

A Review of Key Technologies for Optimising the Efficiency of Dynamic Wireless Power Transfer for Electric Vehicles

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ABSTRACT

The Dynamic wireless power transfer (DWPT) for electric vehicles allows you to charge all the time while the vehicle is moving. In this way, the possibility that the battery is dead will be reduced, and the price of the battery installed in the car will become cheaper. However, if the mutual inductance changes when the car is running, it will lead to the decrease of efficiency and the instability of power supply. This is the most difficult technical problem. In this paper, we look at the technology of improving efficiency from three important points. Three types: magnetic coupler, resonant compensation topology and control strategy. Together, these three factors determine the overall efficiency of the system, and changing the loss of power stage will further reduce the actual efficiency. magnetic coupler determine the upper limit of system efficiency. Its design changed from flat to three-dimensional, from passive to self-adjustment, from trial and error to data. Compensation topology is a representative example of LCC-S. Regardless of the coupling coefficient, the current at the transmitting side is constant to suppress the instability of power. secondary-side model predictive control can also respond to dynamics well. Most validations reported so far, however, have been carried out under simplified operating conditions and on low-power experimental platforms. Future progress calls for breakthroughs in three directions: adaptability across all operating conditions, high-power engineering implementation, and system-level coordination.

Keywords: Dynamic Wireless Power Transfer; Efficiency Optimization; Magnetic Coupler; Resonant Compensation; Model Predictive Control

1. INTRODUCTION

Electric vehicles (EVs) have the advantages of zero exhaust gas, low noise and high energy efficiency, and have become an important direction of automobile industry transformation. However, the uneasiness of “worrying about the distance you can run” and the lack of convenience in charging have become big problems when popularizing EV to many people [1-2]. Traditional wired charging has some problems, such as long charging time, easy wear of connectors and difficult operation. In addition, a large-capacity battery pack will increase the price and weight of the whole vehicle [1,3-4]. Wireless power transfer (WPT) is an electromagnetic connection, which can transmit power without contact, thus well eliminating the above-mentioned problems [5].

Wireless charging is divided into two basic ways: static wireless power transfer and dynamic wireless power transfer [5]. Static charging is to park the car in a specified place to charge, facing parking lots and residential areas. However, it can't solve the limit of mileage-the car still has to stop to charge and install a large battery pack [6-7]. The dynamic wireless power transfer is to place the transmission coil under the road so that the vehicle can be charged all the time while driving [5]. In this way, the time required for charging is reduced, the demand for battery capacity is further reduced, the overall price of the car is also reduced, and the anxiety of “worrying about the distance you can run” is also alleviated [8]. Dynamic wireless power transfer has a greater challenge: when the car is running, the positions of the transmitter and receiver coils are constantly changing, which leads to mutual inductance fluctuation, which leads to the decrease of efficiency and no need for power. This problem involves three levels: magnetic couplers, compensation topologies and control strategies, which is the core technical bottleneck of dynamic wireless power transfer [9].

In order to meet these challenges, researchers have done a lot of research in three areas: magnetic coupler, resonant compensation topologies and control strategies [9-10]. Magnetic coupler determines the upper limit of efficiency, compensation topology creates resonance environment, and control strategy protects the stability of output. In addition, the losses caused by inverter, rectifier and DC/DC converter where the power is changed will also have a great impact on

the overall efficiency of the system ^[9]. These three work together. The better the performance of the magnetic coupler, the less the remaining two burdens. Therefore, improving the stability of coupling is the most important method to improve the efficiency of dynamic wireless power transfer.

With the theme of improving the efficiency of dynamic wireless power transfer, this paper is especially committed to improving the magnetic coupler. In this paper, the main technical approaches and research progress are investigated from the three aspects just mentioned, the development course of this field is traced back, the current topic is found out, and the future research direction is summarized.

2. MAGNETIC COUPLER OPTIMIZATION

Magnetic coupler is the core component of dynamic wireless power transfer system. If the mutual inductance changes due to the continuous change of the relative position of the transmitting coil and the receiving coil, the efficiency will be reduced or the power will be unstable. Therefore, stabilizing multi-industries is a basic design topic. For this reason, researchers have studied on three levels: coil structure, magnetic core and magnetic circuit design, and system-level integration.

2.1 Coil Structure Optimization

The shape of coil and the configuration of winding mode directly determine the nature of combination. In the traditional coil, if it is laterally offset, the overlapping area will become smaller, and the mutual inductance will decrease monotonously ^[11]. To this end, researchers have improved the misalignment tolerance of coils via approaches including in-plane multi-winding compensation, three-dimensional design, and multi-coil coordination.

2.1.1 Topological Innovations in Single-Transmitter, Single-Receiver Coil Configurations

When a planar coil is misaligned, the reduction in coupling area is the direct cause of mutual inductance drop. The basic principle of mutual inductance self-compensation is to modify the winding layout such that even under misalignment conditions, part of the windings remain within the strong coupling region. Yang et al. ^[12] proposed a double-orthogonal DD magnetic coupling structure (DDDQ coil), which introduces an X/Y-axis double-orthogonal receiver array on the basis of the DDQ configuration. By switching operating modes according to operating conditions, this structure allows the system to maintain 52% efficiency under a 200 mm dynamic offset, with coupling fluctuations significantly lower than those of traditional DDQ structures. Fu Guangjie et al. ^[13] optimized the BP coil for curved track conditions, with its two coils fitted to the inner and outer diameters of the track respectively. After optimization, the mutual inductance fluctuation rate at a transmission height of 20 cm is reduced by 5.1% compared with that of the traditional rectangular coil, while the mutual inductance at 10 cm is increased by 28.7% compared with that of the traditional BP coil, thus adapting to both straight and curved track conditions.

When optimization in the plane was constrained by the vehicle's underbody space, researchers expanded into the vertical direction. The three-layer orthogonal bidirectional anti-offset (toba) coil structure ^[14] designed by Cheng Yu, when there is a large "D"-shaped square coil in the middle layer, the magnetic fields of the left and right symmetrical coils in the same layer complement each other, which is a left and right symmetrical configuration in the square, so the offset intensity in the X direction and the Y direction is the same. The experimental results show that the volatility of coupling coefficient is less than 5% and the efficiency is above 94.8% under the bidirectional offset of 170 mm. Garrofy ^[15] considered the vertical coil (VC) structure. This is because the receiver coil is longitudinally wound around the ferrite core, and the magnetic flux line passes horizontally, so the vertical line of the coil is the same as the magnetic flux line. Compared with DDQ, the peak efficiency of VC increased from about 85% to about 93%. Its effective transmission area is expanded by about 50%, and the energy captured per cycle is also increased by more than 50%.

There are obvious differences among the four topology. DDDQ can support both static and dynamic behaviors with 52% efficiency (when the deviation is 200mm). The optimized BP coil reduces the mutual inductance volatility by 5.1 percentage points. TOBA improves the minimum efficiency to 94.8% within the offset range of ± 170 mm in two directions. On the other hand, VC improves the peak efficiency to about 93%. In particular, the design of VC has changed the previous idea that the receiving coil must be placed horizontally, and opened up a new way for future research.

2.1.2 Complementary Coupling and Array Decoupling in Multi-Coil Systems

If the position deviation of Single coils is large or it is the switching point of the track, there will be the problem of the area that cannot be combined. On the other hand, if multi-coil arrays are used, cross-coupling will occur, so it is necessary to strike a balance between compensation and suppression.

Regarding the complementary function of multi-coil, focusing on the sender, Vu ^[16] proposed a multiphase multi-winding transmitter. This is driven by using multiphase inverter, in which currents with the same magnitude and equal phase offset flow in multiple transmission coils. When the number of phases $n \geq 3$, the induced voltage across the receiving coil is position-independent, thereby eliminating power nulls in principle. In a 3 kW three-phase system, the power fluctuation is only 5.6%, and the DC/DC efficiency reaches 87.8%. Constant output is achieved without secondary-side feedback. In complementary work, Li Weilong et al. ^[17] adopted a “primary-side bipolar + secondary-side dual-receiver” structure from the receiver side: bipolar currents with a 180° phase difference are injected into adjacent primary-side coils, while on the secondary side, a rectangular coil and a DD coil are stacked vertically and connected in series following independent compensation. After adjusting the size of the coil, the overall mutual inductance remains unchanged, the fluctuation of the output voltage of the open-loop is controlled within 8.3%, and the efficiency is about 85%.

If coil is extended to an array, the power factor deterioration caused by cross-coupling cannot be ignored. Kim et al ^[18] put forward the standard of the influence of cross-coupling on efficiency and power factor from the perspective of MIMO-WPT. They said that the coupling between the sender and the receiver should be strengthened while maintaining the plane structure for paving roads, and the internal cross-coupling should be suppressed. If magnetic beamforming is merged, when the number of incoming coil increases from 1 to 5, the power factor will remain close to 1.0 and the system efficiency will be improved by 30%. On the other hand, if it is a traditional square array, the efficiency only increases by about 18%, and the power factor decreases to 0.5. The magnetic separation array is superior to the traditional method in efficiency and power factor, which indicates that the electromagnetic coupler has changed from passive dislocation resistance to active electronic electromagnetic control.

2.1.3 Coil Compensation Design under Special Operating Conditions

Segmented rail switching zone and curved section are the special operation states with the largest decline in “mutual inductance”. They often exceed the compensation ability of ordinary design and need fixed-point compensation geometric or magnetic circuit compensation.

In the track switching zone, mutual inductance drops significantly at the gaps between adjacent transmitter coils. Chen Geng et al. ^[19] proposed a variable-spacing anti-misalignment structure in which the receiver coil length is designed to equal the sum of the transmitter coil length and the inter-coil spacing, so that the magnetic flux passing through the receiver coil remains constant before and after lateral misalignment. Experiments show that the coupling coefficient fluctuation is less than 2.6%, and copper consumption is reduced by 50%. On the other hand, Feng Bojun et al. ^[20] focused on magnetic circuit geometry and proposed a triangular-docking magnetic circuit mechanism, employing a triangular-docking transition in the switching zone and increasing the winding turn count. After optimizing docking angle (70.5°) and turn ratio (1.0), the fluctuation range of mutual inductance in the switching area is controlled within 4.14%. In these two methods, the former keeps magnetic flux by adjusting the size, and the latter restrains the multi-dimensional decline by changing the shape.

For the curved track, the way of “mutual inductance” descending is more complicated, because it moves forward and backward. Zhu Guofu and others ^[21] said that the wider the interval, the smaller the effective coupling area where the outer line of the transmission core of the ordinary rectangle is bent. They improved the transmission efficiency from 49.56% to 58.21% at the maximum inclination angle of 3.5 by changing the outer line to adapt to the radius of the curve. Luo Qiang and his colleagues ^[22] embedded the circular compensation coil into the rectangular receiver coil, and used its rotational symmetry to make up for the loss of multi-output. After optimization with genetic algorithm, the fluctuation of mutual inductance is kept within 0.5% at all four bending angles, and the voltage fluctuation is reduced to 3.6%. The above research shows that the magnetic coupler is evolving to be used accurately according to the scene.

2.2 Optimization of Magnetic Core and Magnetic Circuit

Ferrite cores has various functions. Guide the magnetic field lines, strengthen the combination, and prevent redundant magnetic fields. However, using ferrite cores will increase the weight and cost of the system. Finding the right balance between improving performance and reducing cost is the core issue of Core Optimization.

Bensetti and others [23] used three-dimensional finite element simulation to carefully analyze how the parameters such as surface area, thickness and central hole of ferrite affect the coupling coefficient. The results show that the surface area is the most important factor affecting the coupling coefficient, and the thickness has little effect (even if the thickness increases by 10 times, the coupling coefficient will only increase by about 5%). Although the performance of the central hole with a diameter of less than 150mm will hardly decrease, the weight and cost will be greatly reduced. The structure of the best combination made from these results improves the combination coefficient by 26%, and the deviation is stronger in the range of 0 ~ 260 mm. Yin and they [24] thought of two new magnetic cores. They are cover-plate type and loop-type respectively. Both of them adopt the design of putting coil in the groove. In order to seal and protect the magnetic field firmly, the coil is buried in the groove of the magnetic core. Cover-plate type has the best performance, the voltage is five times that of coreless structure, and it is suitable for short-distance fast charging. The magnetic material of loop-type only costs 0.57 m, so the money is much less and it is suitable for long-distance use. In addition, a hybrid method is considered, in which the sender adopts loop-type and the receiver adopts cover-plate type. This can greatly reduce money while maintaining the transmission performance, so the balance between performance and cost is good. Through previous research, it is found that the improvement of Core is carried out in two ways. parametric analysis and topological innovation.

2.3 System-Level Integration Optimization

So far, the optimization has all focused on improving the performance of the magnetic collector itself. However, some researchers have gone beyond this idea, and from the point of view of looking at it as a system, the study of magnetic coupler will be deeply combined with other subsystems.

2.3.1 Magnetic Integration and Multifunctional Multiplexing

In the traditional design, the magnetic collector only has the function of transmitting energy, while the onboard converters needs additional magnetic components, with overlapping functions and occupying space. Kalra and others [25] proposed the integrated boost active bridge (ibab) converter. It installs center tap on DD receiver coil, and uses the inductance of the coil itself to replace two independent DC inductor on the traditional BAB. Because only one shared DC indicator remains, the size of the whole machine can be reduced by about 70%. Even at a power of 7 kW and a wide range of coupling coefficients varying by 43.5%, the efficiency of DC/DC is stable between 92% and 94.2%, and the variation is only 1.7%. This research makes magnetic couplers have functions other than transmitting energy, which destroys the traditional boundary between magnetic couplers and power electronic converters, and makes the component-level friendliness a great progress in system-level integration.

2.3.2 Intelligent Design Methodologies

Due to the nonlinear coupling among magnetic coupler design parameters, traditional iterative finite element methods are inefficient and cannot reliably guarantee a globally optimal solution. Shanmugam [26] used the registration algorithm of machine learning in order to predict the best core structure consistent with DD-type charging pad. They use the previously collected finite element simulation data set to learn the Gaussian process regression model, so that they can immediately predict the parameter combinations that meet the design conditions. The trial production of 3.3 kW has improved the efficiency by 93.21% and greatly shortened the design time. The practice of using this data has exceeded the efficiency limit of previous design methods, and it is expected to become the mainstream tool for magnetic coupler design.

3. OPTIMIZATION OF RESONANT COMPENSATION TOPOLOGY

Resonant compensation networks provides a stable working environment for magnetic couplers and plays a very important role in reducing power fluctuation [9]. With regard to the high-order complementary structure, the LCC-S topology with the primary side being a LCC circuit and the secondary side being connected in series has advantages in keeping the current on the transmitting side constant, making the circuit on the secondary side simple, and making the output voltage or current constant easily [27]. According to Wang et al. [28], the current on the transmitting side of the LCC-S compensation topology is stable even when the load and coupling coefficient change, so it is very suitable for all kinds. In order to adapt to the unpredictable change of coupling coefficient when the car is moving, the researchers thought of using intelligent algorithm to optimize the LCC-S parameters of low-cost airlines. Tian Yong et al. [29] established the offset-weighted mean efficiency (MWWE) index according to the normal distribution characteristics of vehicle lateral deviation, and described the compensation parameters by using a genetic algorithm. Even if the calculation coefficient drops to 0.07, the efficiency of the system can be maintained above 60%. Similarly, Xu [30] used particle swarm optimization (PSO) algorithm to adjust the parameters of LCC-S, while protecting the complete resonance. Theoretically, this method can achieve 98% efficiency.

The experimental results also prove that this method will make the system stronger for the change of load and the deviation of dynamic coupling. Previous research shows that introducing smart optimization algorithm into LCC-S parameterization is a good way to improve the stability of dynamic wireless power transmission system.

In addition to parameter adjustment, LCC-S network, a low-cost airline with multiple transmitter, has strong anti-interference ability when working under harsh conditions. You ^[31] made some overlapping coil array, and used the natural decoupling structure to reduce the influence of cross-coupling between adjacent coils. During dynamic charging, the output voltage is very stable, the fluctuation is only 3%, and the average efficiency remains at an amazing value of 80%. This special design will continue to provide a constant voltage, thus automatically adjusting the current distribution without complicated control system. It shows that a good combination of compensation topologies and magnetic coupler can improve performance.

That is to say, in the current research, we find that the LCC-S compensation topology can reduce the fluctuation of power and improve efficiency when there is a big deviation. There are three important aspects: stable transmitter at present, being able to adjust parameter wisely, and being able to use multiple transmissions jointly. However, it is not enough to compare the LCC-S topology and other high-order components (LCC-LCC, etc.) when the situation changes. Because most of the research so far is carried out on simulation and low power, it is not clear what these methods will do in the actual high power field.

4. CONTROL STRATEGY OPTIMIZATION

“Magnetic couplers” and “compensation topologies” can suppress the change of mutual inductance at hardware and circuit level. However, the remaining changes during the movement cannot be completely eliminated. Therefore, in order to make the system work efficiently, control strategy is needed to make up for the binding changes in real time.

The control strategies of Dynamic wireless power transfer include primary-side control, secondary sliding control and dual-end coordinated control. secondary-side control has been widely used in recent research because it does not need communication between primary side and secondary side, and its response is rapid and reliable ^[9, 32-33]. DC/DC converter is the core component of safety side control, and accurate output control is realized by dynamic duty cycle adjustment. In the initial design, PI controller was used, which was simple in structure, but only adjusted under rated conditions. When the mutual inductance changes rapidly in a large range, these controllers have insufficient reaction speed and large overshoot, which makes it difficult to meet the requirements of constant current or constant voltage charging ^[34].

Model Predictive Control (MPC) has attracted much attention because of its repeatable optimization, clear handling of constraints and strong resistance to parameter deviation ^[35]. Tianyong made a state-space model of buck circuit on the secondary side by using LCC-S compensation topology, and combined Kalman filter with a current sensor to realize constant current control. The experiment shows that under the LCC-S topology, the stability time of MPC is about 15ms, while the traditional pi controller takes 2.2 seconds. In addition, even if the mutual inductance changes suddenly, the output current is basically stable ^[36]. Under the condition that the coupling coefficient changes rapidly and widely, the stability time of MPC is shortened to 1 ms ^[35] in the Zhou of experiment.

In order to solve the problem of large calculation amount of MPC, an improved method is proposed in the following research. Ma people use polynomial fitting to solve the sampling data model by calculation, and convert the calculation of the optimal duty cycle into a direct quadratic function, which greatly reduces the complexity of calculation ^[37]. Li also proposed an adaptive tube-based MPC, which uses neural networks to predict the future state and move and adjust the constraint boundary. In this way, you can better resist mutual inductance interference and model errors ^[38]. In addition, the secondary sliding DC/DC control is also studying nonlinear methods, such as passive control ^[34] and sliding mode control ^[39].

Generally speaking, the control of the secondary-side DC/DC converter has developed from linear control to predictive control. Moreover, the advantages of MPC in reaction speed and firmness are remarkable. However, at present, most confirmation experiments are carried out on low-power prototypes, and the real-time performance of MPC has not been fully confirmed when charging with high power. This has become the biggest problem that hinders the use of technology to improve the efficiency of dynamic wireless power transfer system in actual field.

5. RESEARCH CHALLENGES AND FUTURE PROSPECTS

Looking at the previous research progress, most of the researches are still used to determine the simple motion state (straight running, certain speed, low power, etc.), random misalignment, turning, speed change, high power, etc., using the magnetic integration technology with certain characteristics of LCC-S voltage, multi-transmitter LCC-S network, MPC control research, all of which show the possibility of getting better together in all aspects. However, the method to make the whole system better is not enough, and most of the studies are just getting better in all aspects. The framework for designing all mechanical calculators, compensation topologies and control methods has not yet been formed.

In the future, we need to make breakthroughs in three things. First, we should adapt to all working conditions. Make a topology that can handle misalignment, curve and speed change at the same time and can be used by everyone. The second is the realization in high power engineering. In order to confirm, the base is extended to a real car that can output more than 10 kW of power. The third is system-wide cooperation. Eliminate the traditional boundary between phantom collector, compensation topology and control method so that the design can be centralized.

6. CONCLUSION

For the dynamic wireless power transfer in electric vehicles, paper looks at the key technologies to improve efficiency from three angles: magnetic couplers, resonant compensation topologies, and control strategies, which are the central links to improve efficiency; magnetic coupling mechanism determines the upper limit of efficiency in theory. Compensation topology and control strategy determine it. However, the original loss of changing the power stage, such as inverters and rectifiers, has become a huge constraint that prevents the actual efficiency from reaching the upper limit.

The upper limit of mechanical performance of machining fundamentally determines the possibility of system performance. Moreover, its design has changed from plane to three-dimensional shape, from passive matching method to self-adjustment method, from empirically tried and failed method to data-based method. Regarding resonant compensation topologies, topologies such as LCC-S use certain characteristics of transmitter's current, and use intelligent parameter optimization and multi-transmitter coordination. However, it is not enough to confirm with high power.

Regarding "control strategies", "secondary-side model predictive control" can improve the movement speed and anti-interference ability very well. However, the current research is almost limited to the prototype of low power.

Making the three aspects better together is an important way to operate efficiently. From now on, we should devote ourselves to being suitable for all working conditions, being able to actually use at high power, the cooperation of the whole system, and these advances.

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