REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
16-04-2019	Final Report	1-Sep-2015 - 31-May-2016

4. TITLE AND SUBTITLE
Final Report: STIR: Research Area 4.4: An Efficient Near-Field Wireless Power Transmission System

5a. CONTRACT NUMBER
W911NF-15-1-0463

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Michigan - Ann Arbor
3003 South State Street

Ann Arbor, MI 48109 -1274

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
67839-EL-II.4

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Amir Mortazawi
					19b. TELEPHONE NUMBER
					734-936-2597

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 25-Apr-2019

Agency Code:

Proposal Number: 67839ELII | **Agreement Number: W911NF-15-1-0463**

INVESTIGATOR(S):

Name: Amir Mortazawi
Email: amirm@eecs.umich.edu
Phone Number: 7349362597
Principal: Y

Organization: **University of Michigan - Ann Arbor**
Address: 3003 South State Street, Ann Arbor, MI 481091274
Country: USA
DUNS Number: 073133571 EIN: 386006309

Report Date: 31-Aug-2016 Date Received: 16-Apr-2019
Final Report for Period Beginning 01-Sep-2015 and Ending 31-May-2016
Title: STIR: Research Area 4.4: An Efficient Near-Field Wireless Power Transmission System
Begin Performance Period: 01-Sep-2015 **End Performance Period:** 31-May-2016
Report Term: 0-Other

Submitted By: Amir Mortazawi Email: amirm@eecs.umich.edu
Phone: (734) 936-2597

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:** 2

Major Goals: The objective of this research is to broaden the bandwidth of the resonance-based wireless power transmission (WPT) systems while maintaining their power transmission efficiency (PTE). High Q resonators are widely used in near field WPT systems since they effectively improve the transmission efficiency over distance. Such systems therefore have a limited operating bandwidth; hence, the conventional WPT systems are intolerant to frequency misalignment and coupling factor variation.
We will address the challenges discussed above by employing specific type of nonlinear resonant circuits, known as Duffing nonlinear resonators, for the first time in the design of position-independent WPT circuits. The proposed, position-independent WPT circuits automatically compensate for the coupling factor variation between the transmitter and the receiver without varying the operating frequency or utilizing any active feedback/control circuits. This technique provides the only solution for designing position-independent WPT systems that does not require either frequency tracking or use of tunable matching circuitry. By design, coupled nonlinear resonators are expected to be capable of adapting their resonance frequencies and matching conditions according to a voltage level change across the nonlinear device caused by coupling factor variation between the transmit and receive coils. Thus, incorporation of nonlinear resonant circuits in this technique allows the WPT circuit to track the maximum achievable PTE at a fixed frequency over a range of coupling factors. The proposed technique holds clear advantages over current approaches by providing a low cost, low complexity, and highly reliable solution for position-insensitive WPT design.

Accomplishments: As a proof of concept, a prototype position insensitive WPT circuit employing a nonlinear resonator has been designed, fabricated and tested. This new design addresses a major challenge in WPT systems, which is their strong sensitivity to the coupling factor variation between the transmit and receive coils. The circuit operation relies on harnessing the unique properties of a specific class of nonlinear resonant circuits to design position-insensitive WPT systems that maintain a high power transfer efficiency over a a large variation of coupling factor without tuning the source's operating frequency or employing tunable matching networks, as well as any active feedback/control circuitry. A nonlinear-resonant-based WPT circuit capable of transmitting 60 W at 2.25 MHz is designed and fabricated. The circuit maintains a high PTE of 86% over a transmission distance variation of 20 cm. Furthermore, transmit power and PTE are maintained over a large lateral misalignment up to ±50% of the coil diameter, and angular misalignment up to ±75°. The new design approach enhances the performance of WPT systems by significantly extending the range of coupling factors over which both load power and high PTE are maintained. Please see the uploaded information for details.

Training Opportunities: Two PhD students were partially funded by this award.

Results Dissemination: Through Publication in Journals and Conferences.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nonlinear Resonance Circuit for Wireless Power Transmissions and Wireless Power Harvesting, Amir Mortazawi, Xiaoyu Wang, US20160336810A1

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Xiaoyu Wang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Omar Abdelatty
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Amir Mortazawi
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

The First Realization of a Nonlinear Electrical Resonance Circuit based on Duffing Nonlinear Differential Equation

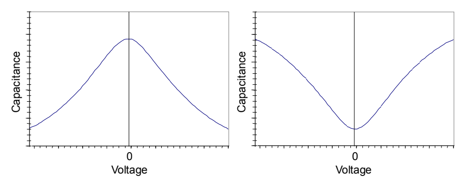
The working principle of the position-insensitive WPT circuit is based on the operation of a specific class of nonlinear resonators. The proposed nonlinear resonator circuits are described by a differential equation known as the Duffing equation. The Duffing equation, created by Georg Duffing in 1918, has been used to characterize mechanical resonance/oscillations with a nonlinear restoring force. The basic form of the Duffing equation is usually written as (1):

$$\ddot{x} + 2\gamma\dot{x} + \omega_0^2 x + \epsilon x^3 = Fcos(\omega t) \qquad (1)$$

where x is displacement, γ is the damping coefficient, ω_o is the resonance/oscillation frequency, ϵ is the third order nonlinearity coefficient, and $\mathrm{Fcos}(\omega t)$ is the excitation with the amplitude F and angular frequency ω. The steady state solution of (1) can be approximated as $\mathrm{x}(\omega, \mathrm{t}) = \mathrm{A}\cos(\omega \mathrm{t} - \theta)$, where "$A$" represents the amplitude, and θ represents the phase difference relative to the excitation signal.

The nonlinear resonators described by the Duffing equation demonstrate several important and unique properties. The properties of Duffing equation have been investigated in a number of fields including mathematics, physics, and mechanical engineering. For example, the hysteresis of a Duffing-type mechanical resonator was studied to address the amplitude-bandwidth limitations in mechanical systems. *The first electrical representation of the Duffing-type nonlinear electrical resonator has been developed by the PI's group to enhance the bandwidth of High-Q resonance circuits.*

The basic series nonlinear electrical resonator is comprised of an inductor, a resistor, and a nonlinear capacitor C. The nonlinear capacitor has a symmetric C-V relationship, i.e. $C(v_C) = C(-v_C)$, which can be either bell-shaped (Fig. 1 (a)) or well-shaped (Fig. 1 (b)). The time domain dynamic equation describing the behavior of the nonlinear series RLC resonant circuit can be obtained by applying the Kirchhoff voltage law (KVL) and with the use of $i = dq\ /\ dt$:



(a) (b)

Fig. 1. (a) Symmetrical bell-shaped C-V curve, and (b) symmetrical well-shaped C-V

$$v_C(t) + R\frac{dq_C}{dt} + L\frac{d^2q_C}{dt^2} = v_s(t) \qquad (2)$$

where $v_s(t) = V_S cos(\omega_S t)$ is the excitation voltage, $v_c(t)$ is the voltage across the nonlinear capacitor, and $q_c(t)$ is the amount of charge stored in the nonlinear capacitor. In order to express the voltage across the nonlinear capacitor in terms of charge q_c, the law of conservation of charge is applied. Consequently, v_c can be expressed in terms of q_c using inverse Taylor expansion as:

$$v_c = \frac{1}{a_1}q_c + \frac{1}{a_3}q_c^3 \qquad (3)$$

where $a_1 = c_o$ is the inverse of the linear coefficient and has a unit of C/V, and $a_3 = -c_o^4 c_2^{-1}$ is the inverse of the nonlinear coefficient with a unit of C^3/V. In general, a_1 and a_3 can be calculated from the capacitance-voltage relationship for any nonlinear capacitor. Higher order terms are neglected for simplicity. Substituting (3) into (2) results in:

$$\ddot{q}_c + \frac{R}{L}\dot{q}_c + \frac{1}{La_1}q_c + \frac{1}{La_3}q_c^3 = \frac{V_s}{L}cos(\omega t) \qquad (4)$$

Equation (4) has the same form as the Duffing equation described in (1). The equation can be solved using the method of multiple scales, and the steady-state frequency response can be written as a sinusoidal function as $q_c(t) = Q_c\ cos(\omega t - \theta)$ where Q_c represents the amplitude of the stored charge in the nonlinear capacitor, and θ represents the phase difference relative to the excitation signal. both the linear term, $(1/La_1)Q_c$, and the nonlinear term, $(1/La_3)\mathrm{Q_c}$ contribute to the restoring force. The resonance frequency of the resonator, ω_o, in the presence of nonlinear restoring term can be written as:

$$\omega_o = \sqrt{\frac{1}{L}\left(\frac{1}{a_1} + \frac{\frac{3}{4}Q_C^2}{a_3}\right)} \tag{5}$$

Equation (6) implies that the resonance frequency ω_o depends on the capacitor charge (Q_c), which is function of the voltage (v_c). The circuit's amplitude-frequency relationship of (5) can be expressed in the frequency domain as:

$$(j\omega)^2\mathcal{Q}_C + \frac{R}{L}(j\omega)\mathcal{Q}_C + \left(\frac{1}{La_1} + \frac{\frac{3}{4}Q_C^2}{\mathrm{La}_3}\right)\mathcal{Q}_C = \frac{V_s}{L} \tag{6}$$

where $\mathcal{Q}_C = Q_c e^{-j\theta}$ is the phasor form of $q_c(t)$. Substituting $\mathcal{Q}_C$ into (7) yields:

$$Q_C^2\left(\frac{1}{La_1} + \frac{\frac{3}{4}Q_C^2}{La_3} - \omega^2\right)^2 + \left(\frac{R}{L}Q_C^2\omega\right)^2 = \left(\frac{V_s}{L}\right)^2 \tag{7}$$

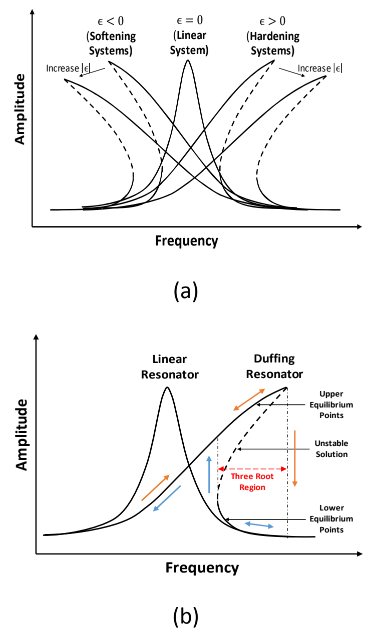


Fig. 2. The amplitude-frequency response of: (a) a single resonator with different nonlinearity coefficient (ϵ),

Based on (7), if the amplitude (V_s) and the frequency (ω), of the excitation are given, the amplitude of (Q_c) can be determined using (8). Subsequently, the capacitor voltage (v_c) can be calculated using (4). Fig. 5(a) shows the typical amplitude response of nonlinear resonators. In Fig. 2(a), the peak of the nonlinear resonator's frequency response is tilted towards one side, which results in an increased bandwidth as compared to a linear resonator having a similar quality factor. The tilt direction of the amplitude-frequency response is dependent on ϵ. Positive ϵ causes the curve to tilt to the right (hardening systems), and a negative ϵ causes the curve to tilt to the left (softening systems). A nonlinear capacitor with a bell-shaped C-V curve shown in Fig. 4(a) has a positive nonlinear term a_3. Resonators using such a nonlinear capacitor will have a frequency response tilted to the right as shown in Fig. 5(b). The tilting characteristic results in a three-root region. It can be proven that the medium solution points (represented by the dashed line) in this region are unstable, while the upper and lower points are stable and called equilibrium points [36]. As a result, the steady state solution of such a system converges to one of the two equilibrium solutions depending on the initial conditions. ***It should be that in forced excitation of such circuit, if the circuit is excited at the high-amplitude equilibrium point, resonance amplitude will remain on the upper curve***. In order to achieve the maximum PTE of a coupled nonlinear resonant-based WPT system, the operating frequency is designed at the frequency of the highest resonance amplitude.

Based on (7), the resonance frequency of a nonlinear resonator is a function of the voltage amplitude across the nonlinear capacitor. Since the voltage amplitudes across the nonlinear capacitors in coupled nonlinear resonant circuits depend on the coupling factor, the resonance frequencies of the nonlinear resonators will be adjusted automatically based on the coupling factor. This self-adjustment characteristic is utilized to design position-insensitive WPT systems.

The coupled nonlinear resonators investigated here allow for the position-insensitive WPT systems that provide self-tracking of the maximum PTE. ***This technique is the only solution for designing position-insensitive WPT systems in which the operating frequency remains fixed.*** Preliminary CAD circuit simulations and experiments based on the proposed coupled nonlinear resonant circuits employing a single nonlinear device at the receiver have already been performed, indicating that a significant performance improvement can be achieved by employing the proposed circuits.

Investigation of the coupled Duffing Nonlinear Resonators' Dynamics

The analysis performed for a single resonator in section (3) can be extended to the inductively or capacitively coupled nonlinear resonant circuits using two nonlinear devices. The analysis of the coupled nonlinear resonant circuits is subject of our study within this proposal. As an example, for the series-series inductively-coupled WPT circuit shown in Fig. 3, the KVL equations of both loops can be expressed as follows:

$$i_1(t)R_p + v_{c1}(t) + L_p\frac{di_1(t)}{dt} + M_{21}\frac{di_2(t)}{dt} = V_s\cos(\omega t) \tag{8}$$

$$i_2(t)R_s + v_{c2}(t) + L_s\frac{di_2(t)}{dt} + M_{12}\frac{di_1(t)}{dt} = 0 \tag{9}$$

where the mutual coupling between the coils is $M_{12} = M_{21} = M$, which is related to both the self-inductance as well as the coupling factor k; $M = k\sqrt{L_s L_p}$.

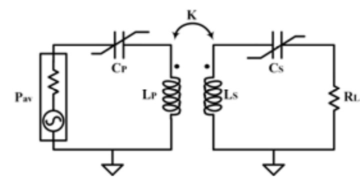


Fig. 3 Circuit schematic of coupled nonlinear series resonant circuits.

The governing coupled Duffing nonlinear differential equations describing the circuit operation can be obtained as follows:

$$\ddot{q}_1 + k_{12}\ddot{q}_2 + 2\gamma_1\dot{q}_1 + \omega_{o,1}^2 q_1 + \epsilon_1 q_1^3 = F\cos(\Omega t) \tag{10}$$

$$\ddot{q}_2 + k_{21}\ddot{q}_1 + 2\gamma_2\dot{q}_2 + \omega_{o,2}^2 q_2 + \epsilon_2 q_2^3 = 0 \tag{11}$$

The coupling term of the coupled electrical nonlinear resonators appears as the coefficient of the second derivative terms. The formulation of coupled nonlinear differential equations depends on the circuit topology (SS, SP, PS, or PP, where “S” denotes series resonance and “P” denotes parallel resonance and the first letter is associated with the transmitter while the second letter is associated with the receiver) and the placement of the nonlinear devices (a single nonlinear device at the transmitter or receiver, or two nonlinear devices at both the transmitter and receiver). Therefore, there are twelve circuit configurations which will be considered when analyzing the coupled nonlinear resonant circuits. Within this research project, a mathematical solution for the above system of equations will be obtained in order to study the dynamics of WPT systems utilizing such nonlinear resonators. Studying the dynamics of the system will provide a complete understanding of the expected response for such systems and their optimization for WPT applications.

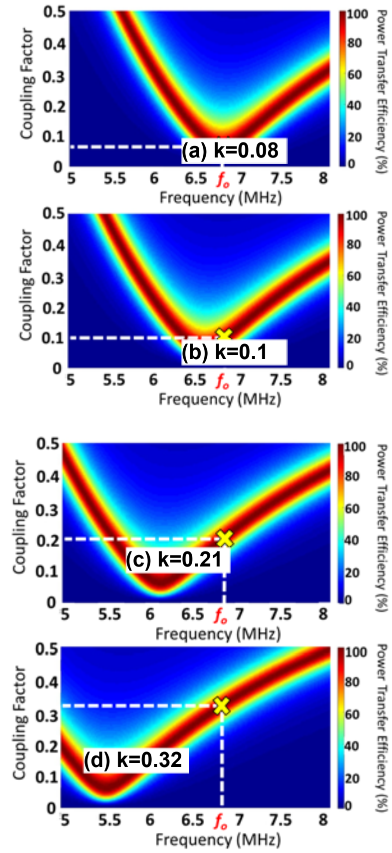


Fig. 5. Multiple plots of the PTE vs. frequency and coupling factor (k), associated with the adjusted resonance frequencies at different coupling factors.

Principle of Operation for the Proposed Position-Insensitive WPT Circuits

In order to visualize the operation of the nonlinear resonant-based WPT circuit behavior, the plot of the PTE versus the frequency and the coupling factor (k), is plotted in 2D in Fig. 4 (represented by the V-shaped curve). This figure shows the behavior of a conventional WPT circuit designed to operate at a critical coupling factor (k_c) of 0.08 and $f_o = 6.78$ MHz. The principle of operation of conventional frequency tracking approaches that rely on adjusting the operating frequency is also shown in Fig. 4. The frequency is adjusted to track the optimum frequency (either odd or even mode) within the over-coupled region to maintain the high power transfer efficiency as the coupling factor varies.

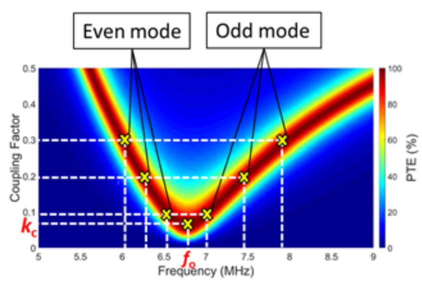


Fig. 4. PTE vs. frequency and coupling factor (k), showing the optimum operating frequency at different coupling factors.

The nonlinear resonant WPT circuits studied under this project allow the circuit to maintain the maximum power level and transfer efficiency at a fixed operating frequency as the coupling factor varies. The principle of operation for the position-insensitive WPT circuit is shown in Fig. 5. Multiple snapshots for shifted versions of the original V-shaped curve (shown in Fig. 4) at different coupling factors are plotted to demonstrate the operation of the nonlinear WPT circuits. The nonlinear WPT circuit’s operation relies on sliding the position of the original V-shaped curve to lower or higher frequencies at each coupling factor such that a solution for maximum PTE exists at the same operating frequency. This mechanism is accomplished by utilizing nonlinear resonant circuits which are capable of adjusting their resonance frequencies automatically. Bell-shaped nonlinearity is utilized in this example, resulting in shifting the V-shaped curves to lower frequencies. Therefore, the WPT circuit effectively “tracks” the odd mode frequency of the original WPT circuit. The approach presented here is general and can also track the even or odd mode frequency branch based on the type of the nonlinearity.

Experimental Verification:

As a proof of concept, a prototype of a series-parallel inductive nonlinear WPT circuit employing a nonlinear resonator at the receiver side has been implemented. The experimental setup along with the prototype is shown in Fig. 6. A signal generator is used to feed a power amplifier (PA). The available power from the power amplifier is 60 W (the maximum power level that PA can provide under perfect matched condition). The receiving coil is connected in parallel with the nonlinear capacitor and the load. In this experiment, a pair of anti-series connected SiC Schottky diodes are utilized to obtain the required nonlinearity. A light bulb with an equivalent load resistance of 2.5 kΩ is utilized as a load. Both the transmit and receive coils have 5 turns with outer diameters of 40 cm. Table I summarizes the component specifications for the nonlinear WPT circuit.

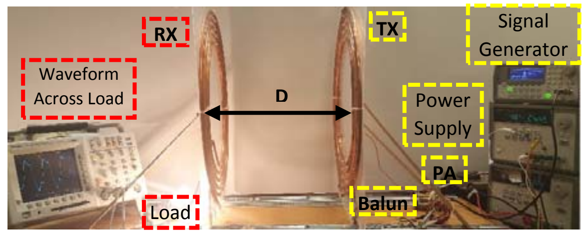


Fig. 6. Experimental setup for the WPT circuit prototype.

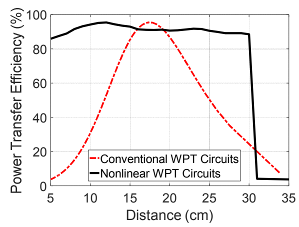


Fig. 7. Measured PTE vs. vertical distance variation.

The output power delivered to the load is measured as a function of transmission distance (D). The measured peak output power is 56 Watts with a PTE of 93.3%. The measured PTE versus distance D for the prototype circuit is shown in Fig. 7 in comparison with to the PTE of a conventional linear WPT. The linear WPT circuit, provides the maximum PTE at a transmission distance of 17.5 cm. As expected, the PTE for the linear WPT drops significantly as distance D is shifted away from its optimum point. The nonlinear WPT circuit not only achieves the same peak PTE of 94%, but also it maintains a high PTE over a distance variation of ΔD=±12.5 cm, indicating that the proposed nonlinear WPT circuits significantly extend the effective charging zones of wireless power transfer systems.