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A New Coupling Insensitive Nonlinear Capacitive Resonant Wireless Power Transfer Circuit

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***Abstract*— This paper presents a nonlinear capacitive WPT system that automatically compensate for the coupling variation between the transmitter and receiver in a capacitive wireless power transfer (WPT) system with no active circuitry. The system is capable of minimizing the output power variation at a fixed operating frequency of 13 MHz as the coupling distance varies. A constant output power is achieved over a wide range of coupling capacitance variation in comparison to the conventional capacitive wireless power transmission circuits. Such an approach is attractive for biomedical implants employing a capacitive WPT system.**

***Keywords*— capacitive wireless power transfer, nonlinear resonator, Duffing resonator, varactor, passive nonlinear device.**

I. Introduction

The concept of wireless power transfer (WPT) was first demonstrated in [1] and [2], where energy is transferred by the time-varying magnetic field between the transmit and receive coils. Thus far, inductive WPT is proven to be popular in many applications, ranging from mm sized implants to electric vehicle charging and being applicable across various power levels. Capacitive based WPT provides an alternate solution to wireless charging, with potential advantages as compared to inductive based WPT. For instance, the issue of magnetic field shielding in inductive power transfer (IPT) is addressed since the electric field in capacitive WPT is confined within the transmit and receive pads. Furthermore, for some biomedical implant applications, the use of capacitive wireless power transmission is shown to be advantageous. A comparative study of inductive and capacitive wireless power transmission systems [3] demonstrated the possibility of transmitting more power within a certain SAR limit based on capacitive WPT.

To increase power transfer distance in WPT systems, resonant circuits have been adopted by both capacitive and inductive based WPT systems. The voltage or current swing on the coupling inductor or capacitor are multiplied by quality factor of the resonant circuit, thereby greatly enhancing the power transfer between the transmit and receive pads. This magnification is achieved at the expense of reduced circuit tolerance to distance variation and misalignment between the transmitter and receiver. Furthermore, component value tolerances can detune the circuit, severely degrading its power transfer efficiency.

To design an efficient and robust WPT system, nonlinear devices within the resonant WPT circuit have been employed to achieve impedance matching over a wide range of coupling parameter variation. This approach has been demonstrated in [4], [5] and [6] for inductive WPT systems that automatically self-adapt to the distance and misalignment between the transmitter and receiver coils. In this paper, for the first time the application of a nonlinear resonance circuit in a L-compensated capacitive WPT system is investigated. Simulation and experimental results show that the nonlinear capacitive WPT circuit is capable of maintaining a constant power transmission across a large distance variation between the transmitter and receiver as compared to a linear capacitive based WPT system.

II. Principle of Operation of the Nonlinear Capacitive WPT Circuit

Multiple circuit configurations have been developed for implementation of capacitive WPT systems, including series L, LC, LCL, CLLC, etc. [7]. In the single series L topology as shown in Figs. 1(a), and 1(b), the circuit complexity can be further reduced by combining L_1 and L_2 on the transmit and receive sides into a single inductor L. The receiving circuit thus consists of only the receiving capacitor pads and a load resistance, without requiring any bulky inductor. This is specifically attractive in applications where there are size constraints on the receiving circuit.

The behaviour of the nonlinear capacitive WPT circuit can be described by Duffing nonlinear differential equation [4]. The general form of Duffing differential equation is given in (1).

$$\ddot{x} + \gamma\dot{x} + x + \alpha x^3 = \cos\omega t \qquad (1)$$

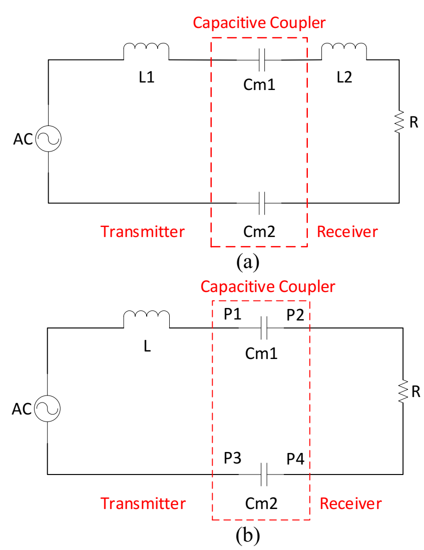

Fig. 1. (a) Series-L compensated capacitive WPT circuit schematic. (b) Simplified circuit (a).

where the third order term αx^3 represents the nonlinear behaviour of the system, A typical frequency-amplitude response of the Duffing equation is provided in Fig. 2 where ω_0 is the resonance frequency of the linear system. In comparison to a linear resonance circuit response, the nonlinear resonator response is tilted to one side, thus providing a smaller amplitude variation around the resonance frequency. When the nonlinearity effect is large, there exists a bistable region near the resonant frequency, in which the equation has three solutions. It is shown [9] that the upper and lower amplitude solutions are stable while the middle solution is unstable. When system is operating at its upper equilibrium, a relatively large amplitude response is obtained over a certain range of excitation frequencies, exhibiting an improved gain bandwidth product without compromising the circuit quality factor.

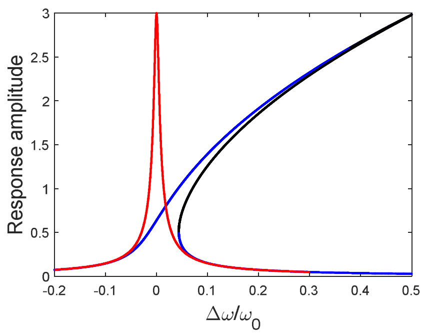

Fig. 2. Comparison of the amplitude-frequency response of a linear resonance circuit and a nonlinear Duffing resonator exhibiting a similar quality factor Stable equilibrium points are shown by the solid red lines.

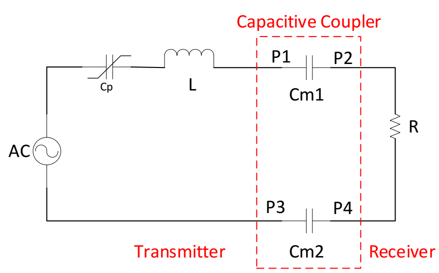

Fig. 3. Nonlinear matching network incorporated into a series L compensated capacitive WPT.

Insensitivity of amplitude response in such nonlinear circuits to excitation frequency and component value variations can be utilized to design nonlinear WPT systems. A nonlinear capacitor having an even C-V response has been added in series with the circuit in Fig. 2. The nonlinear capacitor exhibits a charge-voltage relationship that can be approximated by (2), where C is the zero voltage capacitance and C' is the third order term. C' has negative sign for a nonlinear capacitor with a bell shaped C-V response.

$$v_c = \frac{1}{C}q + \frac{1}{C'}q^3 \tag{2}$$

Fig. 3 depicts a nonlinear RLC resonant circuit with inductor L, load resistor R, mutual capacitor C_m and the nonlinear tuning capacitor from (2). When driven by a sinusoidal source, V_s, the behaviour of the resonant circuit can be described by a second-order nonlinear differential equation (3). The differential equation has a similar form to the Duffing equation, thus it also has a large amplitude response over certain frequency range.

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{1}{C}q + \frac{1}{C'}q^3 + \frac{1}{C_{m1}}q + \frac{1}{C_{m2}}q = V_s \cos \omega t \tag{3}$$

In the capacitive WPT circuit, the circuit is excited at a fixed operating frequency. The coupling capacitor value change results in a shift in circuit resonance frequency with respect to the excitation frequency. In a linear system, this relative frequency shift causes a severe detuning effect, significantly reducing the output current in a linear system. However, in the nonlinear WPT circuit presented here, as the coupling between the transmitter and receiver changes, current passing through the load in the receiver remains constant at its peak value.

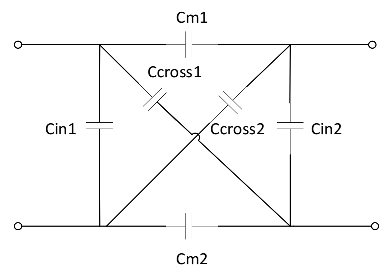

Fig. 4. Equivalent circuit for the capacitive coupler.

III. Nonlinear Capacitive WPT Circuit Design

The capacitive coupler within the WPT circuit is comprised of two pairs of parallel plates, denoted as $P_1 - P_4$ in Fig. 1 (b). In this figure, $P_{1,3}$ are on the transmit side while $P_{2,4}$ are on the receive side. The coupling between four plates is modeled by

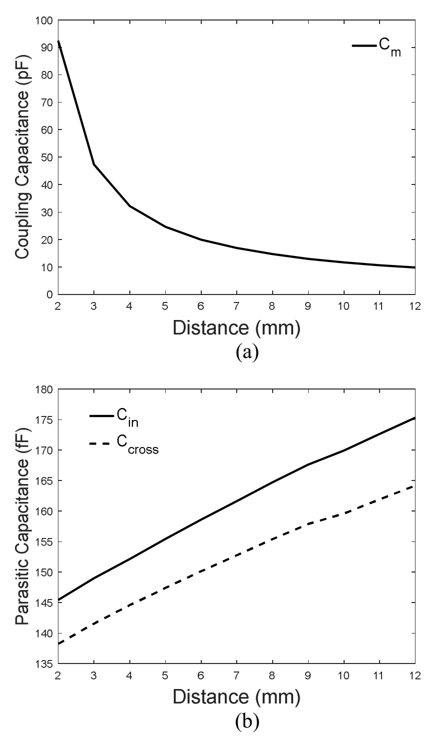

Fig. 5. Simulation results for the capacitive coupler showing (a) Mutual capacitance versus coupling distance (b) Parasitic capacitance versus distance.

the circuit shown in Fig. 4 [10], where C_{m1} and C_{m2} are the mutual capacitance between the transmitter and receiver plates facing each other, C_{in1} and C_{in2} are the internal self-capacitances between two plates on the same side, while C_{cross1} and C_{cross2} are the capacitances between the capacitor plates that are not facing each other. When the distance between the transmitter and receiver vary, both the mutual capacitance and parasitic capacitance values change.

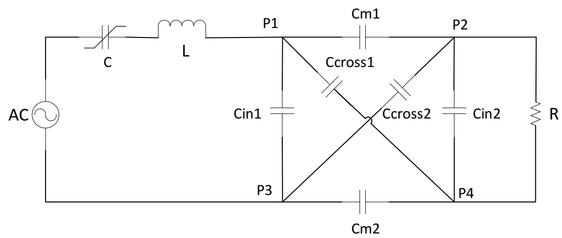

Fig. 6. Nonlinear capacitive WPT circuit schematic incorporating the equivalent circuit for the capacitive coupler.

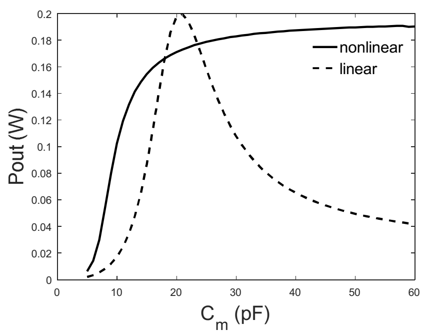

Fig. 7. Comparison of simulation results for the output power of a linear and nonlinear capacitive WPT circuits as a function of the mutual capacitance value between the transmitter and receiver.

EM simulations using ANSYS software is conducted to extract the circuit model parameters for the capacitive coupler. The coupling plates are implemented on a printed circuit board with dimensions of $100\ mm \times 100\ mm$. The lateral distance between two transmit (and receive) pads is 200 mm. The simulated mutual and parasitic capacitance values as function of distance between the transmit and receive pads are plotted in Fig. 5 (a) and (b).

As a proof of concept, a nonlinear capacitive WPT system is designed and simulated. The circuit schematic is presented in Fig. 6. The nonlinear tuning capacitor consists a pair of anti-series hyper-abrupt MAVR00407 varactors. The operating frequency is 13 MHz, which is within the industrial, scientific, and medical (ISM) frequency band.

For comparison purposes, two low power linear and nonlinear capacitive WPT are designed and simulated and. Both linear and nonlinear series - L compensated WPT systems operate at the same frequency and coupling capacitance value. Simulation results for the output power versus mutual capacitance of linear and nonlinear WPT circuits are plotted in Fig. 7. The results show that the nonlinear WPT circuits provides a relatively constant transmit power over a significant variation of coupling capacitance value as compared to its linear circuit counterpart.

Furthermore, both WPT circuits are fabricated and measured. As described previously, four copper plates form the capacitive coupler. The experiment setup is presented in Fig. 8. The measurement results for both the linear and nonlinear WPT circuits are shown in Fig. 9. It can be observed that significant dependence of the output power versus coupling capacitance exhibited by the linear circuit (dashed line) has been completely eliminated by using the nonlinear WPT system (solid line). Power can effectively be delivered within a large range of coupling capacitance variation from 15 pF to 80 pF, demonstrating the utility of the new nonlinear capacitive WPT circuit for various charging applications including various biomedical implants that require a coupling factor insensitive WPT circuit.

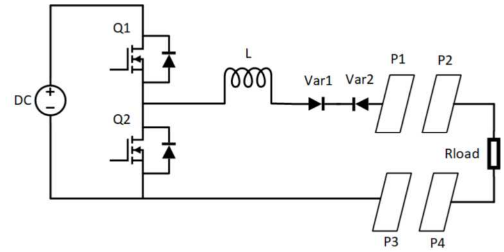

Fig. 8 Nonlinear capacitive WPT experiment setup.

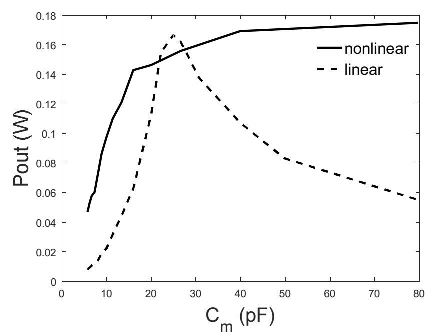

Fig. 9. Experimental result comparing the output power of the linear and nonlinear capacitive WPT circuits as a function of the mutual coupling between the transmitting and receiving capacitors.

IV. Conclusion

Performance of a new nonlinear capacitive WPT system is investigated and compared with a linear capacitive WPT system. Both theoretical and experimental results for the circuits are presented in this paper. The power transmission degradation exhibited by linear resonant-type capacitive WPT system as a function of the coupling capacitance variation is eliminated by introducing a new nonlinear capacitive based WPT circuit. The capacitive WPT system can deliver a relatively constant output power at a fixed operating frequency without using any active circuitry. According to the simulations and experimental data for a low power nonlinear capacitive WPT circuit, a constant output power of 200 mW is provided over a wide range of coupling capacitance values in comparison to the linear capacitive WPT circuit.

Acknowledgment

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References

[1] A. Karalis, J.D. Joannopoulos, and M. Soljačić, "Efficient wireless non-radiative mid-range energy transfer," *Annals of physics*, 323, no. 1, pp,34-48, Jan. 2008

[2] Y. Zhang and Z. Zhao, "Frequency Splitting Analysis of Two-Coil Resonant Wireless Power Transfer," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 400-402, 2014.

[3] A. I. Al-Kalbani, M. R. Yuce and J. Redouté, "A Biosafety Comparison Between Capacitive and Inductive Coupling in Biomedical Implants," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 1168-1171, 2014.

[4] O. Abdelatty, X. Wang and A. Mortazawi, "Position-Insensitive Wireless Power Transfer Based on Nonlinear Resonant Circuits," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 9, pp. 3844-3855, Sept. 2019.

[5] O. Abdelatty, X. Wang and A. Mortazawi, "Nonlinear Resonant Circuits for Coupling-Insensitive Wireless Power Transfer Circuits," *2018 IEEE/MTT-S International Microwave Symposium - IMS*, Philadelphia, PA, 2018, pp. 976-979.

[6] R. Chai and A. Mortazawi, "A Coupling Factor Independent Wireless Power Transfer System Employing Two Nonlinear Circuits," *2020 IEEE/MTT-S International Microwave Symposium (IMS)*, Los Angeles, CA, USA, 2020, pp. 393-396.

[7] Lu, Fei; Zhang, Hua; Mi, Chris. 2017. "A Review on the Recent Development of Capacitive Wireless Power Transfer Technology." *Energies* 10, no. 11: 1752.

[8] R. Erfani, F. Marefat and P. Mohseni, "Biosafety Considerations of a Capacitive Link for Wireless Power Transfer to Biomedical Implants," *2018 IEEE Biomedical Circuits and Systems Conference (BioCAS)*, Cleveland, OH, 2018, pp. 1-4

[9] I. Kovacic, and M. J. Brennan. “The Duffing equation: nonlinear oscillators and their behavior”. John Wiley & Sons, 2011, pp. 144-156.

[10] F. Lu, H. Zhang, H. Hofmann and C. C. Mi, "A Double-Sided LC-Compensation Circuit for Loosely Coupled Capacitive Power Transfer," in *IEEE Transactions on Power Electronics*, vol. 33, no. 2, pp. 1633-1643, Feb. 2018