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Optimal Design of Magnetic Coupling Resonance Principle in Wireless Charging of Substation Inspection Robots

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Abstract. Autonomous charging ability constitutes one important piece among intelligent power system operation and maintenance, for autonomous charging is what really decides if unbroken inspection missions can happen. In view of better transmission distance and effect, it really solves " eternal motion" problems faced by robot systems. For solving the wireless power request of the Sub-Station check, this paper will create 2 outputs to give Energy and will use aluminum-ferrite material for my magnetic shield, and also a strategy related with transmitter coil. From experiments, people can see that using such a way to pass more energy with faster speed also makes it easier to change its load without stray magnetic field, enlarge the operation range and increase the ability for position shift. Improving function in the environment and functional as well as better functionality. Also, it is practicable from a technical aspect to increase the degree of independence of inspecting machines on charged station, there are a lot of electromagnetic interference and limited room. This kind of building proposal can help to improve the current automaticity and ease-of-maintenance characteristics of the power grid system.

Keywords: Substation inspection robot, magnetic-coupling resonance, wireless charging, energy-efficiency optimization

1. Introduction

During the era of digitalisation and intelligent transformation in power network construction, the substation is a vital link connecting power grids to users; hence, its operation should remain reliable on this basis. Traditional manual observation is unable to meet the requirements of frequent and various weather conditions at present. Thus, due to their widespread application for monitoring purposes in ensuring reliable operation of electrical grids [1], numerous types of sensor-equipped surveillance Bots have been deployed. Due to the limitation of battery power, these robots are required to go back regularly at fixed locations after being powered on; therefore, their operation is slow and prone to be interrupted by accidents. In particular, working under harsh conditions, such as substations with high voltage risks.

Many researchers around the world are intensively exploring wireless power supply technologies at present. The majority of the existing methods are induction coupling, magnetic-resonance coupling, and electromagnetic resonance [2]. Magnetic resonance wireless power transfer (MRWPT) technology can solve the problems of other charging methods by providing a contactless working

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mode, a high-safety guarantee mechanism, a wide-area application scenario, and environmental stability adaptation capability. Nevertheless, currently most of the academic works focus on improving overall system efficiency while lacking in-depth studies for issues specific to substation environments such as high-voltage levels, strong electromagnetic interference, metallic obstacles, etc, and there are still insufficient details.

Based on the shortcomings described above, a new development based on the MC-RWPT System is proposed to detect and monitor substation Bots to ensure the stability of the power supply environment. Not only can this exploration enhance the functional Independence and Electrical Supply Stability of These Robots, but it also provides conceptual references for non-contact power distribution frameworks.

2. Magnetic coupling resonant wireless charging technology

2.1. Principles of magnetic coupling resonant wireless charging technology

In terms of digital evolution and the advancement of intelligence in power grid infrastructure, substation inspection drones are used to do a security check on power grid activity. But because its power from its battery is limited, regularly returning to some places where the wires or contacts give it energy back will greatly influence the effectiveness of the inspection, there could be worn parts because of the connection getting electric, and also lots of sparks when electricity reaches a certain voltage.

In terms of wireless power transmission methods, they are all divided into various methods: microwave transmission and electric field in-field [3]. Take MCRWPT like this example delivering power is achievable if the natural resonant frequency of the sending end and receiving end are in sync [4]. Important System metrics are: Transmission Efficiency, Range, Power Delivery Capacity, Tolerance of Load Fluctuation. Currently, most of people's efforts are concentrated on perfecting the ideal state; in terms of investigating systematic problems caused to substations by electromagnetic interference & metal walls, misalignment and differences in loads, etc., they have not given sufficient attention.

For solving above shortcomings of the paper, this article introduces a certain substation inspection robot MCRWPT system architecture. It not only enhances the vehicle's ability to function independently and maintain a stable energy supply but also gives some idea about how to distribute power without coming into contact with specialized equipment. This is very important in terms of theory and practice for advancing more sophisticated inspection device engineering. Figure 1 is the current stage of wireless charging [5].

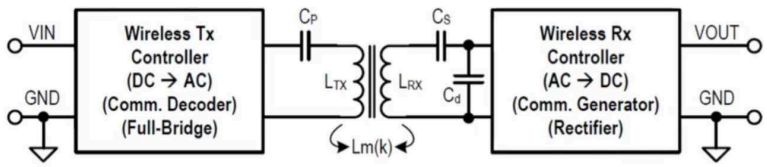

Figure 1. Magnetic coupling resonant magnetic resonance [5]

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2.2. System composition

From the architectural view, it's a joint architecture made up of a send coil, receive coil, magnetic cores and cover housing. The size, winding style, and making of such items actually decide the type of shapes for creating the coupling ratio along with the quality index. But the magnetic core is doing a pretty good job by adding this restricted path for our magnets, also the shielding layer blocks the external EM noise really well, which makes sure it's constant and reliable

From figure 2 people can see that the entire process of wireless power transmission in the substation surveillance drone is: Firstly, it monitors the SOC in real-time via the battery level monitoring module. The moment when SOC goes below some level. It is perceived that charging is needed, then the self-driving navigation process will be activated. It's for the particular docking spot through the use of the laser scanning or the magnetic rail and it has to be aligned by the time transceiving unit happens. Once the proper alignment is done, people turn on the wireless power transmission. The Transmitter turns the Resonant Tank on with a high-frequency oscillator, which creates a variable magnetic field, and the receiver creates an E.M.F. from it by induction. This signal is rectified and stabilized before being used to charge the battery. It's within the loop, continually checking out how well it's done with thermics and voltages/currents. The minute any state such as overheating, overvoltage, or fully charged gets detected, a stop sign is instantly conveyed so as to cease the wireless charge sequence and that's it for the entire operation.

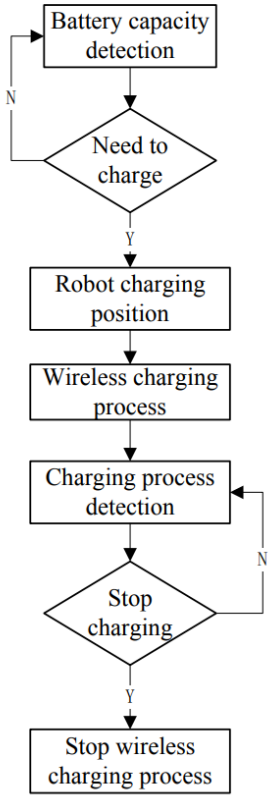

Figure 2. Substation inspection robot charging process [6]

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2.3. Energy transfer efficiency analysis

Magnetic-field-based resonant wireless power delivery makes use of the basic concept of Electromagnetic Induction along with resonant coupling to amplify the interaction between magnetic field power across an intermediate range by means of resonance for the purpose of power transfer. The sender uses high-magnetic-coupling resonant wireless power delivery, based on the basic principles of electromagnetic induction and resonant, it adopts the idea of resonance to improve the coupling and transfer capacity of the magnetic field's power so that it can achieve the purpose of effectively distributing power over a long distance. Sender, it is using high-frequency alternating currents, so it's kind of an oscillating or like electromagnetic field type thing: when the resonant frequency of the coil at the receiver side coincides with that at the sender side, the setup will enter into a resonant mode, where after power can be transmitted from one resonator to the other via the magnetic field in a lossy fashion. The resonant frequency f is given by the formula, which depends on inductance L and capacitance C of coil. It is defined as:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The basic concept of wireless power transfer lies in the resonant coupling, and it's energy transference efficiency η_1 can roughly be analytically figured out with the below expression:

$$\eta_1 = \frac{k^2 Q_1 Q_2}{1+k^2 Q_1 Q_2} \tag{2}$$

K here is just the mutual inductance coupling factor; Q_1 and Q_2 represent the respective quality factors of the sender and receiver [7].

3. Optimization design of wireless charging system for substation inspection robots

3.1. Dual-output architecture

Speaking about how substation inspection robots are always being charged means demand for these kinds of robots when they need to be energized all the time. There is a paper that was published by Ze LI and their dual-output framework, which provides power supply at the same as well as charging batteries simultaneously. The main progress is that the wireless charging receiver unit's energy output is split up into 2 streams; one goes towards recharging the energy battery with the same 3-stage recharge profile as Lithium-Ion Cells but instead of recharging the energy battery directly, its purpose is more for supplying energy to the robot's body via isolation relays. In order to not have any issues with voltage instabilities in the battery charge loop affecting the power fed to the robot platform. It'll power up and run while also being charged at the same time, perform its watchkeeping job at once upon its own charge too, adding in a small amount more to the load management. This framework is able to change the amount of power given out by the two branches according to how much power the robot uses. By looking through my research and experiments see that the Dual Energy System can keep a normal working voltage at all times while robot's body is being charged, not stop for battery phase change in charge. It makes the adaptability much better under dynamic load [6].

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3.2. Aluminum plate - ferrite shielding

Resonant wireless charging technology converts power frequency current to high frequency current, compensates for resonance between capacitors and coil inductors, and transmits in a loosely coupled magnetic field manner [8]. During this time, a considerable quantity of leaking magnetoelectric fields exists within the region where the transmitting coil and the receiving coil are located. The latter is at a much higher energy concentration per unit area than the former's conventional frequency power source. According to epidemiological surveys, continuous exposure to strong magnetic fields or electrical fields for a long time is harmful to human health; In addition, it may cause damage to the heart and reproductive systems in people as well. The same as above: At this point, the commonly applied pure-metal-shielding method cannot be used for eddy-current detection; however, because of its serious eddy-current loss and excessive heat generation, it does not work well. In addition, although pure ferrite shielding guides magnetic circuits, it may cause magnetic saturation problems, and thus is also unsuitable to suppress far-field leakage magnetic fields [9]. Therefore, designing a shielding method that is appropriate for wireless power transfer technology has strong practicality in promoting and developing wireless power transmission technology.

An Yunzhu and other scholars conducted an extensive research study into how aluminium plate shielding structures affect magnetically coupled resonant wireless charging systems through a combined-field and circuit analysis approach using a Field-Function Coupled-Finite Element Model (FF-CFEM) system. The current in the transmitting coil reached as high as 8.1 A with shield treatment. The load voltage decreased from 116.57 V to 59.34 V; the transmission efficiency declined sharply from more than 98% back to only about 58.47% [10].The physical mechanism is that an induced eddy current occurs on the aluminium plate, equivalent to many tiny inductors; therefore, there are more coupling paths between these devices and the original system than before; thus, requiring the transmitter's output current to increase accordingly to keep its own power unchanged, but actually received power drops due to this.

In terms of the magnetic circuit, the magnetisation line tends to have a path with lower magnetic reluctance. As the magnetic resistance of the metal shielding material is much less than that of air, most of the leakage magnetic field in the wireless power transmission system has been absorbed by the metallic plate,s o as to reduce the range where electromagnetic waves spread outside the enclosure; In addition, at high frequencies, eddy currents are generated on conductors due to a high-frequency alternating magnetic field, which produces a counter-magnetic field to cancel out part of the original magnetic field, thus increasing losses and decreasing the effective utilization rate. As per Ohm's Law applied to describe general Principles for Magnetic Fields, and so forth:

$$\varphi = \frac{F}{R} = \frac{N_i}{1(\mu S)^{-1}} \tag{3}$$

In the formula: Φis magnetic flux; F is the magnetic emf; R is magnetic resistance; S is the cross-sectional area of the magnetic circuit;i is the current; l is the average length of the magnetic circuit.

Researchers built an aluminium plate-ferrite composite shielding structure finite element model to investigate how changing factors such as the size and thickness of the aluminium plate and their interlayer distance affect the Shielding effect and system efficiency in detail for the wireless charging system of electric vehicles. The results of the experiment indicated that, in terms of aluminium Plate Size for protection effects were different. When the side lengths of an aluminium plate are greater than normal values, it is more difficult to couple; Component Losses Increase

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proportionately and outside-field strengths accordingly rise. When the ratio of the edge length of the aluminium plate to the length of the ferrite strip is 1.25,the magnetic field strength at this position has dropped to half that without a shield; If it is enlarged, then its attenuation effect will tend towards stability. As the normalised Size increases from 0.5 to 1.5,The Coupling Coefficient decreases from 0.12 to 0.076;DC-DC efficiency decreases by more than 1% to around 93%;External Magnetic Field is approximately half of its original value. It can be seen from this that the aluminium plate size within an optimal range will have a good balance of low energy consumption losses and shield performance.

Aluminum plate's thickness has an impact on its shielding effect to some degree, but below a certain limit, no longer exist; at less than 5mm, the eddy current loss rises sharply, resulting in obvious reductions in efficiency. An excessively thick one is less effective in shield; rather, it will become heavy and expensive. The distance of aluminium plate-ferrite layers does not have a significant effect on system performance compared to the other distances. Increase the distance d between them to minimise electromagnetic compatibility problems caused by proximity to this material. When d = 0-20 mm at each time point, the System's utilisation increases by approximately 2.5%. In comparison, a ring-shaped aluminium shielding Structure can perform well and use less material than a general Aluminium plate. As the Size of the aluminium Ring increases, the external magnetic field decreases; However, the efficiency curve is "V". At a normalised Size of the aluminium Ring at 1.5, the magnetic field reduces by 52% compared with an Unshod condition; And its efficiency is around 96.9 per cent. A 1.1 mm thick aluminium plate can be used as an alternative with the same amount of attenuation; It has about 96.2% efficiency. This indicates that the aluminium ring is slightly more efficient but requires a larger size. There is a certain best size for the width of the aluminium ring. If it is less than 5mm, by increasing the width, the eddy-current loss will be decreased; However, if it exceeds this value, The Efficiency decreases because of a reduction in coupling coefficient [11].

The single metal-shielded cans are going to weaken an external field but when it comes to power transmission efficiency, The Aluminum plate-Ferrite composite shield is one layer that has conductivity and also has more magnetic permeability to do the guiding/cancellation jointly. Adding a ferrite layer after that led to an increase from 59.34 volts to 73.60 volts, and if people optimize the ferrite as a convex lens shape, then it will give almost same shielding effect but using less of material. However, it remains to be seen if they have the same effectiveness and economy in all kinds of other situations with many goals.

3.3. Coil and core optimization

Improving the transmission effectiveness and power density of Magnetic Coupling Resonant Wireless Charging systems is mainly done by this. Tradition coil construction methods rely mostly on finite element modeling and parameter sweeps so it causes worse design productivity, longer time to develop and trouble getting all different parts working well together. Some can also be solved by these people proposing to add in the Machine Learning aspect on having more than one goal objective to improve manufacturing of transmitted coil parameter values based off data that would really help determine and predict what those objects will look like.

And on coil's structure: The most used framework on modern W.P.T.is Rectangular planar helical magnetic coupling. Vital parameters are composed of the outer size of the coil, wire gauge used, number of windings done and the spatial gap between the source and receiver. From the investigations people find that variables such as Winding dimensions, Turns, Wire Caliber do have an effect on the assembly's Self Inductance, Mutual Inductance & Coupling Factor which will

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decide the efficiency of Power delivery. To lessen the extra dissipation caused due to skin and proximity effects of the skin and at higher frequencies people have to use multi strand Leeds wire. Leeds wire can use the method of insulating, interweaving a large number of thin wires with each other to lower AC resistance and improve the quality factor of the coil. On model approach, if you approximate the coils and Ferrites to similar geometry it will save your computing time by around 80 % but still retain same level of accuracy as in sim so makes the process faster [12].

For basic design, a lot of ferrite materials are used, which guide the magnetic fluxes and bundle all those stray magnetic fields due to their high magnetic permeability & very low dielectric dissipation characteristic: still the main generates main dissipation consisting of eddy current heat, hysteresis heat, and remanent heat under high frequency electromagnetic fields, the amount of these has close relationship with worke frequency and peakmagnetic fluxdensity. In order to reduce the amount of core loss, one should select materials such as ferrites that have a smaller Scanmetz coefficient and improve the configuration and morphology of the cores in order to enhance the effect of the magnetic field focus and reduce the amount of core loss. As it is known, placing the ferrite in a convex lens shape will have much less volume but still act similarly with respect to magnetic field focusing.

4. Conclusion

In this article, this paper mainly focus on the development of investigation on using the Magnetic coupling resonant Wireless power transmission in Substation Inspection drone and basically there are 3 different kind of method were used: Double output aluminum plate ferrite mixed shielding refine coil core in terms of making those two out frame works for it drone goes on uninterrupted throughout whole time during which recharging is happening part in way charged battery does pieces, aluminum plates paired with the ferrite combo shields guide along and cancel all stray interfering paths just doesn't block many ways to increase data driven mean balances power transfers creating more. As for the above, this paper provides a part of the technical support to improve the autonomous duration and also the intelligent recognition and repair standards of drones for substations.

In the future, people must make more efforts for better system performance. Coil layouts need to get creative, high-frequency power modules are needed, as well as good compensation. In this way, it is feasible for this to be widely deployed industrially in the field of substation inspection drones.

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