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Optimized Design of Flexible Wireless Charging Coils Using Magnetic Coupling Resonance

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Abstract. At present, many devices still use wired charging. There are many lines, and the interface is easy to break. It is not easy to use if the environment is poor. Ordinary wireless charging uses a rigid coil, which is limited in space. It is easy to be damaged when stretched, and the charging efficiency drops severely. In order to optimize the rigid coil of magnetic coupling resonance wireless charging in wireless charging, this paper first explains the working principle of the system, and then summarizes the existing research on snake wire, island bridge structure, flexible substrate, and ferrite. The main purpose is to optimize the island bridge structure so that the flexible coil is not easily deformed when stressed and select more suitable materials. Therefore, this paper innovatively puts forward the structural scheme of a flexible and stretchable magnetic Snake Island Bridge coil, and after summarizing the existing research, it is concluded that this kind of coil has less structural change under high stress environment, and can also meet the needs of people's daily light travel.

Keywords: Flexible coils, serpentine wires, island-bridge structure

1. Introduction

In recent years, technology has developed rapidly. Electric vehicles have been charged while running on the road, but the traditional wired charging method still has many problems. It is easy to fail when the environment is bad. It is difficult to meet people's flexible, convenient and unmanned power supply needs [1]. Wireless power transmission technology can solve these problems without contact, with good adaptability and is easy to realize intelligent control.

The wireless charging efficiency of magnetic resonance coupling is relatively high, and it can also realize relatively far transmission. Most of the traditional coils use Leeds wire. This kind of wire is twisted together with many wires, which is very hard and difficult to stretch and bend. Once the shape changes, the efficiency will be greatly reduced. Moreover, when charging, the transmitting and receiving coils are difficult to align, the coupling coefficient becomes smaller, and the efficiency will also decline.

Nowadays, the flexible coil can be stretched in a small range, but if it is sewn in the fabric such as clothes and backpacks, it will be stretched hard to predict. In addition, the current power bank is generally biased, and there is not necessarily a charging port outside, which is very inconvenient.

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Considering the characteristics of serpentine conductor, permanent magnet material, Island Bridge Structure and flexible material, this paper proposes an extendable Island Bridge magnetic suction planar spiral coil which can be embedded in flexible material. This kind of coil can make the mobile phone adsorb and charge in the pocket and backpack, without worrying about the charging failure caused by the stretching deformation of the coil.

2. System operating principle

2.1. Basic principles of magnetic coupling resonance wireless charging

WPT is a key technology for short-range wireless power transmission. This technology uses an inverter circuit at the transmitter end to convert direct current (DC) into alternating current (AC), which is then transmitted to the transmitter coil. This generates a non-radiative magnetic field at the transmitter coil. Simultaneously, electrical energy is transmitted via inductive coupling between the transmitter and receiver. By connecting a capacitor in parallel with the inductors at both the transmitter and receiver ends, LC resonance is achieved at both ends, resulting in strong mutual coupling. Finally, the load is charged via a filter circuit and a rectifier circuit [2]. The resonance condition formula is given in Equation (1).

$$\omega_0 = \frac{1}{\sqrt{L_s C_s}} = \frac{1}{\sqrt{L_l C_l}} \tag{1}$$

A simplified flowchart of this principle is shown in Figure 1.

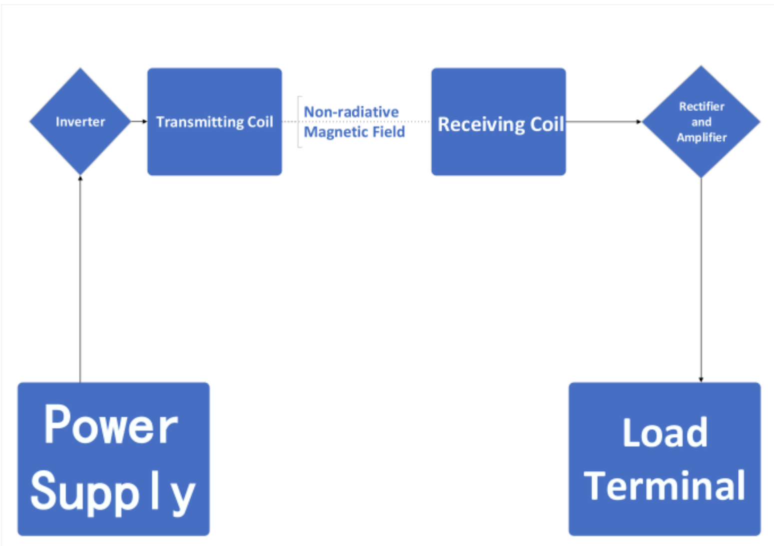

Figure 1. Schematic diagram of the WPT operating principle (picture credit : original)

2.2. Quality factor Q and transmission efficiency η

The quality factor (Q) represents the "excellence" of a coil; it is a key parameter used to measure the magnitude of losses and the strength of resonance in a resonant circuit. The Q-factor is the ratio of the energy stored in the resonant circuit to the energy lost per cycle. As the Q-factor increases, the energy stored in the resonant circuit increases, while resonance losses decrease. The formula for calculating the quality factor (Q) is as follows:

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$$Q_s = \frac{\omega_0 L_s}{R_s},\ Q_L = \frac{\omega_0 L_L}{R_L} \tag{2}$$

Q_s and Q_L represent the quality factors of the transmitter and receiver circuits, respectively. The transmission efficiency (η) depends on the quality factors ($Q_s$and Q_L) of the resonant circuits at the transmitter and receiver ends, as well as the mutual inductance (k) between the two coils. The core formula for efficiency is as follows:

$$\eta \propto k^2 Q_s Q_l \tag{3}$$

3. Design of a flexible, stretchable, magnetic, serpentine bridge coil

3.1. Serpentine conductor

Flexible electrons perform well in micro nano structures, have strong ability to adapt to various shapes, and can also monitor human body movements such as running and turning. In flexible electronic design, the serpentine conductor can significantly reduce the deformation of the conductor, and the resistance increases less than that of a straight line when stretched. Because the serpentine structure is stable, it is suitable to use the serpentine conductor as the connecting bridge in the island bridge structure [3].

3.2. Serpentine island bridge

In the study of flexible electrons, in order to reduce the deformation of the conductor, the serpentine conductor will absorb most of the deformation. When the whole is stretched, the resistance of the serpentine conductor increases less than that of the straight conductor [4]. Because the snake shaped structure is very stable when stretched, the snake shaped conductor bridge in the island bridge structure becomes very useful. Huang Yin team proposed the design strategy of independent fractal snake shaped interconnection, which uses the blank space between islands to improve the expansion limit of the coil, so that the structure will not be unable to use after deformation. Fu Haoran proved in the mechanical analysis and research of the snake shaped conductor that when the snake shaped conductor is stretched, the snake shaped conductor basically absorbs all the deformation forces, so that the components in the island are basically free of strain, which also shows that the snake shaped island bridge structure has great advantages in the application of flexible electronics [5, 6].

Flexible coils are widely used now. Wearable devices such as smart watches and bracelets are basically inseparable from them. Mahmoud wagih team has specially studied the passive flexible receiving circuit used in wireless charging. In order to enable this circuit to handle higher power and higher transmission efficiency in the flexible fabric, they used a planar inductor with a hidden metal insulator metal (MIM) tuning capacitor, and also integrated the printed voltage multiplier rectifier based on silicon carbide (SIC) diode and the coil. Even if it is covered by the fabric, the charging effect is still very good [7].

The serpentine Island Bridge structure does have advantages. When stretched, the structure is stable and the conductivity is continuous. But once it is sewed into the flexible fabrics such as clothes and backpacks, it will encounter unexpected extrusion and bending, and the problem will come out. This kind of snake like structure that centralizes the whole spiral coil on an island, the conductor is easy to reach the stress limit, and the snake like bridge will be pulled too hard, and finally seriously deformed or even directly broken. Moreover, most researches on wireless charging of wearable devices now focus on the embedded passive flexible receiver, and few people optimize the active transmitter. This leads to the fact that the charging efficiency is often very low because the coil is far away and the position is inaccurate.

3.3. Comprehensive innovation scheme

Based on the previous research and problems, this paper proposes a flexible stretch magnetic Snake Island Bridge coil structure. In short, each turn of the serpentine coil is placed on small islands with tiny gaps, which are connected by small serpentine wires. Considering that the actual number of turns of the coil is relatively large, there is no one island per turn, but it is reasonably distributed according to the total number of turns, and the method of using multiple turns to share an island is adopted to make the structure more practical. Both ends of the coil are also connected to other circuits with serpentine wires, and a suitable gap is left between turns, which can also reduce the parasitic capacitance under high-frequency signals. When the cloth is stretched and bent to a large extent, the small islands and the serpentine wire connecting the circuit are stressed together to stabilize the distance and overall shape between the turns of the coil and prevent deformation and damage. In order to further improve the charging efficiency, this scheme also adds a layer of ferrite magnetic sheet between the coil and the flexible substrate, which can not only reduce the magnetic leakage, but also make the ferrite magnetic after power on, and can be close to the coil at the receiving end to automatically close the coil and improve the alignment, so as to improve the charging effect.

3.4. Material design

3.4.1. Coil material

At present, the most commonly used material for an inductance coil is copper, which has good ductility and stable conductivity. Gold is often used in medical implant coils because of its stable chemical properties and good biocompatibility. However, although the overall performance of copper is good, there is still room for improvement in tensile properties and electrical conductivity. Although Jin has excellent performance in all aspects, the cost is too high to be widely used in daily consumer products [8].

In 2023, research showed that the elasticity and conductivity of NiTi, a super elastic memory alloy, were much better than that of copper after it was made into a serpentine structure. Compared with the cost, the price of gold is much higher than that of nickel titanium. Although nickel titanium is more expensive than copper, if it is combined with copper to make Cu/TiNiCuCo/Cu composite material, it can not only reduce the cost, but also make the resistance more stable. Therefore, the prospect of using nickel titanium copper composite instead of pure copper as flexible coil is very good. This scheme also uses this material to wind the coil in the form of Archimedes' spiral [9].

3.4.2. Base material

Polydimethylsiloxane (PDMS) has good biocompatibility and soft texture, which is a common flexible substrate material. When studying its mechanical properties, Songjizhou's team found that the number of small holes on the porous PDMS will directly affect the length, thickness and elasticity of the material, so it is necessary to select PDMS with appropriate pore size in actual use [10]. If the difference between the hardness of the coil and the substrate is too large, the position where the coil and the substrate are bonded together will produce great stress during overall tension, and it is easy to pull the coil directly. Yangjianjun's team has made a comparative study on this. They

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have tested the pdms/sic functionally graded flexible substrate and the substrate using only ordinary PDMS. The results show that this kind of gradient substrate can withstand greater tensile force, the stress at the bonding interface is smaller, and the change of resistance is more stable during the tensile process.

Therefore, if pdms/sic functionally graded flexible substrate can be used as substrate, the risk of coil falling off during stretching can be significantly reduced, and the structural stability is better than that of pure PDMS. In this design, this scheme uses this kind of substrate to cut at the coil position where the number of turns is determined, and then connects multiple PDMS/SiC substrate islands carrying multiple turns of coils through serpentine copper wire [11].

3.4.3. Ferrite magnetic sheet material

In order to further improve the transmission efficiency of radio energy, we installed ferrite magnetic plates between the coil and the flexible substrate to reduce the leakage of electromagnetic radiation. Manganese zinc ferrite is selected as ferrite, which has better performance than nickel zinc ferrite under medium and low frequency conditions, lower cost, more mature production process and higher cost performance in medium and low frequency use scenarios. In the future, it can further improve efficiency and control costs by compounding with other materials.

In addition, MnZn ferrite can also realize magnetic absorption function. It belongs to spinel structure and has ferromagnetism: when there is no external magnetic field, the direction of the magnetic domain inside the material is disordered and does not show magnetism as a whole; Once the external magnetic field is added, the internal magnetic domains will be deflected and arranged along the direction of the magnetic field, and the whole will show magnetism [12]. In this way, the use of MnZn ferrite magnetic sheet can play the role of magnetic field gathering and electromagnetic absorption at the same time. In this scheme, in order to minimize the gap between the magnetic plate and the coil, we cut the ferrite magnetic plate to match the size of the multi turn coil Island, and then closely fit the cut magnetic plate, the corresponding coil and the flexible substrate layer by layer like a sandwich.

4. Outlook

4.1. Coil 3D

At present, the inductance value of the common two-dimensional spiral coil is easy to change when it is stretched and deformed or limited by space. The three-dimensional spiral coil makes the structure into a three-dimensional shape, which is similar to a large spring. When stretching, the force will be more uniform, and the overall service life can be significantly improved.

Jung team found in the research that under the same number of turns, the induced voltage of the three-dimensional spiral receiving coil is higher than that of the two-dimensional coil. Moreover, with the increase of the number of turns, the induced voltage of the three-dimensional coil increases almost in direct proportion; However, the voltage growth of the two-dimensional coil will gradually slow down, with a small increase, and the gap between the two will become larger and larger. More importantly, the three-dimensional coil can not only obtain higher induced voltage, but also lengthen the effective transmission distance, which fully reflects its advantages over the two-dimensional coil, and is very promising to become an alternative to the two-dimensional coil [13].

4.2. Self repairing material

Once there is a tiny crack in the coil material after being stressed, it is easy to cause the circuit to open and the whole system to fail if it is used continuously. We can add repair capsules inside to repair these cracks by releasing liquid conductive materials, so as to extend the service life of the system.

Zhubo team has made relevant research on this, and they analyze its impact on insulation performance by adjusting the doping ratio and external field strength of microcapsules. The experimental results show that under high voltage, the insulation performance of the system with microcapsule doping concentration between 0% and 3% is significantly better than that of the group with microcapsule doping concentration between 4% and 5%; Among them, the insulation performance of undoped microcapsules is the best, which also shows that the addition of microcapsules will reduce the insulation to a certain extent. However, when the doping concentration is less than 3%, the overall insulation level has little difference, so it is most appropriate to control it at about 1% in the actual preparation. The data also show that the insulation performance of the system without doped microcapsules will decline sharply after aging, while the insulation performance of the samples doped with 1% microcapsules can basically return to the level before aging after self repair. It can be seen that the idea of using this microcapsule to repair micro cracks is completely feasible [14].

4.3. Intelligent monitoring

System failures are often sudden and cannot be predicted in advance, so we can embed intelligent monitoring chips and distributed sensors inside to monitor the resonant state of the circuit in real time. As soon as the resonance is offset, the chip will automatically adjust the frequency, allowing the circuit to return to stable resonance.

When the sensor detects that the coil shape changes, it will immediately send the signal to the control terminal, so as to prevent the faults caused by excessive coil deformation, violent inductance fluctuation, and even stress fracture in advance, and avoid burning out the components and structural materials. Liuxiaoshan's team also mentioned in the research on wireless charging of smart factory that such intelligent systems can be tuned in real time using PID algorithm, and then combined with Stochastic Forest regression model to predict the optimal charging process, laying the foundation for the intelligent operation of the whole system [15].

5. Conclusion

In this paper, the flexible and extensible coil scheme of serpentine Island Bridge inductance is proposed by summarizing the research and innovation of serpentine conductor, Island Bridge Structure and ferrite. This scheme can reduce the occurrence of coil fracture caused by high stress tension, enhance the flexibility of the coil, and solve the load problem caused by carrying a power bank in daily commuting. By summarizing the differences in performance and cost between NiTi and copper materials, the advanced design of PDMS new structure substrate, the performance advantages and disadvantages and high cost of nickel type iron and manganese zinc iron ferrite materials in medium and low frequency environment, the Cu/TiNiCuCo/Cu composite material with appropriate cost and comprehensive performance is selected as the coil material, and PDMS/SiC functional gradient flexibility is selected.The substrate is used as the substrate, and the

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ferromanganese zinc iron with low cost and better performance in medium and low frequency environment is used as the ferrite magnetic sheet material.

In a word, if this scheme is to be implemented into a product, it needs to further carry out adaptive design for the power supply and receiver. Therefore, the design of flexible and extensible serpentine Island Bridge inductance coil proposed in this paper can be used as an expansion idea in the functional design of wireless charging technology, and further research will be carried out.

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