

Topology analysis of wireless energy transfer system

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Abstract. *This article deals with analysis of topology configuration of wireless energy transfer system. The analysis is focused on determining efficiency and transfer power to the load depending on the distance between coils. These characteristics are important for charging accumulator in electric vehicles. There are discussed frequency characteristics of current and voltage on capacitors too, which are important for design wireless energy transfer system. In the article are discussed advantages and limits of two compensation method in terms of control and transmission properties. These characteristic were used during the development of real sample of wireless energy transfer system.*

Keywords

Resonant compensation, wireless energy transfer, transfer properties, efficiency, transmitted power.

1. Introduction

Nowadays electrically powered automobiles obtain bigger interest in the automotive industry. Electric vehicles gain this interest thanks to high efficiency. In the case of the asynchronous motor, we can convert electrical energy into mechanical with 90% of the efficiency, what is much higher than efficiency of combustion engine, which has efficiency only 25-34%. [1] Due to the rapid increase of fuel prices - especially diesel and gasoline, the power electronics and energy conversion together with development of new battery types contribute to the development and application of electric vehicles in the automotive industry. [2]

The main disadvantage of the electric car is energy accumulation. Batteries are big, heavy with short lifetime and long charging times. Almost due to these reasons, it is necessary to solve a question about battery charging. In general, charging systems can be divided to wired, replaceable and wireless (inductive) systems. [3]

Wireless system uses electromagnetic field for energy transf. Progress in the area of semiconductor converters allowed to develop power supplies with high switching frequencies (100 kHz and more). [4][5] Together with this, a big attention is given on wireless charging systems due to its simple principal operation. You only need to come to the appointed place and system automatically starts to

charge accumulators of electric vehicle, whereby charging stations can be placed on various places, e. g. bus stops, crossroads etc...[6]

Wireless power transfer and issues relevant to wireless charging of electronic vehicles are still important and emerging trend. Regarding wireless power transfer, each application requires several self - specific operational properties or transfer characteristics. These properties can be defined as transfer characteristics, whereby main parameters which are being optimized are distance between coils as well as mutual displacement between coils. A possible way how to influence these parameters lies in the configuration of the main circuit of compensation network of wireless energy transfer (WET) system. [7] – [9]

The solution of WET system based on the magnetic – resonance coupling represents constantly investigated phenomena. Most of the analyses are based on pure theory of physical interactions, which is unable to provide clear and consistent overview knowledge for researchers in the field of electrical engineering. Based on this it can be said, that some important relationships between system efficiency, amount of transmitted power and transmitting distance for magnetic – resonance coupled WET systems need to be introduced. [10]

In this article we are describing the system of wireless energy transfer with the use of mathematic-physical models for the most used compensation configuration of receiving and transmitting circuit. Efficiency and transmitted power are the most significant parameters for wireless battery charging in electric vehicles. From the component design point of view it is also important to have knowledge about values of voltages and currents in main circuit. At the end of the paper, the general recommendations for practical use of each variant are given. [11] - [13]

2. Magnetic – resonant coupling of WET system

When we use transmission by magnetic resonance, the compensation capacitors are connected to transmitting and receiving coil. This means that the analysed circuit becomes a resonance circuit. For the practical application (battery charging) we analyzed two basic configurations:

- Series-series compensation
- Series-parallel compensation

Each type of compensation is typical with its specific characteristics and transfer properties. In next chapter, the analytical expressions of efficiency and other important circuit parameters in dependency on frequency are being described. Instead of frequency, the mutual inductance (distance between transmitter and receiver) is also considered as variable parameter. [14]

2.1 Series - series compensation

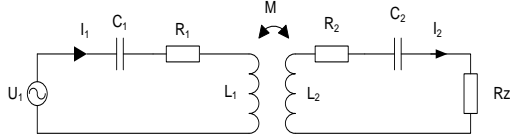


Fig. 1. Equivalent circuit of WET with series – series resonant compensation

For series – series compensation the capacitor is connected in series with transmitter and receiver coil (Fig. 1). Mathematical model of series – series compensation is from complexity point of view much easier than other compensation types. Using the methodology of loop currents, we can express impedance matrix of this configuration (1).

$$\begin{bmatrix} \dot{U}_{1_SS} \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) & -j\omega M \\ -j\omega M & R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \end{bmatrix} \begin{bmatrix} \dot{I}_{1_SS} \\ \dot{I}_{2_SS} \end{bmatrix} \quad (1)$$

From (1) the formula for current of transmitting and receiving part in complex form as (2) and (3) can be derived:

$$\dot{I}_1 = \dot{I}_{1_SS} = \frac{R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS} \quad (2)$$

$$\dot{I}_2 = \dot{I}_{2_SS} = \frac{-j\omega M}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS} \quad (3)$$

If circuit is supplied by harmonic voltage with frequency equal to resonant frequency, then the value of capacitive and inductive part of complex impedance are the same and each other will be subtracted. Then for the previous formulas (4) and (5) are valid:

$$\dot{I}_1 = \dot{I}_{1_SS} = \frac{R_2 + R_Z}{R_1 R_2 + R_1 R_Z + (\omega M)^2} \dot{U}_{1_SS} \quad (4)$$

$$\dot{I}_2 = \dot{I}_{2_SS} = \frac{-j\omega M}{R_1 R_2 + R_1 R_Z + (\omega M)^2} \dot{U}_{1_SS} \quad (5)$$

Equations (4) and (5) show that circuit during resonance has only resistive character and circuit currents are given just by the parasitic resistances of coils, load resistance and supply voltage. Input power and output

power of the circuit with S - S compensation can be expressed as (6) and (7):

$$\dot{S}_{IN_SS} = \dot{I}_1 \dot{U}_{1_SS} = \frac{R_2 + R_Z + j\omega L_2}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS}^2 \quad (6)$$

$$P_{OUT_SS} = R_Z |\dot{I}_2|^2 = R_Z \left| \frac{-j\omega M}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS} \right|^2 \quad (7)$$

Dependence of efficiency for S-S compensated circuit in frequency domain can be expressed using (8):

$$\eta = \frac{\dot{P}_{OUT_SS}}{\dot{S}_{IN_SS} \cdot \cos(\varphi)} = \frac{R_Z \omega^2 M^2}{\left\{ \left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2 \right\} (R_2 + R_Z + j\omega L_2) \cos(\varphi)} \quad (8)$$

, where:

$$\cos(\varphi) = \frac{\Re(\dot{S}_{IN})}{|\dot{S}_{IN}|} = \frac{\Re \left\{ \frac{R_2 + R_Z + j\omega L_2}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS}^2 \right\}}{\left| \frac{R_2 + R_Z + j\omega L_2}{\left[R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right] \left[R_2 + R_Z + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \right] + (\omega M)^2} \dot{U}_{1_SS}^2 \right|} \quad (9)$$

In Fig.2 the frequency dependence of output power for various values of mutual inductance is plotted. Transferred power is very low, when the value of mutual inductance is low. It is consequently rising with the increase of mutual inductance value between the coils.

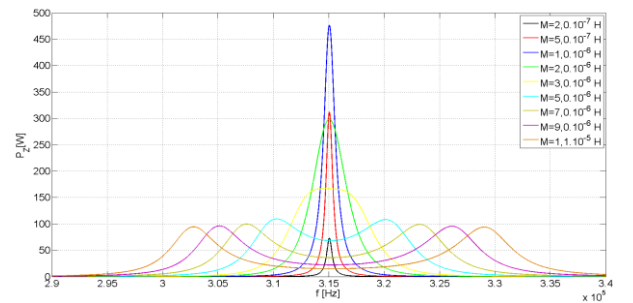


Fig. 2. Frequency dependency of output power for WET system with series – series resonant compensation (variable parameter – mutual inductance M)

When the circuit is supplied by harmonic signal with resonant frequency, then output power is at its maximum. But further increases of mutual inductance above a certain value only decreases the output power. For S-S compensated circuit, the maximum of the output power

isn't exactly at resonant frequency but at frequencies determined by (10).

$$f = \frac{1}{2\pi\sqrt{(L \pm M)C}} \quad (10)$$

For that reason it is better to supply mentioned circuit with the harmonic signal whose frequency is determined by (10). If the value of mutual inductance changes, then maximal power transmission can be kept when switching frequency of supply signal will be modified to the value given by (10).

Magnetic compensated system compared with the wireless energy transfer by magnetic induction, can has the value of mutual inductance significantly smaller, what means that the distance between the coils can be several times higher. Significantly higher value of the transmitted power can be achieved with the use of this type of compensation.

In the Fig. 3 the frequency characteristic of efficiency of S-S compensated system is shown.

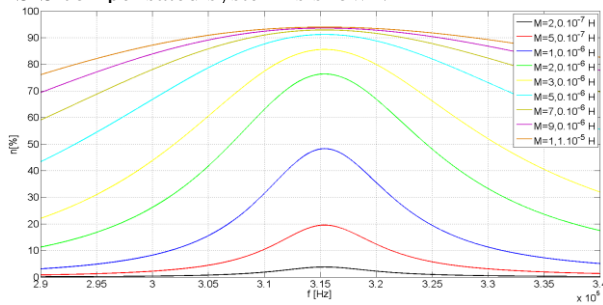


Fig. 3. Frequency dependency of efficiency for WET system with series-series resonant compensation

The peak efficiency is achieved at the point of resonant frequency. The efficiency near resonant frequency is more than 90% for high values of the mutual inductance. The disadvantage is that the power delivered to the load is very low at this point. When considering efficient and proper battery charging process then the results is that we have transfer efficiency greater than 90% but power transfer capability is insufficient. Therefore the operation of the circuit is recommended with the frequencies given by (10). At these points it is possible to transfer much more power to the load (Fig. 2) at acceptable level of system efficiency (80% - 90%).

In terms of system design it is important to know a critical value of the voltages on the capacitor C₁ (Fig.4), which in the case of series - series compensation is very high for a small mutual inductance almost for relatively small input voltage. It can be seen (Fig. 4) that for small values of M, the voltage at capacitor reaches kilovolts at the resonant frequency. With the increase of the supply voltage, the voltage on the capacitor increases too. Due to this extremely high voltage it is required to use a special kind of capacitors for high voltage and high frequency operation. Another possibility is that the frequency of supply source will be kept away from the resonant point. Then the voltage on the capacitor is significantly lower.

Then capacitor is not the only component necessary to be designed for high voltage. The same situation is valid for the voltage at transmitting coil L₁.

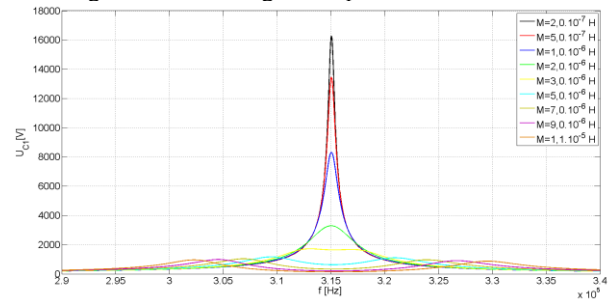


Fig. 4. Voltage on the capacitor C₁ of WET system with series-series resonant compensation

The frequency dependency of the voltage on the capacitor C₂ is shown in Fig. 5. This voltage is lower than the voltage on the capacitor C₁, especially for smaller values of M, but for higher mutual inductance voltage reaches approximately the same values as a voltage on the C₁.

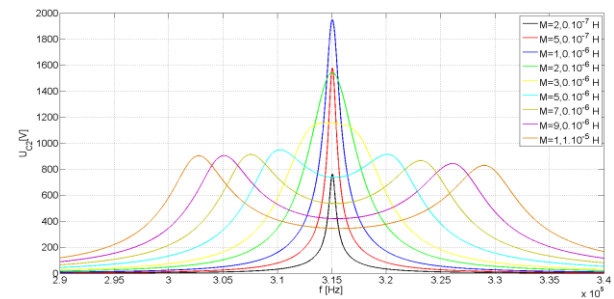


Fig. 5. Voltage on the capacitor C₂ of WET system with series-series resonant compensation

If the frequency is above or below the resonant frequency, and operation will be prohibited from resonant operation point, then capacitor C₂ can be designed for lower voltages. This shall be treated in the control system. Thus, one of the important issues for the correct operation of the system is the identification of the resonant point as well as the range of the frequencies within the circuit can operate. The same situation is valid for the voltage level at the receiving coil L₂.

Consequently, during the design process it is necessary to know the values of the currents flowing through the coil and capacitor on the transmitting and receiving side (Fig.6). The main affected factor is the wire diameter of the coil, which has direct impact on the parasitic resistances R₁ and R₂. For capacitor, in terms of losses, it is important to choose a capacitor with suitable ESR.

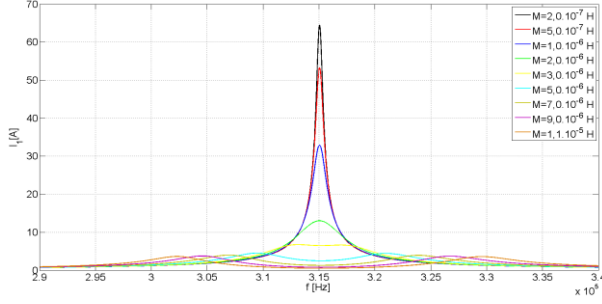


Fig. 6. Frequency dependency of the current I_1 flowing at transmitting side of WET system with series – series resonant compensation

Current flowing through the receiving part I_2 is shown on Fig.7. It is shown that for higher value of M the current peaks are almost on the same level. With the increase of mutual inductance, the peak points slightly decrease. This means, that only with correct frequency control we can achieve same charging current for different distances between coils.

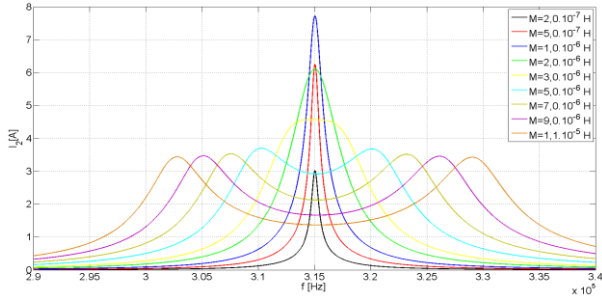


Fig. 7. Frequency dependency of the current I_2 flowing at receiving side of WET system with series – series resonant compensation

2.2 Series – parallel compensation

Series- parallel compensation means that one capacitor is connected in series to the transmitting coil and other one is connected in parallel to the receiving coil Fig. 8.

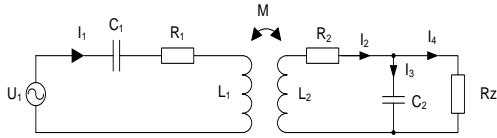


Fig. 8. Equivalent circuit of WET with series – parallel resonant compensation

Using method of loop currents, we can express impedance matrix of SP-compensated circuit (11).

$$\begin{bmatrix} \dot{U}_{1_SP} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) & -j\omega M & 0 \\ -j\omega M & R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) & j\frac{1}{\omega C_2} \\ 0 & j\frac{1}{\omega C_2} & R_Z - j\frac{1}{\omega C_2} \end{bmatrix} \begin{bmatrix} \dot{I}_{1_SP} \\ \dot{I}_{2_SP} \\ \dot{I}_{3_SP} \end{bmatrix} \quad (11)$$

If we substitute $Z_1 = R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right)$ and $Z_2 = R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)$ we can express the circuit currents as follows:

$$\dot{I}_1 = \dot{I}_{1_SP} = \frac{Z_2 + j\frac{1}{\omega C_2(j\omega C_2 R_Z + 1)}}{Z_1 Z_2 + \omega^2 M^2 + j\frac{Z_1}{\omega C_2(j\omega C_2 R_Z + 1)}} \dot{U}_{1_SP} \quad (12)$$

$$\dot{I}_2 = \dot{I}_{2_SP} = \frac{j\omega M}{Z_1 Z_2 + \omega^2 M^2 + j\frac{Z_1}{\omega C_2(j\omega C_2 R_Z + 1)}} \dot{U}_{1_SP} \quad (13)$$

$$\dot{I}_3 = \dot{I}_{2_SP} - \dot{I}_{3_SP} = \frac{-\omega^2 C_2 R_Z M}{(Z_1 Z_2 + \omega^2 M^2)(j\omega C_2 R_Z + 1) + j\frac{Z_1}{\omega C_2}} \dot{U}_{1_SP} \quad (14)$$

$$\dot{I}_4 = \dot{I}_{3_SP} = \frac{j\omega M}{(Z_1 Z_2 + \omega^2 M^2)(j\omega C_2 R_Z + 1) + j\frac{Z_1}{\omega C_2}} \dot{U}_{1_SP} \quad (15)$$

If the circuit is powered by a harmonic voltage with frequency equal to the resonant frequency, then following applies:

$$\dot{I}_1 = \dot{I}_{1_SP} = \frac{R_2 + j\frac{1}{\omega C_2(j\omega C_2 R_Z + 1)}}{R_1 R_2 + \omega^2 M^2 + j\frac{R_1}{\omega C_2(j\omega C_2 R_Z + 1)}} \dot{U}_{1_SP} \quad (16)$$

$$\dot{I}_2 = \dot{I}_{2_SP} = \frac{j\omega M}{R_1 R_2 + \omega^2 M^2 + j\frac{R_1}{\omega C_2(j\omega C_2 R_Z + 1)}} \dot{U}_{1_SP} \quad (17)$$

$$\dot{I}_3 = \dot{I}_{2_SP} - \dot{I}_{3_SP} = \frac{-\omega^2 C_2 R_Z M}{(R_1 R_2 + \omega^2 M^2)(j\omega C_2 R_Z + 1) + j\frac{R_1}{\omega C_2}} \dot{U}_{1_SP} \quad (18)$$

$$\dot{I}_4 = \dot{I}_{3_SP} = \frac{j\omega M}{(R_1 R_2 + \omega^2 M^2)(j\omega C_2 R_Z + 1) + j\frac{R_1}{\omega C_2}} \dot{U}_{1_SP} \quad (19)$$

Compared with the series - series compensation in this case reactance the capacitor C_2 influences circuit variables when circuit is powered by the resonant frequency, because C_2 is in parallel to the load resistance R_Z . In this case the power consumption, output power and efficiency were calculated same as in the case of S-S compensation. Graphical interpretations of mentioned variables are introduced in dependency on frequency as well as on M (Fig. 9 – Fig. 17).

On Fig. 9 the dependency of transferred power for pure resistive load is shown. This power increases with the rise of M , whereby maximum of power is shifted to the area of higher frequencies compared to the resonant frequency. Compared to S-S compensation, for the same values of

mutual inductances, the transferred power for S-P compensation reaches much lower values.

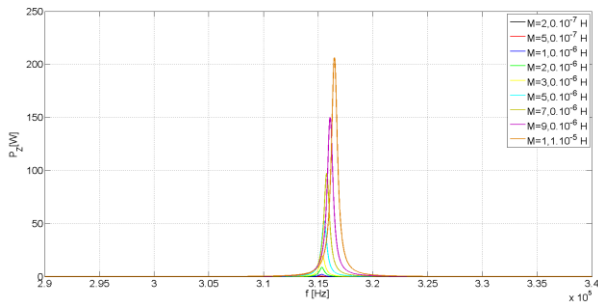


Fig. 9. Frequency dependency of output power for WET system with series – parallel resonant compensation (variable parameter – mutual inductance M)

Small change of frequency from resonant frequency causes that power consumption and power delivered to the load are significantly reduced. Considering similar dependency of efficiency, it shows no change. This is advantageous when power delivery at constant efficiency must be managed. On the other side poor efficiency is the biggest disadvantage (Fig. 10).

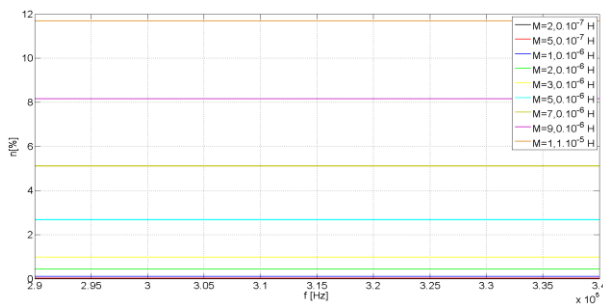


Fig. 10. Frequency dependency of efficiency for WET system with series – parallel resonant compensation (variable parameter – mutual inductance M)

Let now consider different situation, when M is reaching higher values (reduction of distance between coils). Fig. 11 shows, that the efficiency is significantly increased. That means that the best efficiency can be reached for a short distances, while power transfer to the load is comparable with power transfer for series - series compensation Fig. 11.

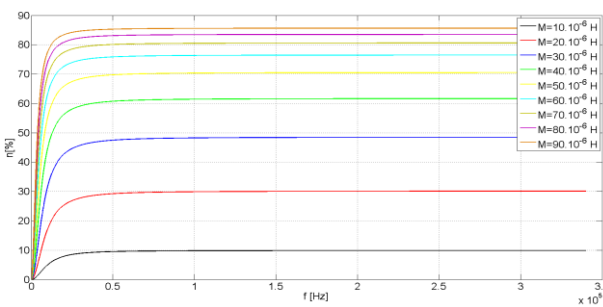


Fig. 11. Dependence of efficiency from frequency for WET with series – parallel resonant compensation for higher values of mutual inductance.

Voltage on the capacitor C_1 in S-P compensated system also achieves high levels. Decrease or increase in the switching frequency reduces voltage stresses on the capacitor, but also significantly reduces the transmitted power. The same situation is valid for the voltage on the coil L_1 .

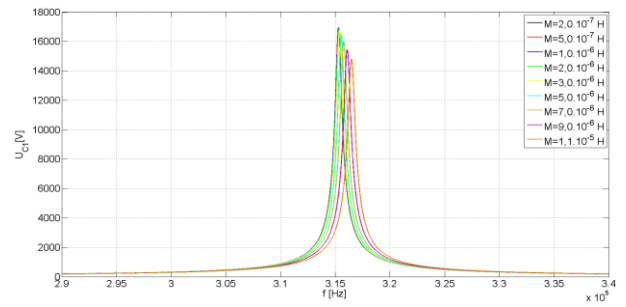


Fig. 12. Frequency dependency of voltage on the capacitor C_1 of WET system with series – parallel resonant compensation

Voltage on the capacitor C_2 (Fig. 13), voltage on the resistive load and the receiver coil L_2 are same, because they are connected in parallel. In contrast to the voltage on the capacitor C_1 , the voltage on the capacitor C_2 is smaller. This voltage is increased when value of M is increased too, but only up to a certain value of the mutual inductance, in our case it is 30uH. Above this value the voltage on capacitor C_2 falls. Capacitor C_2 is not necessary to be designed for high voltage stresses what reduces the cost of the system.

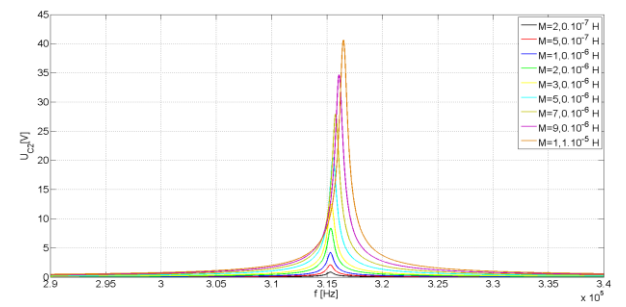


Fig. 13. Frequency dependency of voltage on the capacitor C_2 of WET system with series – parallel resonant compensation

Frequency dependencies of circuit currents are shown on next figures (Fig. 14 – Fig. 17). It can be seen (Fig. 14) that I_1 decreases with the increase of the mutual inductance and its peak point is shifted to higher frequencies oppose to resonant frequency.

Fig. 15 Fig. 16 Fig. 17 show the current of the receiving coil I_2 (Fig. 15) divided into current of the capacitor C_2 (Fig. 16) and a load resistance R_Z (Fig. 17). Because the value of load resistor is relatively small $R_Z = 8\Omega$, the majority of coil current flows just through load resistance - I_4 . Current I_3 of the secondary capacitor C_2 has smaller magnitude. With the increase of mutual inductance the maximum of all currents rises.

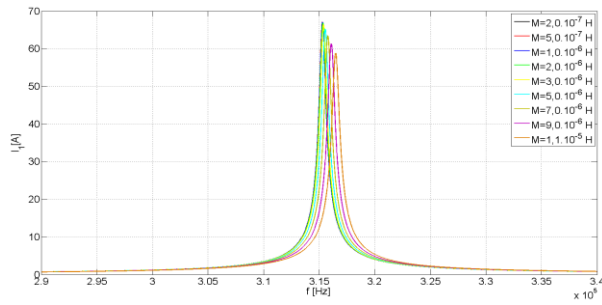


Fig. 14. Frequency dependency of current I_1 of WET system with series – parallel resonant compensation

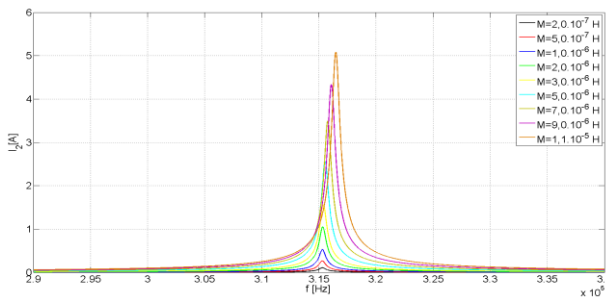


Fig. 15. Frequency dependency of current I_2 of WET system with series – parallel resonant compensation

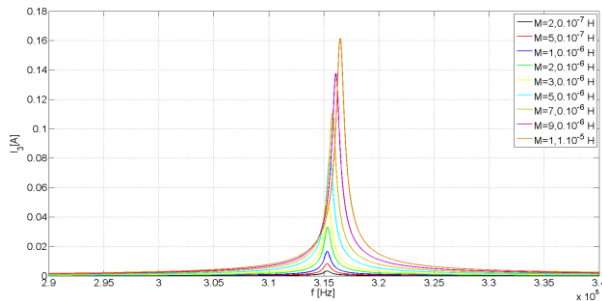


Fig. 16. Frequency dependency of current I_3 of WET system with series – parallel resonant compensation

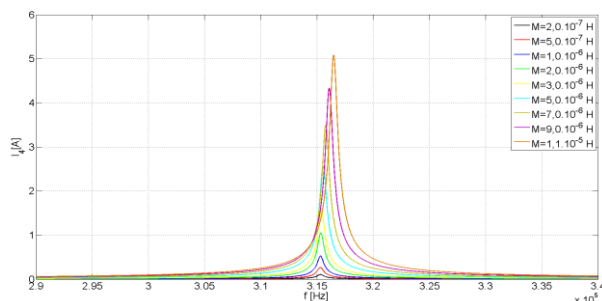


Fig. 17. Frequency dependency of current I_4 of WET system with series – parallel resonant compensation

3. Conclusion

This article shows differences between series - series compensation and series - parallel compensation and important characteristics with respect to the target

application which is charging accumulators in electric vehicles.

Transferred power to the load for series - series compensation is comparable with series - parallel compensation, but efficiency for low values of mutual inductance is advantageous series - series compensation.

Disadvantage of these compensations is high voltage stress of capacitors especially in near of resonant frequency. Therefore is needed to use capacitors for high voltage and frequency with low ESR, or frequency of power source must be higher or lower than the resonant frequency. Coils are suitable made from high frequency cable to reduce skin effect and with bigger gap between turns.

These results are used to optimize the design of the wireless energy transfer.

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