High Efficiency Capacitive Power Transfer Converter

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***Abstract*— Capacitive power transfer (CPT) is gaining interest in the last years in the field of wireless power transfer for different applications, like vehicle charging or portable equipment battery charging. CPT exhibits better tolerance to misalignment and requires simpler hardware design than Inductive Power Transfer (IPT) in some cases. In this paper, a Wireless Capacitive Power Transfer Converter is studied and implemented, which gives a very high efficiency in the inverter and the resonant tank and demonstrates the feasibility of this technology.**

Keywords— Wireless power transfer, Capacitive power transfer, Very high efficiency power conversion, GaN, Wide Band Gap.

I. INTRODUCTION

Wireless power transfer has been gaining interest in the latest years due to some advantages over conventional power transmission, such as position independence, no need for physical connectors, capability to work even when metals are present, etc.

The basic topology used for this kind of power transfer converters is shown on Fig 1. First, the output of a DC source goes through an inverter, to get an AC waveform with no DC value. This square wave is then filtered and compensated, in order to have a sinusoidal waveform of the desired value to be transmitted through the wireless interface (capacitors or a transformer). Once transmitted, it can go through an additional compensation net and then it is rectified in order to get a DC waveform at the output, as seen in Fig 2.

Even though Inductive Power Transfer (IPT) has received most of the interest until now, new researches on Capacitive Power Transfer (CPT) have led to proposals for high power, long distance applications, such as electric vehicle charging [1] or handheld devices [2]. So the traditional conception of Capacitive wireless transmission only for low power and short distances is slowly changing

Significant advantages of CPT versus IPT are: 1) the absence of ferrites, which are normally expensive and fragile; 2) electrical field distribution can be more convenient than magnetic fields in some applications; 3) in the range of low power, capacitive components scale normally better than inductive components [3]; 4) CPT allows working in the presence of metallic objects in the transmission path since there are no eddy currents producing extra losses; 5) CPT is more tolerant to defects in the geometry of the coupling device than IPT, and the shape of coupling device admits more options than IPT. All those advantages result in potential reduction of the total cost [4].

However, CPT exhibits some limitations, related to the security and material limitations. First, materials used as dielectric can be limited by the dielectric strength, which means than the geometry, operation frequency and voltage levels can be limited. Power losses in those materials could be also a limitation. High frequency operation is needed since the coupling devices have a relatively low capacitance or inductance and therefore, the switches technology and operation are essential in the design process. Communication between primary and secondary sides is also a challenge in CPT systems.

State of the art of CPT converters includes a significant variety of resonant topologies, including different number of switches in the inverter, from single switch to a half or full bridge, different resonant tanks and impedance adaptation networks. This work is focused on simplicity, using as simple high frequency inverter and series resonant tank.

In this paper, a CPT is proposed for a new, low power application: a battery charger of a small laptop (45W). This paper is organized as follows: Section II presents a brief description at system level, and enumerates the advantages and drawbacks of this kind of implementation; in section III, three prototypes are made and measured, to validate the ideas given in the first sections and, in Section IV, some conclusions are presented about the work done and the next steps to be taken for future research.

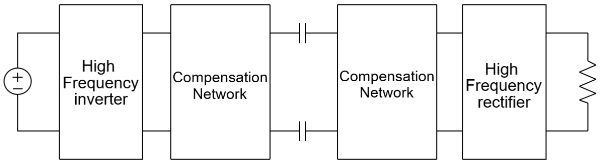

Fig 1. Basic converter scheme for CPT

TABLE I. CONVERTER SPECIFICATIONS

Vin	Pout	Max Area	Switch Technology
60 V	45W	900 cm^2	GaN

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II. SYSTEM DESCRIPTION AND DESIGN CONSIDERATIONS

The specifications chosen for the analysis are intended to emulate the charge of a small laptop, using a DC source as input (Table I).

Bearing in mind that the goal of this research was to achieve an efficiency as high as possible, and that a high switching frequency is needed to compensate for the low capacitance value, the first step was to select the resonant tank and the inverter best suited for the application.

Since losses in the capacitive interface are assumed to be much lower than the losses in the rest of the devices, the main focus is set upon two kinds of power losses: switching losses in the inverter and losses in the inductors. The choice was to reduce as much as possible the number of devices used in the implementation so, for the inverter, a Half-Bridge inverter was selected and, for the compensation network, a series tank, the resonant tank with the lowest component count, was chosen (Fig 3).

In the design and use of the inductor, the two main aspects to be taken into account are: core losses (since they are highly frequency-dependent and will impose a limit at the frequency to be reached) and copper losses, which should be minimized taking into account the AC component of the copper resistance, which can dominate at the working frequencies, that will be in the order of MHz.

The selection of the inverter was also conditioned by the usage of a new kind of device, highly suitable for this application due to their low parasitic capacitances: GaN transistors. In this case, through an intensive research, a device was found that suited the specifications: the Texas Instruments GaN Half bridge LMG5200. This device, capable of handling up to 80 volts at the input and up to 10 Amps, allowed the increase of the operating frequency without reducing the efficiency too much. It also has the advantage of having the drivers for both the High-side and Low-side FETs integrated in the device, so stray inductances are reduced at maximum, getting rid of one of the worst problems when dealing with currents in the order of amps at frequencies higher than the MHz. For the generation of the gate signals, an FPGA was used, which allowed a precise tuning of both period and dead times, in the order of nanoseconds, which were found to be critical for the achievement of high efficiencies.

In order to make the measurements as repetitive as possible, instead of air, different dielectric materials were used for the transference capacitors, which allowed the copper plates to be at a fixed position and assured a constant capacitance amongst measurements. In a final design, the dielectric would consist of both the insulating material covering the devices and the air between them and the laptop.

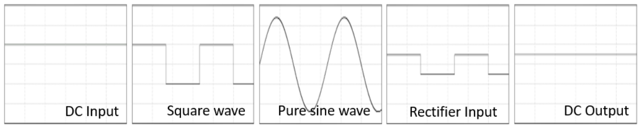

Fig 2. Basic converter voltages waveforms

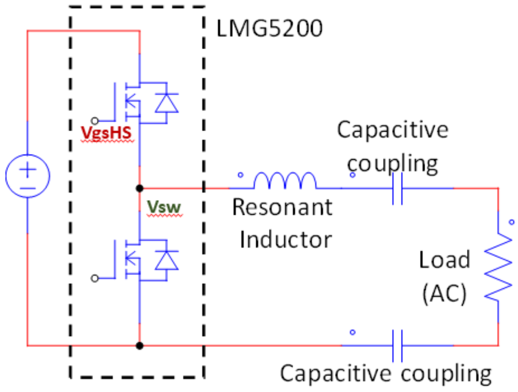

Fig 3. Prototype with half bridge inverter and without rectifier

III. PROTOTYPE RESULTS

A. *Prototype I*

The first prototype was done using the aforementioned GaN Bridge switching at 2 MHz as inverter and commercial shielded inductors to achieve the desired inductance (Table 2), without any rectifier at the output, as seen in Fig 3. After doing every measurement, the efficiency (Calculated as the I·V product at the DC side and as $I^2 \cdot R$ at the AC output) was found to be much lower than expected, also presenting waveforms far from the ones desired, as shown in Fig 4 (Inductor current with High Frequency distortion in purple and voltages at the switching nodes, with high ringing, in green and red). Notice that in this case, not even the full input voltage was used, since the high losses would cause the devices to fail at full power.

Through a thermal analysis using a thermal camera, the losses were found to be mostly in the inductor and, above all, in the GaN bridge, which could reach up to 110ºC transmitting only 20 Watts. It was also found that the ringing in the turn-on of the GaN FETs was unacceptable, since it was almost equal to 2 times the input voltage and would easily lead to device damage. The main conclusions obtained from these tests are stated below.

1) *Inductor*

Even though the commercial devices selected (HCF SMD High Current Inductor 7443642200) were theoretically capable of working at the selected frequency, and with the imposed current levels, the inductor rapidly increased its temperature and, due to the high value of its parasitic series resistance, the waveforms were highly distorted. For this same prototype, an air core inductor was built, using Litz wire to try to reduce the copper losses. Although it improved the results, Litz wire was found to present little to no advantage at these high frequencies, as stated in [5].

2) *GaN FETs*

Even though they were expected to be almost lossless, working near the resonant frequency of the circuit, they heated to up to 110º C, mostly due to two problems: the absence of ZVS, hard to obtain with Voltage and Current waveforms so distorted; and the high voltage spikes during turn on, which could potentially lead to the device's destruction.

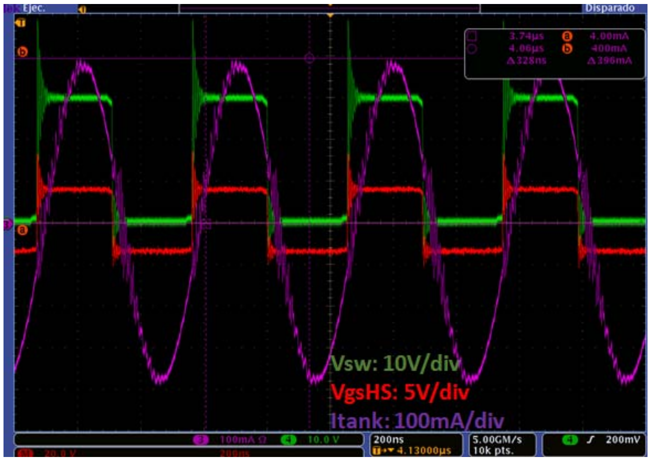

Fig 4. Prototype I waveforms (tank current in purple and voltages in red (High-side Gate-Source) and green (inverter output))

TABLE II. PROTOTYPE I SPECIFICATIONS

Inverter topology	**Freq**	**Inductance**	**Inductor Technology**	**Efficiency (DC-AC)**
Half bridge	2.04 MHz	27.2 µH	Shielded ferrite	60%

Cap	**Area**	**Dielectric**	**Distance**
(470pF/2) 235pF	2x 189cm^2	FR4	1.57mm

3) Overall Efficiency

The efficiency was lower than expected, around 60%. Since the published results (67%) were better than that [6], an improvement was needed. Also, some losses were occurring in the transference capacitances, so FR4, which was used as dielectric due to the easiness to make it as a PCB, was found not to be suitable to realize these tests, for its high loss tangent, as compared with air, which is expected to be almost lossless.

B. Prototype II

To tackle all the problems mentioned in the previous section, a new prototype was built, with the specifications shown in table III. The last measurements are presented in Fig 5. Notice the frequency was lowered in order to increase the time resolution of the controlling device, which allowed a better control of the dead times, which was found to be critical for the achievement of ZVS.

TABLE III. PROTOTYPE II SPECIFICATIONS

Inverter topology	**Freq**	**Inductance**	**Inductor Technology**	**Efficiency (DC-AC)**
Half bridge	1.54 MHz	50.16 µH	Air Core	98%

Cap	**Area**	**Dielectric**	**Distance**
(500pF/2) 250pF	2x 462cm^2	Polypropylene	1.275mm

As can be seen, the waveforms are much closer to the expected ones, and the measured efficiency was higher, so the objectives of the prototype design were fulfilled. The changes made to the prototype are presented below (inductor redesign and ZVS operation of GaN FETs), along with the main impact of these changes and the significant improvement in the efficiency. The green line presented is the voltage at the switching point of the half bridge; the increasing of the dead times, along with the decreasing of the ringing, gives a non-square waveform, which shows the realization of ZVS.

1) Inductor

Since the AC resistance of the wire is inversely proportional to its radius [7], instead of Litz wire, a unifilar, bigger copper wire (AWG15) was employed. In this prototype, the heat dissipated by the inductor was vastly reduced as can be seen in Fig 6, where the hottest spot is only near 35ºC. It shows the low losses produced in the inductor.

2) GaN FETs

Two strategies were taken to deal with the losses:

1) Reduction of the overvoltage during turn-on: following manufacturer recommendations, the inductance loop that goes form the High-side Drain to the Low-side Source was reduced by means of reducing the PCB thickness (from the previous 1.5mm to 0.5mm) and placing two capacitors right beneath the Half Bridge device, making an inductance path as short as possible.

2) Achievement of ZVS: As can be seen in Fig 5, the converter is no longer working at resonance but at a higher frequency. This, along with a fine tune of the dead times, which was found to be critical, led to the discharge of the parasitic capacitances of the devices prior to their turning on, cutting the switching losses to a negligible value, even though some gain is lost due to the frequency difference.

3) Overall Efficiency

Once a very high efficiency is achieved, an accurate measurement of the losses becomes difficult [8], so the efficiency measurement error is of around 2%. Even with that uncertainty, the efficiencies reached up to 98% (measured as the DC I·V product at both input and output), so even in the worst measurement case, the high efficiency of the system is demonstrated.

C. Prototype III

Lastly, and just for the purpose of building a complete DC to DC converter, a High frequency rectifier was implemented. In this case, a Full-Bridge inverter was employed at the input, which didn't have a big impact on efficiency but reduced by half the current going through the capacitors, which was desired for security.

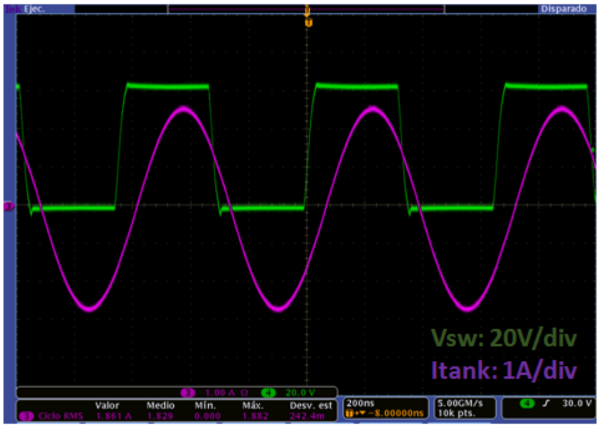

Fig 5. Prototype II output voltage of high frequency inverter (green) and current in the resonant tank (purple). Frequency: 1.54 MHz

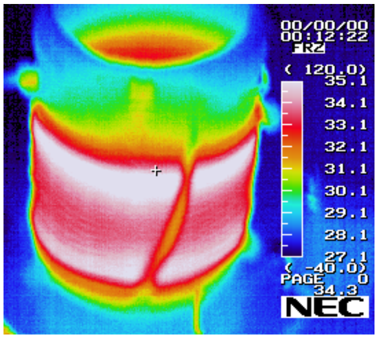

Fig 6. Thermal image of the resonant inductor. Note that the hot spot temperature is 35 ºC, while the room temperature is 25ºC

TABLE IV. CONVERTER III SPECIFICATIONS

Inverter topology	Freq	Inductance	Inductor Technology	Efficiency (DC-DC)
Full bridge	1.56 MHz	50.16 µH	Air Core	93.7%
Cap	**Area**	**Dielectric**	**Distance**	**Rectifier**
(500pF/2) 250pF	2x 462cm^2	Polypropylene	1.275mm	Full diode bridge

For this prototype, the rectifier was done with 4 diodes and a low ESR film capacitor, and the waveforms obtained are shown in Fig 7 and Fig 8. The achieved efficiency in this case is 93.7%, due to the extra losses produced in the high frequency rectifier and the waveforms are distorted.

Since now the highest losses are in the rectifier, a synchronous rectification or optimized semiconductor selection could improve this prototype, and are ongoing work expected for future research, where problems as the correct phase shift between inverter and rectifier will be dealt with, since it is necessary when working at a frequency different from the resonant one to achieve ZVS.

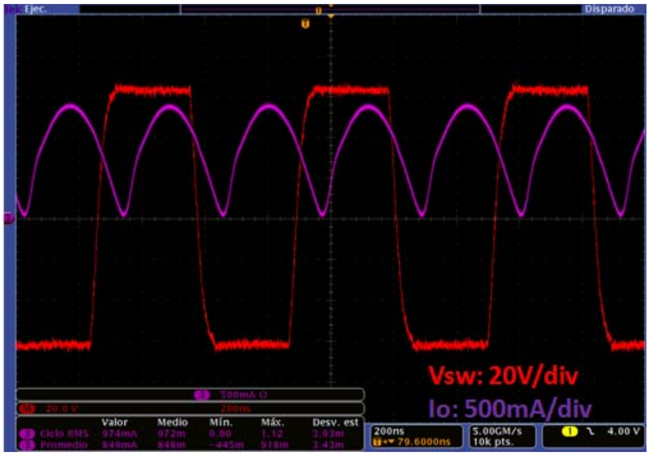

Fig 7. Prototype III inverter voltage (red) and output current (purple) after the rectifier

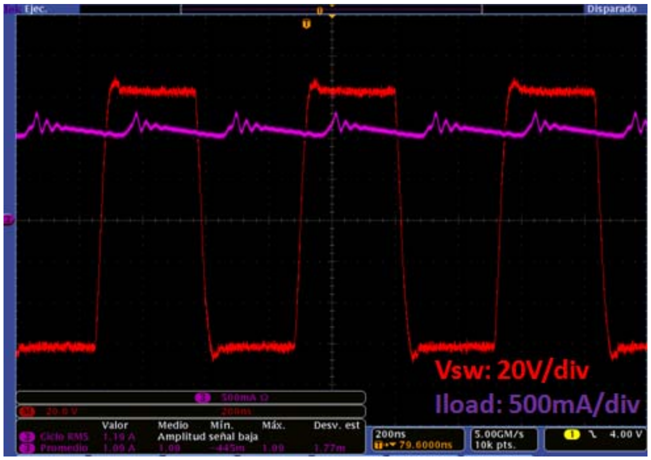

Fig 8. Prototype III inverter voltage (red) and output current through the load (right) in the prototype with rectifier

The actual prototype of the inverter, along with its temperature distribution is shown in Fig 9 and Fig 10, where the maximum temperature is found in the half bridge, which does not reach 40ºC even though no heatsink or blower is used.

IV. SAFETY

One of the main problems found during the building of the prototype was the huge voltage difference that appears between the two plates of each capacitor, due to the fact that it's related to current, frequency and capacitance:

$$V_c = \frac{I_c}{C \cdot \omega} \tag{1}$$

In this particular design, with the values: C=500pF; $\omega=2\pi f_{sw}$; f_{sw}=1.54MHz; I_{Cpeak}=1.4A; the voltage between the plates is: 289V, which would make compulsory the use of an isolator, even with this low power level and this high frequency. If the dielectric is composed mainly of an air gap, the capacitance will go down and so the voltage will go up, so special care has to be taken when designing and manipulating the device.

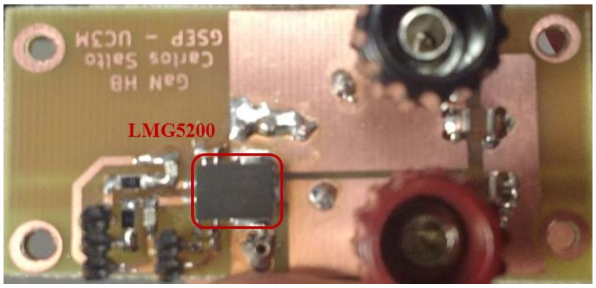

Fig 9. Prototype III

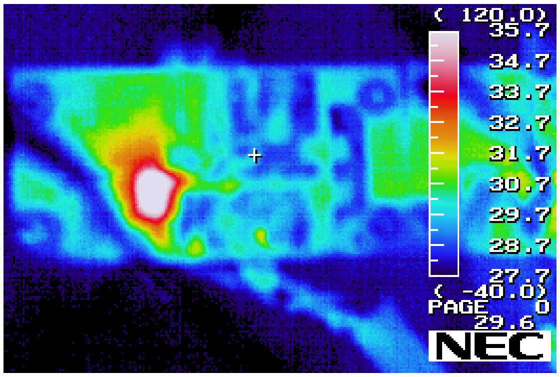

Fig 10. Thermal image of the prototype

Even though the specific normative changes in every country, the recommendations when dealing with high frequency (100kHz – 300GHz) electric fields are set by the ICNIRP (International Commission on Non-Ionizing Radiation Protection) [9], which can be seen in Fig 11. In case the power level goes up, or the distance between plates increased, these recommendations would need to be taken into account.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a high efficiency Capacitive Wireless converter is proposed and tested. Measurements show a very high efficiency, 98% in DC/AC and 93.4% in DC/DC including output rectifier and filter. Such high efficiency can be achieved through a proper operation of GaN devices (ZVS and ringing control) and through the reduction of the losses in the inductor (air core). The obtained results show the feasibility of the CPT technology in applications where, traditionally, inductive transfer or wired transfer has been used. Immediate future work includes the optimization of the output rectifier and the study of synchronous rectification as an improvement to a classic diode rectifier. Also, the advantages and disadvantages of using either a Half- or a Full-bridge, should be studied more carefully in order to know in which applications will each one be the best choice.

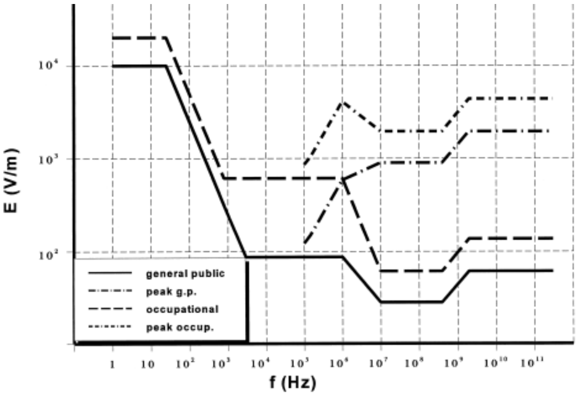

Fig 11. ICNIRP recommendations for high frequency electric fields.

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