Advances in Inductively Coupled Power Transfer Technology for Rail Transit

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Abstract—**Traditional power supply method for moving electric railway vehicles is based on contact type power collection technology. This sometimes cannot meet the requirements of modern rail transportation. A new wireless power transfer (WPT) technology can offer significant benefits in modern rail transportation particularly in some stringent environments. This paper reviews the status and the development of rail transit power supply technology, and introduces a new challenging technology--inductive power transfer (IPT) technology for rail transit. Tesla established the underpinning of IPT technology and creatively and significantly demonstrated power transfer by using highly resonant tuned coils long time ago. However, only in recent years the IPT technology has been significantly improved including the transfer air-gap length, transfer efficiency, coupling factor, power transfer capability and so on. This is mainly due to innovative semiconductor switches, higher control frequency, better coil designs and high performance material, new track and vehicle construction techniques. Recent advances in IPT for rail transit and major milestones of the developments are summarized in this paper. Some important technical issues such as coupling coil structures, power supply schemes, segmentation switching techniques for long-distance power supply, and bidirectional IPT systems for braking energy feedback are discussed.**

Index Terms—**Bidirectional energy transfer, inductive power transfer (IPT), magnetic coupling, rail transit, segmented power supply, wireless power transfer (WPT).**

I. Introduction

TRADITIONAL power supply method for electric railway vehicles is based on contact-type power collection technology. This technology includes an overhead pantograph system or a third rail system which is efficient and maybe low cost at present application. However, these systems suffer from several disadvantages such as generation of noise from pantograph, abrasion and spark of pantograph shoe and contact wires, much maintenance, and power disruption risk due to natural calamity. Also, it is easy to cause communication breakdown by the potential hazards, and it affect the landscape in city and scenic area as well. For the third rail system of power supply, beside the disadvantages as mentioned in overhead pantograph system, it cannot be applied to the train when vehicle speed is higher than 100 km/h because it is difficult for collector boots to accurately grasp the power rail. Moreover, it makes the contact rails interval maintenance and passenger evacuation difficult due to accidental touch electric shock [1].

For these reasons, the realization of new power transmission technology to vehicle is solicitous. One solution is the onboard battery system which is to power the vehicle by charged battery set or super capacitor set. In this technology, the battery or super capacitor set is charged in station during the standstill, meanwhile the vehicle braking energy is utilized to be stored in the onboard battery or super capacitor set to increase the system efficiency [1, 2].

But onboard battery system will take up the volume and increase the weight of the vehicle. Besides, it reduces the effective load and affects the system efficiency. So, new contactless power supply technology is desired.

These problems are also same to the electric vehicle (EV), therefore, a "dynamic powering" which is independent on heavy battery, is under development for EV [2].

Now, the active study on applying the IPT to the electric car is in rapid progress [3-11]. The IPT system for a rail transit has yet to be put into practical use including some enterprises such as Bombardier in Germany [9, 10].

Beside, as we know, maglev train system is a promising transportation system, where a contactless power supply system is more necessary. A typical example is the transrapid (TR) maglev system from Germany.

A main feature of the TR is the long stator concept with the motor winding being part of the guide way equipment. The power is supplied to the magnets for support and guidance, climate control and vehicle electronics, but not for propulsion as conventional rail transit systems [12, 13]. This energy is provided by linear generators with the coils integrated into the poles of the support magnets as shown in Fig.1. The linear generator uses the cogging effect to produce the harmonic flux from propulsion magnetic field and the relative motion of the generator coil to generate the induced voltage which is proportional to the velocity of the vehicle. In TR08 system, a 100% supply is achieved above 100 km/h by this way [13].

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But, at low velocities or standstill, the TR uses a conventional system of current collectors and power rails attached to the guide way. This mechanical system is contrary to the basic concept of the maglev train - contact free operation in the whole velocity range from standstill to 500 km/h [13].

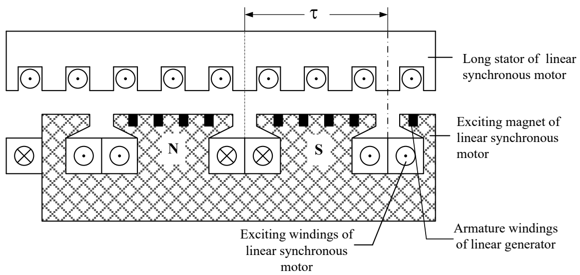


Fig. 1. Principle of linear generator for TR maglev train.

High speed superconducting maglev system has been developed in Japan, Yamanashi Maglev Test Line since 1997, and it has been decided to take revenue service as a part of Chuo-Shinkansen line between Tokyo and Nagoya in 2027. The On-board power supply is gas turbine generator now, but inductive power collection is being developed as shown in Fig. 2 [14].

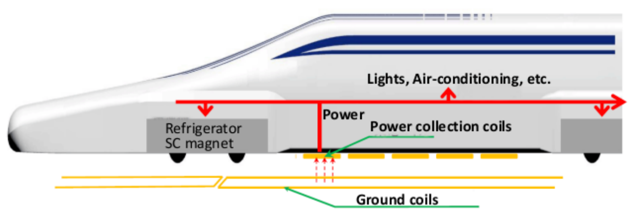


Fig. 2. Inductive power collection developed for superconducting maglev.

Therefore, a new promising solution of the contactless power supply (CPS) or wireless power transmission (WPT) system is required, which should do not rely on large and heavy battery but on the vehicle directly and can efficiently get enough power while moving along a track.

In this paper, first we review the essential characteristics required to develop high power IPT systems and comments on the key technologies. Then, we discuss some important technical issues such as coupling coil structures, power supply control, segmentation switching techniques and bidirectional energy transfer for braking energy feedback applied to rail transit. This study shows that the IPT system is applicable to the rail transit system in the near future.

II. Choice Of IPT System For Rail Transit

According to the different transmission mechanism, wireless power transmission can be divided into several types as shown in Fig.3 [15, 16].

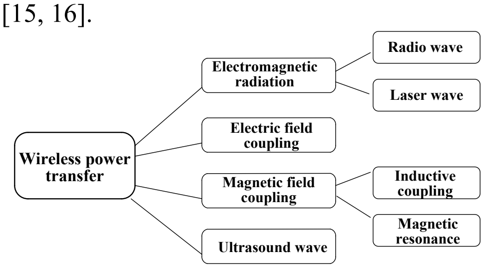


Fig. 3. Category of wireless power transimission.

At present, more attention is paid to magnetic field among these wireless power transfer technologies. In this way, an alternating magnetic field is generated by the coil on the power supply side, and the energy is coupled to the coil on load side. According to the occurrence of resonance and transmission distance relative to the size of the transmission coil, it is divided into induction type and resonance type. The mechanism of induction type which is called inductively coupled power transfer (ICPT) is similar to that of separable transformer as shown in Fig.4 [13].

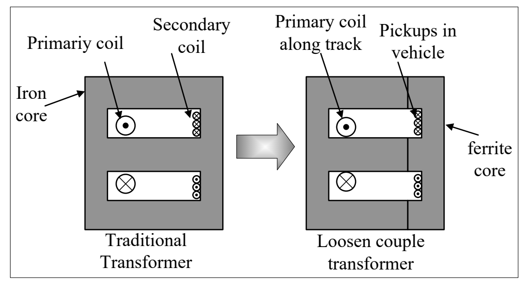


Fig. 4. Physical principle of the ICPT system.

Because the air gap portion replaces the core, it results in a non-directional line of magnetic field and a coil-side hinge on the load side. So only in a short distance, high power can be transferred efficiently. With the distance increases, the transmission efficiency drops rapidly [15, 16].

In ICPT technology, the power is up to hundreds of kW or more, the efficiency is up to 90% or more, the transmission distance is generally a few centimeters. The transmission distance of magnetic resonant power transmission technology at this stage can be up to a several meters, transmission power ranges from tens of W to several kW, and the efficiency ranges from 40% to 90% [13, 15, 16].

By comparing these WPT above, it is clear that the IPT technology is the most promising and applicable method for rail transit. When the IPT system is applied to a train, the power could be stably supplied compared with that of the EV system because the train runs on the track. A configuration of the IPT system for a rail transit is shown in Fig.5 [17].

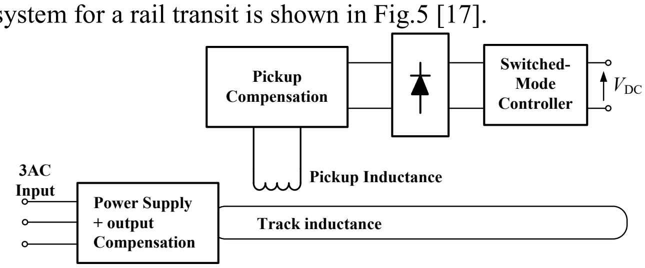


Fig. 5. ICPT system for rail transit.

III. Fundamental Principles And Key Technology Of IPTS

A typical ICPT system is shown in Fig. 6. It comprises of the follows: (1) a convert circuit that takes electric AC power from grid to DC voltage, (2) primary high frequency inverter which outputs high frequency voltage, (3) primary compensated circuit to cause the primary resonance, (4) an primary coil along the rail driven by the power supply whereby current in the coil causes a high frequency magnetic field, (5) secondary coil or pickups moving along the rail that intercept the magnetic field and convert that field energy to controlled electricity, (6) secondary compensated circuit to cause the secondary resonance, (7) rectifiers that convert the current induced in secondary to required voltage or current.

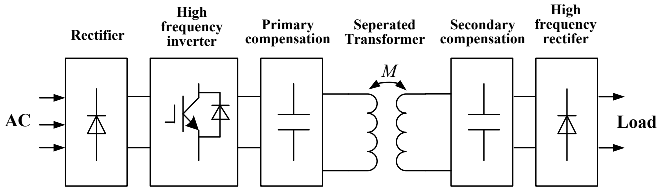


Fig. 6. Basic structure of inductive power transmission system.

A. A Power Supply

The primary converter is a high frequency inverter as shown in Fig.7. The basic inverter structure is push-pull converter [18], a half-bridge inverter (Fig.7.a) or a full-bridge inverter Fig.7.b). In medium and high power applications, full-bridge inverter which is flexible control but without the voltage-sharing capacitors are widely used. Although there are some differences drive methods for these inverters, but it is same in the end that a certain frequency square wave voltage is output. Because the primary compensation circuit and the primary winding inductance form a resonant circuit [19], the square wave voltage is converted to a sine wave current output to the primary winding coil.

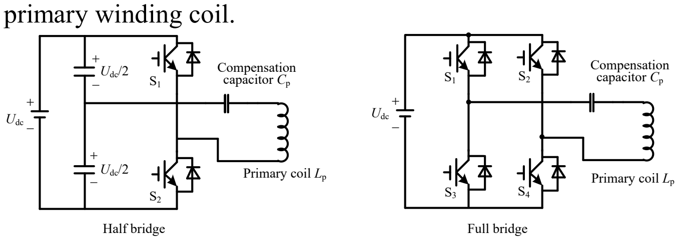


Fig. 7. Primary inverter structure.

The secondary rectifier firstly converter high frequency induced voltage to DC, and then convert DC to required voltage. For the occasion of the low voltage and high current of the secondary side, MOSFET is often applied instead of the diode to reduce the conduction loss because of the advantage of the low on-state voltage drop. The structure of the diode rectifier bridge and the MOSFET synchronous rectification bridge is shown in Fig.8 with MOSFET power devices Q1 ~ Q4 [20].

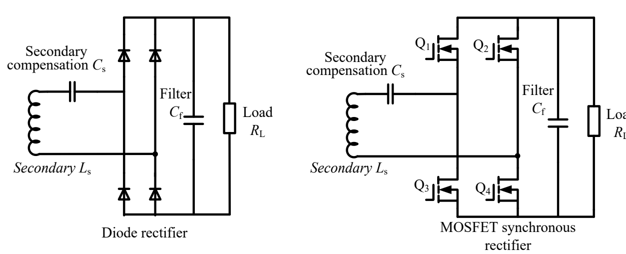


Fig. 8. Secondary rectifier structure.

In high-frequency applications, especially for high power in rail transit, the converter switching losses will become very obvious. Therefore, to achieve system control and to minimize the loss of the converter is very important.

Because of the difficulty in realizing the high-power system with a unit module, several inverters using insulated gate bipolar transistor(IGBT) switching elements were linked in parallel or series to realize the high power output[21, 62].

Fig.9 shows a topology of IPT system based on cascaded inverter with matching transformer.

The inverter consists of several inverter modules that convert dc power to a high frequency power source, and a set of three matching transformers that convert to the required output current.

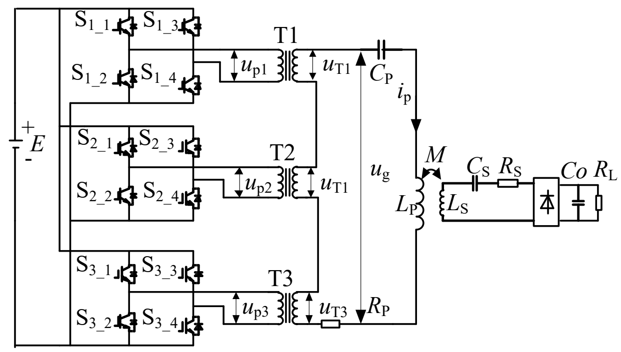


Fig. 9. Topology of IPT system based on cascaded inverter with matching transformer.

B. Magnetic Coupling and the IPT Model for Rail Transit

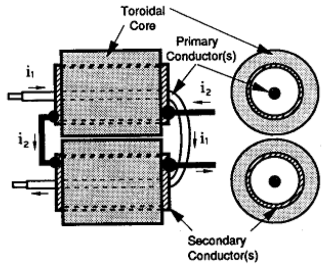
Mobile separable transformer is the most important devices in contactless power transmission systems. Chun T. Rim etc. gave the detail description on wireless power transfer systems for roadway-powered electric vehicles [22, 23].

Several main structures of mobile separable transformer are described in Fig.10.

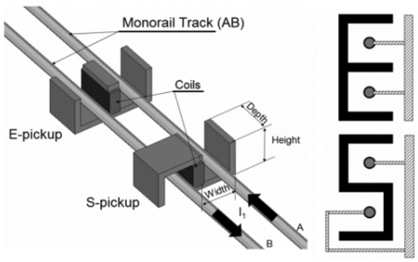
(1) The primary side is a powered long wire whereby current in the track causes a magnetic field that follows the track. The secondary side core surrounds the primary side wire. The shape of the core may be the coaxial core [24], an S-type core [25], an E-type core [26], etc. These electromagnetic mechanisms have the characteristics of better coupling, but the scope of the activities of the secondary coil is strictly limited and the application is inconvenient.

(2) If the primary and secondary sides are all rectangular coils, it is suitable for mobile applications [12, 27]. The secondary side can be hollow [28-30] or with a magnetic core [31] to improve the coupling performance. German researchers use a sandwich core structure on the secondary side applied in German TR09 maglev train [12]. The secondary windings are surrounded by ferrite on three sides to act as a magnetic flux concentrator while shielding the metal in the vicinity of the secondary connector.

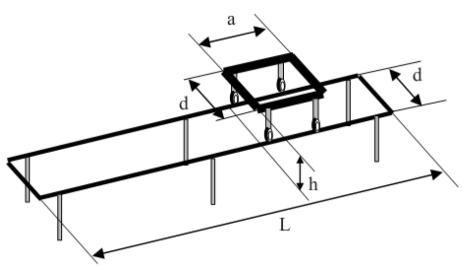
For the rectangular coils, when the width of the coil is constant, the greater the ratio of the length of the primary side to the secondary side, the longer the coupling stable region and the best coupling performance can be obtained. When the secondary coil and the primary coil are aligned at the end, the coupling coefficient is the largest. As the overlap area between primary and secondary decreases, the coupling coefficient also decreases [32-34].



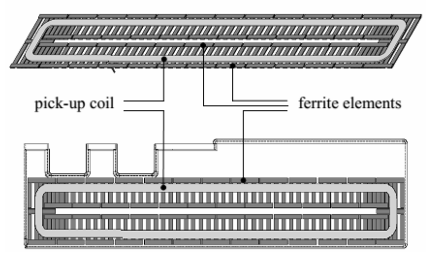
(a) Coaxial Winding Transformer



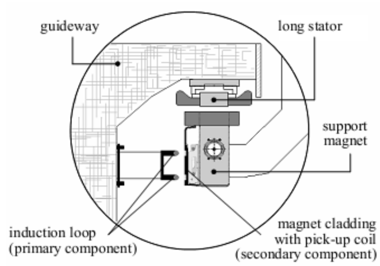
(b) E or S core pickup side structure



(c) Hollow rectangular transformer



(d) Rectangular winding sandwich core arrangement



(e) Components of the IPS® system

Fig. 10. Mobile contactless transformer several structures.

To increase the coupling coefficient and mutual inductance, trapezoidal winding cross section for vehicle was proposed as shown in Fig.11 [35].

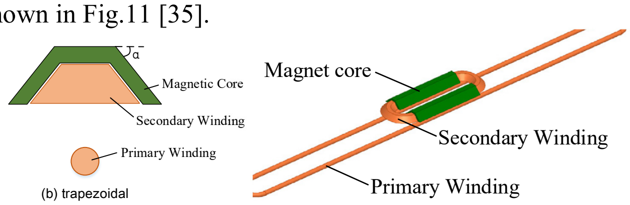


Fig. 11. Separable transformer with primary trapezoidal winding cross section

Fig. 12 shows the conventional 60kW-class WPT model and ground power feeding line applied to the Wireless-Tram. As shown in Fig.12, the ground power feeding line has a lot of ferrite-core. In this core-type WPT model, the construction for the ground power feeding line and equipment is difficult and the cost is high because the ground power feeding system has to be installed throughout the entire tram route. Therefore, derivation of a coreless-type WPT model with low-cost structure is necessary. In general, the flux linkage into the secondary pickup coil is reduced when the ferrite core is eliminated from the ground power feeding line. Consequently, in order to apply a coreless-type ground power feeding line to WPT model, a derivation of an appropriate secondary pickup structure is necessary [36].

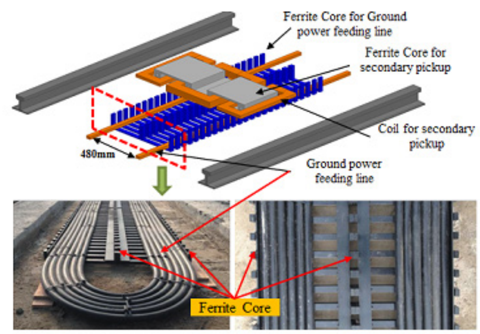


Fig. 12. WPT model and ground power feeding line for wireless tram.

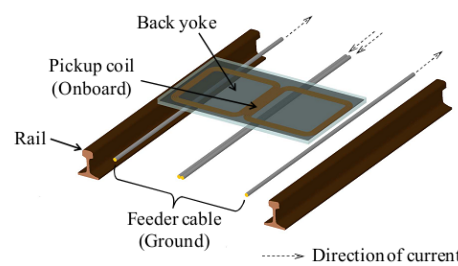
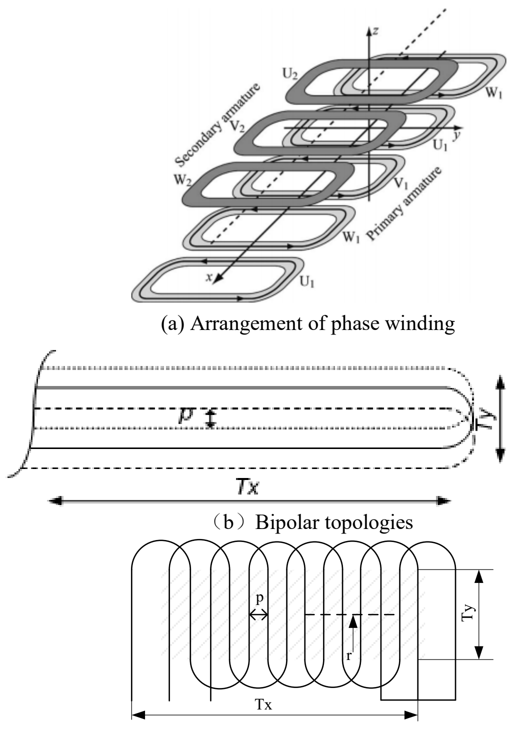


Fig. 13. A figure-of-eight coil for IPT in rail vehicle.

Keigo Ukita, *et al*. proposed a figure-of-eight coil which is able to decrease the leakage flux used in rail vehicle as shown in Fig.13 [37].

In order to increase the stability of coupling under different motion positions and reduce the sensitivity to position deviation, scholars have studied the characteristics of three-phase separated transformers [38-42]. A proposed three-phase contactless transformer structure is shown in Fig.14 (a), and it prove the conclusion that stable energy can be obtained in the direction of the secondary edge movement [39].

Another type of three-phase contactless transformer structure shown in Fig.14 (b) and (c), we can reduce the secondary side of the lateral offset sensitivity. The benefits of the three-phase structure are that the secondary rectifier filter capacitor requirements are relatively low [43]. Compared to rectangular coils, the three-phase winding structure and the converter structure are complex and the required winding length is significantly increased, so, no more application in rail transit has been noticed.



(a) Arrangement of phase winding
(b) Bipolar topologies
(c) Unipolar topologies

Fig. 14. Structures of three-phase contactless transformer.

The influence of motion on the contactless transformer has been clear. It is explicit that the change rate of mutual inductance with time could be ignored relative to the change rate of current with time, namely that motion potential can be ignored [44].

The air gap between the primary side and the secondary side of the separable transformer in IPT is large. Generally, there are two equivalent models as shown in Fig.15 [45-48]. One is leakage inductance model (also called T-type equivalent circuit model) and the other is mutual inductance model.

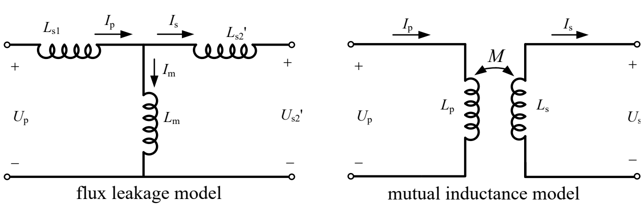


Fig. 15. Two equivalent models of contactless transformer.

It is distinct that two models are equivalent. The difference between the two models is that the flux is divided differently and the inductance is also expressed differently. The mutual inductance model uses a controlled voltage source to describe the coupling effect between the primary and secondary sides without the need to separate the leakage inductance from the self inductance. The equivalent circuit can be used to separate the primary side and the secondary side of the transformer into two separate circuits which can be easily analyzed.

C. Iron Core of Separated Transformer

The coupling coefficient is very low because of the large air gap of contactless transformers. In order to improve the magnetic effect and increase the coupling capacity of the magnetic field, the core is usually used. Compared with metallic iron core and iron powder core, although the saturation magnetic induction Bs of ferrite is relatively low and is affected by temperature, it has high resistivity, small eddy current and small iron loss, i.e., high frequency loss. In high-frequency applications, the loss of the magnetic flux density are usually much less than the saturation magnetic flux density, so the disadvantage of low saturation magnetic flux density is not important. Therefore, ferrite is particularly suitable for contactless transformers. For mobile applications, since adding the long core is more complicated and uneconomical, the ferrite core is laid only near the secondary coils. The addition of a magnetic core improves the coupling ability of the system, but also introduces the core loss. So, under the condition of meeting system coupling, it is better to choose the material with low core loss as much as possible. MnZn power ferrites have been widely used due to their relatively high saturation flux density, high resistivity and low loss, covering the range of frequencies from kHz to MHz [49].

IV. Output Power Adjustment and Control Methods

To control the output power for a given contactless transformer and load conditions, the inverter output voltage and switching frequency are regulated. Unlike conventional PWM converters with only tens to hundreds Hertz fundamental frequencies, an ICPT system is typically tens of kilohertz. The resonant converter is utilized, which switching frequency and resonant frequency are close to the general use of square wave modulation.

Fig.16 is the equivalent circuit with the series compensation for both primary and secondary according the fundamental analysis.

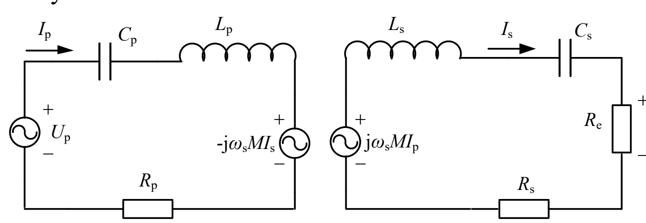


Fig. 16. Equivalent circuit with SS compensation of ICPT system.

$$P_{out} = \frac{U_p^2 (\omega_s M)^2 R_e}{\left| (j\omega_s L_p + \frac{1}{j\omega_s C_p} + R_p)(j\omega_s L_s + \frac{1}{j\omega_s C_s} + R_s + R_e) + (\omega_s M)^2 \right|^2} \tag{1}$$

It is known that the output power is related with the inverter's effective output voltage U_p, switching frequency f_s and load.

The power control methods of primary side are generally includes amplitude modulation (AM), frequency modulation (FM), phase shift control (PHC), intermittent energy injection control (IEIC), Pulse density adjustment (PDM). Because the advantages of the pulse density modulation method, such as the output frequency is basically the same, the switching loss is relatively small, easy to achieve digital control, more suitable for open-loop work situations, it is widely used especially in heavy load. [50-56].

Under the occasion of one primary side powering to multiple loads, the primary current generally keeps unchanged, and each secondary side regulates their own output power.

A special power regulation method which utilizes harmonic component of resonant inverter output voltage other than fundamental component to regulate the transferred power was proposed [57]. In this method, the switching frequency is set to be much lower than the resonant frequency, but the frequency of selected harmonic component is the same as the resonant frequency.

The power conditioning methods on the secondary side are summarized as:

(1) Keep primary side current constant: The secondary side is rectified, and the output voltage is regulated by a DC / DC converter to achieve the secondary side voltage regulation [58]. This method applies in the case of multiple loads in one primary side.

(2) High frequency chopper to secondary voltage: The method is to chop the high-frequency voltage induced by the secondary side and change the effective value of the AC voltage obtained by the load. The output waveform of the control method is suitable for occasions such as incandescent lamp where the quality of the power supply is not high and without rectifier capacitors. This mode reduces the inrush current at startup for the secondary side.

(3) Direct AC-AC mode: The secondary outputs a specific waveform directly, where the bus support links is unnecessary, and the output voltage dependents on the given original AC voltage envelope frequency. This is suitable for a specific frequency AC power supply load. Since there is no capacitive energy storage part, the output voltage is greatly affected by the power quality of the primary input power supply [58-59].

V. Long-Distance Power Supply Method

For rail transit, the primary side is much longer than the secondary side to ensure a smooth power supply during the vehicle moving. However, in the face of long-distance power supply, the long primary coil will cause a large copper loss and reactive power, especially the harmful flux leakage to outside. So, the primary side of power supply is designed in segments to overcome these problems.

Segmentation of power supply rail requires many IPTS along a road because a power supply rail cannot be infinitely deployed. It should be segmented so that each segment can be independently turned ON and OFF. The length of a power supply rail is an important design issue because it would be too expensive if the length is very short due to an increased number of inverters and switch boxes, whereas the power loss would be too large if the length is very long due to increased resistance. Besides these issues, the amount of cable use, EMF level, and car length should be considered when determining the segmentation scheme [23].

At present, the research on segmented power supply technology of ICPT system for long distance power supply is mainly focused on segmented power supply topology, segment crossing stability control and vehicle position detection and so on[60-67]. Typical methods are as follows.

A. Method 1: Segmented power supply

The method has been applied by Bombardier in mobile power supply. Each segment of the inverter is powered by 750V DC power supply. Each segment of primary coil is 8m long as shown in Fig.17 [68]. The primary coils are installed in the middle of two parallel rails and it is flush with rails or pavement. The test line is divided into five sections, the first and fifth section is 240 m long and the second to fourth sections are each 10 m long. The total length is 510m long. Only in the area covered by the vehicle, the primary coil is energized to reduce the unnecessary primary side conduct losses and electromagnetic interference. In this system, one inverter supplies power to two adjacent sections.

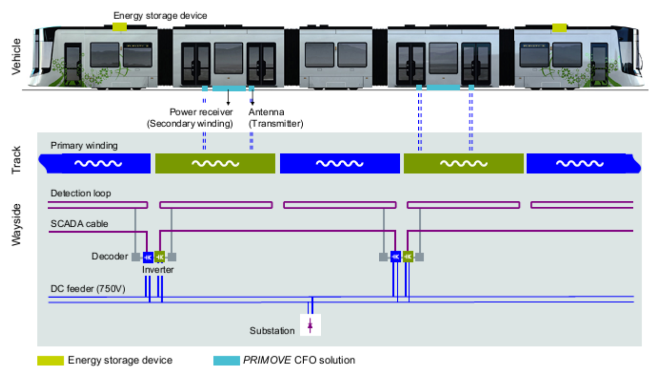


Fig. 17. Power supply diagram of Bombardier Primove system.

B. Method 2: intermittent energy supply

KAIST on-line electric vehicle (OLEV) is an advanced and referenced ICPT system in which only 5% to 15% of the roads have power supply rails laid in the road. When the electric vehicle passes through the power supply section, the corresponding primary coils are energized to transfer power to the secondary side to reduce the electromagnetic radiation and power loss. In this method, instead of continuously providing power to the vehicle, intermittent energy is provided to charge the electric vehicle. In the topology of circuit, based on the primary single-phase full-bridge inverter, an additional bridge arm is added to supply power to another adjacent segment to eliminate the mechanical switch [69]. This corresponds to two segments full-bridge inverter share a bridge arm in converter as shown in Fig. 18.

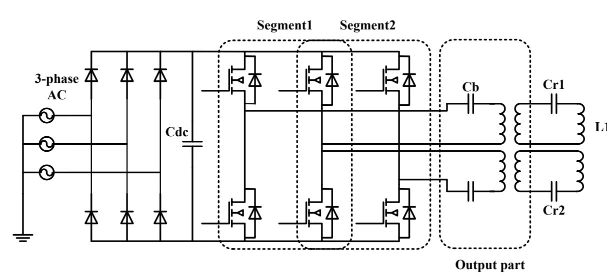


Fig. 18. Power supply topology of KAIST OLEV system.

John T. Boys provided an IPT power pad known as the double-D (DD) was proposed in [70, 71] and consists of two coplanar coils, multiple ferrite strips, and an aluminum sheet backing (Fig. 19) to an EV on the move.

In a lumped DD- and DDQ-based IPT highway, there are two main ways in which the pads may be orientated along the highway. In Fig. 19(a), the DD primary and secondary pads are orientated so that the DD coils are parallel to the direction of EV travel, while in Fig. 19(b), the pads are orientated so that the DD coils are perpendicular to the direction of EV travel. In both orientations, the distance between the centers of the primary pads is referred to as the primary pad pitch (PP), and the spacing between the primary pad cases is referred to as the primary pad spacing (PS). Both possible orientations offer certain benefits for dynamic EV powering applications.

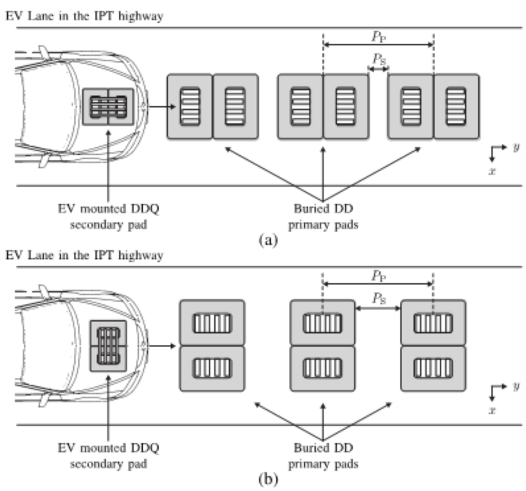


Fig. 19. Possible pad orientations in the proposed IPT EV highway with (a) pads arranged parallel to the direction of EV travel and (b) pads arranged perpendicular to the direction of EV travel.

C. *Method 3: double-coupled system (DCS).*

For roadway IPT system, a unique double-coupled system (DCS) is proposed [72]. The DCS utilize an elongate primary coil along the track to power multiple EVs while at the same time. It allows independent control of individual charging sections through the use of an additional circuit called an intermediary coupler circuit (ICC) as shown in Fig.20. That allows frequency changing and synchronization without reflecting unwanted reactive onto the backbone supply.

The DCS is shown in Fig. 21. Here, an extra ICC is added between the power supply primary track and each ground pad. The functionality of the ICC is more than just to switch the ground pad ON and OFF. A separate system that detects the approaching or leaving of EVs is used to signal each intermediary coupler when to energize the ground pad or not. This enables sections of the road in proximity to the EVs to be energized and reduces magnetic field emission. Because the power transfer is now coupled twice (i.e., between the power supply and the ICC, and then between the ICC and the EV), the system is called double-coupled.

A similar circuit for OLEV is that of a distribution or local mode power supply system for OLEV [73]. It includes a high frequency step-up transformer, a high frequency step-down transformer. The inverter supplies power to only one primary winding.

In summary, Method 3 requires a large number of local devices with cost and losses. Method 2 is not continuous power supply, electric vehicles need to bring their own part of the energy storage system, in specific applications is possible. In the method 1, the primary coil provides continuous power supply to the vehicle. However, when the vehicle passes the section, an inverter cannot supply power to the two windings at the same time, which may causes the fluctuation of energy and burdens the energy storage system of the vehicle. But, by using a closed control of the load voltage with variable frequency for the ground inverter, we can restrain the fluctuation of energy effectively [77].

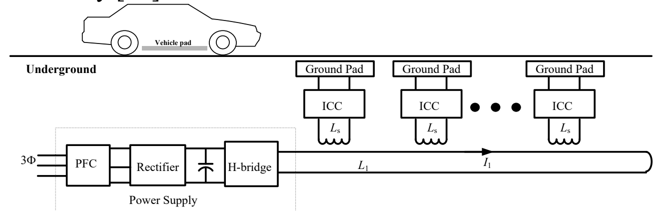


Fig. 20. An example of double-coupled system.

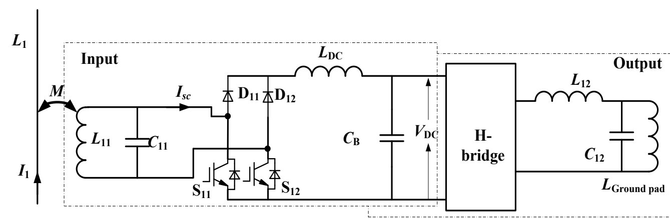


Fig. 21. Schematics of intermediary coupler circuit.

D. *Segmentation control*

A power supply topology of the terrestrial inverter based on the multi-coil parallel connection is a solution as shown in Fig.22~Fig.24. The input impedance model of the ground power supply based on the original secondary string compensation is deduced [74]. It is concluded that when the receiving unit is insufficient compensation, input impedance of the section will be reduced when the receiving unit enters the given coil section. When the receiving module is not on the range of the ground power supply, the inverter input impedance increases and the ground coil current of the section naturally decreases. This scheme may realize automatic segmentation control by using suitable resonance compensation.

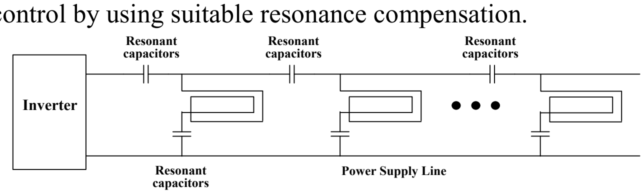


Fig. 22. Power supply model of automatic segmentation control.

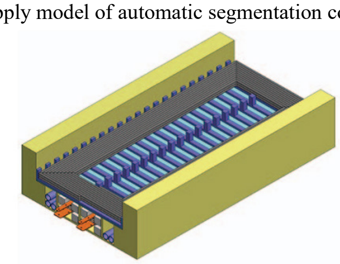


Fig. 23. Power supply line module.

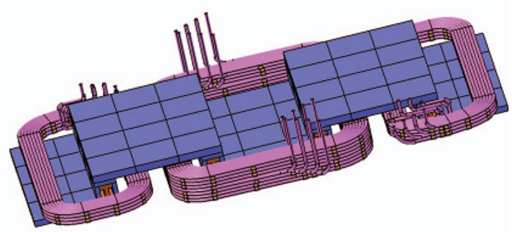


Fig. 24. Pick Up module.

Chun T. Rim proposed a new cross-segmented power supply for segmented power rail topology for the electric car online charging [74]. As shown in Fig.25, on the ground one inverter is connected in series to multi-stage primary coil, each series coil is then connected to the automatic compensation switchgear. Two wires are laid on ground. Through the control of the switch cabinet, the magnetic field of two wires is in the same direction when the vehicle is passing by. But the magnetic fields of the two wires are mutually cancelled in the no vehicle section through the switch cabinet. This scheme of power supply rail can use a single terrestrial inverter to accomplish multiple power supply at the same time. Meanwhile, this also can effectively reduce the total length of the ground power supply cable, reduce the cost of the system and ensure that electromagnetic radiation can meet the standards.

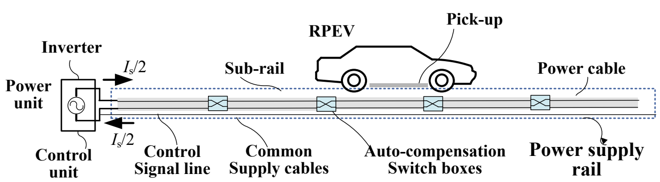


Fig. 25. Proposed cross-segmented power supply rail consists of switch boxes and sub-rails without any common supply cable.

To OLEV, sub-power supply section length, vehicle speed and some factors on the transmission efficiency is important. The relationship between the primary and secondary coupling coefficients, the relationship between the primary power factor and the length of the power supply section was plotted. The coupling coefficient change is calculated and the average weighting coefficient is obtained. The sectional track will allow a smooth flux transition when a vehicle is moving from one track to the next track for a smooth power transmission. Multiple sectional tracks can also be powered simultaneously to form effectively a longer track [75, 76].

To solve the problem of voltage fluctuation due to the change of the secondary coil coupling characteristic when the secondary coil is crossing the different primary section, a closed control scheme of the load voltage and primary current with variable frequency for the ground inverter power supply is applied based on the secondary coil position. In this control, position feed forward compensation was adapted in the current loop. Also a variable resonant frequency tracking method based on the secondary position was proposed. The test conducted on the 200kW contactless power supply prototype showed that the control strategy was able to ensure the stability of the output voltage when the vehicle crossed the interval of primary segments [77].

Yugang Su, *et al*. proposed an embedded transmission coil structure, analyzed the electromagnetic characteristics of the proposed structure and presented design method of the embedded transmission coil. The fluctuation of the mutual inductance between primary and secondary is about 5% when the car across the interval of primary segments which is better than the rectangular transmission coils [78].

The primary transmitting coil is wound according to Fig.26. There are three coil domains for the embedded primary transmitting coil. Each coil domain has different numbers of turns and sizes, but the winding direction of each domain is the same. Domains 1 and 2 are switching area where switching operations occur, domains 3 are operating area that are normally operating without switching operations.

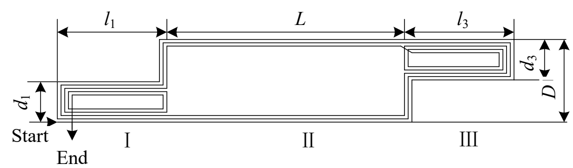


Fig. 26. Embeddable power supply coil and their cascading mode.

In summary, segmented power supply technology of ICPT system for long distance power supply are accepted by the improvement of segmented power supply topology, segment switching stability control and vehicle position detection and so on. A reasonable design of the sub-power supply scheme and control method is of great significance for reducing the copper loss of the primary winding and the system cost, and improving the stability of the power transmission.

VI. Bidirectional Inductive Power Transfer Systems

In the power supply system for rail transit, the electric brake is the first choice which usually adopts the energy regeneration. At present, there are two ways to deal with the regenerative energy. First, the braking energy is feed back to the electric bus for other train operation and balance the entire power line energy. If the electric bus voltage is over high, energy will be consumed by resistance in the substation or vehicle box. The second is that the energy is utilized for the charging of the battery or super capacitor bank or other energy storage equipment on board, and the energy stored is then used to accelerate vehicle accompanied by external power supply. The braking energy feedback mode is shown in Fig.27.

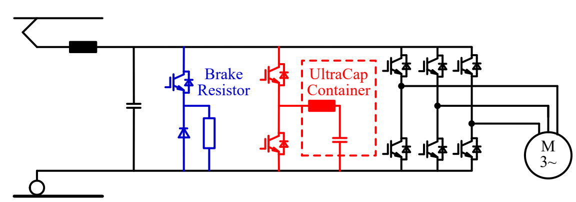


Fig. 27. The braking energy feedback mode.

If braking energy is consumed by on board braking resistor or stored by on-board battery or super capacitor, the resistor on the vehicle will take up the volume and increase the weight of the train. In order to reduce the weight and energy consumption of vehicle and improve the system efficiency, it is a wise solution to feed back the energy generated by braking to the grid or substation.

In order to feed back the energy generated by braking to the grid or substation when IPT is applied for contactless power supply, it is necessary to adopt a bidirectional inductive power transmission system topology. A typical topology is shown in Fig.28. A PWM rectifier is used on the grid side and the secondary converter of IPT system adopts a controllable converter.

When the vehicle is propelled, the IPT system is in a positive energy flow state and supplies power to the vehicle. The PWM rectifier stabilizes the input voltage U_{dc} and the IPT system stabilizes the output voltage U_o. When the vehicle is braked and the electric bus voltage of the vehicle exceeds the threshold value, the IPT system is in the reverse energy flow state, and the braking energy is fed back to the power grid.

A. The model of bidirectional IPT System

A typical bi-directional IPT system is that the primary-side transmitter and secondary-side receiver are both series compensation (SS) as shown in Fig. 28. The system includes primary H bridge converter (S_1-S_4), primary compensation capacitor C_p, contactless transformer M, secondary compensation capacitor Cs and secondary H bridge converter (S_5-S_8).

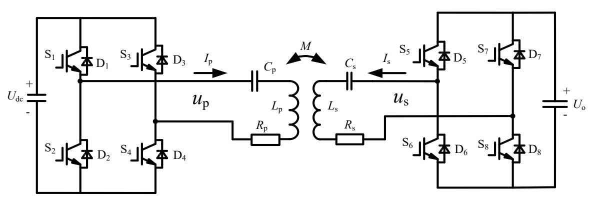


Fig. 28. SS type bi-directional IPT system.

The output voltage fundamental components of primary and secondary converters are as follows,

$$u_p(t) = \frac{4}{\pi} U_{dc} \sin(\frac{\varphi_1}{2}) \cos(\omega t) \tag{2}$$

$$u_s(t) = \frac{4}{\pi} U_o \sin(\frac{\varphi_2}{2}) \cos(\omega t + \theta) \tag{3}$$

where φ_1 and φ_2 are the phase shift angles of the primary and secondary converters, respectively. θ is the electrical angle of secondary converter output AC voltage ahead of the primary converter output voltage.

The output voltage phasor of primary and secondary converter are as follows,

$$\dot{U}_p = U_p \angle 0 \tag{4}$$

$$\dot{U}_s = U_s \angle \theta \tag{5}$$

$$U_p = \frac{2\sqrt{2}}{\pi} U_{dc} \sin(\frac{\varphi_1}{2}) \tag{6}$$

$$U_s = \frac{2\sqrt{2}}{\pi} U_o \sin(\frac{\varphi_2}{2}) \tag{7}$$

where, U_p and U_s are the output RMS voltage of primary and secondary respectively.

When the primary coil and secondary coil are fully resonant, we get $\omega^2 = 1/L_pC_p = 1/L_sC_s$. By deduction, we can obtain the coil currents of primary and secondary as

$$\dot{I}_p = \frac{R_s \dot{U}_p - j\omega M \dot{U}_s}{(\omega M)^2 + R_p R_s} \tag{8}$$

$$\dot{I}_s = \frac{-j\omega M \dot{U}_p + R_p \dot{U}_s}{(\omega M)^2 + R_p R_s} \tag{9}$$

The active power and reactive power of the primary converter are as follows,

$$P_p = \mathrm{Re}[\dot{U}_p \dot{I}_p^*] = \frac{U_p\left(R_s U_p + \omega M U_s \sin\theta\right)}{(\omega M)^2 + R_p R_s} \tag{10}$$

$$Q_p = \mathrm{Im}[\dot{U}_p \dot{I}_p^*] = \frac{\omega M U_p U_s \cos\theta}{(\omega M)^2 + R_p R_s} \tag{11}$$

The active power and reactive power of the secondary converter are as follows

$$P_s = \mathrm{Re}[\dot{U}_s \dot{I}_s^*] = \frac{U_s\left(R_p U_s - \omega M U_p \sin\theta\right)}{(\omega M)^2 + R_p R_s} \tag{12}$$

$$Q_s = \mathrm{Im}[\dot{U}_s \dot{I}_s^*] = -\frac{\omega M U_p U_s \cos\theta}{(\omega M)^2 + R_p R_s} \tag{13}$$

The phasor diagram of the system voltage and current is shown in Fig.29.

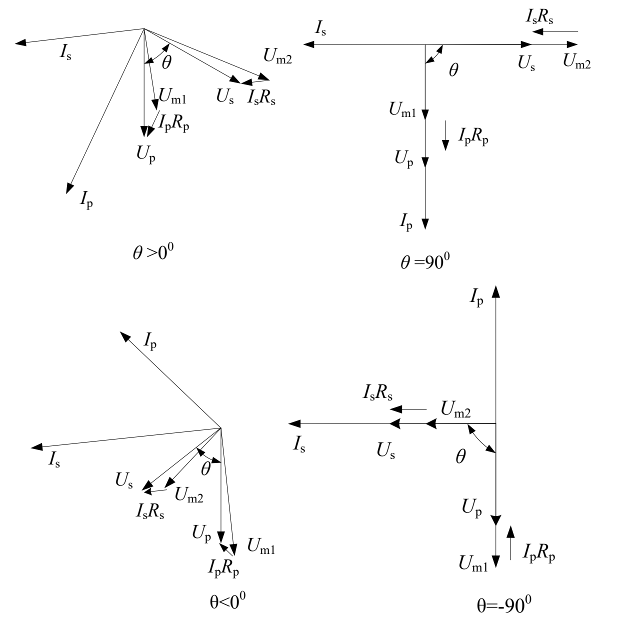


Fig. 29. A phasor diagram of the system voltage and current.

when $R_p << \omega M$, $R_s << \omega M$, the output power of the primary and secondary converters are simplified to

$$P_p \approx \frac{U_p U_s}{\omega M} \sin\theta = \frac{8 U_{dc} U_o}{\pi^2 \omega M} \sin(\frac{\varphi_1}{2}) \sin(\frac{\varphi_2}{2}) \sin\theta \tag{14}$$

$$Q_p \approx \frac{U_p U_s}{\omega M} \cos\theta = \frac{8 U_{dc} U_o}{\pi^2 \omega M} \sin(\frac{\varphi_1}{2}) \sin(\frac{\varphi_2}{2}) \cos\theta \tag{15}$$

$$P_s \approx -\frac{U_p U_s}{\omega M} \sin\theta = -\frac{8 U_{dc} U_o}{\pi^2 \omega M} \sin(\frac{\varphi_1}{2}) \sin(\frac{\varphi_2}{2}) \sin\theta \tag{16}$$

$$Q_s \approx -\frac{U_p U_s}{\omega M} \cos\theta = -\frac{8 U_{dc} U_o}{\pi^2 \omega M} \sin(\frac{\varphi_1}{2}) \sin(\frac{\varphi_2}{2}) \cos\theta \tag{17}$$

From (14) ~ (17), we can conclude,

(1) The transmitted power is related to the magnitude and phase difference of the output voltage of the primary and secondary converters.

(2) When $\theta = \pm 90^0$, the system reactive power is 0 ($Q_p = 0$, $Q_s = 0$) and system operates in unit power factor.

(3) When $\theta = +90^0$, the energy is transferred from the primary side to the secondary side ($P_p > 0$, $P_s < 0$). When $\theta = -90^0$, the energy is transferred backwards ($P_p < 0$, $P_s > 0$).

(4) With unit power factor, the transmission power of the system is proportional to the magnitude of the output voltage of the primary and the secondary converters, and the output power can be adjusted by adjusting the magnitude of the AC voltage output of the primary and secondary converters.

When $\theta = \pm 90^0$ and the output voltage of the primary and secondary is the maximum ($\varphi_1 = 180^0$, $\varphi_2 = 180^0$), the system delivers the maximum power as follows

$$P_{\max} \approx \frac{8U_{dc}U_o}{\pi^2 \omega M} \tag{18}$$

By analysis, we know the maximum transmission power is proportional to the input DC voltage U_{dc} and the output DC voltage U_o. Besides, it is clear that the maximum transmission power in the reverse energy transfer is approximately the same to the forward energy transfer.

B. Control Strategy

For bidirectional IPT system, it is required to solve the problems such as converter topologies, resonant networks, control strategies, efficiency optimization and the phase synchronization of the output voltage of the primary and secondary converters.

Several bidirectional IPT system converter topology have been proposed, which are H-bridge topologies [79-83], multi-level topologies [84, 85], matrix converter topologies [86, 87], soft DC segments [88], hybrid topologies [89], three-phase topology [90-93], multi-module topology [94], and so on.

According to the type of resonant network, it can be divided into SS topology [95], LCL topology [96], LCC topology [97] and CLCL topology [98, 99].

Till now, two power conditioning methods have been studied deeply.

One method is to control the output power by adjusting the output voltage of the secondary converter as shown in Fig.30 [81].

The phase difference between the primary and secondary converters is fixed at 90° or -90°. The actual output voltage V_{out}, is subtracted from the reference voltage V_{ref} .The error of the output voltage is given to the PI regulator and the output of the PI regulator acts as the phase-shift angle α of the secondary-side converter. The detected voltage of the secondary coil EMF is dealt with the phase-locked loop PLL to get the primary coil voltage phase φ. The phase angle ($\varphi - \alpha/2$ and $\varphi + \alpha/2$) of the modulation signal of the left and right arm of the converter can be obtained according to the primary coil voltage phase φ and the secondary converter phase-shift α. Then the output power can be regulated by adjusting the secondary converter output voltage. With this method, the system is always running at unity power factor.

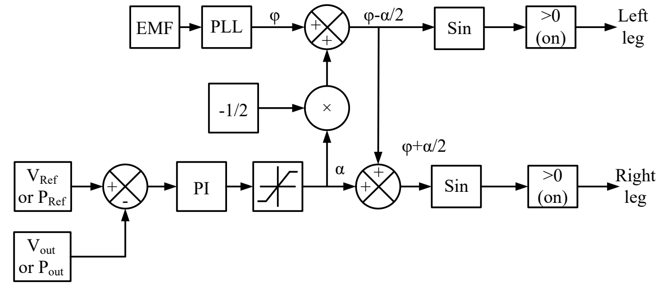


Fig. 30. Regulating scheme of IPT output power by adjusting the secondary converter output voltage.

The other method is to adjust the phase difference of the output voltage of the primary and secondary converters [79], [80] as shown in Fig.31.

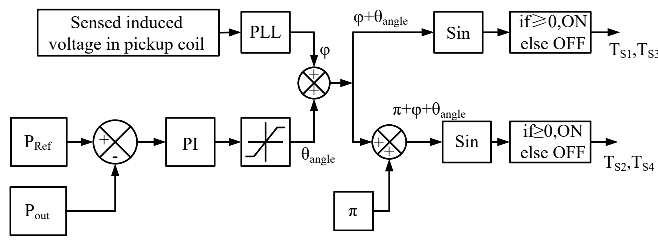


Fig. 31. Regulating scheme of IPT output power by adjusting the converter output voltage phase difference between the primary and secondary.

In this control scheme, the output voltages of the primary and secondary converters are constant. The actual output power P_{out} is subtracted from the reference power P_{ref}. Then the error of the output power is sent to the PI regulator, the output of the PI regulator is used as the output voltage phase difference θ_{angle} of the primary and secondary converters.

The secondary coil voltage is detected and the primary coil voltage phase φ is obtained by the phase-locked loop (PLL). The phase angle ($\varphi + \theta_{angle}$ and $\pi + \varphi + \theta_{angle}$) of the modulation signals of the left and right arm of the converter can be obtained according to the phase angle φ of the primary coil and the phase difference θ_{angle} of the primary and secondary output voltage. By adjusting the converter output voltage phase difference, the output power can be adjusted. With this method, the power factor of the system is not unit since the phase difference of the output voltage of the primary and secondary is not equal to $\pm 90^0$. The power factor will decreases as the system transmission power decreases.

In the bidirectional IPT system, the output voltage of the primary and secondary converters can be used to adjust the output power. The relationship between the output voltages can be determined by the maximum transmission efficiency. The loss is minimized by using appropriate output voltage ratios [100, 101].

By wireless communication, the phase of the primary output voltage can be transmitted to the secondary control system. However, there is a time delay in the wireless communication process. A technique for synchronizing the voltage phase of the primary and secondary converters in a bidirectional LCL IPT system has been proposed as shown in Fig.32 [102, 103].

Instead of using wireless communication, this method adds a detection coil to the receive coil. According to the detected induced voltage on the coil, converter output voltage phase of primary side can be calculated.

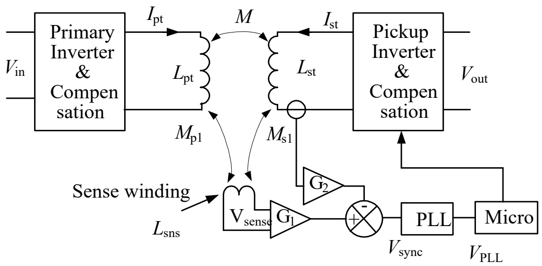


Fig. 32. A synchronization technique for bidirectional IPT systems.

VII. CONCLUSION

The development of key technologies for IPT system in rail transit from its advent to its current status has been introduced in this paper. Researchers have found the methods to solve the issues such as coupling coil structures, power supply control, segmentation switching for long-distance power supply, bidirectional energy transfer for braking energy feedback and so on. Thanks to their continuous effort, the volume, weight, efficiency, air gap, lateral tolerance and cost of the IPT system during this decade are improving and rail transit powered by IPT is becoming viable solutions for near-future transportation. It is specially applicable for maglev trains. Although the first cost of IPT system itself is more expensive than traditional contact mode power supply system, its long term economics, compactness, efficiency, reliability, safety and easy maintenance make it promising in application for modern rail transportation.

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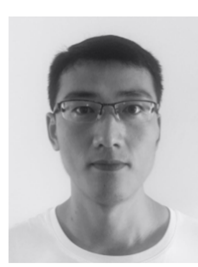

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