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Design and Analysis of Improved Efficiency of Wireless Power Transfer System with Non-Linear Resonator

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Abstract: *In recent years, wireless power transfer technology (WPT) has advanced at a breakneck pace. The main advantage of WPT is that it eliminates the need for traditional wire charging in favour of a cordless charging technique. WPT technology has been used in a variety of applications, including bio-implants, electric vehicles, and wireless charging. WPT technology is classified as magnetic field coupling (including magnetically coupled inductive and magnetically coupled resonant), microwave radiation, laser emission, electrical-field coupling, and ultrasonic transmission type based on the distinct energy transmission mechanisms. Because of its long transfer distance and great efficiency, the magnetic resonance coupling approach has the most promise among these technologies. However, there are still unanswered problems, the most important of which is that the technology has a limited tolerance for changes in the coupling factor due to the frequency splitting phenomena, which would result in transmission efficiency reduction in magnetic resonance coupling WPT systems. As a result, this paper analyses the frequency-splitting phenomenon of the wireless power transfer system, discusses the duffing resonator circuit and its properties, and designs a type of high-efficiency wireless power transfer inductive system with both non-linear inductors and non-linear capacitors, based on a review of the research status and trend of WPT technology.*

Keywords: *Wireless power transfer; Inductive power transfer; Efficiency, Resonator, Radiation loss*

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1. Introduction

The wireless power transmission technology (WPT) is a new power transmission technology, which achieved power transmission without electrical contact from the power supply to the load by electromagnetic effect or energy exchange function.

Comparing with the traditional wire transmission technology, it has advantages of safe and reliable and so on, especially in some applications. Therefore, it has been paid more and more attention [1-7]. In recent years, the growth momentum of WPT technology has become more powerful, which has gone from theoretical to commercialization, especially in bio-Implants, electric vehicles, and wirelessly charging systems etc. The two application examples of WPT technology are introduced as follows:

Wireless charging is also widely used in electric vehicle charging [6]. The basic concept of the wireless power transfer system of EV structure is shown in figure 1. The RX coil is implanted at the bottom of the electric vehicle. Through the redesigned RX coil structure, which is a circular and bar-shaped core, the total size of this coil is reduced by 30%, and the core loss reduces by 17.5% comparing to the traditional wireless charging. This cordless charging technology could make charging convenient, and the EV can be charged anytime and anywhere, like the technology in [7]. When people drive the electric vehicle and cross to the “charging” rod, which sets up a series TX coil in the ground, the battery can be charged during the driving. This novel charging method saves much time compared to the traditional charging method.

In the field of bio-implants, previously, most biomedical charging devices need cable, which means the conventional devices cannot be designed as compacted and wholly implanted into the human body because of this limitation of charging. However, as the wireless power transfer technology development, this new method gives an opportunity for implanted biomedical devices. It can make the implanted biomedical devices entirely embedded into the human body and recharge the devices without cord [8-10]. Due to this technology, the implanted devices can be designed to be very small and embedded into the human body for a whole life without taking out for charging.

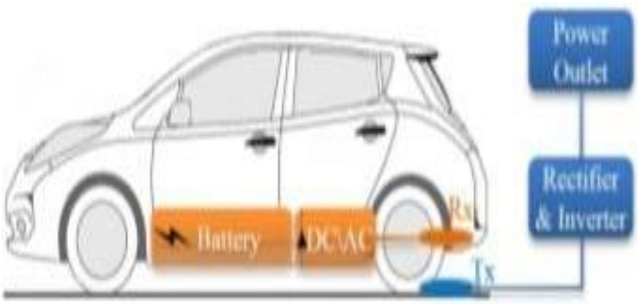


Figure 1 EV basic wireless charging concept [6]

2. WPT Technology

The study of wireless power transfer (WPT) technology began in the 1880s, American scientist Nikola Tesla conducted the first WPT experiment. Thereafter, researches on wireless power transfer began [12]. In the early 1960s, W. C. Brown had done a lot of researches on WPT, which laid the foundation of its experiment and made this concept a reality [13]. In 1968, American aviation engineer P. E. Glaser [14] proposed using the microwave to transmit power from the solar satellites to the ground, namely the establishment of space solar power stations (SPS) in geosynchronous orbit. In the following 1977-1980, the U.S Department of Energy and National Aeronautics and Space Administration (NASA) jointly organized a study to demonstrate the concept of the SPS plan and confirmed its feasibility. In response to the global energy crisis, the central developed countries, such as America and Japan, have carried out the study of space solar power, which significantly promoted the development of WPT technology [15, 16]. In the 1990s, J. T. Boys and others at the University of Auckland in New Zealand conducted thorough research on the WPT technology and firstly proposed the Inductively Coupled Power Transfer (ICPT) technology [16]. Since the beginning of the 21st century, WPT technology research has made breakthrough progress. In 2007, Marin Soljacic used the magnetic coupling resonant principle to realize the transmission of medium-range radio energy and light a 60 W bulb in more than 2 m distance with a transmission efficiency of about 40% [6]. In recent years, researchers from all over the world have made an in-depth study on WPT and have made significant progress in theory and practice.

Comparison of the advantages and disadvantages of several typical WPT technology

According to the different transmission mechanisms, WPT technology can be divided into magnetic field coupling, microwave radiation, laser emission, electrical-field coupling and ultrasonic transmission type, etc. According to the distance from the source, it can be divided into the near-field coupling and far-field. The magnetic field coupling includes magnetically-coupled inductive and magnetically-coupled resonant, which with the electric field coupling belong to the near-field coupling type. The microwave radiant and laser emission belong to far-field type. Due to these two groups are categorized by the distance or air gap of the transmitter and receiver coils. So, if the wavelength of the wave signal is smaller than the transfer distance, it can be considering as far filed technology. However, if the signal wavelength is larger than transmission distance, it is near field technology. Far field transmission or radiative transmission can always transfer the energy over a long distance with electromagnetic wave. While the system efficiency is lower than near field method because of the radiative power emission’s omnidirectional nature. But the transfer frequency band is quite wide, from GHz to THz. The near field techniques can deliver high power with high efficiency. Nevertheless, it is sensitive to the distance various and only can achieve the high power transfer in short distance.

Magnetically coupled inductive WPT (MCI-WPT) technology is the oldest power transfer technology, which is still widely used now. During the inductive coupling transmission, the power passes through two coupled coils by the magnetic field. This mode of power transmission is similar to the transformer as shown in figure1.3 and figure1.4. Moreover, the inductive coupling technique is the only method applied to commercial products [18]. The transmission power depends on the mutual inductance M, $M = k/\sqrt{L1L2}$, where K is the coupling factor. L1 and L2 represent the two power transfer coils value, separately. The energy crosses the first coil and couples to the second coils. However, the distance between these two coils is not always fixed. In addition, the power transfer efficiency and power delivered to the load are influenced by the distance and misalignment of the two coils, L1 and L2. So, how to decide the distance and misalignment for the two coils is crucial when designing the traditional wireless power transfer system.

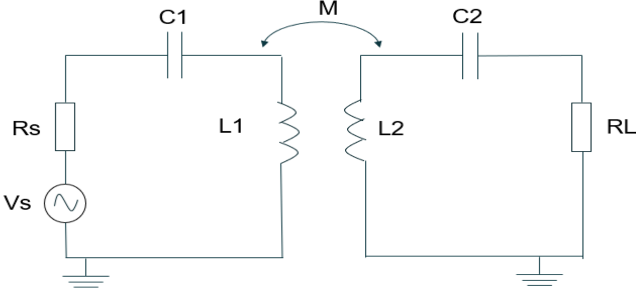


Figure 2 Topology of WPT system

Table 1 Comparison of different WPT technologies

Technology	Transmission Range	Frequency	Benefit/ Drawback
Magneticall y- coupled inductive WPT	A few millimeters to tens of millimeters	Hz to MHz	High efficiency but short range
Magneticall y- coupled resonant WPT	Several centimeters to hundreds of cm	KHz to MHz	High efficiency but frequency splitting
Microwave radiation WPT	Hundreds of meters to thousands of meters	MHz to GHz	Long distance transmission but safety and health issue
laser emission WPT	Tens of meters to thousands of meters	THz	Compact size, high energy concentration but safety and health issues

3. Duffing Resonator Based Wireless Power Transfer System Theory

Although magnetically coupled resonant WPT (MCR-WPT) technology has become the mainstream method for wireless power transfer due to its high efficiency, MCR - based systems are prone to efficiency degradation as the operating condition changes. Additionally, one of the most significant challenges in the design of SCMR WPT systems is its low tolerance to the coupling factor variations because of the frequency split phenomenon. To fundamentally solve the above problems, we investigate a nonlinear resonance circuit described by the duffing equation replacing linear capacitor into the nonlinear capacitor, as well as the properties of the duffing resonator circuit by MATLAB software. The representative amplitude response of a Duffing resonator is shown in figure 3. It can be observed that the frequency response curve of the linear resonator and duffing resonator amplitude are drawn into the same axis, and the duffing resonator response always tilted to one side (right side in this figure). Unlike the frequency response curve of the linear resonator which only has one maximum stable amplitude point, the frequency response curve of the duffing resonator has three distinct root regions (upper equilibrium brunch/point, unstable solution, and lower equilibrium brunch/point). Among these three root regions, the middle solution point is unstable, while the upper and lower points are stable (called equilibrium points). It can also be observed from figure 3 that a steady-state solution of the system converges to the upper equilibrium point or lower equilibrium point.

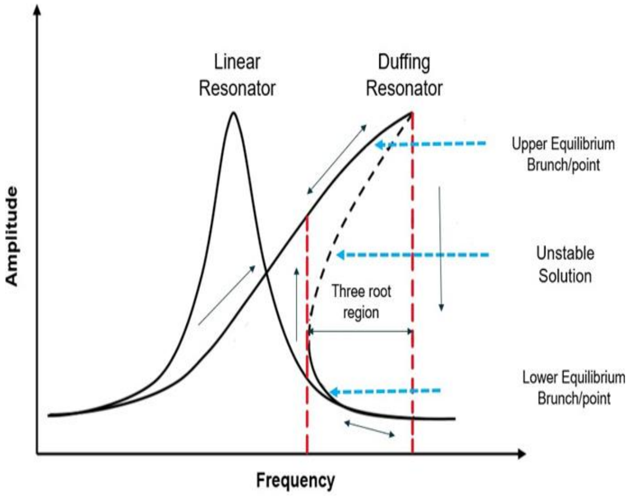


Figure 3 The amplitude-frequency responses of duffing resonator and linear resonator

In addition, it can also be observed that the region between the two red dash lines is an unstable solution, which is very important when the response of the duffing resonator is analyzed. If the circuit is excited to converge to the high-amplitude solution point, the amplitude will follow the upper curve when frequency changes. Once the right boundary of the three-root region is crossed, the amplitude drops, which is known as a drop-down phenomenon. However, if the circuit is excited to converge to the low-amplitude solution point, the amplitude will remain the small unless the three-root region’s left boundary (the jump up to point) is crossed. So, when nonlinear duffing resonator has the same Q with linear resonator, the nonlinear duffing resonator has more bandwidth.

The direction of the response curve of the duffing resonator is dependent on ϵ. When ϵ is larger than zero, the amplitude-frequency response curve tends to move to the right which is hardening system, shown as figure 4. When ϵ equals to zero, the system is linear. However, when ϵ is a negative number, the curve is tended to move to the left.

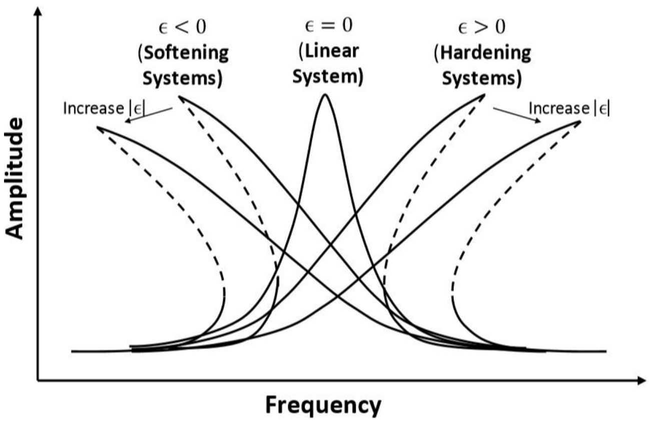


Figure 4 The amplitude-frequency responses of duffing resonator with different nonlinearity coefficient ϵ.

Analysis on Nonlinear duffing resonator

After analyzing the characteristic of the duffing equation, we implant this method into a magnetic coupled WPT circuit, as shown in figure 5. In figure 5, C2 is a nonlinear capacitor. Differently with the traditional WPT circuit, in the nonlinear system, the original linear capacitor of the second circuit has been replaced by nonlinear capacitor C2. The linear capacitor and a sinusoidal excitation voltage $Vs(t) = vs(\omega t)$ still be used in the primary circuit. According to Thevenin's theorem, the coupled wireless power transfer circuits can be synthesized into one RLC circuit, and the equivalent circuit is shown as figure 6. The circuit consists of a voltage source, an inductor, load, and a nonlinear capacitor C.

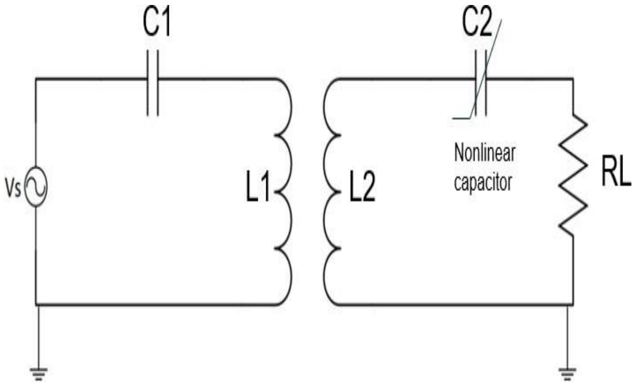


Figure 5 Topology of nonlinear WPT system

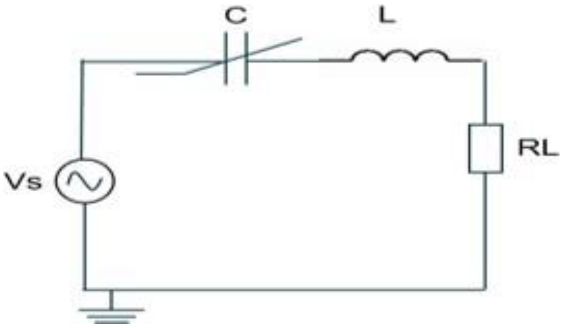


Figure 6 Equivalent nonlinear WPT system circuit

4. Simulation and Results

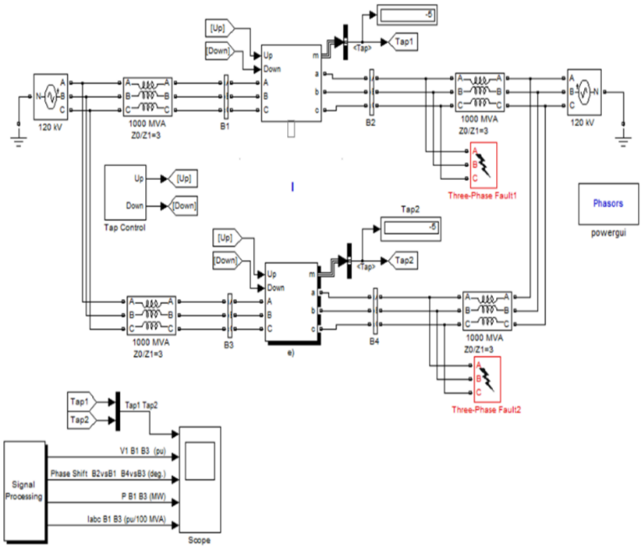
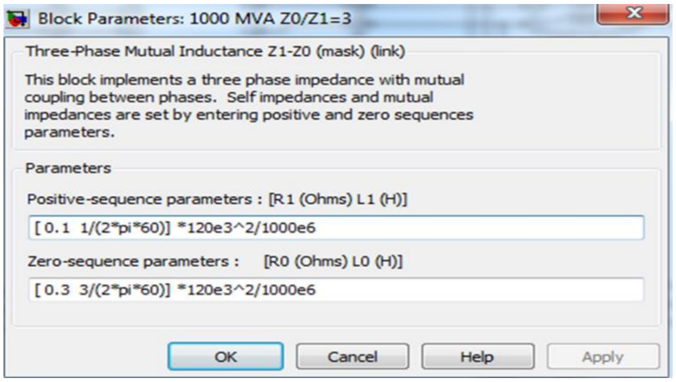


Figure 7 Wireless Power Transmission MATLAB simulation


Block Parameters: 1000 MVA Z0/Z1=3

Three-Phase Mutual Inductance Z1-Z0 (mask) (link)

This block implements a three phase impedance with mutual coupling between phases. Self impedances and mutual impedances are set by entering positive and zero sequences parameters.

Parameters

Positive-sequence parameters : [R1 (Ohms) L1 (H)]

[0.1 1/(2*pi*60)] *120e3^2/1000e6

Zero-sequence parameters : [R0 (Ohms) L0 (H)]

[0.3 3/(2*pi*60)] *120e3^2/1000e6

Figure 8 Block Parameters Mutual Inductance

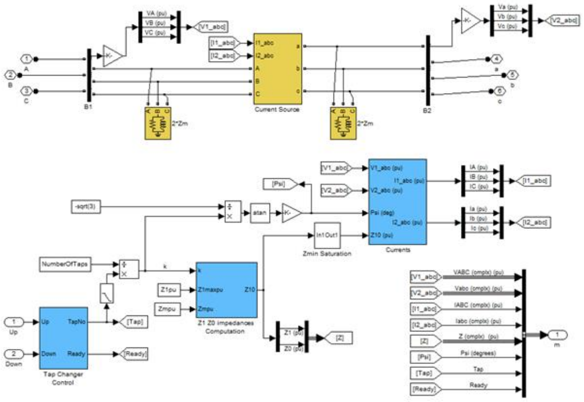


Figure 9 wireless power transmission system

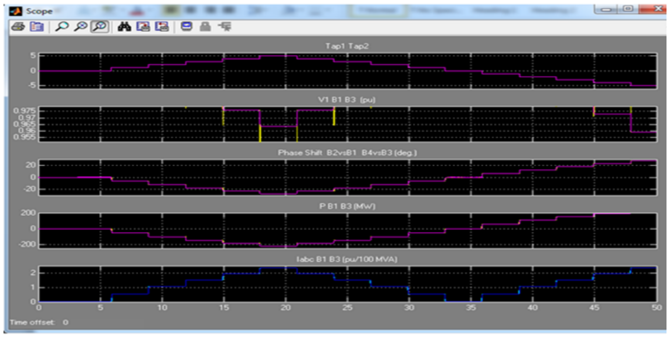


Figure 10

Figure 10 The resonant frequency of the designed spiral geometry A good way to find the resonant frequency is to study the impedance of the spiral resonator. Since the spiral is a magnetic resonator, a lorentz shaped reactance is expected and observed in the calculated impedance result.Cascade-3/3 Inverter Control

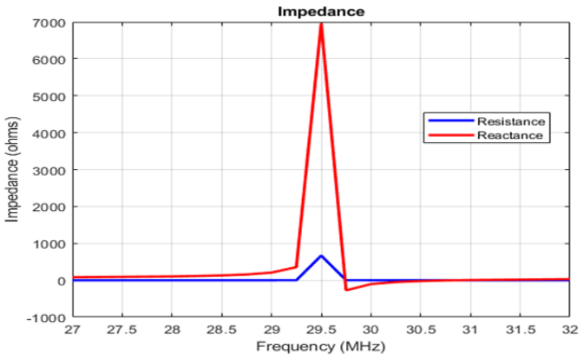


Figure 11

Figure 11 the spiral is a magnetic resonator, the dominant field component of this resonance is the magnetic field. A strongly localized magnetic field is observed when the near field is plotted.

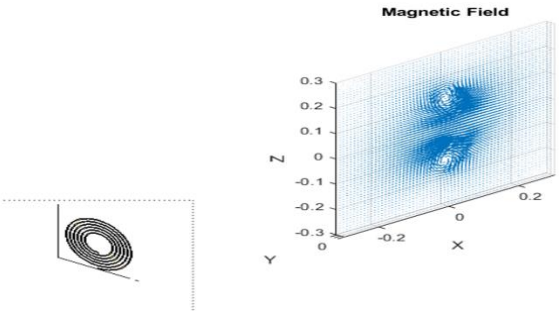


Figure 12

Figure 12 Power Transfer System The complete wireless power transfer system is composed of two parts: the transmitter(Tx) and receiver(Rx). Choose identical resonators for both transmitter and receiver to maximize the transfer efficiency. Here, the wireless power transfer system is modeled as a linear array.

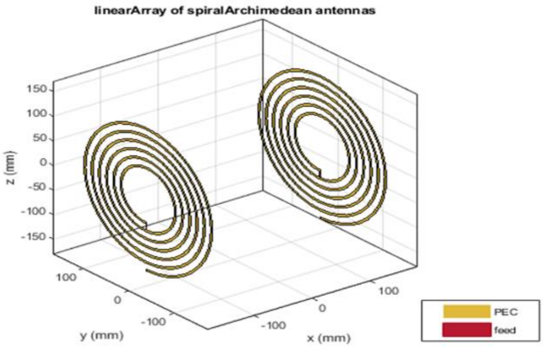


Figure 13

Figure 13 Variation of System Efficiency with Transfer Distance One way to evaluate the efficiency of the system is by studying the parameter. As presented in the system efficiency changes rapidly with operating frequency and the coupling strength between the transmitter and receiver resonator. Peak efficiency occurs when the system is operating at its resonant frequency, and the two resonators are strongly coupled.

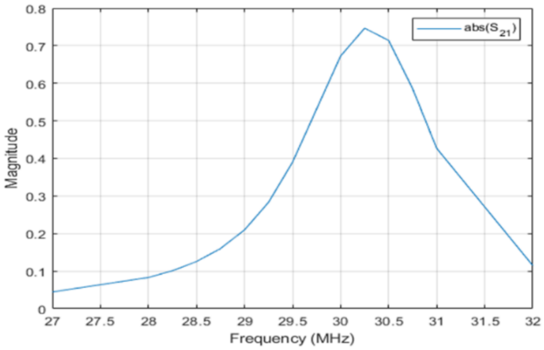


Figure 14

Figure 14 Critical Coupled Point The coupling between two spirals increases with decreasing distance between two resonators. This trend is approximately proportional to 1/d. Therefore, the system efficiency increases with shorter transfer distance until it reaches the critical coupled regime When the two spirals are over coupled, exceeding the critical coupled threshold, system efficiency remains at its peak, as shown in We observe this critical coupling point and over coupling effect during modeling of the system. Perform a parametric study of the system s-parameters as a function of the transfer distance. The transfer distance is varied by changing the Element Spacing. It is varied from half of the spiral dimension to one and half times of the spiral dimension, which is twice of the spiral's outer radius. The frequency range is expanded and set from 25 MHz to 36 MHz.

5. Simulation and Results

This work analyses the frequency splitting phenomena for wireless power transfer systems, explains the duffing resonator circuit and its features, and designs a high-efficiency wireless power transfer inductive system using both non-linear inductors and non-linear capacitors. A duffing resonator circuit with a nonlinear capacitor has been devised to avoid frequency splitting while maintaining good transmission efficiency and power provided to the load. The features of the duffing resonance circuit are described using MATLAB software. The results show that a duffing resonator can not only improve the WPT system's tolerance to coupling factor fluctuations without sacrificing efficiency, but it can also have a broader bandwidth than a normal linear resonator. As a result, it's a promising solution for WPT systems that need to be insensitive to coupling factor fluctuations. Finally, we develop a more efficient nonlinear resonator using nonlinear ferromagnetic thin film core inductors and nonlinear ferroelectric thin film dielectric capacitors, and extract the nonlinear differential equations regulating the nonlinear resonator's nonlinear dynamical behaviour. The numerical findings suggest that the new system has good hardening characteristics. In the future, we will test the performance and attributes of this circuit in experiments and real-world applications to see how well it responds to efficiency and distance. We will try to employ other material manufactured nonlinear inductors and nonlinear capacitors in the next step's experiment, in addition to testing the required phenomenon.

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