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Resonance phenomena in wireless power supply systems

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The article presents the prospects for application of wireless power supply in electronic devices. A short description of advantages of using this technology including the principle of its operation and construction of typical systems applied in devices of everyday use was provided. Two types of resonance systems used for wireless transmission of energy were presented. Also, advantages and disadvantages of using each of these systems were listed. Furthermore, the impedance and performance analyses of the wireless electric energy transmission systems were discussed. The performance characteristics were presented depending on several parameters in the three–dimensional form. The minimum quality factor of the resonance system, which allows the achievement of the high system performance at low interface between the primary and secondary coil winding was demonstrated. Two tested circuits were compared and the areas of application were determined for each of them. Difficulties related to maintenance of the circuit in resonance and to limitation of losses were determined.

KEYWORDS: wireless power supply, q–factor, system performance, inductance compensation

1. Introduction

The application of the wireless electric energy transmission system is possible in many areas of technology. In particular, it can be applied in mobile devices, i.e. telephones and smartphones, where the use of such a method of charging affects the price of purchase and comfort of use. Savings result from the purchase of one charger, which can be used for different devices. The charging of the devices is more comfortable as it is enough to place them on an appropriate pad. In this case, we eliminate the mechanical wear of, for instance the micro USB port. Wireless power supply is supposed to contribute to the user safety. During the cable connection, electric discharges may appear, leading potentially to explosion when in contact with a flammable gas. What is also important, is the possibility of using this technology in machines which comprise mobile elements. Here, the examples include electric vehicles, in which the battery charging process is long and may be replaced by wireless charging during the vehicle's movement.

The wireless power supply systems operate based on the principle of energy transfer via the electromagnetic field just as is the case with air–core transformers. There are different versions of transformers aimed at improvement of the system performance. It is possible to distinguish systems in which primary winding is characterized by a coil wound on the core or an air coil. And on the side of the receiver, that is, on the secondary side of the transformer, no core coils are used as they are mounted in the device and are not supposed to increase its mass. Assuming that the system is powered from the power grid, the system consists of several converter blocks and the control system. At the inlet of each transmitter system, there is the AC/DC voltage converter, whose function is to convert the mains AC voltage to DC voltage. Further on, there is the DC/AC converter which turns DC voltage to high frequency AC voltage. AC voltage is applied to the serially connected coil and capacitor, whose parameters are selected in such a way as to operate in resonance. The receiver system is provided with the resonance system including the fixed AC voltage converter and the switching mode system which serves the purpose of powering the receiver.

The construction of the system which transfers energy in the form of the electromagnetic field, is complex due to the used DC–AC converters which serve the purpose of matching the appropriate operating frequency. To a great extent, the effective use of the wireless electric energy transmission depends on the system performance, that is, as low energy losses as possible. The dispersed electromagnetic field stream has the greatest effect on the losses [3].

In order to analyse the operation and construction of such a system, several necessary tests for the two selected methods of secondary winding coil reactance compensation were carried out.

2. Analysed systems

The article describes the performance of impedance analysis of the wireless power supply system. Three modes of the system compensation in the following configurations [2] were compared [2]:

- serial–serial compensation (Fig. 1),
- serial–parallel compensation (Fig. 2),
- parallel–serial compensation (Fig. 3).

For two types of compensation: serial (1), parallel (2), and parallel–serial (3), equations, which describe the system impedance, take the following form:

$$Z = Z_{11} + \frac{(X_M)^2}{R_2 + R_o + j(X_{L2} - X_{C2})} \tag{1}$$

$$Z = Z_{11} + \frac{(X_M)^2 C}{R_2 C - jR_o^2 X_{C2} + R_o + jX_{L2} C} \tag{2}$$

$$Z = -jX_{C1} + \frac{{X_{C1}}^2 Z_{22}}{Z_{11} Z_{22} - (jX_M)^2} \tag{3}$$

where $Z_{11} = R_1 + j(X_{L1} - X_{C1})$, $C = R_o^2 X_{C2}^2 + 1$, $\mathrm{Z}_{22} = \mathrm{R}_2 + \mathrm{R}_\mathrm{o} + \mathrm{j}(\mathrm{X}_{\mathrm{L}2} - \mathrm{X}_{\mathrm{C}2})$.

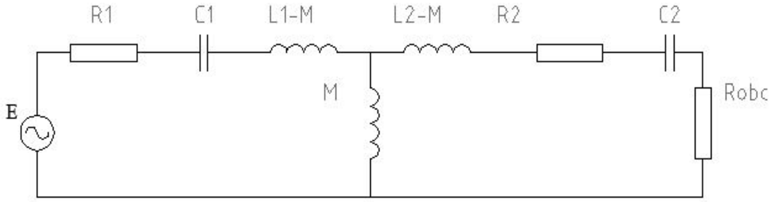

Fig. 1. Serial–serial compensation system

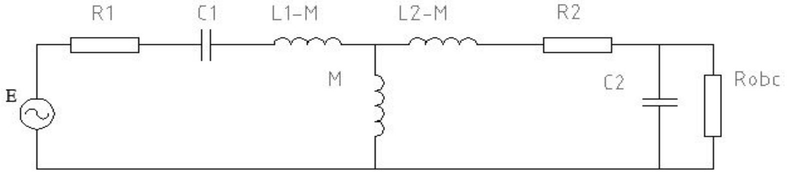

Fig. 2. Serial–parallel compensation system

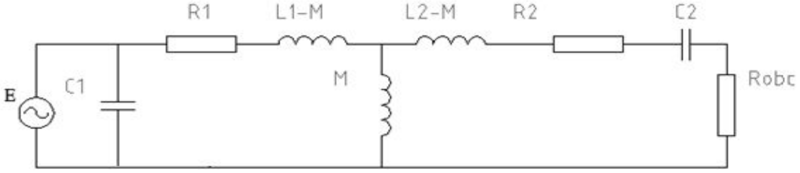

Fig. 3. Parallel–serial compensation system

Input impedances were determined for the presented systems and impedance and performance characteristics were drawn up for the constant value of interface between coils k = 0.2. In order to present the best point of operation of devices using the wireless electric energy transmission system, identical coils L1 and L2 were taken into consideration. The tests were carried out with regards to different load resistances and frequencies.

3. Serial – serial compensation

Impedance characteristics for the system with the serial–serial compensation is presented in Fig. 4, while Fig. 5 presents the impedance characteristics for the serial–parallel system.

In chart 4, it is possible to notice that the system in the state of resonance has the greatest impedance for load resistance ranging between 0.1 Ω and 2 Ω, and for $R_{obc} > 2\ \Omega$ the system impedance strives to reach resistance value R1. Another characteristics (Fig. 5) presents the system performance. Up to the load resistance at the level of 10 Ω there are local function maxima, in the frequency close to resonance frequency. Such a situation has an adverse effect on the correct operation of adaptive systems, which search frequency in order to specify the maximum system performance.

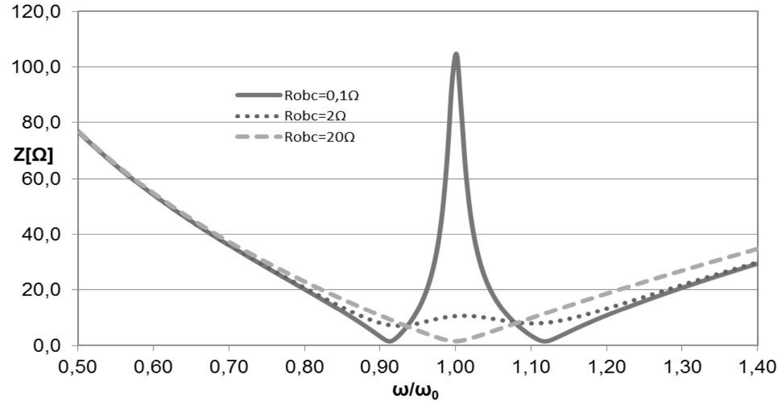

Fig. 4. Impedance Z of the system with serial–serial compensation for selected load resistances

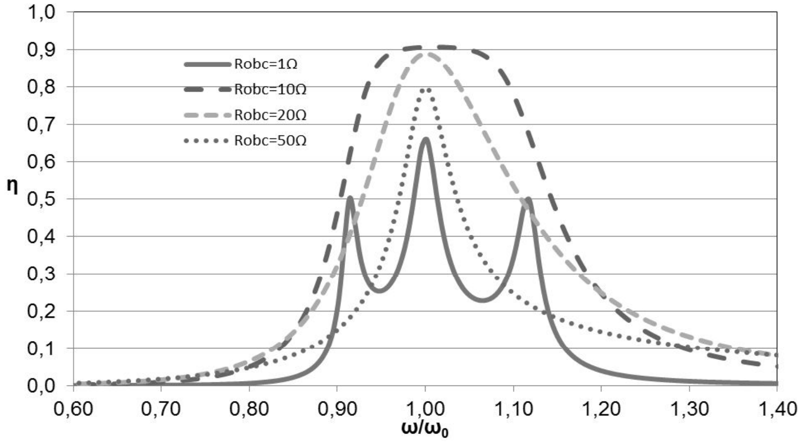

Fig. 5. Performance η of the system with serial–serial compensation for selected load resistances

Based on the developed characteristics (Fig. 5 and Fig. 6), it can be concluded that the greatest system performance is obtained for resonance frequencies. Any deviations from the state of resonance in the secondary winding have an adverse effect on the power transferred to the receiver. Within the load resistance range R_{obc} between 10 and 20 Ω, 90% performance was obtained, while each consecutive increase in load resistance R_{obc} decreases the performance.

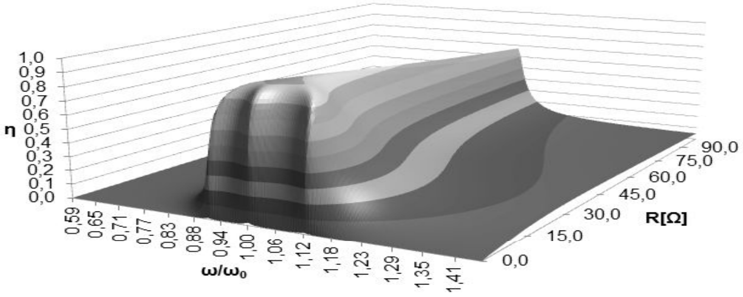

Fig. 6. Performance η of the system with serial–serial compensation

4. Serial – parallel compensation

The system with the serial–parallel compensation is also subject to an analysis in this paper. The tests carried out in reference to this system were identical to those carried out for the system with serial compensation. The developed characteristics are presented in Figs. 7 – 11. Fig. 7 presents only one characteristics as it was subject to a change at tested load resistance R_{obc} within the range between 0 and 50 Ω.

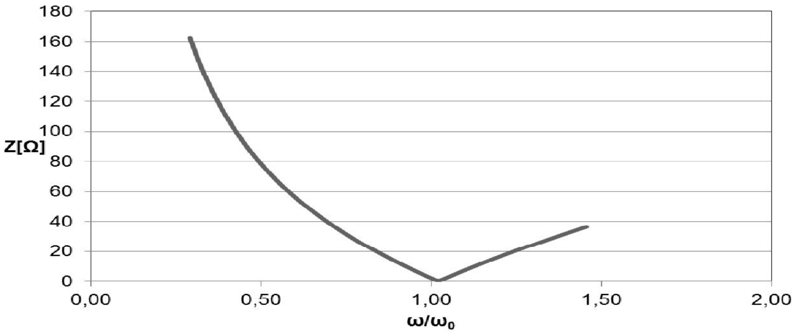

Fig. 7. Impedance Z of the system with serial–parallel compensation

The characteristics (Fig. 7) demonstrates that for the load resistance ranging between 0.1 and 50 Ω, the impedance was the lowest for the state of resonance. Unfortunately, in order to obtain this state in each point of the system while changing the interface between the primary and secondary windings and while changing the load, each time it is necessary to select capacitance value C2 (Fig. 2). The inaccurate selection of the capacitor results in achieving the resonance point that is shifted in relation to the supply frequency. This was presented in Fig. 8. In order to adapt the system correctly to the state of resonance, the change in the value of capacitor C2 is not sufficient and must be adapted together with coil L2 for the supply frequency.

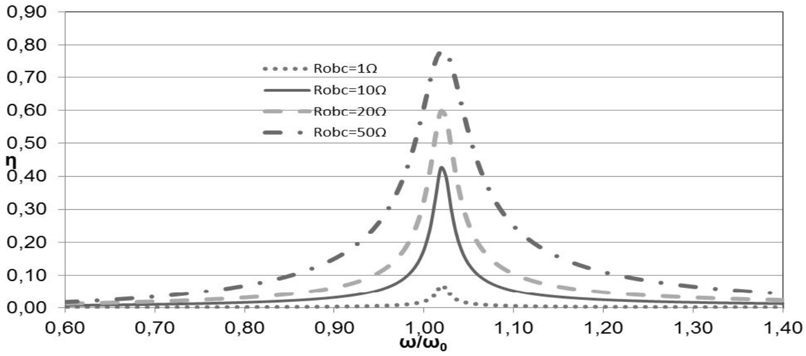

Fig. 8. Performance η of the system with serial–parallel compensation for selected load resistances

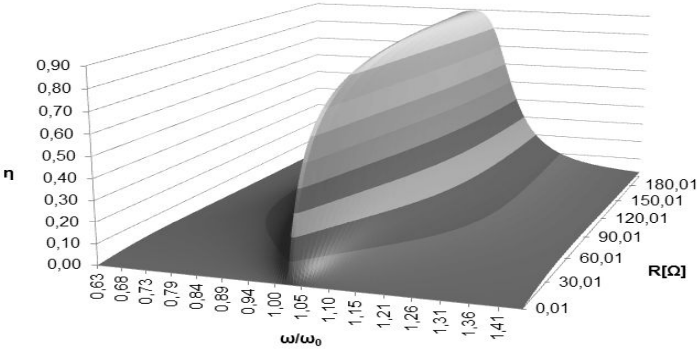

Fig. 9. Performance η of the system with serial–parallel compensation

5. Parallel – serial compensation

The paper presents the characteristics for the system with parallel–serial compensation. Tests were carried out within the load range between 0.2 and 50 Ω. The impedance characteristics for the system with the parallel–serial impedance is presented in Fig. 10.

Based on the developed characteristics, it can be concluded that the system impedance is the lowest at the resonance point of the system. Simulations at different loads were performed for the constant frequency. The system impedance in the state of resonance rose from 0.2 Ω to 10 Ω, and then went down to zero with the load higher than 50 Ω. For the wireless transfer of the energy, it is necessary to increase the supply frequency for higher loads.

In accordance with the impedance characteristics, the performance of the circuit where the system performance is the highest at the lowest impedance, is presented. In this system, a difficulty is created by the selection of coil inductance at the constant frequency of the system. Such an adaptation can be seen in the characteristics from Fig. 11, where the phase shift in relation to the resonance is visible for the highest system performance. In this case, it is much easier to adapt the supply frequency to the system than to adapt induction and capacity elements.

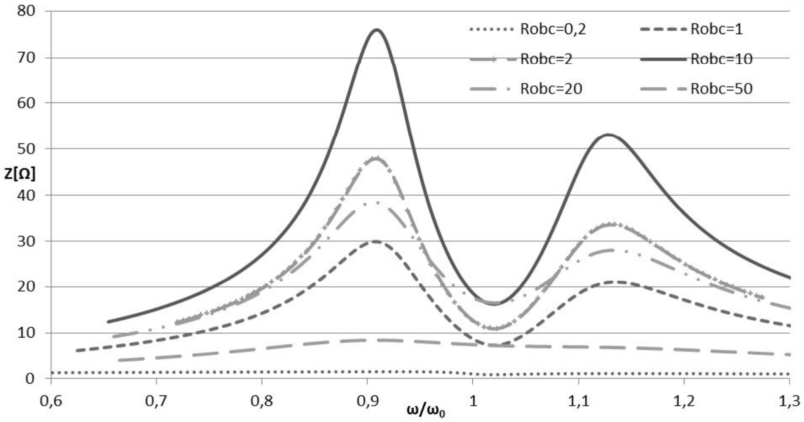

Fig. 10. Impedance Z of the system with parallel–serial compensation

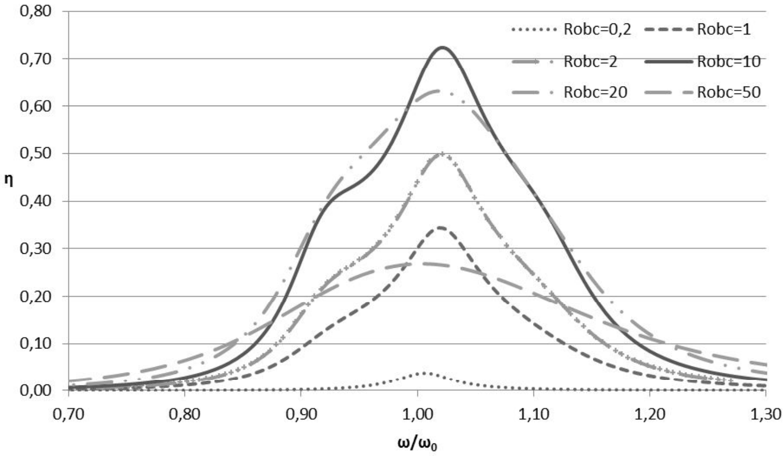

Fig. 11. Performance η of the system with parallel–serial compensation for selected load resistances

6. Analysis of performance of the tested systems

The change in the system performance depending on the quality factor of the resonance system was also subjected to tests in the present paper. The results are presented in Figures 12 – 15.

The characteristics for the serial–serial compensation (Fig. 12) demonstrates that the satisfactory 90% performance can be obtained by creating the resonance system with the q–factor equal to 100.

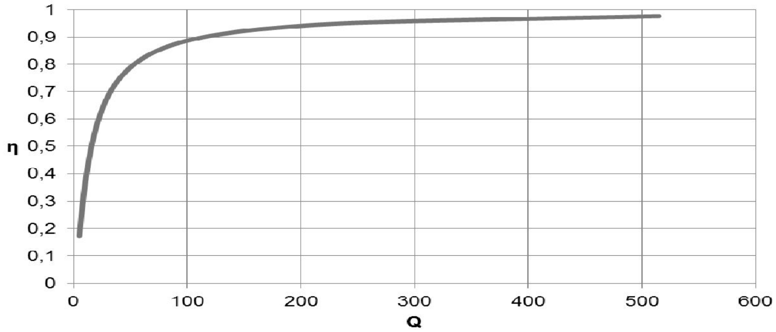

Fig. 12. Performance η of the system with serial–serial compensation as a function of quality factor Q of the resonance system

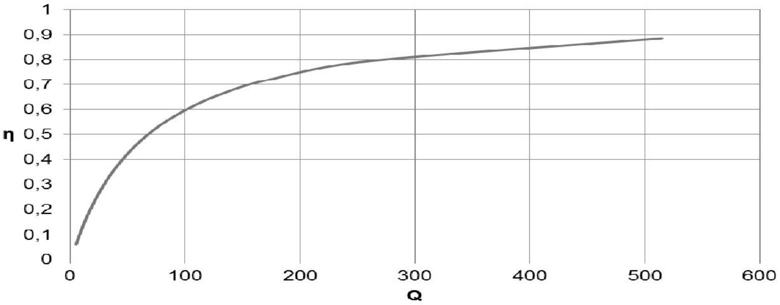

Fig. 13. Performance η of the system with serial–parallel compensation as a function of quality factor Q of the coil in the secondary winding

Performance characteristics as a function of quality factor for the system with serial–parallel compensation was demonstrated in a similar manner. The result is that the performance is affected by the quality factor of the secondary side of the air–core transformer. Figure 13 shows that with q–factor equal to 100, the system performance was at the level of 60%. An increase in the quality factor increases also the system performance, but the accomplishment of a result at the level of 90% requires the accomplishment of the quality factor greater than 500.

In the case of the charts from Figure 14 and 15, the constant quality factor for the serial system of the primary side and variable quality factor for the secondary side were assumed. This allows the determination of the maximum performance of the whole system.

The aforementioned analysis shows that in the case of the serial–serial system, it is just enough to apply the known relations for the resonance frequency in order to adapt the system to resonance.

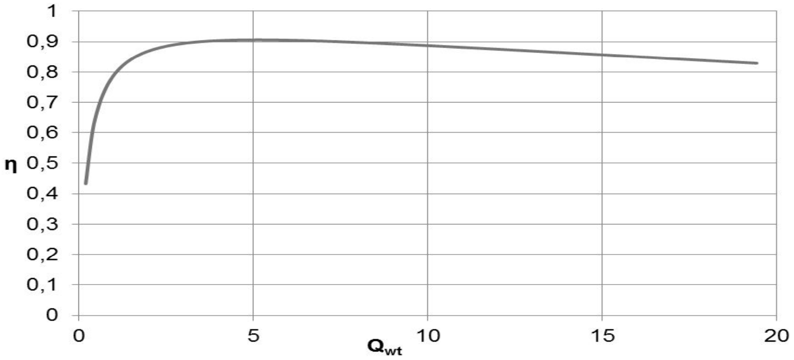

Fig. 14. Performance η of the system with serial–parallel compensation as a function of quality factor of the coil Q_{wt} in the secondary winding for the constant quality factor of the primary resonance system

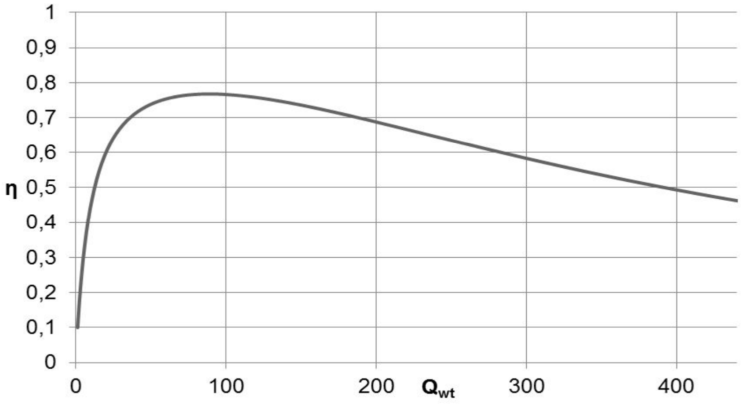

Fig. 15. Performance η of the system with parallel–serial compensation as a function of quality factor of the coil Q_{wt} in the secondary winding for the constant quality factor of the primary resonance system

On the other hand in the serial–parallel system and parallel–serial system, the primary side must be regarded separately as the serial one and the secondary side as the parallel one in order to adapt the system to resonance.

7. Summary

The presented analysis of two methods of compensation of the wireless electric energy transmission system demonstrates that with the constant values of reactance elements for the load resistance value up to 50 Ω, the serial–serial compensation is more effective. Above this value, the situation is reversed and the system with the serial–parallel compensation becomes a better solution with better performance. The adaptation to the state of resonance in the serial–parallel system becomes more difficult, as it is necessary to adapt the resonance frequency of the serial system to the parallel system. While using identical inductance values for the primary side and secondary side, there are problems with achieving the resonance point of the system. The solution for this situation is the adaptation of the system to the resonance while changing the inductance of the secondary winding coil as changing just the capacitance is not enough.

Based on the presented characteristics of the system with the parallel–serial compensation, a conclusion can be drawn that the system has the lowest performance for the applied constant coil inductance values and constant frequency. The system performance was the highest at the constant load resistance equal to 10 Ω. The load range for the tested frequency was between 0.2 and 100 Ω. In order to increase the load resistance, it is necessary to increase the resonance frequency of the system.

The performance characteristics of the resonance system as a function of quality factor shows that it is of key significance for the performance of the whole system. In the case of the structure from Fig. 1, the satisfactory performance is obtained for the quality factor exceeding 100. Its further increase may improve the performance by maximum 10%. Increasing the quality factor for the frequency at the level of hundreds of kHz becomes a difficult technological task and increases the costs of construction of the circuit. For the system presented in Fig. 2, it is not enough to increase the quality factor of the serial and parallel system, as it is only above value Q = 500 that we obtain the satisfactory performance at the level of 90%. A conclusion was also drawn that the performance of the serial–parallel system depends on the load resistance (R_{obc}). The value of the greatest performance amounted to 90% within the quality factor range between Q = 3 and Q = 8, which corresponded to the load resistance within the range between 100 and 700 Ω. In the last system, the quality factor of the secondary side was sufficient at the level between 80 and 100 in order to obtain the highest performance.

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