopasowanie falownika do nagrzewania indukcyjnego**)*

Keywords: induction heating, inverter, impedance matching.
Słowa kluczowe: nagrzewanie indukcyjne, falownik, dopasowanie impedancyjne.

Introduction

Induction heating technology is widely applied in heat treatment processes. For more than a hundred years its development continues, both knowledge of phenomena occurring in heated material and new technologies of semiconductor power generation are introduced, which, together with the advances in microprocessor control and computer technology, enhances the parameters and functionality of built generators.

For over a hundred years it has continued both its permanent increase of knowledge about of phenomena occurring in heated material and new technologies of semiconductor power generation are being introduced which together with the advances in microprocessor control and IT technology, improves the parameters and functionality of built-in generators.

One of the very important functions of the power source is the flexibility the load impedance matching.

This concerns impedance matching of the source (usually the voltage inverter) to the varying load, both in the aspect of static changes (different types of inductor-charge systems) and dynamic ones occurring during the heating process, entailing changes in the magnetic and electrical properties of the charge material.

A poor impedance matching results in reducing of the energy transferred from the source to the charge. By using a standard constant-voltage ratio transformer, we can obtain static matching for only one load impedance.

In the literature [1, 2, 3], various concepts of complex passive adaptation systems are presented which together with the load form the 3rd or 4th order resonant circuits.

Compared to the standard LC 2nd order resonance circuit of voltage inverters, they have an additional capacitive or inductive reactance. Depending on the value of the used reactance, the different load impedance characteristic of the inverter output can be obtained.

This allows by change of the operating frequency and forced by it corresponding change of the value of the reactance to compensate impedance changes of the charge parameters, thus maintaining the transfer of energy from the source at the desired level.

Passive impedance matching systems can simultaneously function as a resonant circuit and a matching transformer, and analytic equations can be derived for them [4].

In one-frequency induction heating systems, 3-order systems consisting of two inductive and one capacitive elements of the LLC type or two capacitive and one inductive elements type LCC are most often considered [4].

In addition to its basic function, the impedance matching circuit should also reduce the effects of unwanted phenomena, hazard of various failures that may occur in the device, such as short circuit or control malfunctions. In the case of a fault in the inverter load circuit (rapid impedance change, short circuit or break in the inverter winding), the presence of series inductance limits the rate of change of the output current of the inverter so that the diagnostics and control will effectively will turned off the generator and eliminate any damage.

For this reason, in the frequency inverter for one-frequency induction heating especially are useful systems such as the LLC, which in their structure have a choke directly connected to the output terminals

The simulation results of the co-operation the power source and load [5-8] show the strong (both direct and indirect by varying the resonance frequency) influence of changing (with temperature) the load electrical parameters on impedance matching level. The results of the performed simulations of the LLC circuits [9] show that for the constant value of the additional inductance and resonant capacitor, the substitute circuit impedance value of this structure is strongly sensitive to changes in the load impedance, which from the point of view of the source-load impedance matching , can lead to even worse effects than in classic 2 order LC resonance circuits.

Applying of the resonant circuit LLC type for impedance matching of resonant inverter and load

Passive systems used in resonant inverters can simultaneously function both as a part of the resonant circuit and as the components of the impedance matching circuit. In this case, the matching system is usually complemented by a transformer that functions both as a matching system and as a galvanic separator.

The electric diagram representing loading of the inverter valves , is shown in Fig. 1. The equivalent load impedance (on the secondary side of the transformer) is defined as $Z_{\mathrm{eq,load}} = U_{\mathrm{z}} / I_{\mathrm{z}}$.

In the general case, two resonance frequencies are possible, under which the complex load impedance $Z_{\mathrm{eq,load}}$ is equal to a certain resonant resistance of load $R^{rez}_{eq,load}$.

The phenomenon of two voltage resonances for which imaginary part Im $\{Z_{\mathrm{eq,load}}\} = 0$ is due to the nature of change the imaginary part Im $\{Z_{\mathrm{row}}\}$ of the resonant impedance of parallel (Fig.1) connection of the resonant capacitor C_r and the inductive load, represented by R_{load} and L_{load}.

This phenomenon is easily to analyze on a specific numerical example. The Fig. 2 shows the changes in frequency dependencies the imaginary part of parallel circuit Im $\{Z_{row}\}$ as well as the other parts of imaginary impedance of the resonant circuit, ωL_s for the case where: C_r = 11μF, R_{load} = 36mΩ, L_{load} = 1.5μH, L_s = 5.0μH.

The cross points of the curves ωL_s (f) and Im $\{Z_{row}(f)\}$ define the resonance frequencies $f_{s,d}$ and $f_{s,g}$ for which Im $\{Z_{eq,load}\}$ = 0.

By changing the angle of the slope of the line $X_s = \omega L_s$ (in fact not straight, the variability $L_s(f)$ = var can be clearly seen for frequencies of the inductive heating), by change of L_s inductance value, it is possible to change the resonant frequencies $f_{s,d}$ and $f_{s,g}$, where change of $f_{s,g}$ are much larger.

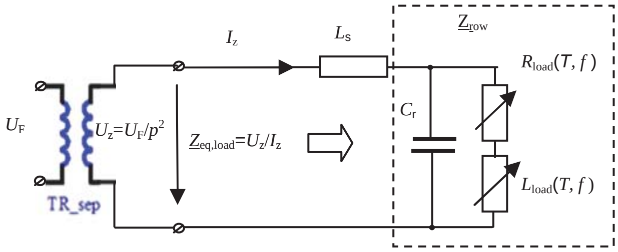

Fig.1. Electric diagram of the resonant matching system LLC [9].

The real part of the load impedance- the equivalent load resistance Im $\{Z_{eq,load}\}$ = $R_{eq,load}$ can be defined by the relation [9]:

$$R_{eq,load} = \frac{R_{load}}{(1-\omega^2 \cdot L_{load} \cdot C_r)^2 + (\omega \cdot C_r \cdot R_{load})^2} \quad (1)$$

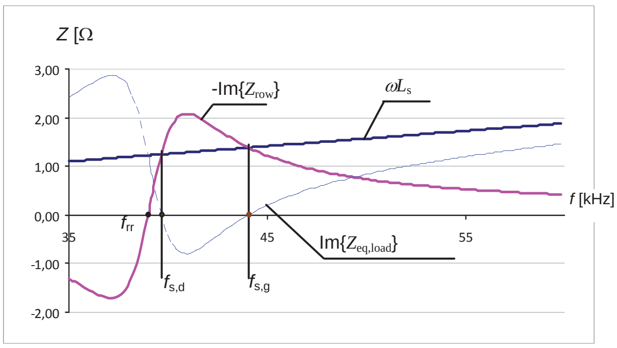

Fig. 2. Examples of the impedance changes in LLC circuit from Fig.1, [9].

The equation (1) shows that by changing the frequency it is possible to change the equivalent load resistance $R_{eq,load}$ value.

The change the resonant frequency (especially $f_{s,g}$), caused by the change the inductance value of the L_s results the change resonance value of the resistor $R^{rez}_{eq,load}$, for given constant load resistance value R_{load}.

The above-described feature of the LLC, as an example of a higher order resonance circuit characteristic, is used in induction heating, resonant inverters also for the impedance matching function. From this point of view it is important, how the change of load parameters (for example affected by heating of charge) have influence, in a resonance configuration type LLC, on changing the resonant resistance of the load $R^{rez}_{eq,load}$ and what is the relation of these changes in other typical serial or parallel resonance with 2 order arrangement.

Comparative calculations for these three typical resonance systems are presented in [9] for the case of the cylindrical inductor-charge system. Taking into account that during induction heating the influence of the higher harmonics on the simulation accuracy can be usually neglected [10], the time harmonic calculations of electromagnetic field were performed by using the developed [11,12] at the Institute of Applied Computer Science the API interface for the commercial program Flux.

The comparison of the relative equivalent resonance resistance change in the LLC system presented in [9] shows that this arrangement does not significantly improve the flexibility of the source matching to the load (similar changes of equivalent resistance), and in relation to the parallel resonance circuit can be even worse.

This system in its classical form does not therefore function as a self-matching impedance system.

The system of self-acting impedance matching of impedance loading

Efficient use of the potential capabilities of the LLC system in the impedance matching area of the source and load is heavily dependent on the possibility of adjusting the L_S inductance correlated to the load identifying procedures and correspondingly changing the resonant frequency.

It is expected that such complex technical operations can be carried out for the widest possible variation of load parameters without excessive user intervention.

The technical ability to adjust the Ls inductance is the main reason for limiting the range of load changes for which an impedance matching can be obtained to the inverter.

This results in a predicted range of load changes and a permissible operating frequency range, which entails proper selection of both resonant capacitors tank and ratio of the isolating transformer

Figure 3 illustrates a flow chart for the design of the source to determine the capacitance of the CR capacitor banks of the inverter equipped with LLC circuit for the simplest design case, i.e. at the predetermined load of the source of the precisely defined set (for the "cold" state) electrical parameters.

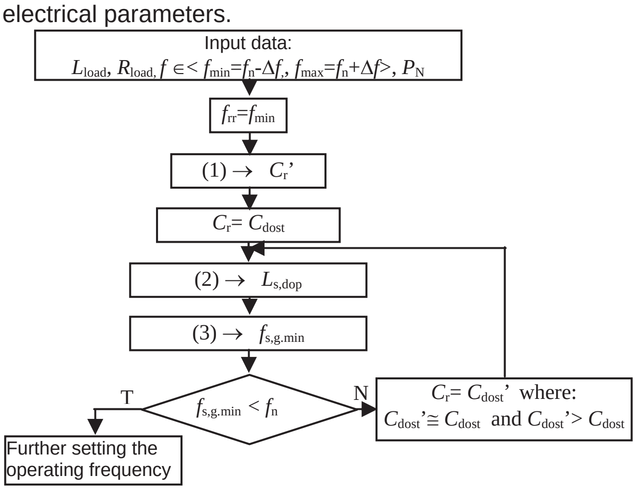

Fig.3. Network of algorithms for pre-selection of resonant capacitance values C_r.

At the Fig. 3:

- Frequency f_{rr} is the resonance frequency of the parallel part of circuit LLC,
- capacity C_r value is calculated from the equation [9]:

(2) $$C_r = \frac{1}{[(2\cdot\pi\cdot f_{rr})^2 + \frac{R_{load}^2}{L_{load}^2}]\cdot L_{load}}$$

- C_{dost} capacity available on the market,
- The maximum permissible value of the series inductance $L_{s,\,dop}$, under resonant condition can be calculated as a positive solution of equation (3) [9]:

(3) $$(C_r^4 R_{load}^4 - 4C_r^3 R_{load}^2 L_{load})L_s^2 + \\ + (4L_{load}^2 C_r^3 R_{load}^2 - 2C_r^3 L_{load}^2 R_{load}^2)L_s + L_{load}^4 C_r^2 = 0$$

- the lowest possible value of the upper resonance frequency (Fig. 2) can be calculated from the equation (4) [9]:

(4) $$f_{s,g,\min} = \frac{1}{2\cdot\pi}\sqrt{\frac{-(C_r^2\cdot R_{load}^2\cdot L_{s,dop} - 2\cdot L_{load}\cdot C_r\cdot L_{s,dop} - L_{load}^2\cdot C_r)}{2\cdot L_{load}^2\cdot C_r^2\cdot L_{s,dop}}}$$

Making an assumption of the resonant capacitance value at a user-defined nominal frequency and specific electrical load parameters, determines the value of the inductance L_s of the series choke. It can be calculated from the equation (5) [9] (where f_r=f_N -rated frequency):

(5) $$L_s = \frac{(2\cdot\pi\cdot f_r)^2\cdot L_{obc}^2\cdot C_r + R_{obc}^2\cdot C_r - L_{obc}}{\left(1-(2\cdot\pi\cdot f_r)^2\cdot L_{obc}\cdot C_r\right)^2 + (2\cdot\pi\cdot f_r\cdot C_r\cdot R_{obc})^2}$$

Taking into account, the power limitation, compact construction, limiting stray flux, and the ability to easily adjust the L_s inductance value, it is desirable that the isolation transformer with the series choke is a single complex magnetic module functioning as an autotransformer with galvanic separation.

Fig. 4 schematically illustrates the construction of the developed solution that was used in the constructed physical model as part of the project No. PBS1/A4/ 2/2012) and part of the patent solution [13] too.

In the presented solution, the secondary winding of the transformer and the series choke L_s is, in design terms, a one element, terminated only by two leads without any additional tapping.

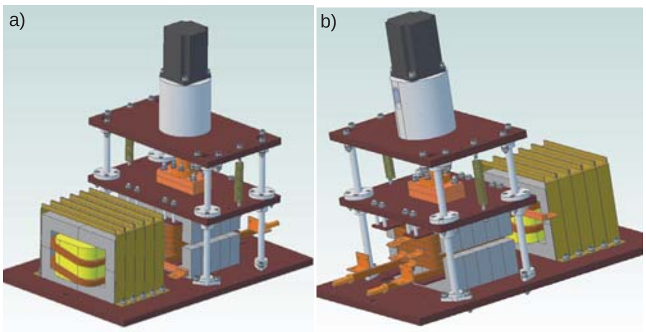

Fig. 4. Construction model of the magnetic unit together with the servo drive: a) the view from transformer side, b) the view from the reactor side.

How the estimated construction analysis show, the using the commercially available ferrite cores the value of the range of inductance variation, $L_{s,max}$÷L_{smin}, can reach a coefficient of 3.5 [9]:

(6) $$\frac{L_{s,\max}}{L_{s,\min}} \le 3{,}5$$

The beginning of the impedance matching process, on the one hand, requires to identify the user demands, and on the other, the identification of the parameters and condition of the source is and (and even above) the parameters of the connected inductor- charge circuit (ICC) [14].

These general requirements should be change to specific signals and information and procedures for processing them.

The procedure for active impedance matching of sources should be based on the following general principles:

A) Specified by the user:
- o expected frequency of work and acceptable changes $f_n \pm \Delta f$;
- o expected output power P_z;

B) Collection by the procedure management system
- o Information on the rated parameters of the inverter $P_{F,N}$, $U_{F,N}$, $I_{F,N}$ and the technically possible range of frequency changes;
- o Information about the ratio p of the separating-matching transformer;
- o Information about the number of N_m modules and their present status, *RP*=”S” (serial) or *RP*=”P” (parallel connection);
- o Information about the characteristic of $L_s(N_{obr})$ inductance from the revolutions of the stepper motor regulating it;
- o Information about the possible N -section $C_{r,i}$ (i=1..N) of the resonant capacitor;
- o Information about the capacitance of the present connected resonant capacitor C_r ;
- o Information about the acceptable voltage effective on the resonant capacitor $U_{c,dop}$.

C) The managing system commands the inverter to execute test consisting of:
- o Setting the maximum value of the inductance L_s=$L_{s,max}$;
- o Finding in the whole technically possible frequency range, the equivalent resonances of the voltage (lower frequency $f_{s,d}$, and upper $f_{s,g}$) for which there is zero current and voltage phase shift in the inverter blocks and resonance currents (f_{rr} frequency) characterized by maximization voltage on the resonant capacitor.

If no resonances can be determined, then the action should be repeated for the average L_s=($L_{s,max}$+ $L_{s,min}$) and then the minimum L_s=$L_{s,min}$, of the inductance achievable;

D) Collection by managing system information about resonant frequency values $f_{s,d}$, $f_{s,g}$, f_{rr} and settings of L_s else error signal;

E) Make a decision and display the message:
- o about the possibility of realization of heating,
- o about the need to change the resonance capacitance,
- o lack of heating capability

F) The managing system commands the inverter to execute test at reduced supply voltage and resonant frequency $f_{s,g}$. Under these conditions are measured: output inverter voltage U_f , capacitor voltage U_C , also current inverter I_f and current chopper I_{DC} .

G) Receiving and appropriate processing of the measured signal values by the management system.

H) With a positive decision in point. E take the essential actions of the algorithm of matching selection. This is based on the current circuit configuration of the power circuit (information from p. B) i.e. the current connecting of the inverter block modules and resonant capacitor as well as on collected information about possible changes the L_s value, the transformer ratio p and the other source-related data.

This is to limit manual operations related to changing capacitance of the resonant capacitor or module connections. After into account all the expectations of the user the goal of the algorithm is, to define the resonant frequency, L_s value, possibly the capacitance of the resonant capacitor and the module connections, and also to send this information to the generator microcontroller to execute.

Conclusions

Effective use of the source power, without exceeding the rated voltage or current parameters, is only possible when equivalent impedance load similar to the rated impedance of the source.

In case of the absence of impedance matching, there is a problem with the use of available theoretical power, which on the one hand determines the possibility of the enforcement technological process, and on the other hand unnecessarily increases costs of the over-dimensioned source.

Changes in electrical parameters of the load are typical for induction heating and although it is difficult to expect that a given power source can be used to heat up all types of shapes and types of details and in different technological processes, when the substitution impedances can change up to several hundred times, this should be noted that even a relatively small change in dimensions or load material may result in several times change of equivalent resistance value, which the source should be able to handle.

The classic way of counteracting this phenomenon with adaptive matching transformers or passive circuits does not solve the problem. Because this way of matching always applies to one specific case of load impedance values and does not change during heating.

In the resonant circuit type LLC, however, it is possible to obtain an almost constant value of the power input (also $R_{eq,load}$) provided that resonant system LLC becomes a controlled circuit (Fig. 5) so that the resonance frequency effected by change of the inductance value L_s allows correct modification of the equivalent load $R_{eq,load}$.

This study discusses the connection of a controlled LLC system with an active impedance matching algorithm to improve the self-matching capability of an impedance resonant voltage inverter. The discussed solution was used in the built 30 kW generator model, shown in Fig. 5.

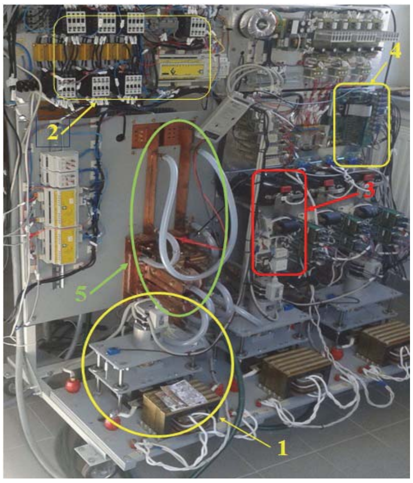

Fig. 5. Foto of the 30 kW test stand: Item.1 - magnetic module, item 2nd power supply, item 3. - inverter block, item 4.- FPGA / ARM test stand controller, item 5.- resonant capacitor circuit.

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REFERENCES

[1] Zheng Gao, Yueqig Zhou, 'Research on Switching Losses for Induction Heating Power Supply with LLC Resonan Load', IEEE 2011, *International Conference on Electronic & Mechanical Engineering and Information Technology*, vol. 5, pp.2474-2477

[2] W. Kobos, J. Zgraja, 'Passive LLC and LCCL systems for impedance matching of induction heating load', *Przegląd Elektrotechniczny*, No. 2, 2014, pp. 40-43 (in Polish)

[3] J.M. Espi, E.J. Dede,A. Ferreres, R. Garcia, 'Steady State Frequency Analysis of the LLC Resonant Inverter for Induction Heating', *IEEE 1996 CIEP Cuernavaca Mexico* , October pp.14-17

[4] Li Jingang, Z. Yanru, Z. Yang, 'Study on Static Electricity Induction Load-matched of Voltage-Source Converter for Induction Heating', *IEEE Trans. Power Elektro*, 2005, pp.1284-1287

[5] J. Zgraja, J. Bereza, 'Computer simulation of induction heating system with series inverter', *COMPEL*, Vol. 22, no 1, 2003, pp. 48-57

[6] J. Zgraja, 'Computer simulation of induction hardening of moving flat charge', *IEEE Transaction on Magnetics*, Vol. 39, no 3, May 2003,pp. 1523-1526

[7] J. Zgraja, 'Simulation of Induction Hardening of Flat Surfaces of Moving Massive Elements', *Int. Journal of Materials & Product Technology*, Vol. 29, no. 1/2/3/4, 2007, pp. 103-123

[8] J. Zgraja, 'Computer simulation of induction heating process for system powered from series inverter', *Przegląd Elektrotechniczny*, no. 2, 2014, pp. 48-51

[9] W. Kobos, 'Aktywne dopasowanie impedancji obciążenia generatorów falownikowych do jedno i dwuczęstotliwościowego nagrzewania indukcyjnego', praca doktorska, WEEIA PŁ, 2017

[10] J. Zgraja, 'The influence of high harmonic on calculation accuracy of induction heating system supplied by series inverter', *Przegląd Elektrotechniczny* no. 7, 2008, pp. 83-85 (in Polish)

[11] J. Zgraja, 'Calculation of induction heating systems using API of Flux® package', *Przegląd Elektrotechniczny*, No. 1, 2017, pp. 17-20 (in Polish)

[12] J. Zgraja, 'Simplified model for simulation the heat transfer between induction heated calender rolls and wet paper', *Przeglad Elektrotechniczny,* No. 11, 2011, pp. 85-88

[13] Patent RP, NR 225064, W. Kobos, J. Zgraja, 'Sposób dopasowania nadążnego układu impedancji falownika do indukcyjnego nagrzewania oraz układ nadążnego dopasowania impedancji falownika do indukcyjnego nagrzewania', z dnia 06.09.2016

[14] P. Chudzik, G. Lisowski, J. Zgraja, Ł. Kazimierski, 'Układy pomiarowe do identyfikacji obciążenia i wyznaczania mocy w generatorze LLC do nagrzewania indukcyjnego', *Przegląd Elektrotechniczny*, Nr 3, 2016, ss. 53-56