

Coupling and load estimation with current and voltage primary sensing in free communication wireless power charging

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Abstract— In recent years the implementation of wireless power systems has increased due to improvements in technology and efficiency. Some advantages of wireless power transfer technology are reliability, safety, and convenience of use. One of the challenges with these systems is output regulation, as there are no physical wires to access it. Further complications are the variability of coil coupling and output power in the case of chargers. Firstly, this paper has summarized some of the main techniques for controlling the output of inductive power technology. Moreover, a predictive free communication control from the primary is proposed. It is aimed at charging systems with constant but unknown coupling, using a small drone charger as a reference. This control allows the secondary side to be simplified and acts faster than a control loop at the output due to the predictive measurement and feedforward operation. The simulation results for an output voltage of 5 V show an error of less than 3 % for a coupling range of 0.25 to 0.5.

Keywords— battery chargers, control systems, energy management, inductive power transfer, wireless power transfer.

I. INTRODUCTION

Wireless charging is a convenient, reliable, and safe technology for powering and charging electrical devices. The advantages over other power methods are that they are cost-effective and safer by eliminating physical connectors [1]. Wireless Power Transfer (WPT) systems can be either near field or radiative far field, depending on the transfer distance. The first ones can be capacitive and inductive transfer, and the second ones can be microwave, laser, optic, radiofrequency, or ultrasound [2].

Inductive power transfer (IPT) is the oldest and most widely used WPT technology. The advantages of magnetic inductive coupling over other types include ease of application, high efficiency over a short distance, and guaranteed safety [3]. The typical mode of operation of IPT converters is magnetic coupling resonance (MCR) [4].

A typical IPT system in MCR consists of four basic

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components (Fig. 1): an inverter stage that generates a periodic current, a transmitter coil that includes a resonance tank (primary compensation), a receiver coil that includes a resonance tank (secondary compensation), and a rectifier with high-frequency filtering [5]. In this architecture a pre-regulator is included. The main parameters that define these systems are the resonant frequency, the magnetic coupling in the coils, the communication transfer, and the battery.

The main problem with wireless transfer systems is the lack of physical wires for output regulation. In applications such as battery charging for drones or pacemakers, the system is variable in both the power demanded and the coupling of the coils [6]. To meet these challenges, researchers take different control strategies, which are presented in this paper.

Some research aims to mitigate the coupling variation by physically placing the coils at the design point position while others use different coil designs [7]. However, in this paper, only regulation strategies are included. A novel method of voltage regulation by predictive estimation, together with a pre-regulator, is presented in the paper. This method suits applications with constant but unknown coupling and variable power output, such as battery charging. It is also suitable for systems with space and/or weight restrictions on the receiver, such as small drone charging systems or biomedical devices.

II. CONTROL OF WIRELESS CHARGERS

There are different classifications according to the control approach. In [6], the strategies are classified according to transmission performance, divided into three types: resonance state control, efficiency optimization control, and expected output control. Resonance control is required to compensate for coupling and load dependence. Some possible techniques include frequency tracking, reactive component tuning or impedance matching. Examples of efficiency control are soft switching or active rectifiers.[8]. Finally, the control of the output can be done via the output power, the output voltage or the output current. In this case, the aim of the design architecture is to control the output voltage that feeds the battery charger.

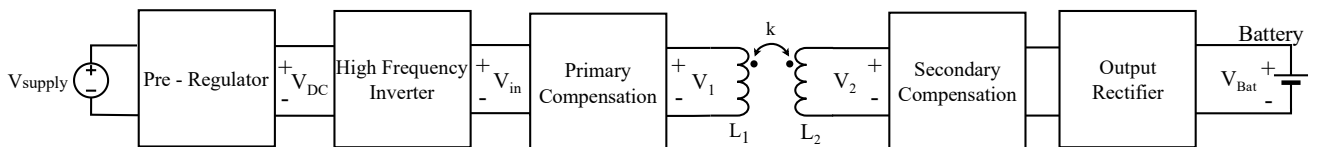


Fig. 1. Fundamental blocks of proposed inductive power transfer system

This paper proposes a classification according to the part of the WPT system where the control is performed.

It can be divided into control from the primary and control from the secondary. The purpose of these two methods is to measure a system variable and compensate for the error in the target parameter. The sensing information can be obtained from the secondary to control the secondary, from the secondary to control the primary, or from the primary to control the primary. Some of the target parameters used to regulate the power transfer are the frequency, the equivalent resistance, or the reactive elements of the circuit.

A. Secondary control strategies

Secondary control strategies are the most immediate to implement because the output information is available in the controller. The limitations of these architectures depend on the application, e.g., in environments with space or weight restrictions on the secondary such as biomedical.

The aim of the different papers is similar: to regulate the output voltage by using a post regulator before the charger. In some cases, this post regulator is a DC-DC converter, as in [9] using a LM2596 step-down. In other cases, a linear voltage regulator is used as in [7] for charging a pacemaker.

In [10], the objective is not voltage regulation but efficiency regulation. The maximum efficiency is estimated by measuring the rectifier's DC voltage and current. As in this paper, the coupling is estimated from the voltage and current.

B. Primary control strategies

Communication between the two sides of the system is required when a variable in the primary circuit, such as frequency, is controlled by information from the secondary circuit. One of the methods to access secondary information is communication by wireless modules outside the operating frequency band. Examples are RF communication for charging drones [11] or pacemakers [12].

The other transmission method is in-band communication, which is analogue communication using pulse coupling [13], [14]. Communication from the primary to the secondary, called forward telemetry or downlink, can be done directly by modulating the input source in amplitude or frequency. However, communication from the secondary to the primary, or back telemetry or uplink, can be done by perturbing the signal transmitted by the coupling. The two types of perturbation are load modulation called load shift keying (LSK) or frequency shift keying (FSK) [15], [16].

Some researchers implement primary control without secondary information. The advantages are control simplification, communication free and cost reduction.

A possible method is frequency adjustment. In [17], the inverter is self-oscillating to maintain power but not gain. Resonance is found using a current zero-crossing detector to obtain a sinusoidal waveform with no harmonics. In [18], the frequency is adjusted by looking at the phase shift between the inverter voltage and the primary current.

Another method is the idea of coupling and load estimation, which has been used in other papers. In [19], the operating point is calculated from the voltage and current phases and then controlled by a variable capacitor. In [20],

the transmitter side input current harmonics are sensed to solve the expressions. The latest strategies estimate these parameters by monitoring primary variables, but need to communicate with the secondary active rectifier to switch between short-circuit and open-circuit [21].

The design strategy proposed in this paper is to operate at resonance, at a constant or near-constant frequency, and to regulate the output voltage before the charger with a primary pre-regulator. The coupling and the equivalent resistance are estimated to calculate transfer function between input and output. Constant output value is obtained with the pre-regulator and the transfer function. Further details are given in section IV. First, the modeling process is described in detail.

III. MODELING A BASIC COMPENSATION TANK

Within the basic resonators, the most efficient topologies are series-series (SS) and series-parallel (SP). Fig. 2 shows the equivalent SS circuit with the parasitic resistances of the coils (R_1 and R_2) and the equivalent resistance (R_{AC}). The main advantages over other topologies are their simplicity and efficiency, which are suitable for the designed architecture. These resonant tanks ease the modeling of the circuit, since the compensation (1) is independent of the coupling factor (k) and R_{AC} [1].

$$\omega_{r1}^2 = \frac{1}{L_1 C_1} \quad (1)$$

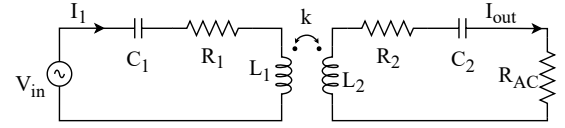


Fig. 2. A series – series basic topology

As shown in the introduction, coupling and load resistance are the parameters that modify the operating point. The coupling affects the mutual inductance (M), which depends on L_1 and L_2 by the coupling factor k (2). R_{AC} is the equivalent of the load resistance (R_L) and the rectifier. R_L depends on the power transmitted in the battery charge as shown in (3). The rectifier and conditioning circuits determine the factor between them.

$$M = k\sqrt{L_1 L_2} \quad (2)$$

$$R_{AC} \propto R_L = \frac{V_{Bat}}{I_{Bat}} \quad (3)$$

The First Harmonic Approximation (FHA) is used for the modeling process. The approximation is sufficiently accurate for a circuit working close to resonance. In resonance, the inductor current and capacitor voltage waveforms are sinusoidal [22].

The most common time domain equivalent circuit models are the M-equivalent, T-equivalent, and ideal transformer models [1]. The M model consists of current-controlled voltage sources (V_1 and V_2) that reflect the effect of one side on the other through the current of the tanks (Fig. 3). The primary and secondary impedances (Z_1 and Z_2) are marked with dashed lines.

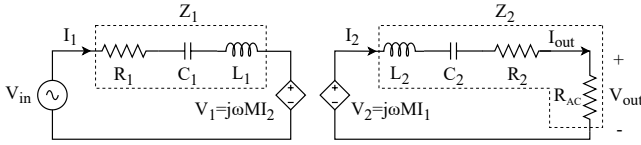


Fig. 3. M – equivalent model series – series

The most important equations of the two basic topologies are summarized in TABLE I. The term Z_r shown in Fig. 5 is the impedance of the secondary (Z_2) reflected in the primary. From the equations, the time response G_v of the output voltage (V_{out}) with respect to the input (V_{in}) can be obtained. G_v depends on the primary and secondary impedances (Z_1 and Z_2), the operating frequency (ω), the mutual inductance (M), and the AC resistance (4).

$$G_v = \frac{V_{out}}{V_{in}} = \frac{I_{out} R_{AC}}{V_{in}} = \frac{j\omega M}{Z_1 Z_2 + \omega^2 M^2} R_{AC} \quad (4)$$

Analytically, the influence of coupling and load can be seen in Fig. 4. The plots correspond to SS compensation at a frequency of 500 kHz. G_v increases with load and decreases with coupling. The challenge with resonant converters is to maintain the output voltage as the operating point changes.

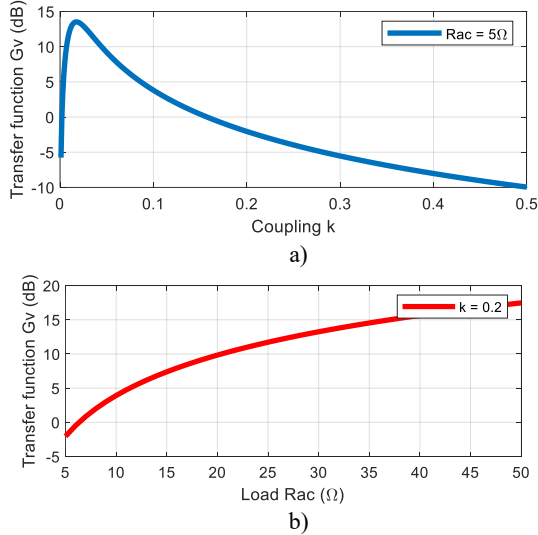


Fig. 4. Evolution of the G_v transfer function for a) $R_{ac} = 5\Omega$ and variable k and b) $k = 0.2$ and variable load

TABLE I. BASIC EQUATIONS OF SS AND SP TOPOLOGIES

M - Model	Series – Series	Series – Parallel
Z_1	$R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right)$	
Z_2	$R_2 + R_{AC} + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)$	$R_2 + j\omega L_2 + \frac{R_{AC}}{1 + j\omega C_2 R_{AC}}$
Z_r	$\frac{(\omega M)^2}{Z_2}$	
I_1	$\frac{V_{in}}{Z_1 + Z_r}$	
I_2	$\frac{j\omega M}{Z_1 Z_2 + \omega^2 M^2} V_{in}$	
I_{out}	I_2	$I_2 \cdot \frac{1}{1 + j\omega C_2 R_{AC}}$
V_{out}	$I_{out} R_{AC}$	
G_v	$\frac{j\omega M}{Z_1 Z_2 + \omega^2 M^2} R_{AC}$	$\frac{j\omega M}{Z_1 Z_2 + \omega^2 M^2} \frac{R_{AC}}{1 + j\omega C_2 R_{AC}}$

IV. DESIGN OF THE ARCHITECTURE

Using the transfer function G_v as a reference, the input voltage controls the system to regulate the output voltage. The resonance is assumed to be constant, which means that the capacitors and coils are fixed parameters. Therefore, the resonant frequency is not altered in order to operate at maximum efficiency. In the following sections, the designed architecture is explained, and the simulation results are shown.

A. Series – Series Class E with a full bridge rectifier

The inverter, resonant tank and rectifier topologies have been selected for low-medium power applications such as biomedical devices, drones and mobile phones. The Class E inverter is suitable for higher frequencies as it is able to operate in the Zero Voltage Switching range. It reduces the size of the system without compromising efficiency [23]. The SS tank and full diode rectifier were also chosen for its simple design that simplify modeling.

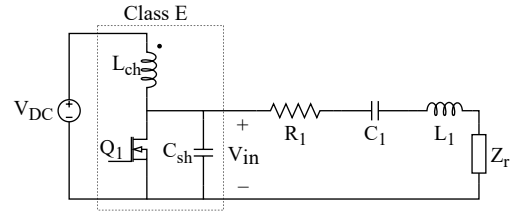


Fig. 5. Class E SS circuit with reflected impedance (Z_r)

Fig. 5 shows the class E inverter consisting of a choke coil (L_{ch}), a shunt capacitor (C_{sh}) in resonance with each other and a single transistor (Q_1). For the design purposes, the secondary is considered as an impedance reflected in the primary (Z_r). The reactive impedance of Z_2 can be assumed to be zero, as operation is at the resonant frequency. Thus, Z_r is approximately $(\omega M)^2 / (R_{AC} + R_2)$. R_{out} is the reflected resistance together with R_1 (5).

$$R_{out} = Z_r(\omega_r) + R_1 = \frac{(\omega M)^2}{R_{AC} + R_2} + R_1 \quad (5)$$

Firstly, solving the equations from [24], resonance frequency for L_{ch} and C_{sh} (ω_h) needs to be approximately 1.29 times the operating frequency ω_r to achieve Zero Voltage Switching. Secondly, the parameter A_f is a design factor that is normally equal to 1.3 to balance resonance losses and load modulation range [23]. The two design equations (6) and (7) are used to calculate L_{ch} and C_{sh} .

$$\omega_h = 1/\sqrt{L_{ch} C_{sh}} = 1.29\omega_r \quad (6)$$

$$A_f = \frac{\sqrt{L_{ch}/C_{sh}}}{R_{out}} \quad (7)$$

According to [25], the effect of inverter impedance must be corrected to achieve load independence. The residual reactance X_h due to the above frequency shift has to be considered to calculate the tank. Solving the integrals from [25] at fixed duty cycle, the value X_h respect $j\omega L_{ch}$ can be used to calculate C_1 by setting L_1 at resonance frequency (8).

$$j\omega_r L_1 + \frac{1}{j\omega_r C_1} = X_h \quad (8)$$

It is important to note that the model and expressions are under the fundamental component approximation. The input and output voltages are non-sinusoidal signals, including the inverter and rectifier. When working at resonance, the non-fundamental components are filtered out, and the current and voltage in the coils are completely sinusoidal. However, the RMS values are considered to reflect the value for the expression.

The equivalent resistance R_{AC} concerning the full bridge rectifier is:

$$R_{AC} = \frac{8}{\pi^2} R_L = \frac{8}{\pi^2} \frac{V_{Bat}}{I_{Bat}} \quad (9)$$

B. Control loop process

From TABLE I, an expression dependent on R_{AC} and k can be cleared with primary variables (10). The aim is to determine the value of these parameters to identify the operating point of the system. Once the transfer function is known, the battery voltage can be regulated by modifying the DC voltage.

$$I_1 = \frac{V_{in}}{Z_1 + \frac{\omega^2 M^2}{Z_2}} \approx \frac{V_{DC}}{R_1 + \frac{\omega^2 (k \sqrt{L_1 L_2})^2}{R_2 + R_{AC}}} \quad (10)$$

The first step is to sense the primary current and the DC input voltage, giving information for the equation. However, there are two unknown factors (R_{AC} and k) and only one equation. As it is not possible to access the secondary information because it is one of the system's restrictions, it was decided to perform a previous calibration stage.

Pre-calibration allows the uncertainty of the coupling to be resolved when connecting the charger. Once k is known, the voltage is regulated during battery charging.

The flowchart with the complete system process is depicted in Fig. 6. First, the system is connected by coupling the coils, i.e., the drone is parked. It starts by sensing voltage and current to proceed with the first stage, the calibration. At this stage, a known resistor R_{cal} is connected in place of the battery (or the battery charger). In this case, there is only one unknown parameter: the coupling. k is calculated with equation (11), cleared from (10), once the system is stabilized. Since the operating point is unknown, an arbitrary V_{DC} is set from G_v for the start of the charger.

$$k = \sqrt{\frac{(R_2 + R_{cal}) \left(\frac{V_{DC}(t)}{I_1(t)} - R_1 \right)}{\omega^2 L_1 L_2}} \quad (11)$$

Calibration time is set according to the pre-regulator dynamics regulator. After the calibration time has elapsed, the load regulation stage is next. R_{cal} is switched off, and the load is switched on. Now the only unknown parameter in equation (10) is R_{AC} , which can be obtained then by (12).

$$R_{AC} = \frac{k^2 L_1 L_2 \omega^2}{\frac{V_{DC}(t)}{I_1(t)} - R_1} - R_2 \quad (12)$$

Once the operating point of the system is known, the output voltage can be regulated from the expression G_v (4).

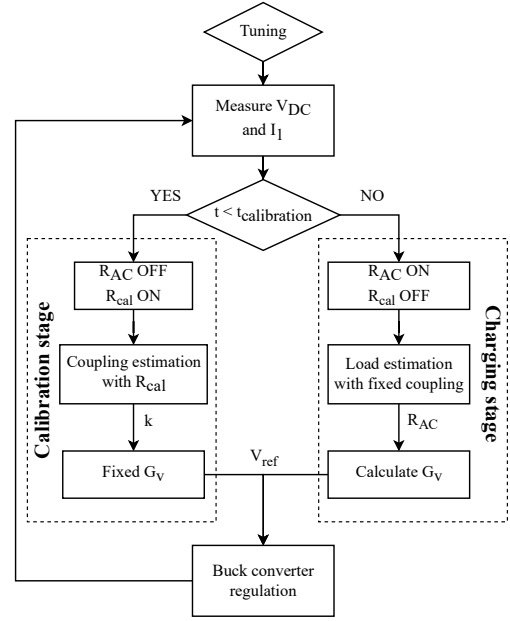


Fig. 6. Flow chart of the estimation process

The regulation strategy to control the output is to use this pre-regulator which can be a simple buck converter. This pre-regulator buck converter supplies the inverter with the calculated reference voltage in order to have the charging voltage at the output. Then, the idea is to adjust the reference voltage to obtain the required V_{DC} .

Using the resistor network (R_1 , R_2 and R_3) at the feedback input (V_{FB}), a linear relationship between the reference (V_{ref}) and the buck converter voltage (V_{DC}) can be obtained from (13). The pre-regulation circuit is shown in Fig. 7.

$$V_{DC} = -\frac{R_1}{R_3} V_{ref} + V_{FB} \left(1 + \frac{R_1}{R_2} + \frac{R_1}{R_3} \right) \quad (13)$$

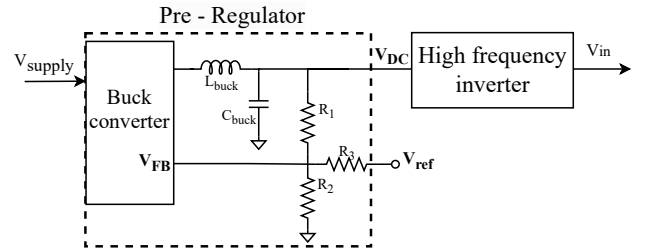


Fig. 7. Variable voltage Buck Pre - Regulator

To summarize, there are two operation modes. The first mode aims to calibrate the system using a known calibration resistance called the calibration stage. The second mode is the charging stage, which consists of the system's control during battery charging. To test the feasibility, the complete architecture has been simulated.

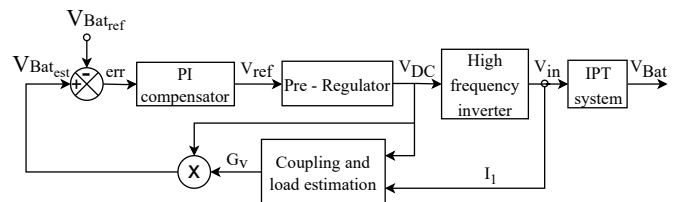


Fig. 8. Closed-loop control by the estimation process

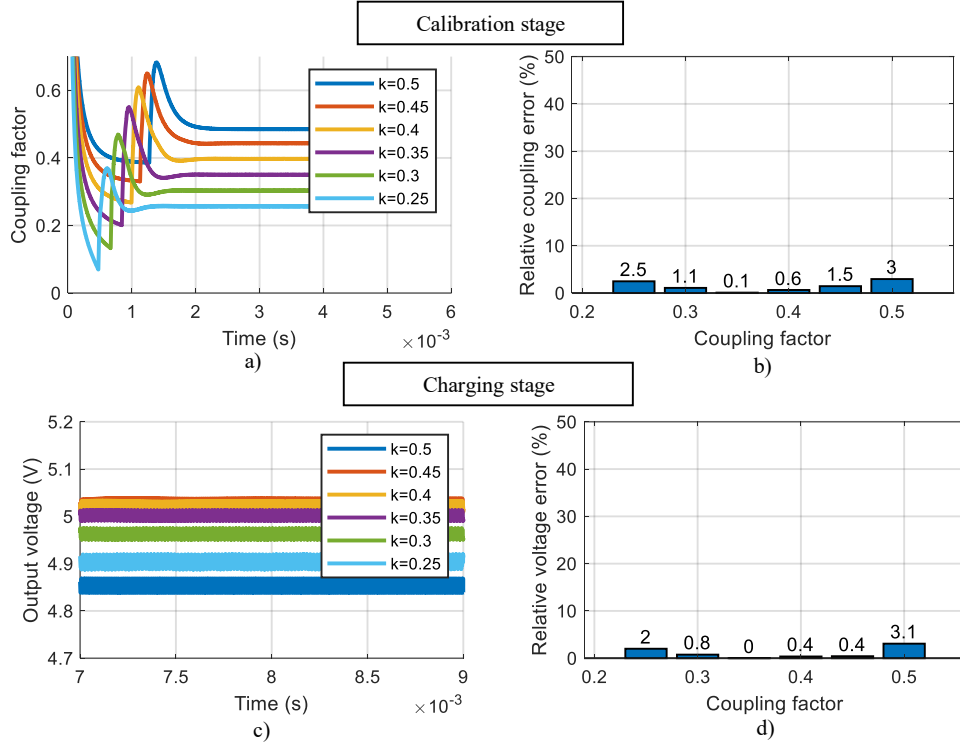


Fig. 9. Simulation results of a $f = 500 \text{ kHz}$ and $R_L = 10 \Omega$ at different coupling factors. Calibration stage figures of a) coupling estimation and b) relative coupling error. Charging stage figures of c) output voltage and d) relative voltage error.

The implemented control loop in the simulation (Fig. 8) starts with sensing the signals V_{DC} and I_1 . Then the expressions are processed to estimate the coupling and the load depending on the stage. With the transfer function G_V and V_{DC} , the estimated battery voltage $V_{Bat_{est}}$ can be determined. Compensating for the error of $V_{Bat_{est}}$ with respect to the desire $V_{Bat_{ref}}$ provides the V_{ref} required to control the pre-regulator. From this V_{ref} voltage, the buck supplies the system with the V_{DC} required to obtain $V_{Bat_{ref}}$.

V. SIMULATION RESULTS

The simulated circuit includes the buck converter, the class E inverter, the resonant tanks, the rectifier, and a load R_L equivalent to the power consumed by the battery. The control loop includes current and voltage sensing for V_{DC} and I_1 , a block of operations and expressions, the regulator, and the buck reference resistor network.

The software used for the simulation is PSIM. The system was first simulated with constant resistance $R_L = 10$ and different couplings. The simulation results of the circuit with the estimation control are shown in Fig. 9.

A. Calibration Stage

The simulations have been performed by varying the coupling in the range of 0.25 to 0.5. The system is started up in the open loop during the calibration stage. The voltage and current are monitored long enough for the coupling calculation to stabilize. In Fig. 9a), the coupling estimation k has a calibration time of 3 ms, although in the simulations performed it has been less than 5 ms. For this architecture, the value is obtained with an error of less than 3 %, Fig. 9b).

This design's calculation range is limited between 0.25 and 0.5, due to the class E design conditions. It also depends on the compensator and the buck converter, so they must be designed according to the system specifications.

B. Charging Stage

During charging, Fig. 9c) shows how the coupling estimate affects the charging output voltage calculation. The voltage remains regulated at the set voltage of 5 V with an error of less than 3.1 % at couplings close from 0.25 to 0.5, Fig. 9d).

Different states of charge of the battery were also simulated with different resistance steps. The simulation results in Fig. 10 show the regulation in different output power states. After calibration at 5 ms, the charging stage starts with an $R_L = 10 \Omega$. Then a step of $3 \cdot R_L$ and $1.5 \cdot R_L$ has been introduced. The system regulates the voltage to the designed 5V. It is important to consider, as with the coupling, that the range of power regulation is dependent on the design parameters of the regulator and the range of buck voltages it is capable of supplying.

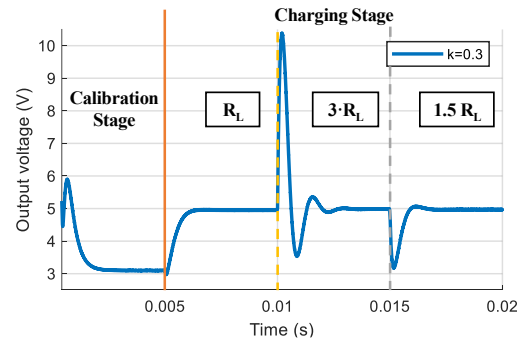


Fig. 10. Output voltage for different load conditions for $k = 0.3$

VI. CONCLUSION

A review of architectures designed for wireless charging systems in low to medium power applications such as biomedical or drones has been conducted. The proposed classification has been divided according to the location of the control and the communication strategy used.

A control architecture has also been proposed based on a primary side with any communication with the secondary side and with a simplified control system.

The basic SS compensation was modeled from this architecture. In addition, the design process of the charging system with class E inverter and full bridge, topologies used in pacemakers or drones, has been included.

The estimation calculated by the proposed architecture has been quite accurate (less than 3%) over a wide coupling factor k range. It allows the transfer function to be accurately calculated and the voltage to be regulated from the input (less than 3% error).

Future work would include implementing this system in a prototype drone charging station to ensure estimation outside the simulation.

REFERENCES

- [1] L. Shi, 'Advanced Wireless Power Transfer Technologies: Reactance Cancelling and Inverse Coupled Current Doubler Rectifier', phd, E.T.S.I. Industriales (UPM), 2021. Accessed: Jul. 21, 2023. [Online]. Available: <https://oa.upm.es/69243/>
- [2] V. Shevchenko, O. Husev, R. Strzelecki, B. Pakhaliuk, N. Poliakov, and N. Strzelecka, 'Compensation Topologies in IPT Systems: Standards, Requirements, Classification, Analysis, Comparison and Application', *IEEE Access*, vol. 7, pp. 120559–120580, 2019, doi: 10.1109/ACCESS.2019.2937891.
- [3] W. Zhang and C. C. Mi, 'Compensation Topologies of High-Power Wireless Power Transfer Systems', *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4768–4778, Jun. 2016, doi: 10.1109/TVT.2015.2454292.
- [4] C. Xiao, K. Wei, D. Cheng, and Y. Liu, 'Wireless Charging System Considering Eddy Current in Cardiac Pacemaker Shell: Theoretical Modeling, Experiments, and Safety Simulations', *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3978–3988, May 2017, doi: 10.1109/TIE.2016.2645142.
- [5] A. Delgado, N. A. Requena, R. Ramos, J. A. Oliver, P. Alou, and J. A. Cobos, 'Design of Inductive Power Transfer System With a Behavior of Voltage Source in Open-Loop Considering Wide Mutual Inductance Variation', *IEEE Trans. Power Electron.*, vol. 35, no. 11, pp. 11453–11462, Nov. 2020, doi: 10.1109/TPEL.2020.2984097.
- [6] Z. Zhang and H. Pang, 'Control for Single Pickup', in *Wireless Power Transfer: Principles and Applications*, IEEE, 2023, pp. 141–177. doi: 10.1002/9781119654117.ch5.
- [7] C. Liu, C. Jiang, J. Song, and K. T. Chau, 'An Effective Sandwiched Wireless Power Transfer System for Charging Implantable Cardiac Pacemaker', *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 4108–4117, May 2019, doi: 10.1109/TIE.2018.2840522.
- [8] K. Colak, E. Asa, M. Bojarski, D. Czarkowski, and O. C. Onar, 'A Novel Phase-Shift Control of Semibridgeless Active Rectifier for Wireless Power Transfer', *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6288–6297, Nov. 2015, doi: 10.1109/TPEL.2015.2430832.
- [9] A. M. Jawad, H. M. Jawad, R. Nordin, S. K. Gharghan, N. F. Abdullah, and M. J. Abu-Alshaeer, 'Wireless Power Transfer With Magnetic Resonator Coupling and Sleep/Active Strategy for a Drone Charging Station in Smart Agriculture', *IEEE Access*, vol. 7, pp. 139839–139851, 2019, doi: 10.1109/ACCESS.2019.2943120.
- [10] D. Kobayashi, T. Imura, and Y. Hori, 'Real-time coupling coefficient estimation and maximum efficiency control on dynamic wireless power transfer using secondary DC-DC converter', in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2015, pp. 004650–004655. doi: 10.1109/IECON.2015.7392825.
- [11] T. Campi, S. Cruciani, and M. Feliziani, 'Wireless Power Transfer Technology Applied to an Autonomous Electric UAV with a Small Secondary Coil', *Energies*, vol. 11, p. 352, Feb. 2018, doi: 10.3390/en11020352.
- [12] B. Lee, M. Kiani, and M. Ghovanloo, 'A Triple-Loop Inductive Power Transmission System for Biomedical Applications', *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 1, pp. 138–148, Feb. 2016, doi: 10.1109/TBCAS.2014.2376965.
- [13] W. Li, 'Close the Loop Between Wireless Charger Receiver and Transmitter without Digital Controllers', p. 4.
- [14] 'Introduction to In-band Communication of Qi-based Wireless Power Designs and System-Level Challenges', p. 6, 2021.
- [15] G. Yilmaz and C. Dehollain, 'Wireless Data Communication', in *Wireless Power Transfer and Data Communication for Neural Implants: Case Study: Epilepsy Monitoring*, G. Yilmaz and C. Dehollain, Eds., in Analog Circuits and Signal Processing. Cham: Springer International Publishing, 2017, pp. 57–80. doi: 10.1007/978-3-319-49337-4_4.
- [16] P. Pérez-Nicoli, F. Silveira, and M. Ghovanloo, 'Back Telemetry', in *Inductive Links for Wireless Power Transfer: Fundamental Concepts for Designing High-efficiency Wireless Power Transfer Links*, P. Pérez-Nicoli, F. Silveira, and M. Ghovanloo, Eds., Cham: Springer International Publishing, 2021, pp. 77–91. doi: 10.1007/978-3-030-65477-1_4.
- [17] J. Zhou, B. Zhang, W. Xiao, D. Qiu, and Y. Chen, 'Nonlinear Parity-Time-Symmetric Model for Constant Efficiency Wireless Power Transfer: Application to a Drone-in-Flight Wireless Charging Platform', *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 4097–4107, May 2019, doi: 10.1109/TIE.2018.2864515.
- [18] E. Gati, S. Kokosis, N. Patsourakis, and S. Manias, 'Comparison of Series Compensation Topologies for Inductive Chargers of Biomedical Implantable Devices', *Electronics*, vol. 9, no. 1, p. 8, Dec. 2019, doi: 10.3390/electronics9010008.
- [19] L. Murlik, R. W. Porto, V. J. Brusamarello, F. Rangel de Sousa, and A. Triviño-Cabrera, 'Active Tuning of Wireless Power Transfer System for compensating coil misalignment and variable load conditions', *AEU - International Journal of Electronics and Communications*, vol. 119, p. 153166, May 2020, doi: 10.1016/j.aue.2020.153166.
- [20] K. Yue, Y. Liu, P. Zhao, M. Fu, H. Wang, and J. Liang, 'Coupling Coefficient and Load Estimation for Wireless Power Transfer Systems with Transmitter Side Input Current', in *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Jun. 2021, pp. 709–713. doi: 10.1109/APEC42165.2021.9487120.
- [21] J. Zeng, S. Chen, Y. Yang, and S. Y. R. Hui, 'A Primary-Side Method for Ultrafast Determination of Mutual Coupling Coefficient in Milliseconds for Wireless Power Transfer Systems', *IEEE Transactions on Power Electronics*, vol. 37, no. 12, pp. 15706–15716, Dec. 2022, doi: 10.1109/TPEL.2022.3188288.
- [22] W. Zhang, S.-C. Wong, C. K. Tse, and Q. Chen, 'Analysis and Comparison of Secondary Series- and Parallel-Compensated Inductive Power Transfer Systems Operating for Optimal Efficiency and Load-Independent Voltage-Transfer Ratio', *IEEE Trans. Power Electron.*, vol. 29, no. 6, pp. 2979–2990, Jun. 2014, doi: 10.1109/TPEL.2013.2273364.
- [23] H. Zhang, Y. Shao, C. Ma, and M. Liu, 'A High-Power Density Finite Class E Power Amplifier with "Edge Inductor" for Wireless Power Transfer Application', in *2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, Nov. 2020, pp. 1001–1005. doi: 10.1109/IPEMC-ECCEAsia48364.2020.9367874.
- [24] L. Roslaniec, A. S. Jurkov, A. A. Bastami, and D. J. Perreault, 'Design of Single-Switch Inverters for Variable Resistance/Load Modulation Operation', *IEEE Transactions on Power Electronics*, vol. 30, no. 6, pp. 3200–3214, Jun. 2015, doi: 10.1109/TPEL.2014.2331494.
- [25] S. Aldhaher, D. C. Yates, and P. D. Mitcheson, 'Load-Independent Class E/EF Inverters and Rectifiers for MHz-Switching Applications', *IEEE Transactions on Power Electronics*, vol. 33, no. 10, pp. 8270–8287, Oct. 2018, doi: 10.1109/TPEL.2018.2813760.