Development of Experimental Bench for Wireless Power Transfer

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Wireless-power-transfer (WPT) for powering low-power devices has increased in recent years. The inductive resonant coupling method is the most used technique for this application and consists of taking advantage of the magnetic field generated in a coil so that there is current circulation in another nearby coil. In this work, using this technique, the series-series (SS) compensation topology was used to develop a test bench that should supply a load of up to 10W. Therefore, a brief explanation of the topic, calculations used, defined parameters, and we presented preliminary results of the proposed system.
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Introduction

Systems based on wireless energy transfer have been applied in various areas such as electronic devices, electric vehicles, autonomous underwater vehicles (AUVs), biomedical implants, and the military field. Consequently, the need to develop increasingly efficient topologies to meet the needs of these applications.

With this project, we seek to define the parameters and infrastructure of a test bench for wireless energy transfer outdoors over short distances for small loads and low power. For this, we showed the theory that supports the technology, simulations, and calculations of the system parameters. We planned to validate the efficiency of the developed system.

Theoretical Foundation

In this section, We used the theory as the basis for the development of the system will be discussed.

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Input Circuit

There are several ways to power a WPT system. In the literature, the most used form is using an inverter in bridge H. This circuit has the function of transforming a direct current (DC) into an alternating current (AC) for the resonant grid at the desired frequency. For this, you need a power signal that provides a sinusoidal signal on the inductive link. There are several techniques for obtaining this sinusoidal signal, both analog and digital.

Its working principle consists of the operation of two transistors at a time, responsible for generating the two half cycles of the AC network. In this context, conduction provokes the positive half-cycle, while the others are in cut. The others are cut-off, and the negative half-cycle is generated [1].

In this scenario, the LC compensation circuit works as a filter, eliminating the harmonics of the fundamental frequency, thus approximating a sinusoidal output signal.

Inductive Resonant Coupling

The inductive resonant coupling is currently the most used transmission method for WPT systems and consists of the induction of time-varying magnetic fields to transport energy. In it, operating frequencies of up to tens of MHz are used because in the inductive coupling, the transmitter and receiver are in means of very low magnetic permeability, making the coupling weak and the transfer of energy impracticable to traditional frequencies. Furthermore, the magnetic field is easily dispersed in all directions, resulting in large losses and low efficiency. When using inductive resonant coupling, the transmitter and receiver operate at the resonant frequency, significantly reducing losses. The type of capacitor connection (series or parallel) will depend on the source and load characteristics [2]. Due to frequency, the source must be AC (to generate a varying magnetic field of adjustable frequency) and for transmission, there will be a compensation circuit. Finally, there is a rectifier circuit that will supply the load. Figure 1 shows the standard diagram of a WPT system.

LC circuits are used in the resonant loop so that the system operates at the resonant frequency, and the efficiency is improved. There is also a concern when using high frequencies because the current suffers losses resulting from the Skin effect. It is recommended the use of wire Litz, hollow or larger cross-section wires to reduce these losses.

Main System Parameters

Coupling Factor (k)

In addition to the operation at the resonance frequency, other parameters are crucial for the proper functioning of the WPT system, such as the coupling factor (k). The value of "k" is directly linked to the distance and position between the coils. Its value decreases with the distance and misalignment of the coils, making the use of inductive resonant coupling restricted to short-distance applications. The greater the number of magnetic field lines, the greater the coupling factor between them. However, the coupling is not perfect, which makes it necessary to use capacitors to compensate for inductive losses [3].

The coupling factor is calculated by expression (1):

$$k = \frac{1}{\left[1 + 2^{\frac{2}{3}}\left(\frac{d}{\sqrt{a.b}}\right)^{2}\right]^{\frac{3}{2}}} \qquad (1)$$

Where *d* is the distance between the coils, and *a* and *b* are the radius of the transmitting and receiving coils, respectively.

Quality factor (Q)

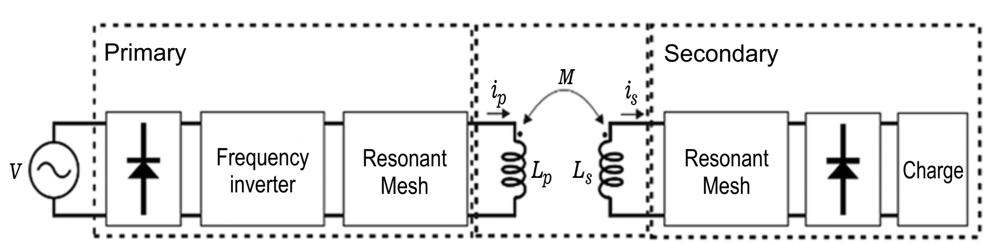
The quality factor (Q) guarantees "optimal" resonance at high frequencies. It usually has a high value for work frequency. This parameter counterbalances the drop in the coupling factor with the variation in the distance. So that efficiency can be maintained [4].

Increasing the value of Q reduces stray resistances, hence system losses, and can be optimized by reducing losses due to high frequency. It is a relationship between the energy that the system stores and the energy that it dissipates [4]. It is a parameter of the coils and the compensation circuits and can be mathematically described in expression (2):

$$Q = \omega \frac{L}{R} \qquad (2)$$

Where ω is the angular frequency of the system, L is the coil's self-inductance and *R* is its resistance.

Figure 1. Standard diagram - WPT system.



Coil Geometry

Geometry is a parameter that directly affects system efficiency. When comparing spiral-type and helix-type coils, [2] we obtained the following results: when changing the distance between the coils, the coupling coefficient between the helical coils is much smaller than that of the spiral-shaped coil. Subsequently, the spiral-type coil is significantly superior to the helix-type coil in terms of higher inductance value and, as a result, has a higher coupling coefficient [2]. Therefore, the helix-type coil topology is not feasible (Figure 2).

Thus, the flat spiral geometry was adopted in the project. In this geometry, the length of the conductor can be expressed by calculating the Archimedean spiral given by (3):

$$l = \pi . x . y^2 + \pi y \left(2 \frac{d_{int}}{2} + x \right) \quad (3)$$

Where x is the diameter of the conductor and, $y = \frac{\left(\frac{d_{ext}}{2} - \frac{d_{int}}{2}\right)}{x}$, d_{ext} and d_{int} are the inner and outer diameters of the coil, respectively.

Coil Self-Inductance

There are several approaches to coil models and geometries, as well as their respective advantages and disadvantages in the literature. Also, there are several ways to calculate the self-inductance of the coils. The self-inductance of the planar circular coil is calculated by the following approximate Equation (4):

$$L = \frac{\mu . N^2 (d_{int} + d_{ext})}{4} \left[\ln \left(\frac{2.46}{\phi} + 0.20\phi^2 \right) \right] \quad (4)$$

Where $\phi = (d_{ext} - d_{int})/(d_{ext} + d_{int})$

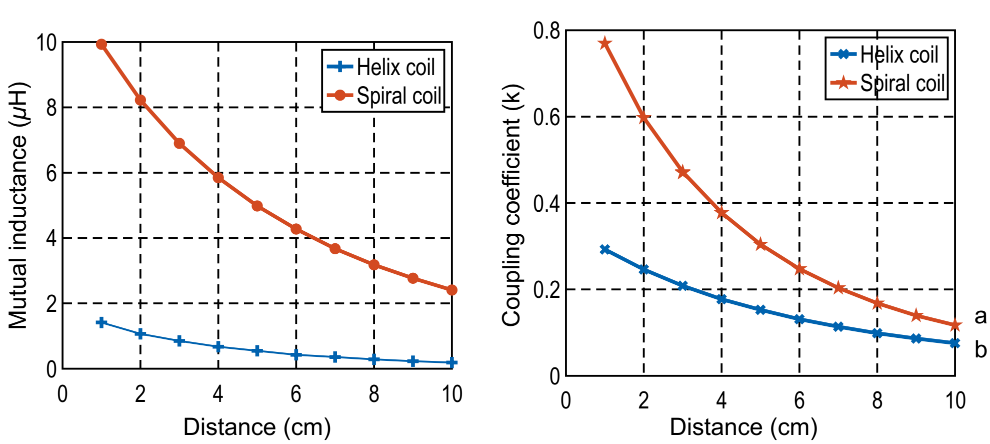
Mutual Inductance

Mutual inductance (M) represents the interaction between the primary and the secondary. Faraday and Lenz's Law explains the theory that governs mutual inductance. The greater the mutual inductance, the greater the number of magnetic field lines delivered to the receiver [4]. The simplest way to get the value of *M* is to use the approximate Equation of k, making $M = k\sqrt{L_p . L_s}$, since M has a complex analytical solution.

Compensation Circuit - Series-Series (SS) Topology

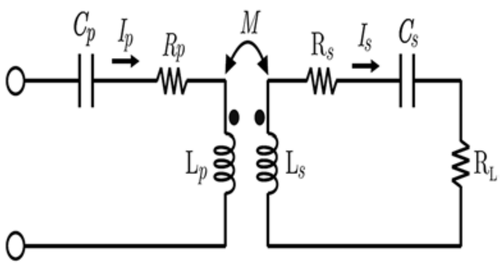
The compensation circuit is used so that the system operates at the resonance frequency and reduces losses due to the influence of harmonics and electromagnetic interference [3]. Of the studied topologies, the one that best meets the project requirements, whose results are found a simple only way, is the SS topology, shown in Figure 3. Its main advantage is the independence between the values of the

Figure 2. Comparison between spiral and helix coils [2].



primary capacitance (C_p), the magnetic coupling coefficient (k), and the quality factor (Q) [5].

Figure 3. Compensation Circuit - Series-Series (SS) Topology.



Where:
L_P and L_s are the primary and secondary auto inductances, respectively;
C_p and C_s are the primary and secondary capacitances, respectively;
R_p and R_s are the primary and secondary ohmic losses, respectively;
I_p and I_s are the currents flowing in the primary and secondary, respectively.
The resonant frequency is obtained by:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

Physical Infrastructure

Coils are made using wires Litz. In its use, the number of intertwined conductors must be observed because it directly affects the shunt capacitance. In its structure, the material is generally used that interferes insignificantly with the quality factor and the resonance frequency, such as glass, styrofoam, and acrylic.

Materials and Methods

Based on the theory described in item 1 (Introduction), initially, the shape of the coil, the circular planar geometry, was defined. After that, combinations of the number of turns and how they influenced the efficiency of the system were tested. Thus, the geometric parameters were chosen.

With the coil geometry defined, frequency x efficiency calculations were made to define the working frequency.Then, the other parameters of the project were calculated, such as self-inductance, mutual inductance, and quality factor.

After defining the calculated parameters, the functioning of the electrical circuit was tested in the PSIM software. Two forms of input signal were tested: using a PWM signal as a carrier and a square wave signal at the resonant frequency. Then the input form was defined. The bench was assembled in acrylic and the tests began.

Results and Discussion

After tests, it was concluded that the best efficiency results are for coils whose transmitter is slightly larger than the receiver, because of this, N of 20 and 10 turns was chosen for the transmitter and receiver. Based on the studies studied, frequencies of 85 kHz, 500 kHz, and 13.56 MHz were tested. The most efficient result was for a frequency of 500 kHz. In the process of assembling the coil, the Litz AWG 12 wire conductor (2.052mm in diameter) was used and the winding was manual, as shown in Figure 4.

The self-inductance of the coils was measured using an LCR meter.

As the coils were manually wound, some specified parameters were not met, such as the spacing between the turns, central alignment, and the length, factors that directly change the value of the auto inductance L. Considering these divergences, the values of L are satisfactory. We presented a summary of the calculated and actual parameters (Table 1).

We assembled the circuit to analyze the behavior of the system (Figure 5).

For the circuit presented, an input signal of 12V, a load of 4.1Ω, $C_P = 5nF$, and $C_s = 36nF$. The simulation results were $V_L = 6.41\ V$ and $I_L = 1{,}56A$ (Figure 6).

After the simulation, the bench assembly process was carried out. With the infrastructure

Figure 4. Transmitting and receiving coils.

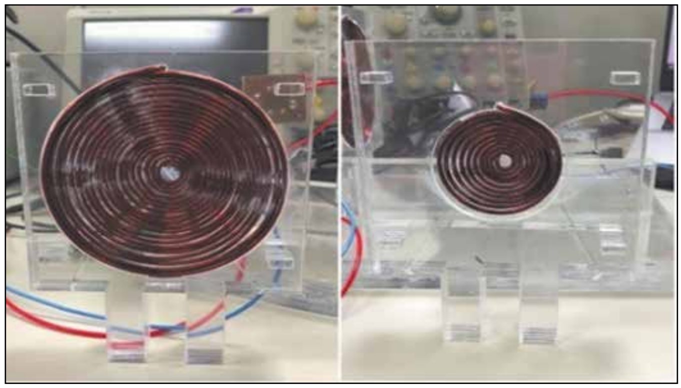


Figure 5. Assembled circuit diagram.

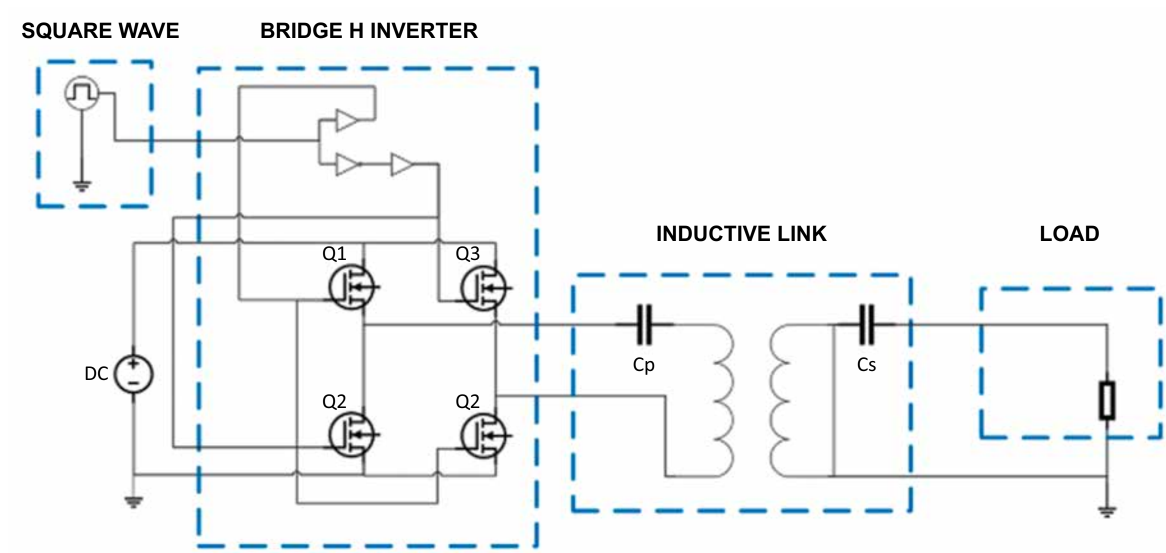


Figure 6. Voltage and current in the simulated resistive load.

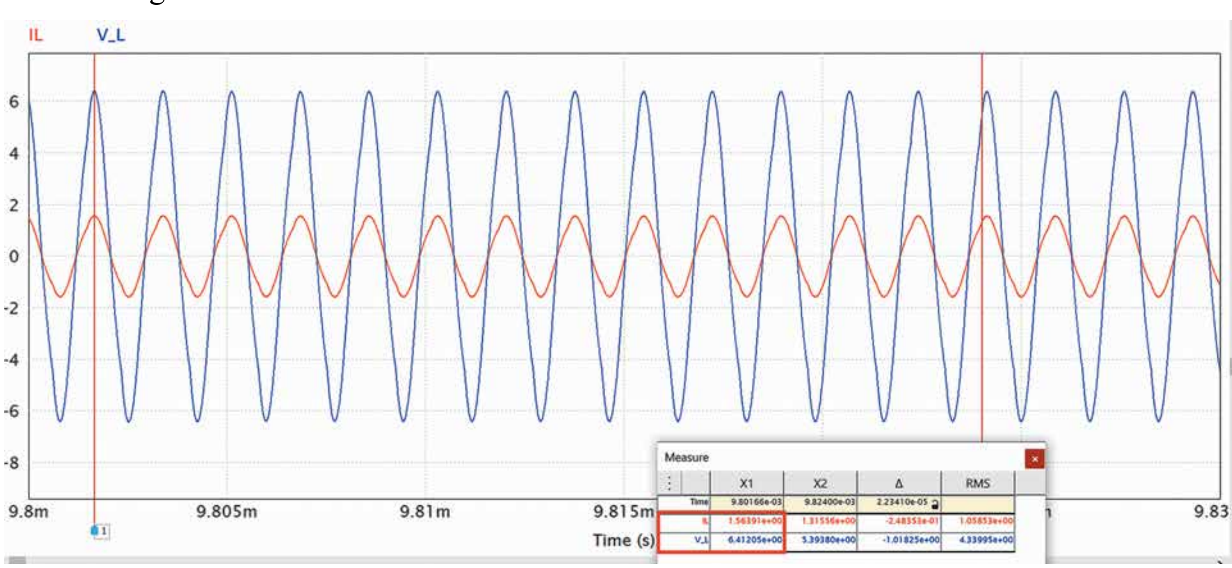


Table 1. Coil parameters.

Constructive parameter	Calculated value	Real value
Working frequency (kHz)	500	578.81
Number of turns Tx (N_1)	20	20
Number of turns Rx (N_2)	10	10
Coil inner diameter (d_{in}) (cm)	1	1
Conductor diameter (w) (mm)	2.052	2.052
Spacing between turns (s) (mm)	0.25	0.0
Coil outside diameter Tx ($d_{ext_{Tx}}$) (cm)	10.21	10.20
Coil outside diameter Rx ($d_{ext_{Rx}}$) (cm)	5.6	5.6
Coil length Tx (l_{Tx}) (m)	3.81	3.91
Coil length Rx (l_{Rx}) (m)	1.10	1.21

ready, the system components were connected for testing (Figure 7).

After validating the functioning of the system, performance tests were performed, varying the distance and alignment between the coils (Figure 8).

Analyzing the Figures, we verified that voltage and current values drop significantly with increasing distance and misalignment between the coils, as expected based on the studied theory. We compared calculated, simulated, and measured values (Figure 9).

Considering that some Equations used in the calculations are approximations found in the literature and that the simulation works with ideal conditions, the measurement results were expected and proved satisfactory.

Conclusion

The project was divided into phases. In the first phase, a survey of the state of the art was carried out to support the development of the bench. After that, studies related to the inductive link and physical structure were deepened. Subsequently, the design of the compensation circuit and the other components of the system were assembled, and the assembly and testing were carried out. Currently, more performance tests are being done and at the end of the period defined in the schedule, it is expected to obtain a functional test bench with all expected results validated.

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Figure 7. Test-lined and vertical misalignment between the coils.

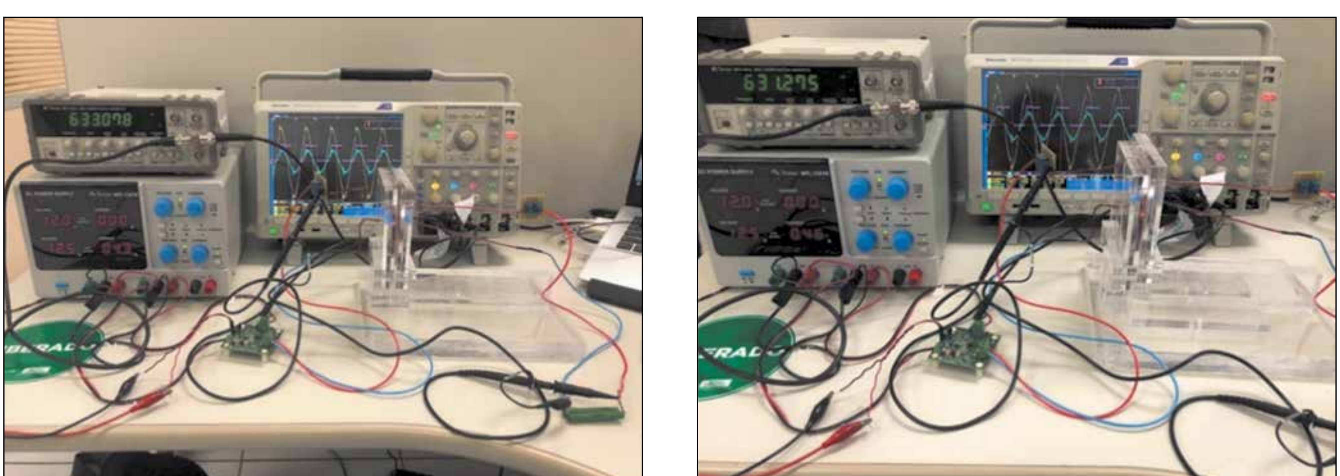


Figure 8. Vertical misalignment between the coils – Voltage and current.

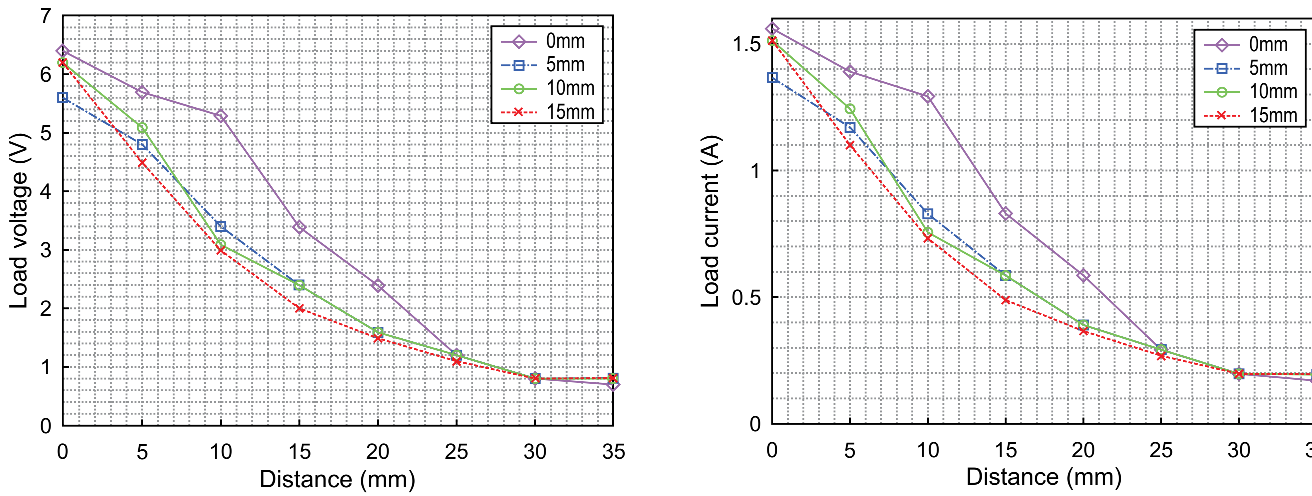
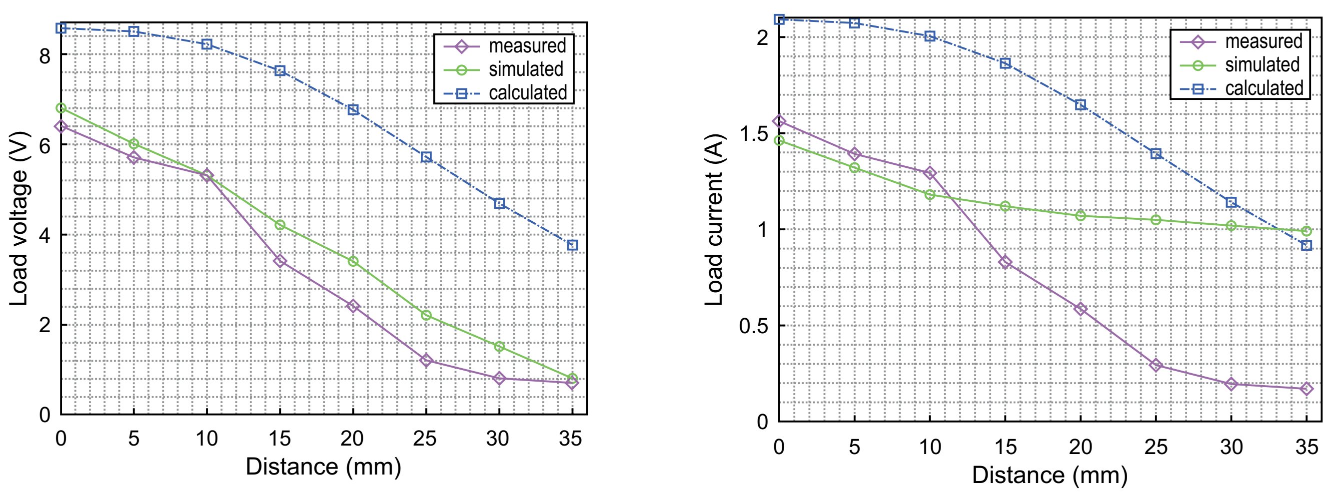


Figure 9. Results – Voltage and current.



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