Self-Oscillating Capacitive Power Transfer with Multiple Receiver Capability and Coupling Path Adaption

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Keywords

≪Capacitive Coupling≫, ≪Half Bridge≫, ≪Wireless power transmission≫, ≪Gallium Nitride (GaN)≫, ≪HEMT≫, ≪Contactless energy transfer≫, ≪High frequency power converter≫.

Abstract

We present a capacitive power transfer system with self-adapting capability to multiple, variable load receivers. The proposed self-oscillating GaN-based half-bridge converter with load current feedback automatically adapts to the coupling path. We show design equations based on network theory and demonstrate experimentally more than 100W power transfer at 92% efficiency.

Introduction

Numerous research and development projects are currently devoted to the wireless power transfer (WPT) to portable electronic systems and electric vehicles [1]. A general challenge in conventional wireless power transmission is matching the transmission system to varying coupling paths and to changing loads (impedance matching approach), which theoretically limits the overall efficiency. On the other hand, high efficiency is achieved by energy transfer with sub-optimal power transfer, i.e. at unmatched loads in order to reduce the losses in the passive and active components (high-efficiency approach) [1].

Wireless energy transfer could be based on quasi-static electric fields (capacitive power transmission, CPT), on quasi-static magnetic fields (inductive power transmission, IPT [2] or on non-stationary electromagnetic fields [3]. Our study focuses on contactless power transfer via electric fields (capacitive power transmission, CPT), which is the preferred technique for bridging short distances [4].

If applications do not rely on regulations for constant frequency operation (which have been mainly issued for IPT systems), then improved system performance by self-tuning (self-oscillating) WPT approaches for voltage and power control [5, 6] have been proposed. Sun et al. [7] have published a self-oscillation resonant switching converter coping with multiple receiver loads and compensating changes in transfer spacing and coil misalignment, respectively. In such systems, however, sophisticated detection and control circuitry at the primary side is needed for self-adjustment.

A recent self-oscillation technique introduced as over-the-air positive wireless power transfer overcomes these limitations [8]. Liu et al. [9] have demonstrated a robust operation for a self-oscillating CPT system operating at variable loads. A multiple receiver operation for low power levels has been discussed in [10].

In this paper we follow the approach recently published by Seliger in [11] to design a self-adapting capacitive energy transfer for multiple receivers with the capability of robust operation at variable coupling paths. The next section briefly describes the converter system, followed by a section presenting first experimental results on a prototype demonstrator.

Self-oscillating Half-Bridge Converter

We report on a wireless energy transfer via the quasi-static electric field (capacitive power transmission, CPT). The structures for field coupling are good conductors of arbitrary shape acting as electrodes, with a dielectric material or air in between. In the following analysis, we represent these structures by lumped circuit elements (coupling capacitors).

The self-oscillating half-bridge converter driving a capacitively coupled load is depicted in Fig. 1. The wireless power system consists of n multiple receivers (load resistances $R_{load,n}$), each supplied with coupling capacitors $C_{p1,n}$ and $C_{p2,n}$, respectively. A supposed operation stage of the half-bridge converter

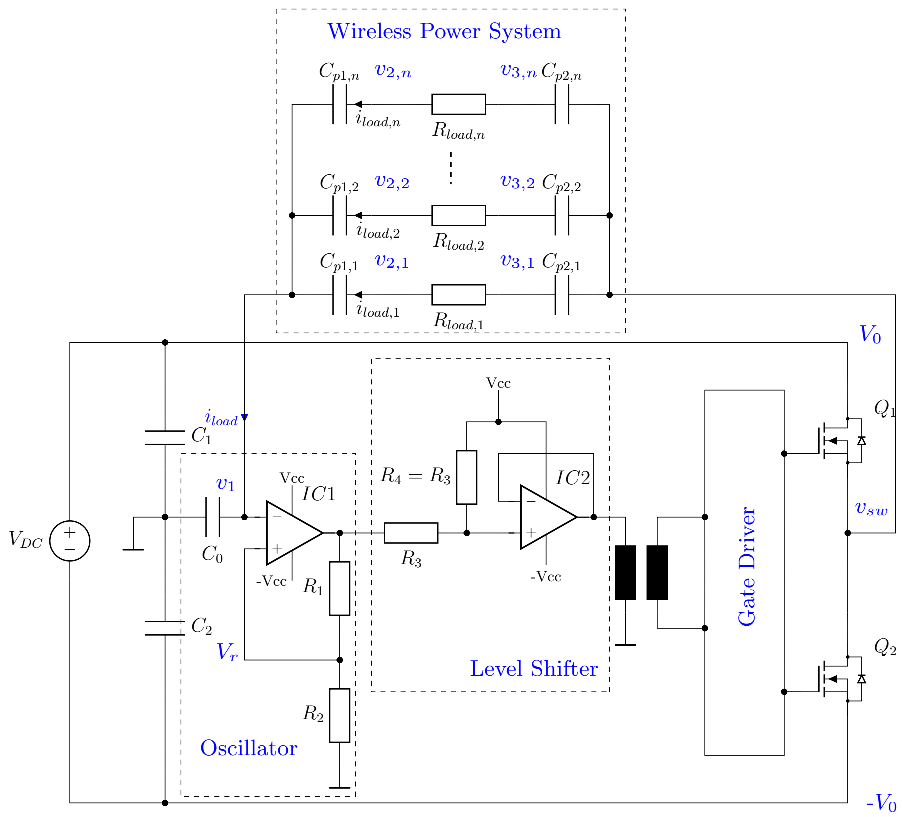


Fig. 1: Schematics of the self-oscillating half-bridge converter.

with transistor Q_1 as turned-on (and voltage $v_{sw}(t) = V_0$), gives a positive current i_{load} through the Wireless Power System in Fig. 1. The voltage $v_1(t)$ across capacitor C_0 rises until it reaches the reference voltage V_r, which is given by

$$V_r = \frac{R_2}{R_1 + R_2} V_{cc} = \beta V_{cc} \tag{1}$$

with the supply voltage $\pm V_{cc}$ of the operational amplifier $IC1$ forming the oscillator. Exceeding this reference voltage reverses the output voltage of $IC1$ to $-V_{cc}$ and changes the logic level of the level shifter circuit ($IC2$). The output voltage of this stage directly drives the gate signals of the half-bridge converter via a digital isolator circuit. Since the logical signal at the gate driver input has changed, transistor Q_1 is turned off and the low-side switch Q_2 is turned on. The switching node voltage $v_{sw}(t)$ changes from V_0 to $-V_0$ and impresses a negative load current i_{load} (reversed as shown in Fig. 1). Capacitor C_0 is discharged until it reaches the lower threshold voltage of $V_r = -\beta V_{cc}$, which completes one period of self-oscillation.

It should be noted that the load current i_{load} is the sum of the individual currents $i_{load,n}$ impressed on multiple receiver loads. Whenever there is a change in the loads, i.e. a change of an individual load $R_{load,n}$, or a change in the number of applied loads, n, the circuit will immediately react on that by the charging dynamics of C_0. Furthermore, variation in the coupling path capacitances $C_{p1,n}$ and $C_{p2,n}$ directly influences the charging/discharging current of C_0.

Multiple Load Operation

Referring to [12] and to Fig. 1, for a given load and coupling path arrangement, the switching node voltage is a rectangular waveform with 50% duty cycle and amplitude $V_0 = \frac{V_{DC}}{2}$. We write for each individual load current $i_{load,n}$ from network theory:

$$\begin{aligned} i_{load,n} &= C_{p1,n}\frac{d}{dt}\left[v_{2,n}(t) - v_1(t)\right] \\ &= \frac{v_{3,n}(t) - v_{2,n}(t)}{R_{load,n}} \\ &= C_{p2,n}\frac{d}{dt}\left[v_{sw}(t) - v_{3,n}(t)\right] \end{aligned} \tag{2}$$

An analytical solution for the circuit waveforms can be found for the special case of N multiple receivers of the same load $R_{load,n} = R_{load}$, with coupling capacitances $C_{p1,n} = C_{p1}$ and $C_{p2,n} = C_{p2}$, respectively [10]. The total load current $i_{load} = N i_{load,n}$ is expressed by Eq. (2):

$$\begin{aligned} i_{load} &= C_0\frac{dv_1(t)}{dt} \\ &= NC_{p1}\frac{d}{dt}\left[v_2(t) - v_1(t)\right] \\ &= N\frac{v_3(t) - v_2(t)}{R_{load}} \\ &= NC_{p2}\frac{d}{dt}\left[v_{sw}(t) - v_3(t)\right] \end{aligned} \tag{3}$$

where the individual voltages are now $v_{2,n} = v_2$ and $v_{3,n} = v_3$. Solving for $v_1(t)$ during the charging of C_0 gives

$$v_1(t) = \frac{1}{\gamma}\left[V_0 - (V_0 + \beta\gamma V_{cc})\, e^{-\frac{t}{\tau}}\right] \tag{4}$$

The capacitance ratio γ is given by $\gamma = 1 + \frac{C_0}{NC_{p1}} + \frac{C_0}{NC_{p2}}$. The time constant $\tau = \frac{C_0 R_{load}}{\gamma N}$ reflects the self-adapting behavior of the circuit. The switching period T is obtained as

$$T = 2\tau \ln\left(\frac{V_0 + \beta\gamma V_{cc}}{V_0 - \beta\gamma V_{cc}}\right) \tag{5}$$

According to [12], the condition for start-up of the self-oscillation is derived from Eq. (4) and given by

$$V_0 > \beta\gamma V_{cc} \tag{6}$$

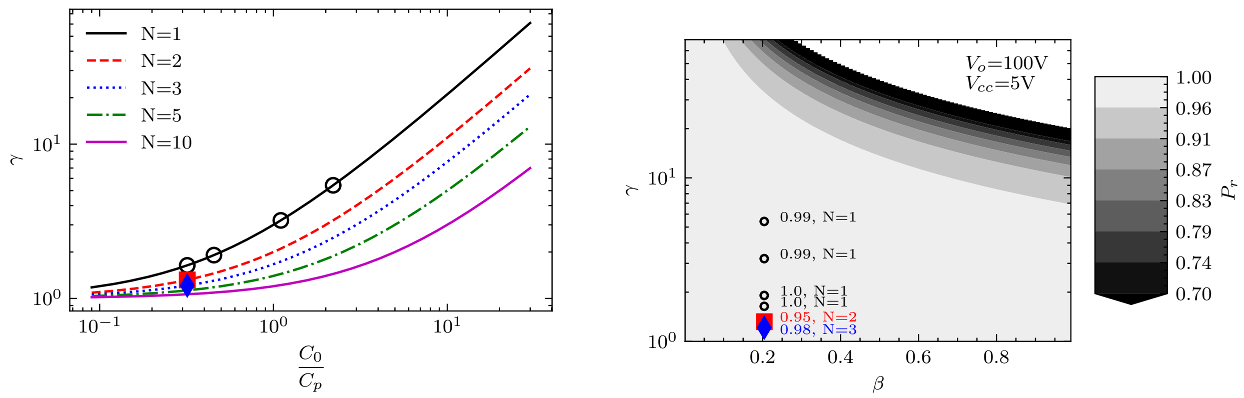
From the analytical solution we find some remarkable properties of the self-oscillating CPT system: Changes in the number of receivers, N, or changes in the loads, R_{load}, or changes in the coupling paths (C_{p1}, C_{p2}) are compensated by adapting the switching period. We can further calculate the total average power at the loads, P_{load}, as

$$P_{load} = N\frac{\tau}{T}\frac{(V_0 + \beta\gamma\, V_{cc})^2}{R_{load}}\left(1 - e^{-\frac{T}{\tau}}\right) \tag{7}$$

and compare with the load power for a direct wired connection, $P_0 = N\frac{V_0^2}{R_{load}}$. The resulting power ratio P_r is then

$$P_r = \frac{P_{load}}{P_0} = \frac{\tau}{T}\left(1+\frac{\beta\gamma V_{cc}}{V_0}\right)^2\left(1-e^{-\frac{T}{\tau}}\right) \tag{8}$$

It should be emphasized that the power ratio is independent of the load resistance R_{load} [11] and weakly dependent on the capacitance ratio γ. It expresses the power transfer of the WPT system in comparison to a direct wired connection. Fig. 2a shows exemplary the variation of the capacitance ratio γ for the case of N equal loads with fixed C_0 and variable $C_{p1,n} = C_{p2,n} = C_p$. The related power ratio P_r is calculated in Fig. 2b for different resistance ratios β from Eq. (1) and for a switching amplitude of $V_0 = 100\,\text{V}$. We find a power ratio close to 1 for a large variability in β and for $1 < \gamma < 10$, i.e. resulting in a high power transfer for multiple receiver operation ($N = 1\dots10$) and changes in the coupling capacitances C_p according to Fig. 2a.



(a) Computed capacitance ratio γ for variable coupling capacitances ($C_{p1,n} = C_{p2,n} = C_p$) and N equal loads. Marked points: Experimental data.

(b) Computed power ratio P_r for variable coupling ratios γ and variable β. Marked points: Experimental results.

Fig. 2: Capacitance and power ratios for multiple load operation and variable coupling path.

For a given load scenario (N loads, load resistance R_{load}), the load power is controllable by the DC-link voltage V_{DC}, since $V_0 = \frac{V_{DC}}{2}$, and according to Eq. (7). For that purpose, a DC/DC converter (buck or boost converter) would be additionally required to connect a constant DC power supply with the variable DC link voltage V_{DC}.

Experimental Set-Up and Results

Prototype System

Fig. 3 shows the set-up of the prototype system. We have built a PCB for the self-oscillation circuit and for the half-bridge converter (operating with 650 V rated GaN-HEMTs). The loads (halogen lamps or power resistors mounted on a heat sink) are connected by coupling capacitors. For convenience, we use discrete capacitors of the same size $C_{p1,n} = C_{p2,n}$. Multiple receiver operation can be studied by changing the number of loads (in series with the capacitors) connected to the half-bridge inverter board. A high voltage power supply provides the DC link voltage V_{DC} and a second laboratory power source supplies the gate drive circuit and the oscillator board, respectively (cf. Fig. 3).

Alternatively, as has been shown in [11], the self-oscillating CPT transfer via parallel brass plates with a plastic sheet as a dielectric instead of using discrete components can be applied for a large range of capacitance values. Furthermore, utilizing the high permittivity of water enables self-oscillating CPT via metallic plates even in tap water [12].

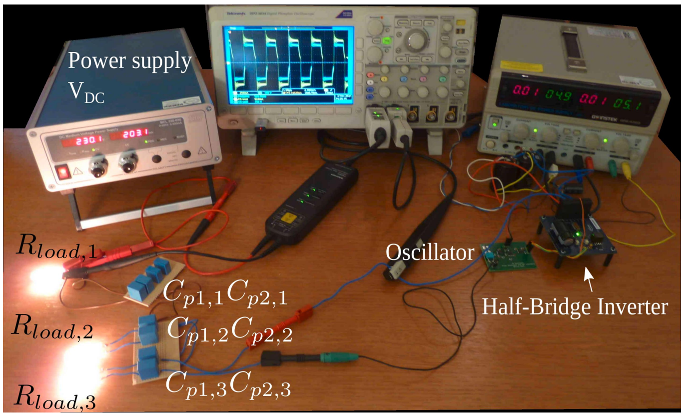


Fig. 3: Experimental set-up with three 42 W halogen lamps ($N = 3$ loads) and equal capacitances $C_{p1,n} = C_{p2,n}$.

Measurement results

In Fig. 4 we compare the analytical result for the load voltage $v_{load}(t)$ derived from the solution of $i_{load}(t)$ in Eq. (3) with a circuit simulation [13], and with the measurement on the prototype system. The simulated waveform nicely matches with the experimental signal. Since the analytical result is based on an ideal switching behavior, we expect an overestimation of the rise and fall times, and the switching period as well, for periods $T < 4\,\mu$s [11].

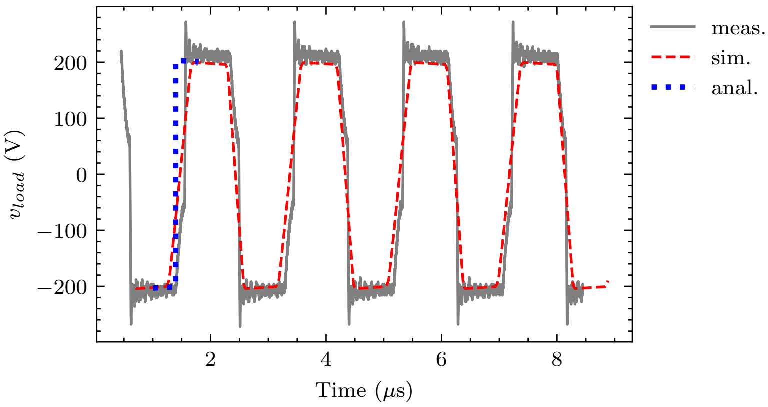


Fig. 4: Load voltage for a total load of three 42 W halogen lamps ($N = 3$) at a DC-bias voltage $V_{DC} = 2V_0 = 404$ V. The switching period automatically adapts to $T = 1.9\,\mu$s. The total power P_{load} is 104 W.

From measurements of the root-mean-square values of the load currents and voltages, respectively, we determine the average power at the load, P_{load}. With the root-mean-square voltage measured at the switching node, $v_{sw}(t)$, we determine the maximum power to be transferable to the load for a direct wired connection, P_0. The experimental power ratios P_r are given in Fig. 2b, for the cases of multiple loads ($N = 1\ldots3$) and variation in coupling capacitances C_p. The related values for γ are indicated in Fig. 2a. Our experiments confirm the capability for high power transfer with multiple receivers and with changing coupling path conditions: The measured power ratio P_r is higher than 0.99 for a coupling ratio changing by a factor of 10 for a single load ($N = 1$), and slightly smaller (0.95…0.98) for multiple loads.

With the input power P_{in} measured at the converter DC power supplies, we determine the efficiency η of the CPT system as:

$$\eta = \frac{P_{load}}{P_{in}} \tag{9}$$

For the operation data in Fig. 4 we get $\eta = 92\%$. We have determined the efficiency of the CPT system for a variety of parameters, i.e. the DC link supply voltage $V_{DC} = 2V_0$ and the load resistance R_{load}. Table I summarizes some of the experimental results. The half-bridge converter assures an efficiency over 90% for fundamental oscillation frequencies up to f_{osc}=600 kHz and supply voltages up to $V_{DC} = 400V$.

Table I: DC link voltage V_{DC}, R_{load} for $N = 1$, fundamental oscillation frequency $f_{osc} = 1/T$ and efficiency η (experimental results). The value of 291 kHz is computed for ideal switching (Eq.(5)).

V_{DC} (V)	$R_{load}(\Omega)$	f_{osc} (kHz)	η (%)
100	286	246 (291)	93
200	404	304	91
240	248	528	91
375	303	556	90

This prototype half-bridge converter can be operated up to 10 A at a maximum DC link voltage of $V_{DC} =$ 450 V. Therefore, power transfer up to kilowatts would be feasible.

Discussion

Self-oscillating capacitive power transfer has some major advantages as compared to conventional CPT systems. In our proposed converter, the load voltage and thus the load current are almost rectangular signals (cf. Fig. 4). The time-integrated load current results in a triangular voltage signal across the coupling capacitors, i.e. the energy transfer is due to a triangular electric field signal. Thus in a Fourier series representation, odd numbered harmonic signals for a specific oscillation period according to Eq. (5) can be identified, which are contributing with the corresponding harmonic amplitude to the overall transferred power.

Due to the non-resonant operation, there is no need for a compensation network on the transmitter as well as on the receiver side. Such compensation networks are adding complexity and costs to single frequency and multiple frequency resonant topologies [14], cause limited coupling distances (by network detuning due to reduced coupling capacitances), and deteriorate system efficiency [15].

By self-adapting to a change in the impedance of the coupling link, the self-oscillating CPT is robust against lateral misalignment in a Four Plate-horizontal or -vertical coupling path [16]. The system reacts analogous to a vertical displacement, i.e. it automatically responds by increasing or decreasing the oscillation period. The CPT answers to changes in the load R_{load} by adapting the time constant τ and period T in a comparable way. Adding multiple receivers to the wireless link has a similar effect.

Our analytical and experimental analysis reveals that, for a given coupling link, reducing the individual load, R_{load}, for a constant number of loads, N, reduces the period T. A corresponding lowering in T is found for a grow in N at constant individual loads R_{load}. Both operation conditions raise the switching losses in the converter resulting in a lower efficiency η. The drop in η at elevated DC link voltages in Table I, keeping the coupling link almost unchanged, manifest contributions of the oscillation frequency f_{osc}, the device voltage $V_{ds} = V_{DC}$ and the load current to the switching losses for the GaN-HEMTS [17].

The broadband energy transmission with variable switching period found here serves as a potential source for EMI disturbances. On the other hand, design strategies for the coupling structures in order to minimize electric field emission are already available [18].

Conclusion

A novel CPT system for multiple receiver operation and capability to self-adapting to the transfer path impedance has been developed and parametrically studied. The prototype system confirms the characteristics from network analysis, where a high power transfer and a high efficiency makes the self-adapting CPT system attractive for multiple load applications.

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