Class-E Power Converters for AC (50/60 Hz) Wireless Transmission

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Abstract — In this paper, class-E power amplifiers (PAs) and rectifiers, operating at UHF band, are properly integrated in efficient AC-to-RF and RF-to-AC converters for their use in 50/60 Hz wireless power transmission (WPT). Slightly modifying a center-tap full-wave rectifier, it is proved that a 915 MHz frequency carrier may be high-level amplitude modulated by each of the semi-cycles of the utility waveform. Assuming those components are transmitted by means of orthogonal antenna polarizations, the high-fidelity recovery of both semi-sinusoids in the remote position is also demonstrated, to be stepped-up and combined at the Δ port of an additional center-tap transformer. GaN HEMT packaged devices were selected for the designed PAs, while Schottky diodes for the rectifiers, resulting in average efficiency figures of 83.3% and 75.4%, respectively.

Index Terms — AC, Class-E, DC, GaN HEMT, inverter, power amplifier, rectenna, rectifier, Schottky diode, wireless power transmission.

I. Introduction

The far-field electric power transmission via radiowaves is mainly dependent on the use of high-efficiency frequency converters operating from DC (or 50/60 Hz) to RF/microwave and vice versa [1]. High power semiconductor and tube amplifiers (or oscillators) are required in the transmitting side, being the use of rectifying diodes generally common in the other. Most of these systems are certainly conceived for direct current WPT [2], influenced by the relevant role fuel cells and photovoltaics are currently playing as environmentally friendly energies, but mainly due to the ever-increasing amount of DC loads (sensors, mobiles, computers, etc.) to be powered. However, considering the prevailing power system infrastructures are based on alternating current and that multiple loads in a variety of sizes (motors, lighting, household appliances, etc.) still work on AC [3], a great interest also exists on the transmission of the line waveform.

Powering a PA or an oscillator with a sinusoid is not a trivial task, as it is not performing an efficient down-conversion back from the MHz or GHz frequency range to 50/60 Hz with the use of diodes [1]. This is one of the reasons why intermediate AC-to-DC, DC-to-DC and DC-to-AC converters are usually mandatory as part of a microwave AC WPT link, in detriment of the simplicity and flexibility that could be provided by the use of a transformer for reducing or boosting the AC voltage levels.

In this work, UHF class-E power amplifiers and rectifiers are designed and properly combined to implement AC-to-RF and RF-to-AC converters for the wireless transmission of a 50/60 Hz utility waveform without the need of intermediate conversions to DC. After a brief overview of the system, design details and measurements over both converters will allow validating the proposed approach.

II. System Overview

In Fig. 1, a simplified diagram of the proposed AC WPT architecture is presented. On the transmission side, a center-tap full-wave rectifier, widely employed for AC-to-DC conversion, is slightly modified. Instead of connecting the two diodes back-to-back by the cathode, each rectifying branch is used to dynamically bias the drain terminal of a class-E RF PA. Being that the amplitude of its output voltage, V_{out}, is proportional to the employed supply voltage, V_{DD}, as theoretically described through eq. (1) from the assumptions taken in [4], these PAs could implement a high-level amplitude modulation (AM) over a 915 MHz carrier with each of the semi-cycles of the utility waveform. An auxiliary AC-to-DC converter, dealing only with a small portion of the power to be transmitted and not included in the diagram for simplicity, would be required to bias the 915 MHz oscillator.

$$V_{out} = \frac{4 \cdot V_{DD}}{\sqrt{(\pi^2+4)}} \tag{1}$$

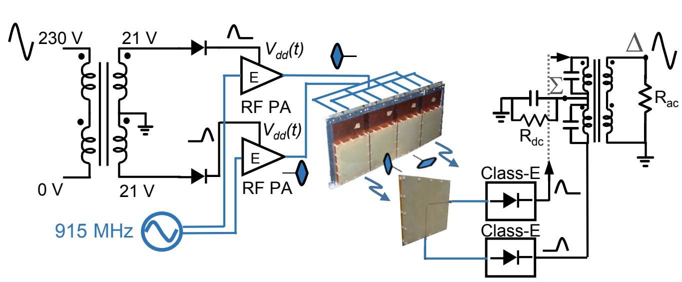

Fig. 1. Simplified diagram of the proposed AC WPT architecture, combining AM modulation with the use of orthogonal linear polarizations.

Selecting orthogonal antenna polarizations for the transmission of the AM signals (horizontal and vertical polarizations in the case of the 4x1 array of dual-fed aperture-coupled square patches in the diagram of Fig. 1), both semi-sinusoids may be recovered in the remote position thanks to the use of class-E rectifiers (diode- or transistor-based, depending on the available power levels). Connected to the orthogonal ports of a single patch of the same type, they would operate in this scenario as highly efficient envelope demodulators. With the aid of an additional center-tap transformer, used as a sort of 180º hybrid combiner [5], the desired AC component may be properly boosted in amplitude while extracted from the Δ port. The remaining common mode DC component could be also obtained through the center tap or Σ port.

III. AC-to-RF and RF-to-AC Power Conversion

A. Class-E Power Amplifiers

A packaged GaN HEMT device from Cree Inc., the CGH35030F, with an equivalent measured capacitance, C_{out} = 3.6 pF at 915 MHz, and a breakdown voltage over 120 V, was selected for the class-E PA design. In Fig. 2a, its schematic is presented, together with the employed values. A lumped element multi-resonant version of the transmission line topology in [6] was followed, where the series resonant circuits may be combined with a parallel tank and a small coil in order to synthesize the desired open-circuit terminations at the third and second order harmonics, respectively.

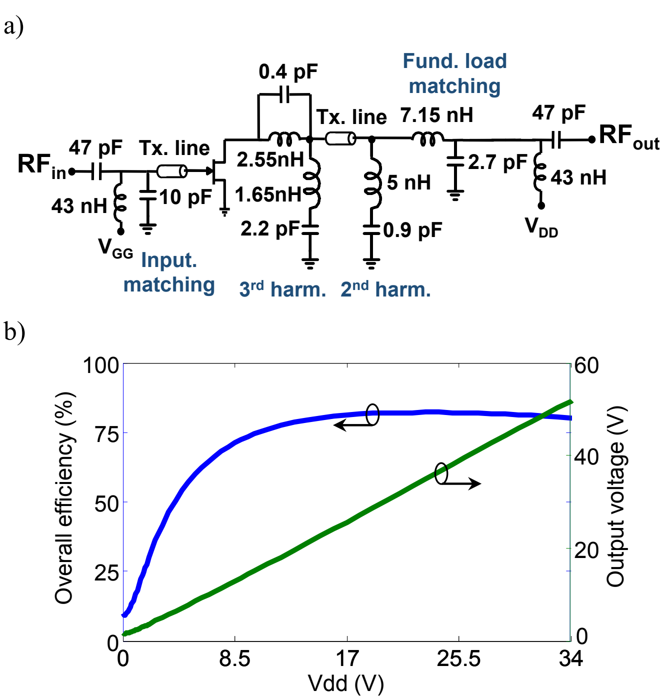

Fig. 2. Designed class-E PA. a) Schematic, including coil and capacitor values. b) V_{dd}-to-*AM* measured profile, with the overall efficiency, $\eta_{ov} = 100{\cdot}P_{out}/(P_{DC}+P_{in})$, included.

As it can be appreciated from Fig. 2b, the amplitude of the output voltage, measured across a 50 Ω load, follows V_{DD} in a highly linear way, with the overall efficiency over 80% along a significant 19 V range. Considering the peak of the zero voltage and zero voltage derivative switching (ZVS & ZVDS) waveform may be as high as $3.562{\cdot}V_{DD}$, a reliable operation up to a drain biasing voltage of 34 V may be perfectly possible.

B. Parallel-circuit Class-E rectifiers

According to the device employed at the transmitting side and in order to test the proposed approach in a condition close to the desired far-field operation (calculated to exist at distances from the source greater than 2.6 m, according to the array physical length), a Schottky diode of the HSMS-282 series from Avago Tech. was selected for the rectifiers. Measured values for the parasitic resistance, OFF-state capacitance and inverse breakdown voltage are R_s = 9 Ω, C_j = 0.76 pF and V_{br} = 24 V, respectively. A class-E variant with parallel-circuit [7] was selected. The continuity of the ZVS/ZVDS modes around:

$$q = \frac{1}{\omega \cdot \sqrt{L_b \cdot C_j}} = 1.412 \qquad (2)$$

with L_b the finite dc-path inductance, may lead to designs with a wider frequency coverage in terms of efficiency, but also to an improved performance under light loading conditions, of interest for this particular application [8].

The rectifier schematic is shown in Fig. 3a, together with its voltage transfer profile in Fig. 3b. The recovered DC voltage linearly follows the input amplitude, as expected, except for values below or in the range of the diode knee voltage.

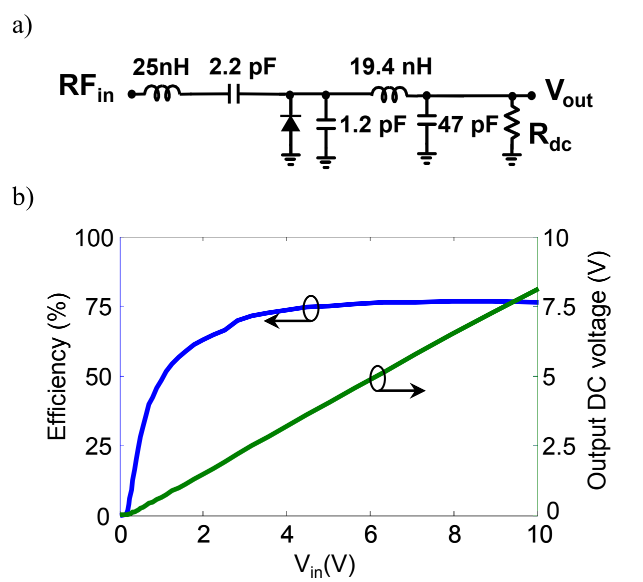

Fig. 3. Designed rectifier. a) Schematic and values. b) DC voltage and efficiency vs. the amplitude of the 915 MHz signal.

C. Combined Power Converters

In order to modulate the PAs with each of the semi-sinusoids of the utility waveform, a commercial off-the-shelf (COTS) center-tap transformer with 21 V of *rms* voltage at the secondary windings was selected. This would lead to 30 V peaks in the $V_{dd}(t)$ waveforms, below the limit for a safe class-E operation of the GaN HEMT. A damping 1 kΩ resistance, quite over the 34 Ω value offered by the PA to its drain power supply, was added in parallel. Not affecting the efficiency, it avoids current discontinuities, waveform distortion and reliability issues. In Fig. 4a, a photograph with implementation details may be appreciated. Oscilloscope captures of the $V_{dd}(t)$ waveforms, together with the envelope evolution in time at each PA output, as obtained from a VSA, are presented in Fig. 4b. The observed waveform distortion came from the Uninterruptible Power Source (UPS) used for the experiments. The estimated average output power and efficiency for both branches were of 5 W and 83.3%, respectively. A 300 Hz bandwidth (99% of total power) was measured for the signals to be transmitted.

a)

b)

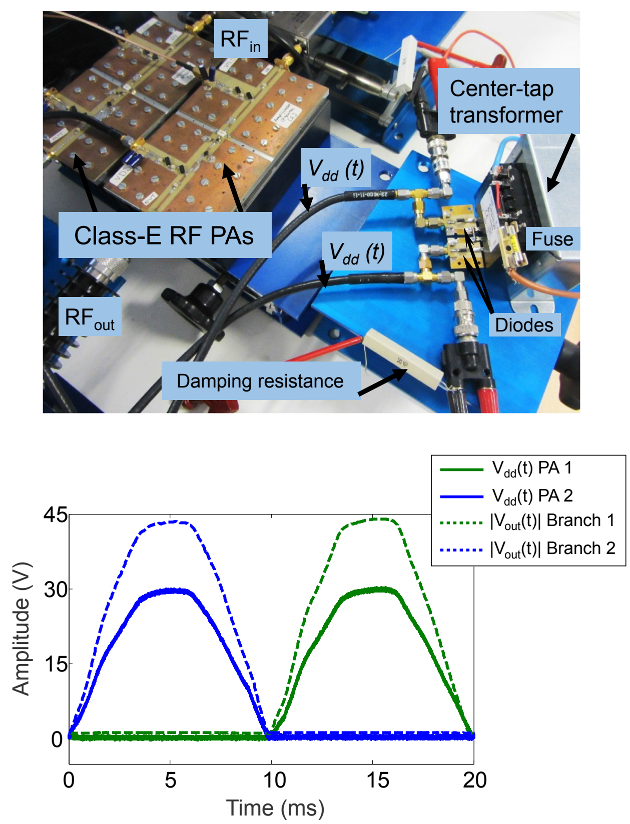

Fig. 4. AC-to-RF power converter. a) Photograph of the implemented hardware. b) Comparison of $V_{dd}(t)$ and $|V_{out}(t)|$ (over 50 Ω), as measured with an oscilloscope and a VSA, respectively.

A photograph with details of the rectifiers and the combining transformer is also presented in Fig. 5a. The demodulated envelope waveforms, measured over 330 Ω DC loads, have been included in Fig. 5b. The approximate 20 dB difference in level between the power provided by the AC-to-RF converter and the available power at the inputs of the RF-to-AC one, was set for taking into account the gains of the transmitting array and the receiving patch, as well as the losses of a 3 m link (in the far-field region). The measured average efficiency was of 75.4% for each branch, resulting in a combined AC-to-RF and RF-to-AC conversion efficiency slightly over 60%. These values are not far from those to be obtained for DC WPT converters, working with these power levels and employing similar devices.

Finally, another COTS center-tap transformer was added in order to combine the recovered waveforms in an analogous way to the use of a transformer-based hybrid coupler at RF [5]. A 1000-μF bypass capacitor was added in parallel to the 150 Ω DC loading resistance (from the parallel of the optimum rectifier loads) at the center tap or Σ port, while the AC load in the Δ port was dimensioned according to the square of the ratio between the primary and secondary wire turns (N = 10). Unfortunately, these COTS transformers are not generally conceived for stepping-up the voltage, but to be operated downwards, reason why the reactance offered by the windings to be connected to the rectifiers could be even lower than their output impedance (close to 330 Ω). This undesired loading effect was reduced by resonating them with the use of parallel 33-μF capacitors.

a)

b)

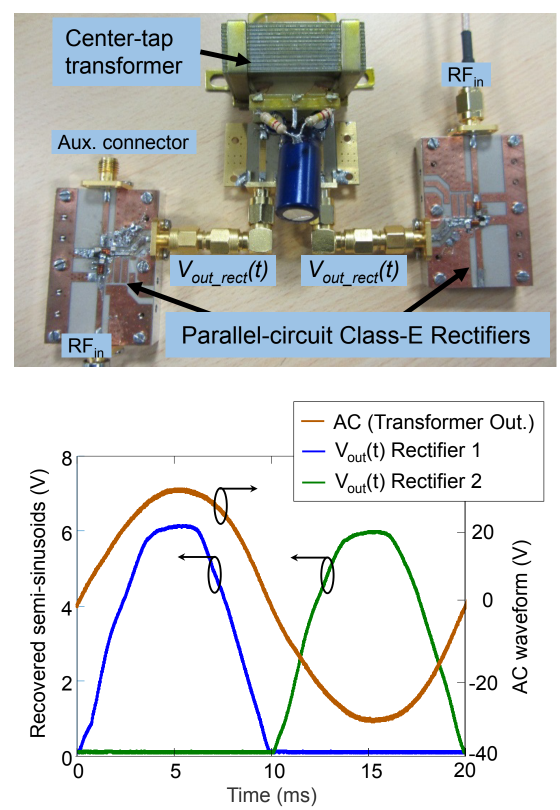

Fig. 5. Rectifying branches of the RF-to-AC power converter. a) Photograph with implementation details. b) Recovered semi-sinusoids and output AC waveform from the transformer.

Despite the losses in terms of efficiency associated to this fact, an AC signal with 32.6 V of amplitude was recovered at its output (Fig. 5b), but with a much lower power level when compared to the one provided by the secondary side of the transformer in the AC-to-RF converter of Fig. 4a. The power reduction may be associated to the link losses as well as those in the converters, besides the undesired contribution due to a transformer not designed for voltage step-up.

IV. CONCLUSION

The use of class-E power amplifiers (PAs) and rectifiers as linear and efficient high-level AM modulators and envelope detectors, respectively, have been shown to be valid for implementing the AC-to-RF and RF-to-AC converters required for the direct wireless transmission of the 50/60 Hz utility waveform. Average efficiency figures of 83.3% and 75.4% have been measured for the implemented circuits, thanks to the use of GaN HEMT and Schottky diode technologies. Besides being amenable for the far-field powering with higher AC frequencies, if appropriate transformers were used instead, or for the high-level transmission of information signals (a wideband envelope modulator would be required [9]), the proposed architecture may be also reconfigured to the most common DC WPT mode if an appropriate filtering capacitor were connected to each of the PA drain biasing terminals in the transmitter side. The recovered DC power would appear at the Σ port of the transformer in the receiving side, with the secondary windings only acting as chokes.

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