Optimization of series-series compensated wireless power transfer system using alternative secondary side rectification

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Abstract

This paper focuses on the operational analysis of wireless power transfer (WPT) system, while the topology of the secondary side rectifier represents the main element, for which the properties of WPT system are being investigated. Initially the system description and technical specifications are given. Because WPT systems are designed for a certain type and value of the load (impedance matching) in order to achieve the highest possible efficiency, the definitions for those values are identified for individual topologies of the secondary side rectifiers. Consequently, the results are compared and discussed and followed by the simulation analysis to prove the operational behavior in time-domain for each of investigated alternative of rectifier. Several relationships have been identified in relation to secondary side electrical variables, and discussion for stress-optimization are given as well. The simulation results are verified by the experimental measurements, while individual solutions for secondary side rectifiers are evaluated from efficiency point of view followed by the recommendations of the operational conditions.

1. Introduction

The global trend of mobile devices, rapid advances in electric vehicles, and the deployment of smart grids that require millions of energy-saving sensors have put wireless technology back in the spotlight. Unlike Information and Communication Technology (ICT), which requires small amounts of energy to transmit useful data, the goal of WPT is to safely transmit large amounts of electrical energy over a given distance to a load. In recent decades, the use of battery-powered devices such as mobile phones, electric vehicles, and medical implants has increased significantly around the world, and WPT can find significant applications.

WPT is used in a variety of industrial applications and robotics, such as transferring electrical energy through bent joints without physical contact [1,4], and robotic devices performing tasks such as disaster relief in inaccessible or hazardous locations. It can also be used for applications [5,8]. For these reasons, there is a need to develop more efficient and secure designs for WPT technology. The purpose of this paper is to provide an up-to-date overview of current WPT topologies and highlight the limitations of the most commonly used technology, inductive power transfer systems, through simulations and hands-on analysis.

It is common knowledge that in order to transfer actual power to the load side of an IPT system, the leakage inductors of a loosely coupled transformer (LCT) must be corrected. To compensate the primary side and/or secondary side, a number of compensation networks have been proposed. Their major objectives are to attain or enhance the good traits listed below [10,14]: an output with a constant current and voltage that is unaffected by load resistance; zero voltage switching (ZVS), which can achieve great efficiency by soft switching, requires a weak inductive input impedance; Less sensitivity to the fluctuating coupling coefficient, which significantly broadens the range of applications.
In an IPT system, it is generally challenging for a compensation circuit to satisfy all the requirements. Tolerance for IPT namely, serial-serial (SS), serial-parallel (SP), parallel-serial (PS), and parallel-parallel (PP), are widely used in many scenarios. The SS compensation architecture, which achieves zero voltage switching and nearly zero reactive power without experiencing bifurcation occurrences, has more desirable properties than the other three topologies. For SS topology, only two compensating capacitors are required, which leads to less power loss, smaller size, higher power density, and lower cost. The performance of the converter's transfer, however, is almost fixed after the transformer has been identified unless a new LTC is substituted. Low design freedom and high sensitivity to misalignment highly restrict the practical promotion of SS-compensated IPT system.

Higher order compensation techniques, such LCL compensation topology, are suggested [15,17] as a solution to the issue of ultra-large current in SS topology. Inverter and resonant tank power exchange is balanced by the additional compensating inductance. By using magnetic coupling, the primary coil current behaves as a current source and gives the secondary side a steady voltage. The LCC compensation topologies provide many desirable performances, such as ZPA operations, high freedom of design, but more resonant elements, resulting in complex tune and the increase of system size and cost.

Once the practical and/or commercial use is under consideration the cost, size efficiency and power performance are the main issues, which are defining the qualitative indicators of the system. It is therefore desirable to utilize trusted, reliable, and robust solutions. This paper focuses on the standard SS compensated WPT system, while the analysis is related to the properties investigation of the secondary side rectifier configurations. The common bridge diode rectifier is compared to alternative solutions. First it is discussed about the impedance matching requirement, so for this purpose the determination of the reflecting AC side resistance is provided. Consequently, the operational properties of certain rectifier types are evaluated through simulation analysis in time domain followed by the performance investigation through laboratory measurements. Individual rectifier configurations are evaluated from efficiency point of view, while the recommendations for the target application use are given at the end of the paper.

2. Materials and Methods

Wireless power transfer systems are being under development for more than a decade. Through the time, many configurations of compensation network have been analyzed, while various application purposes have been identified as well. This research is focused on the series-series (SS) compensated WPT system, which is well suited to the application area of high-power vehicle battery chargers due to their electrical and transfer properties. SS compensated WPT system, similarly to other configurations, has certain specifications which must be considered when designing a WPT system for defined parameters of target application. The correct system settings, or impedance matching considering the type of the load is crucial according to achieve optimal operating parameters, especially efficiency and performance.
The investigated system can be illustrated using Fig. 1, which shows the input WPT system supply source, the WPT inverter, the coupling elements in series-series topology and power electronics of the on-board part of the secondary side system. Because presented research is focused on the optimization of the WPT system performance using alternative configuration of secondary side rectifier, four topologies as a direct connection to the load (resistor or battery) are considered.

- standard bridge diode rectifier,
- diode rectifier in combination with a DC-DC converter,
- diode rectifier with current output ($I_{\text{type}}$),
- diode rectifier with voltage output ($U_{\text{type}}$).

The entire system control and data acquisition from measurements are supervised by the PC equipped by relevant control algorithm. The parameters of individual core components are listed in Table 1.

### Table 1
Tested assembly and variants of experimental set-up

<table>
<thead>
<tr>
<th>Compensation components</th>
<th>L</th>
<th>23 µH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>3.3 nF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable load</th>
<th>$R_{\text{trim}}$</th>
<th>0–20 Ω</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>On-board electronics</th>
<th>Diode bridge</th>
<th>H-bridge SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Secondary side of WPT system)</td>
<td>Diode Bridge + DCDC</td>
<td>$L_{\text{DCDC}} = 10$ µH</td>
</tr>
<tr>
<td></td>
<td>$I_{\text{type}}$ Bridge</td>
<td>$2\times L = 10$ µH, SiC</td>
</tr>
<tr>
<td></td>
<td>$U_{\text{type}}$ Bridge</td>
<td>CMM = 900 µH, SiC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Off-board electronics</th>
<th>Inverter</th>
<th>H-bridge SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Primary side of WPT system)</td>
<td>Power supply</td>
<td>universal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical parameters</th>
<th>Voltage range</th>
<th>up to 312 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current range</td>
<td>up to 15 A</td>
</tr>
<tr>
<td></td>
<td>Power limit</td>
<td>500 W</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>577 kHz</td>
</tr>
</tbody>
</table>

2.1. Background theory of the impedance matching for SS WPT system considering topology variations for secondary side rectifier

Several key conclusions can be derived from the theory of coupling elements of a WPT system using series-series configuration of the compensation network. First of all, it is about defining the basic circuit...
description (Eq. 1) and consequently identify the optimal value of the load resistance (Eq. 2, 3), i.e. targeting maximum system efficiency [18]–[20].

\[
\frac{1}{C_1} \int_0^T i_{s1}(t) dt + u_{c1(0)} + L_1 \frac{di_{s1(t)}}{dt} - M \frac{di_{s2(t)}}{dt} + R_1 i_{s1(t)} - u_{1(t)} = 0
\]

\[
+ \frac{1}{C_2} \int_0^T i_{s2(t)} dt - u_{c2(0)} + L_2 \frac{di_{s2(t)}}{dt} - M \frac{di_{s1(t)}}{dt} + R_2 i_{s2} + R_z i_{s2} = 0
\]

1

\[
R_{z_{\text{max}}} = \sqrt{R_1 R_2 + M^2 \omega_0^2}
\]

2

\[
R_{z_{\text{max}}} = M_0 R_1, R_2 = 0
\]

3

Since it is a resonance coupling, then Eq. 4 must be satisfied. It defines the resonant frequency as the operating frequency of the WPT system.

\[
f_0 = \frac{1}{2 \sqrt{LC}}
\]

4

The dependency of the load resistance on the optimal operation point regarding efficiency and output power of the WPT system is graphically interpreted on Fig. 2, which is valid for the 65 kW system power. As it is clear from this figure, if the load of the coupling elements is not impedance-matched, then efficiency decrease would happen, which is an undesirable phenomenon that must be minimized. The highest efficiency (97.5%) refers to the 50 kW of the output power.

As follows from Eq. 2, the optimal load resistance is dependent on the parasitic resistance of the circuit R (R_1 = R_2 = R), i.e. due to thermal changes of the ESRL and ESRC parameters. Apart from changes in R, R_{z_{\text{max}}} also depends on the operating parameter in the form of mutual inductance M, which is a function of the coupling factor between the coupling elements and thus on their relative position (alignment) and distance (transmission distance). A more detailed description regarding coupling elements influences can be found in the literature [1].

2.1.1. Impedance matching of the standard bridge diode rectifier

According to the terms of impedance matching for direct connection of the DC load using the bridge diode rectifier, the situation can be described by Eq. 5. Impedance conversion is independent of the circuit parameters and is defined only by a physical principle. For the real case, however, Eq. 4 incomplete, as it does not respect the static and dynamic resistance of individual diodes. Ultimately, the impedance
conversion of the diode rectifier will be slightly dependent on the circuit parameters, which can be neglected with minimal error.

Achieving the optimal operating condition of the WPT is therefore possible only by changing the design of the coupling elements, or by changing the resistance of the DC load in order to fulfill the condition of Eq. 3.

\[ R_{zAC} = \frac{8}{2} R_{zDC} \cong 0.811 R_{zDC} \]

2.1.2. Impedance matching of the standard bridge diode rectifier with DC/DC converter

Adding a buck DC-DC type of the converter to the diode bridge rectifier, it is possible to achieve an active and continuous impedance matching of the load and compensation element. The impedance conversion is then given by the combination of the rectifier conversion rate (Eq. 5) and the DC-DC converter (Eq. 6). The resistance on the DC side of the rectifier \( R_{zDC} \) is given by the magnitude of the equivalent resistance of the load \( R_{\text{load,eq}} \) given by Ohm's law at the output terminals (resistor, battery, ...) and the alternating current value of the DC-DC converter.

The resulting impedance matching function of this combination is given by Eq. 7.

\[ R_{zDC} = \frac{R_{\text{load,eq}}}{z^2} z\langle 0; 1 \rangle \]

\[ R_{zAC} = \frac{8}{2z^2} R_{\text{load,eq}} z\langle 0; 1 \rangle \]

According to proper operation of the system, the condition defined by Eq. 8 must be met, i.e. the value of the resistance at the DC side of the rectifier (\( R_{zDC} \)) must be lower than the value of the equivalent resistance. The second condition concerns the battery-type load, when the current cannot exceed the maximum battery current while the minimum current cannot be lower that the ripple's own value (Eq. 9–10).

\[ R_{zDC} \geq R_{\text{load,eq}} \]

\[ I_{\text{bat}} \epsilon \left( I_{\text{bat, min}}; I_{\text{bat, max}} CC \right) \langle I_{\text{bat, min}}; \frac{U_{\text{bat, max}}}{R_{\text{eq}}}; \right) \]
2.1.3. Impedance matching of the current-doubler diode rectifier

Equivalent schematic of the WPT system equipped by a special, current-type rectifier with is shown in Fig. 3. Its topology replaces the upper diodes of the standard H-bridge rectifier by inductors, while there is no common coupling between them. The value of the inductance to meet preferable operational conditions according to the best efficiency performance is given by Eq. 11. So, as is clear, the size of the inductances of $I_{\text{type RECT}}$ (current type rectifier) is dependent on the size of the load and thus the condition from Eq. 3 is fulfilled only for one specific value of the load for which the $L_{I\_\text{RECT}}$ and the coupling elements are designed.

$$L_{I\_\text{RECT}} = \frac{R_{\text{loadeqv}}}{0} (-1)$$

11

The impedance matching ratio for the $I_{\text{type}}$ rectifier is defined by Eq. 12, while it is seen that main specific according to the operation of this rectifier type is impedance increasing function.

$$R_{zAC} = \frac{2}{2} R_{\text{loadeqv}} \approx 4.93 R_{\text{loadeqv}}$$

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2.1.4. Impedance matching of the voltage-doubler diode rectifier

The last alternative considers the second variant of a special type of rectifier with voltage output. The upper diodes of the H-bridge topology are replaced with magnetically coupled inductances in the “common mode” connection according to Fig. 1. Unlike $I_{\text{type RECT}}$, the size of the inductances can be designed for the wide range of values. $L_{U\_\text{RECT}}$ is limited by a minimum value so that discontinuous character do not occur during the operation with the lowest load current. The $U_{\text{type RECT}}$ impedance conversion ratio is given by Eq. 13, which results in a clear increasing impedance function, but approximately half that of the standard $U_{\text{type H-bridge rectifier}}$.

$$R_{zAC} \approx \frac{32}{2} R_{\text{loadeqv}} \approx 3.24 R_{\text{loadeqv}}$$

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3. Results
From Eq. (5–13) is seen that the value of the impedance matching in relation to the optimal load (3) is specific for individual variants of secondary side rectifiers discussed in previous part of the paper. Figure 4 shows comparison of the impedance matching values of discussed rectifier types and its relationship to the optimal value of the $R_{AC}$. From this figure is seen, what is the optimal value of the load resistance considering individual secondary side types of rectification.

Table 2 is listing these values for each type. At this point it must be noted that DCDC connection on the secondary side can adapt the optimal value of $R_{AC}$ due to the possibility of the regulation of the output voltage and/or current.

<table>
<thead>
<tr>
<th>Variant</th>
<th>$R_{load,opt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>11.5</td>
</tr>
<tr>
<td>DCDC</td>
<td>—</td>
</tr>
<tr>
<td>$I_{type}$</td>
<td>1.8</td>
</tr>
<tr>
<td>$U_{type}$</td>
<td>2.8</td>
</tr>
</tbody>
</table>

### 3.1. Time-domain simulation

In order to be able to realize the physical prototypes and to provide experimental measurements, first the simulation models in time domain have been realized. Figure 5 and Fig. 6 are showing circuit diagrams of considered secondary side rectifiers. The primary side of the WPT system is replaced by the voltage-sourced equivalent circuit, representing the functionality of the primary side inverter. All circuit parameters are defined in Table 1. Regarding $U_{type}$ rectifier, the common mode inductors with very high magnetic coupling must be considered ($k \to 1$).

The simulation results shown on Fig. 7 – Fig. 8 are representing leg currents of the secondary side rectifier ($I_a$, $I_b$), load current ($I_{load}$), the current from rectifier to DCDC converter ($I_{dcdc}$) and the voltage on the secondary/receiving coil of the WPT system ($U_2$). Individual waveforms are represented for the nominal – steady state operation of the system.

In the case of direct load connection (Fig. 6-left), the presented waveforms are referring to the common operation of diode-bridge rectifier. The currents $I_a$ and $I_b$ are forming the pulsation of the load current $I_{load}$. The voltage $U_2$ has naturally rectangular shape, what is caused by the operational principle of the diode
rectifier and with capacitive filter on the DC side. At the same time, for the presented case \( R_{\text{load}} = R_{\text{load opt}} \), \( U_{1m} = U_{2m} \) and \( I_{1m} = I_{2m} \) apply here.

In the case of connecting a load via a combination of a diode rectifier and a DCDC converter (Fig. 6 – right), which has the responsibility for resistance variation, the presented waveforms are similar to the situation when direct connection is considered (\( R_{\text{load}} = 6.37 \Omega \), duty-cycle = 0.75).

For the situation, when I_{\text{type rectier}} is considered, a phase shift of 90° is visible between the currents \( I_a \) and \( I_b \). \( I_{\text{load}} \) is formed by these two leg currents, while the current ripple is less compared to direct connection. Due to the triangular character of the current, a very unfavorable waveform of the voltage is visible, if transmitting and receiving coil are under consideration. This time waveform of \( U_2 \) (Fig. 7 – left) is typical for power supplies which behave as a very stiff current source. It is seen that at the moment of diode commutation, extreme rise of voltage exists, while during the gradual increase of the \( I_{\text{load}} \) the gradual decrease of \( U_2 \) applies. After this transient the \( U_2 \) voltage is practically zero. The amplitude of the \( U_2 \) pulse is given by Eq. 14.

\[
U_{2m} = L \frac{I_{2rms}}{tc} = L \frac{I_{\text{load}}^2}{2\sqrt{2}} L_{\text{type}} \frac{\frac{1}{2f_0} I_{\text{load}}}{R_{\text{load}} I_{\text{load}}} = L \frac{I_{\text{load}}^2}{2\sqrt{2}} L_{\text{type}} \frac{1}{2f_0} = L \frac{I_{\text{load}}^2}{2\sqrt{2}} L_{\text{type}} \frac{1}{2f_0} = L \frac{I_{\text{load}}}{2\sqrt{2}}
\]

14

In the case of the variant with the \( U_{\text{type rectier}} \) rectifier, a phase-shift is 0° between the currents \( I_a \) and \( I_b \). Similarly to previous situation, \( I_{\text{load}} \) is formed by the leg currents. Depending on the quality (coupling factor) of the common-mode inductor, the currents are half-wave in nature, which has a positive impact on the \( U_2 \) voltage waveform. After reaching right the \( I_{\text{load}} \) effective value, \( U_2 \) begins to fall (Fig. 7 – right). The amplitude of the \( U_2 \) pulse is given by Eq. 15.

\[
U_{2m} = L \frac{I_{2rms}}{tc} = \frac{\sqrt{2}}{1} \frac{1}{2f_0} = 2L f_0 I_{\text{load}}
\]

15

From the previous simulation analysis is seen, that the unfavorable effect for \( U_{\text{type rectier}} \) and \( I_{\text{type rectier}} \) rectifier is reflected within the time-waveform of the voltage on coupling coils of WPT system. Both types use inductors within the main circuit. It is therefore desirable to investigate the influence of the values of inductances on the operational behavior of \( I_{\text{type rectier}} \) and \( U_{\text{type rectier}} \) rectifiers. For the case of \( U_{\text{type rectier}} \) rectifier, the variable parameter is coupling factor of the common mode choke (from 0.8–0.999). \( I_{\text{type rectier}} \) rectifier has
variation within the value of the inductance of both inductors within the range 1 µH – 900 µH. Figure 8 is showing time-waveforms for individual situations.

As a result of this analysis, next assumption can be made:

- reduction of the value of inductances of \(I_{\text{type}}\) rectifier inductors, below the value, which is determined by Eq. (11) leads to decrease of the average value of rectifier leg’s currents resulting in generation of circulation currents. This causes reduction of the commutation voltage, efficiency and the amount of the transferred power.
- In the case of \(U_{\text{type}}\) rectifier, the reduction of the coupling factor below 0.97 leads to gradual transition from \(U_{\text{type}}\) rectifier to \(I_{\text{type}}\) rectifier. At first, the commutation voltage only increases, which later saturates and the average value of the currents begins to decrease rapidly.

3.1. Experimental measurements

The aim of the experimental measurements is to verify the properties of individual rectifier types, while efficiency performance of whole WPT system will be evaluated. The experimental set-up is shown in Fig. 9. Table 2 shows the input-output parameter during measurements. Figure 10 is representing the prototype of reconfigurable topology of secondary side rectifier, i.e. PCB enables to configure all of discussed types of rectifier.

The measurements were processed automatically, i.e. with the help of the supervisor control system (PC), and after the setting of the measuring algorithm, individual devices were automatically controlled, e.g. electronic load, where the load of the WPT system changed in defined steps. Subsequently, the measured data were automatically uploaded to the computer, where graphical visualization have been performed.
Table 2
Operational parameters, component values and instrumentation list of designed WPT system

<table>
<thead>
<tr>
<th>Input voltage (V)</th>
<th>up to 312 V, based on battery voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulated current (A)</td>
<td>up to 15 A</td>
</tr>
<tr>
<td>Switching frequency (kHz)</td>
<td>577 kHz</td>
</tr>
<tr>
<td>Output power (W)</td>
<td>up to 500 W</td>
</tr>
<tr>
<td>Coupling elements values</td>
<td>L₁ = L₂ = 23 µH</td>
</tr>
<tr>
<td></td>
<td>H-bridge SiC</td>
</tr>
<tr>
<td></td>
<td>C₁ = C₂ = 3.3 nF</td>
</tr>
<tr>
<td></td>
<td>universal</td>
</tr>
<tr>
<td>Diode rectifier</td>
<td>H-bridge SiC</td>
</tr>
<tr>
<td>Rectifiers components</td>
<td>H-bridge SiC + DCDC</td>
</tr>
<tr>
<td></td>
<td>L_{DCDC} = 10 µH</td>
</tr>
<tr>
<td></td>
<td>I_{type} Bridge</td>
</tr>
<tr>
<td></td>
<td>2*L of 10 µH, SiC</td>
</tr>
<tr>
<td></td>
<td>U_{type} Bridge</td>
</tr>
<tr>
<td></td>
<td>CMM = 900 µH, SiC</td>
</tr>
<tr>
<td>Power source</td>
<td>California Instruments</td>
</tr>
<tr>
<td></td>
<td>CSW 5550</td>
</tr>
<tr>
<td>Power analyzes</td>
<td>ZES Zimmer</td>
</tr>
<tr>
<td></td>
<td>LMG 500</td>
</tr>
<tr>
<td>Electronic load</td>
<td>H&amp;H</td>
</tr>
<tr>
<td></td>
<td>ZS 7080</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Tektronix</td>
</tr>
<tr>
<td></td>
<td>MSO 4104B</td>
</tr>
<tr>
<td>Control board</td>
<td>RICE</td>
</tr>
<tr>
<td></td>
<td>Include TMS320F28335</td>
</tr>
<tr>
<td>Laboratory source</td>
<td>TTI</td>
</tr>
<tr>
<td></td>
<td>EX354 RT</td>
</tr>
</tbody>
</table>

To confirm results from the simulation analyses, the measurement of time-waveforms was performed, while the influence of the type of rectifier was validated. Recorded variables are:

- Voltage on the transmitting coil – light blue waveform
- Current of the transmitting coil – dark blue waveform
- Voltage on the receiving coil – green waveform
- Current on the receiving coil/leg of the rectifier - pink waveform

The goal of this investigation was to proof the time-waveforms of the simulation analysis, while focus is given on the voltage amplitudes on the secondary side receiving coil, as well as the current of the rectifier leg. Table 3 is listing the values on the individual components. It is seen that the simulation expectations...
are confirmed, and the differences between the measurement and simulation are very low (considering value of the rectifier leg current the relative error is approximately 0.14%).

<table>
<thead>
<tr>
<th>Rectifier variant</th>
<th>(U_2) (Vp-p)</th>
<th>(I_2) (Ap-p)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>simulation</td>
<td>measurement</td>
</tr>
<tr>
<td>(l_{type})</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>(U_{type})</td>
<td>180</td>
<td>250 (180 without oscillations)</td>
</tr>
</tbody>
</table>

The results from the experimental verification are presented in three ways. First, they are represented as efficiency map, next as the load current map and finally as the efficiency dependency on the load current. The load current is representing eventual battery current, therefore electronic load was operated equally to the operation of battery charging.

### 3.2. Discussion to experimental results

From Fig. 13 left is seen, that direct connection between coupling element and rectifier is advantageous only for the applications, where almost constant load is expected. For this specific value of load, the coupling elements are designed adequately. Alternative with DCDC converter between load and coupling element has the possibility to match the impedance for the whole range of the load values and power variations. The only limitation would be a small value of currents if low load resistance is considered (Fig. 13 right).

The \(l_{type}\) connection of the rectifier is suitable for very small values of load resistances, i.e., for high values of secondary side currents (Fig. 14 left). The area of the effective utilization of this configuration is slightly narrow compared to the other options, so the application with variable load is not preferable. The last configuration of the rectifier, \(U_{type}\) is applicable for the systems with higher resistive load. The effective area of its utilization is wider compared to the \(l_{type}\) rectifier; thus the use is preferable also for the applications with variable load resistance.

### 4. Conclusion

The main objective of this research was to investigate the possibilities of alternative solutions of the on-board electronics of the wireless power charging system. We are discussing here about the secondary side rectification of WPT system, whereby focus was given on four circuit topologies. The investigated variants were standard bridge diode rectifier, standard bridge diode rectifier supplemented by DC/DC converter at the output, modified diode bridge rectifier to current type (\(l_{type}\)) and modified diode bridge rectifier to voltage type (\(U_{type}\)). It was discovered that each of the rectifier has different properties related
to the identification of optimal value of the load resistance. In other words, the possibilities for impedance matching adjustments have been identified. From the simulation and experimental results, the conclusion can be summarized that the derived variants of the bridge rectifiers, i.e. $I_{\text{type}}$ and $U_{\text{type}}$ are equivalent, but in detail the variant with a voltage output (with a common-mode inductor) is more suitable. It is simpler to design, takes up less space, does not exhibit large commutation overvoltage and has a voltage output. In the case of high-quality design and determination of load change limits, the variants are effectively comparable to the rectifier variant equipped by DC/DC converter. In general, $I_{\text{type}}$ and $U_{\text{type}}$ rectifier variants are more suitable for a fixed load than for a battery charging, where CV/CC charging profile is preferred. Once the battery charging is considered, the most suitable option is the use of active impedance adaptation, i.e. the utilization of secondary side rectifier with DC/DC converter, when multiple times higher efficiency and its stability are achieved throughout the entire charging in the CC-CV cycle compared to other investigated topologies. The only disadvantage here can be operat within the region with small values of the charging currents, when DC/DC converter is forced to the discontinuous mode of operation resulting in the reduction of the system efficiency. However, this can be largely eliminated with appropriate design. Partial results of this research also show a certain feature of the derived topologies of the diode rectifier, for example enabling the transfer of Joule losses from the primary side of the WPT system to the secondary side. This ability was also proven by measurements, thus for special applications, the $U_{\text{type}}$ rectifier may be a more suitable choice (airtight applications, etc).

**Declarations**

**Author Contributions:** “Conceptualization, M.F. and D.A.; methodology, M.Z.; validation, M.Z.; formal analysis, V.K.; investigation, V.K and M.Z., data curation, M.Z.; writing—original draft preparation, M.F.; writing—review and editing, D.A

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**Figures**
Figure 1

Block diagram and principal schematic of researched WPT system alternatives.

Figure 2
Example of the graphical interpretation of the optimal value of load resistance (65 kW prototype of WPT system), left – dependency of output power, right – dependency of efficiency

Figure 3

Equivalent schematics of WPT system with current type rectifier

Figure 4

Equivalent schematics of WPT system with current type rectifier
Figure 5
Impedance matching values of individual secondary side rectifiers

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Simulation model of direct connection (left) and with DCDC regulation (right)
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Simulation model of $I_{\text{type}}$ (left) and $U_{\text{type}}$ (right)

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Character maps from experimental measurements of $I_{\text{type}}$ rectifier connection (left) and $U_{\text{type}}$ rectifier connection.