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Comparative Study of the Transmission Characteristic of Unequal Compensated Inductive Power Supply Systems for Electric Vehicles

***Abstract**. Four basic capacitor arrangements are available to compensate the large amount of reactive power required by inductive power supply systems. This paper deals with a comparative investigation of these compensation topologies. They differ in transmission characteristic, which single parameters are strongly nonlinear dependent on operation frequency and load, as well as in transmission efficiency. This survey shall help to decide, which topology is the most reasonable to be deployed as charging device in e-mobility applications.*

Streszczenie.** W artykule porównano cztery podstawowe układy pojemnościowe stosowane do kompensacji mocy biernej w systemach samochodów elektrycznych. Analizowano właściwości w zależności od częstotliwości i obciążenia, a także od skuteczności transmisji. **Studium porównawcze charakterystyk przenoszenia systemów zasilania samochodów elektrycznych z kompensacją mocy biernej

Keywords: Contactless power supply, resonant inverter operation, electric vehicle, reactive power compensation.
Słowa kluczowe: zasilanie bezprzewodowe, przekształtnik rezonansowy, .samochód elektryczny, kompensacja mocy biernej

Introduction

The German government's energy concept contains the aim to reduce the country's CO_2 emissions by increasing the percentage of the registration of new full electric vehicles (FEV) or new hybrid electric vehicles (HEV) within Germany [1, 2]. If charged by renewable energies, FEV and HEV can significantly contribute to a reduction of CO_2 emissions. Former works describe how the deployment of inductive power transmission (IPT) as charging method support efforts of increasing the acceptance of e-mobility within the society [3]: Non-contact charging on the basis of inductive energy transfer allows for a simple and reliable charging process. Moreover, the deployment of an IPT charging solution causes a low deterioration compared to plug afflicted systems.

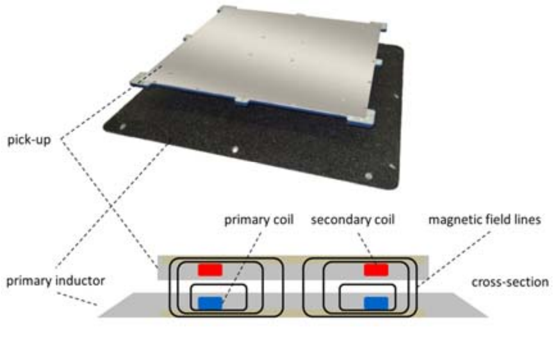
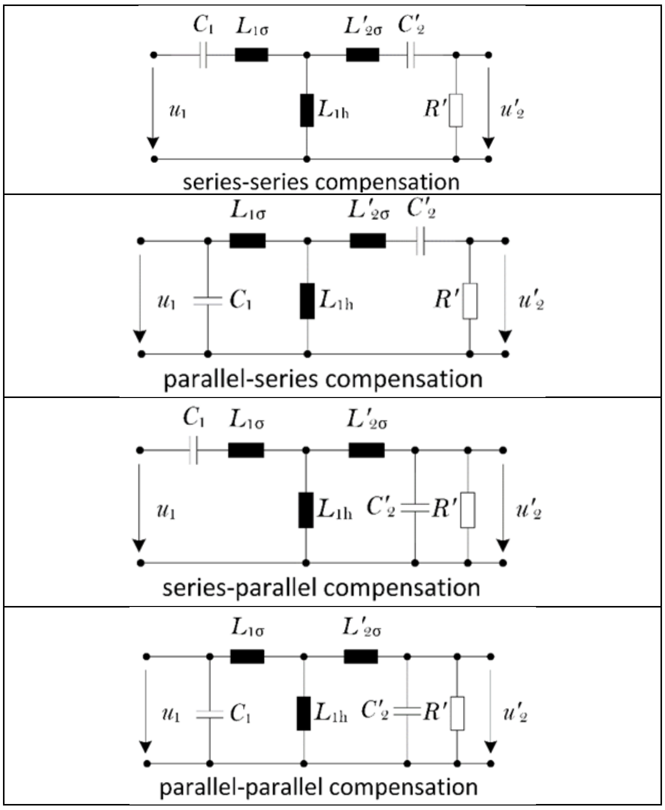


Fig. 1 Prototype of an IPT system for electric vehicle charging

Actually, a lot of companies and research labs work on this topic. A large number of IPT prototypes for vehicle charging applications were presented within the last few years [3 - 8]. As an example, a prototype solution of Vahle Inc. [2, 3] is presented in Figure 1.



series-series compensation

parallel-series compensation

series-parallel compensation

parallel-parallel compensation

Fig. 2. Four basic compensation topologies for IPT systems

Reactive Power Compensation

An IPT system operates like an electrical transformer. An alternating current (ac) in a primary coil excites an alternating electromagnetic field. This electromagnetic field is coupled with a secondary coil which is mounted to a mobile carrier (e.g. an electric vehicle). The field excites an alternating voltage within the wire of that secondary coil. This voltage can be utilised as voltage source for the operation of on-board loads. This working principle can be described by a transformer's equivalent circuit drawing [3]. Due to several reasons, the values of the reactances, which describe the IPT's transmission characteristic, are quite high when compared to reactances within conventional transformers. Therefore, the required amount of reactive power of these systems is very high as well. A compensation of the reactive power is unavoidable. Otherwise, the transmission efficiency of an IPT would nearly be zero. To compensate the IPT system, it is additionally equipped by capacitors on the primary side and on the secondary side. The compensation can occur in series connection or in parallel connection. Figure 2 presents the four resulting compensation topologies. In these drawings, $L_{1\sigma}$ is the primary leakage inductance, $L'_{2\sigma}$ is the secondary leakage inductance, and L_{1h} is the main inductance. The capacitors C_1 and C'_2 are the respective compensation elements of primary winding and secondary winding. R' is the load resistance (e.g., the FEV's on-board battery) connected to the IPT's secondary side. All values marked with an inverted comma are not the measurable values but related to the primary side by the ratio of the primary and secondary winding factors w_1/w_2. The total impedances for each transmission system can be obtained as follows:

For series-series compensation:

$$(1)\qquad Z_{total} = jX_{C1} + jX_{L1\sigma} + \frac{\left(\left(jX_{L'_{2\sigma}}+jX_{C'_2}+R'\right)\cdot jX_{L1h}\right)}{jX_{L'_{2\sigma}}+jX_{C'_2}+R'+jX_{L1h}}$$

For series-parallel compensation:

$$(2)\qquad Z_{total} = jX_{C1} + jX_{L1\sigma} + \frac{\left(\left(jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}\right)\cdot jX_{L1h}\right)}{jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}+jX_{L1h}}$$

For parallel-series compensation:

$$(3)\qquad Z_{total} = \frac{jX_{C1}\cdot\left(jX_{L1\sigma}+\frac{jX_{L1h}\cdot\left(jX_{L'_{2\sigma}}+jX_{C'_2}+R'\right)}{jX_{L1h}+jX_{L'_{2\sigma}}+jX_{C'_2}+R'}\right)}{jX_{C1}+jX_{L1\sigma}+\frac{jX_{L1h}\cdot\left(jX_{L'_{2\sigma}}+jX_{C'_2}+R'\right)}{jX_{L1h}+jX_{L'_{2\sigma}}+jX_{C'_2}+R'}}$$

For parallel-parallel compensation:

$$(4)\qquad Z_{total} = \frac{jX_{C1}\cdot\left(jX_{L1\sigma}+\frac{jX_{L1h}\cdot\left(jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}\right)}{jX_{L1h}+jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}}\right)}{jX_{C1}+jX_{L1\sigma}+\frac{jX_{L1h}\cdot\left(jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}\right)}{jX_{L1h}+jX_{L'_{2\sigma}}+\frac{jX_{C'_2}\cdot R'}{jX_{C'_2}+R'}}}$$

The angular frequency is defined as

$$(5)\qquad \omega = 2\cdot\pi\cdot f$$

and the phase angle of the transmission system is calculated by

$$(6)\qquad \varphi = arctan\left\{\frac{Im(Z_{total})}{Re(Z_{total})}\right\}.$$

In principle, the IPT is able to transmit its rated amount of active power if it is driven by a simple inverter, which is constantly operated by the circuit's resonant frequency. However, if applied to charge FEVs or HEVs, there is at minimum one challenge left which needs to be solved: The inductivity values of mutual and leakage inductances are not constant. They strongly depend on vertical distance between the coils as well as on the lateral deviation between both primary inductor and pick-up [3]. Due to parking inaccuracies and different distances between vehicle and ground surface, the inductances fluctuate in IPT systems for vehicle applications. This leads to problems to compensate the entire amount of reactive power: The compensation is designed to compensate the reactive power amount of only one value for each of the circuit's inductances. Since variable capacitors are too expensive, the most reasonable solution is the deployment of a frequency adaptive power inverter. These inverters are able to adjust their operating frequency to always drive the oscillating circuit with its resonant frequency.

Transmission Characteristics

In experiments with frequency adaptive IPT systems is obtained, that in some cases more resonant frequencies occur than the desired one. The transmission characteristic, described by the phase angle φ and the amount $|Z|$ of the system's impedance Z, is strongly nonlinear dependent on the electrical load R connected to the secondary coil. The characteristic of phase angle φ shows if a system resonance is available. If φ is equal to zero, the system impedance's imaginary part is zero as well. This indicates that the system is in resonance.

To learn how the transmission characteristic exactly is related to the compensation strategy, measurement aided investigations utilising a prototypical IPT system, designed and constructed at the University of Wuppertal, are performed. To discover the respective characteristic, the inductivity values, measured at the test bench, are used to configure an analytic equivalent circuit simulation. Table 1 presents the respective equivalent circuit values of the IPT's inductivities and the system's rated frequency.

Table 1. The characteristic values of the IPT System deployed at the University of Wuppertal

primary leakage inductivity $L_{1\sigma}$	43.27 µH
main inductivity L_{1h}	137.43 µH
secondary leakage inductivity $L'_{2\sigma}$	46.03 µH
rated frequency f_R	140 kHz

The calculations for exploring the transmission characteristic of the four systems are performed in a frequency interval of 130 kHz ≤ f < 170 kHz. The interval for the load resistance is selected between 20 Ω < R < 70 Ω.

In Figure 3, the phase angle characteristic of a series-series compensated IPT system is displayed. It can be seen, that there is only one resonant frequency, near f = 140 kHz, if the load resistance value approximately is $R \geq$ 50 Ω. For smaller values of R, more than one frequency value for a phase angle of $\varphi = 0$ exists. This means, there is no explicit solution for a resonant frequency value. This can lead to an instable operation in a realistic application of a frequency adaptive IPT feeding an electrical load with a high power input.

Another example is the phase angle characteristic of a series-parallel compensated IPT, which is depicted in Figure 4. Here, phase angle φ is independent of the load resistance. The resonant frequency ($\varphi = 0$) is always f = 140 kHz. This indicates, that a series-parallel compensated

IPT system driven by a resonant frequency adaptive inverter allows for a stable and reliant operation. However, the series-parallel compensated system possesses not only advantages, when compared with the series-series compensated IPT. Losses generated by the ohmic resistance (including the skin effect) of the wires of primary and secondary coil may be much higher when the reactive power is compensated by parallel connected capacitors. This is caused by an additional reactive current, which does not appear in series compensated circuits.

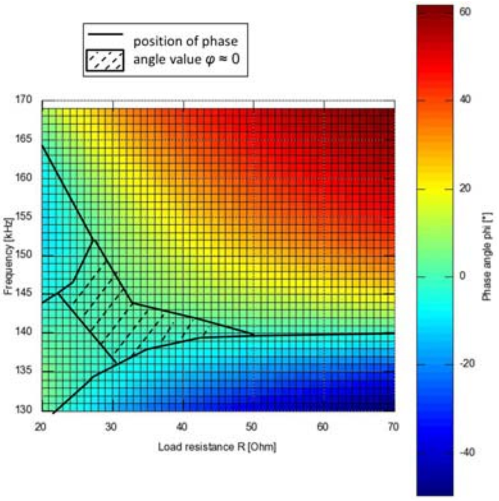


Fig. 3. Phase angle characteristic of a series-series compensated IPT system dependent on load resistance and frequency

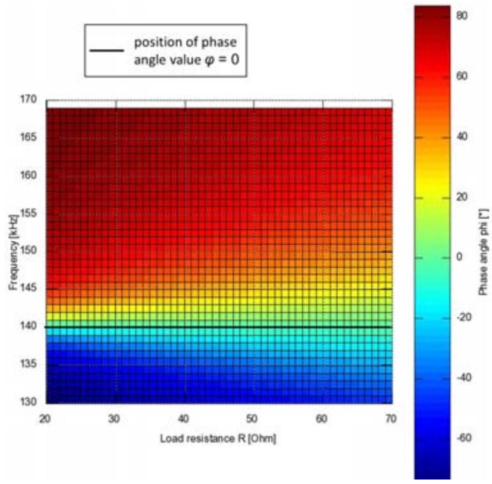


Fig. 4. Phase angle characteristic of a series-parallel compensated IPT system dependent on load resistance and frequency

When analysing the other two compensation topologies, it is obtained that the phase angle φ depends on the load resistance. However, the dependency factor in both cases is much lower when compared to the series-series topology but it is not completely independent. In Figure 5, the phase angle φ of parallel-parallel compensated circuit is displayed. It can be seen, that the rated frequency value of f_R = 140 kHz solely matches with the real resonant frequency if a short circuit operation on the secondary side occurs (R = 0). If using a parallel-series compensated transmission circuit, the phase angle amounts $\varphi = 0$ only if the load is very small or under no-load operation conditions. Figure 6 presents a section of the resonant frequency characteristic of this kind of compensation topology, which shows that the curve of phase angle $\varphi = 0$ tends to rated frequency value f_R = 140 kHz for higher values of load resistance R.

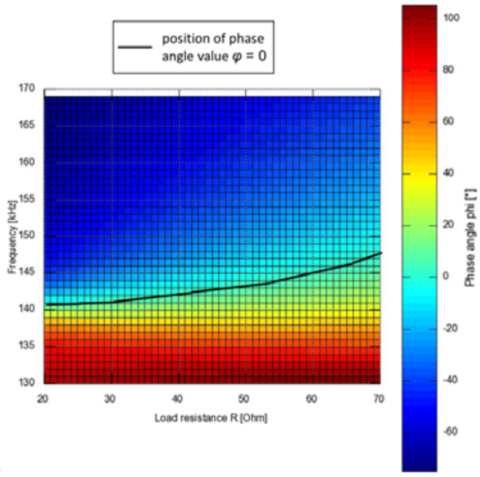


Fig. 5. Phase angle characteristic of a parallel-parallel compensated IPT system dependent on load resistance and frequency

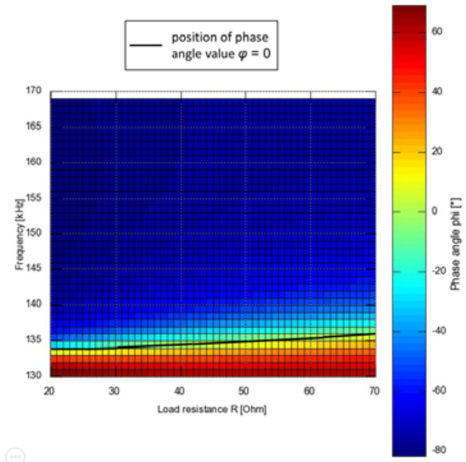


Fig. 6. Phase angle characteristic of a parallel-series compensated IPT system dependent on load resistance and frequency

Due to additional reactive currents, parallel compensated parts of IPT systems potentially are less efficient than series compensated parts. For this, series-series compensated circuits have the highest efficiency potential when compared to similar designed other compensated IPT-Systems.

Table 2. Ability evaluation of the analysed topologies for operation with the IPT prototype

	series-series compen-sated	series-parallel compen-sated	parallel-series compen-sated	parallel-parallel compen-sated
efficiency (copper losses)	+ +	+	-	- -
frequency stability (rated frequency f=140kHz)	- -	+ +	-	+

Conclusion

IPT Systems designed with different compensation topologies differ in transmission characteristic and efficiency. A comparative study is performed to be able to name benefits and disadvantages of the presented topologies, if they are used in contactless charging stations for electric vehicles. Table 2 presents an overview of the results obtained.

The series-series topology possesses the highest efficiency potential when compared to the other compensation topologies. However, if employed in systems with frequency adaptive inverter operation, series-series compensated systems are able to get to an unstable operation area since there is no explicit solution for a resonant frequency value under certain load conditions. The other compensation topologies do always exhibit one concrete resonant frequency value. The best overall transmission performance (concerning frequency stability and efficiency) is reached by the series-parallel compensation topology.

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