Chapter 6

A Review of Dynamic Wireless Power Transfer for In-Motion Electric Vehicles

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Additional information is available at the end of the chapter

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Abstract

Dynamic wireless power transfer system (DWPT) in urban area ensures an uninterrupted power supply for electric vehicles (EVs), extending or even providing an infinite driving range with significantly reduced battery capacity. The underground power supply network also saves more space and hence is important in urban areas. It must be noted that the railways have become an indispensable form of public transportation to reduce pollution and traffic congestion. In recent years, there has been a consistent increase in the number of high-speed railways in major cities of China, thereby improving accessibility. Wireless power transfer for train is safer and more robust when compared with conductive power transfer through pantograph mounted on the trains. Direct contact is subject to wear and tear; in particular, the average speed of modern trains has been increasing. When the pressure of pantograph is not sufficient, arcs, variations of the current, and even interruption in power supply may occur. This chapter provides a review of the latest research and development of dynamic wireless power transfer for urban EV and electric train (ET). The following key technology issues have been discussed: (1) power rails and pickups, (2) segmentations and power supply schemes, (3) circuit topologies and dynamic impedance matching, (4) control strategies, and (5) electromagnetic interference.

Keywords: dynamic wireless power transfer, magnetic coupler, circuit topologies, control strategies, electromagnetic interference

1. Introduction

In recent years, studies on DWPT have gained traction especially from The University of Auckland, Korea Advanced Institute of Science and Technology (KAIST), The University of Tokyo, Oak Ridge National Laboratory (ORNL), and many other international institutions. The topics discussed include system modeling, control theories, converter topologies, magnetic coupling optimization, and electromagnetic shielding technologies for DWPT.

The University of Auckland and Conductix-Wampfler manufactured the world's first WPT bus with 30 kW power. A demo ET with 100 kW WPT capability and a 400 m long track without any on-board battery was also constructed [1] as shown in **Figure 1**.

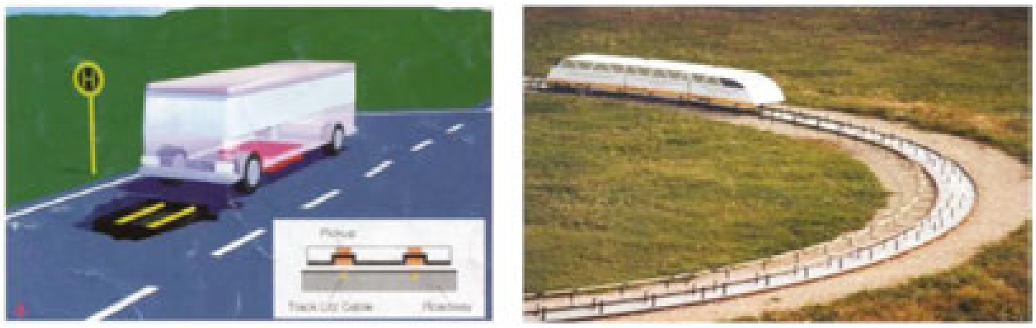


Figure 1. WPT for EV and ET.

KAIST constructed electric buses powered by an online electric vehicle (OLEV) system. The buses are deployed in Gumi city for public transportation, running on two fixed routes covering a total distance of 24 km as shown in **Figure 2**. The OLEV system on these routes is able to supply 100 kW power with 85% of transfer efficiency [2].

Figure 2. KAIST OLEV.

The research in Oak Ridge National Laboratory focuses on coupling configuration, transfer characteristics, medium loss, and magnetic shielding. The dynamic charging system as shown in **Figure 3** constructed by ORNL consists of a full bridge inverter powering two transmitters simultaneously through a series connection. The experimental results show that the positions of the electric vehicle significantly affect the transferred power and efficiency [3].

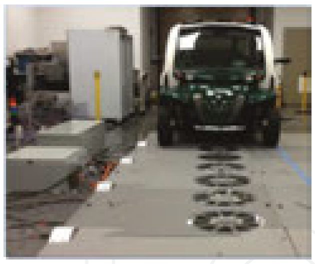


Figure 3. DWPT system of ORNL.

Researchers in The University of Tokyo proposed using the combination of a feedforward controller and a feedback controller to adjust the duty cycle of the power converters in the DWPT system to achieve optimum efficiency. With the advanced control method, a wireless in-wheel motor is developed as shown in **Figure 4**. The current WPT is from the car body to the in-wheel motor. In future, the wireless in-wheel motor can be powered directly from the ground using a dynamic charging system [4].

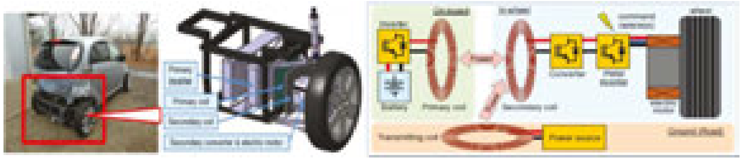


Figure 4. Wireless in-wheel motor.

On the other hand, the Korea Railroad Corporation (KRRI) designed a WPT system for the implementation in railway track. A 1 MW, 128-m-long railway track was developed to demonstrate the dynamic charging technology for EV. The coupling mechanism consists of a long transmitter track and two small U-shaped magnetic ferrites to increase the coupling strength. As a long transmitter track has high inductance, high voltage drop will occur when the current flows through it. In order to reduce this voltage stress, the compensation capacitors are distributed along the track as shown in **Figure 5** [5].

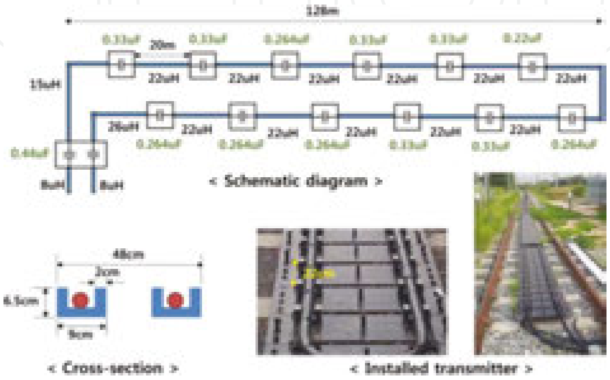


Figure 5. Wireless power rail developed by KRRI.

The researchers from the Japan Railway Technical Research Institute proposed a different design of coupling mechanism for the ET. The transmitters are long bipolar coils, and "figure-8" coils are used as the matching pickups as shown in **Figure 6**. The system is able to transfer 50 kW of power across a 7.5-mm gap with 10-kHz frequency [6].

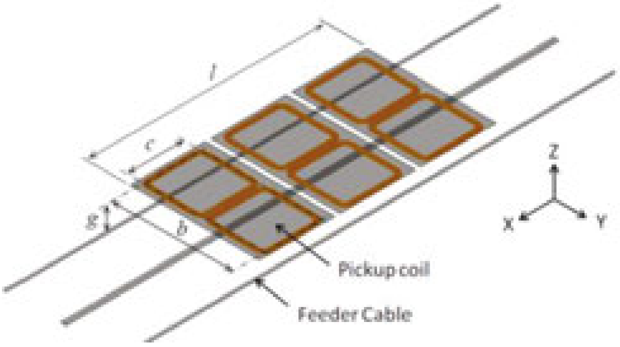


Figure 6. The non-contact power supply system for railway vehicle.

Bombardier Primove from Germany is currently leading in WPT technology for EV and ET. Studies have been primarily conducted for better exploitation of the technology. Apparently, the technical information of the WPT system developed by Bombardier Primove has not been published. In 2013, the company proposed a design shown in **Figure 7** to ensure high reliability when powering the EV. The main DC bus is supplied by k-number of AC/DC substations connected in parallel. This configuration is used to increase the robustness of the system. If one of the AC/DC substations breaks down, that particular substation will be disconnected from the system and other neighboring substations can continue functioning normally, thus avoiding power interruption. Each transmitter cluster is supplied by multiple high-frequency DC/AC inverters in parallel. Similar to the DC bus, the power supply at the AC bus will not be interrupted if an inverter breaks down. At the receiver side, the train contains a DC bus as shown in **Figure 7**. Multiple receivers are supplying to the DC bus simultaneously via AC/DC rectification. The DC bus powers the motor through a controller. If any of the rectifiers is damaged, other receivers can continue providing sufficient power to the DC bus [7].

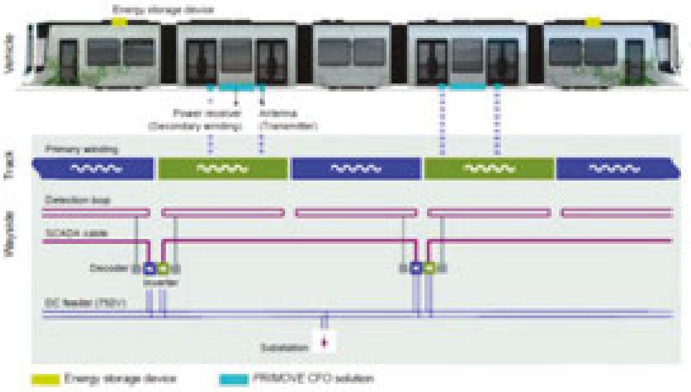


Figure 7. DWPT system for railway vehicle.

The Harbin Institute of Technology demonstrated dynamic charging using segmented transmitters with parallel connections to the inverter [8]. At the receiver side, two layers of flat coils wounded in the same direction are stacked against each other to cancel the points, where transferred power is zero, thereby increasing the overall efficiency. Using the decoupling principle to design the size and position of the two-phase coil, the cross-coupling is cancelled and high efficiency is then achieved at any position [9].

Although several studies have been conducted all over the world yielding exceptional results, factors such as power transfer performance, construction cost, and maintenance cost still require improvement. Other important considerations for practical DWPT implementation include high-power rail, robust control strategies, and EMC.

2. Power rails and pickups

Core-less rectangular coils and bipolar coils are the two general types of coils used in WPT. The University of Auckland proposed using long rectangular rails to transfer power. A larger surface area for road construction necessitates less amount of power to be transferred per surface area. The design is also sensitive to lateral displacement of the electric vehicles. Moreover, a high level of magnetic field leakage occurs at both sides of the rail [10]. KAIST proposed an improved version by adding a magnetic core with an optimized design. Compared to the transmitter rail proposed by the University of Auckland, the transfer efficiency and transfer distance are increased. However, the construction cost is also higher.

KAIST presented an advanced coupling mechanism design and optimization technology in their past research. In 2009, the first-generation OLEV was successfully produced. An E-shaped magnetic core is used as the power transmission rail. The air gap is only 1 cm and the transfer efficiency 80% [2]. A U-shaped transmission rail was also proposed in the same year by significantly increasing the transmission gap to 17 cm with an efficiency of 72%. In 2010, a skeleton-type W-shaped magnetic core is proposed, thus further increasing the transfer distance to 20 cm and efficiency to 83% [2]. From 2011 to 2015, researchers from KAIST designed fourth-generation I-shaped bipolar rails and fifth-generation S-shaped bipolar rails with even larger transfer gap, narrower frame, and higher efficiency [2]. With bipolar rails, the magnetic field path is parallel to the moving direction of the vehicle instead of being orthogonal to the moving direction. The new design is well suited for DWPT due to its advantages such as high power density, narrow frame, and therefore lower construction complexity, robust to lateral displacement, and lower magnetic field exposure on both sides of the rail [10–12] (**Tables 1** and **2**).

In 2015, KAIST proposed using a dq-two-phase transmitter rail for cancelling the zero coupling points along the moving direction [13] using the control method which is relatively complex. A double loop control is implemented by detecting the phase of the primary current. The amplitudes and phases of the d-q currents are controlled using a phase-locked loop and DC chopper according to the position of the receiver.

Type	Coreless long coil	Bipolar rail
Merits	Even magnetic field distribution, stable power transfer, coreless, and low manufacturing cost	High power density, narrow design, robust to lateral displacement, low construction complexity, and low level of magnetic field exposure
Demerits	Low power density, sensitive to lateral displacement, large surface area is needed for construction, and high level of magnetic field exposure	Uneven magnetic field distribution, zero coupling point. High cost due to the usage of ferrite core

Table 1. Advantages and disadvantages of commonly used powering rail.

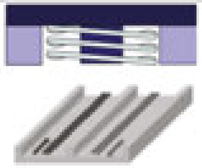
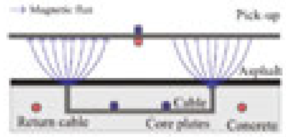
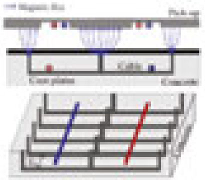
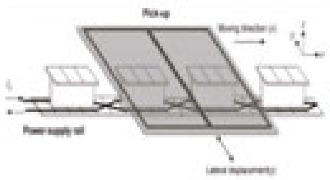
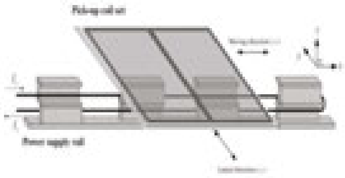
 1st generation E type	 2nd generation E type
 3rd generation W type	 4th generation I type
 5th generation S type	 6th generation dq type

Table 2. Wireless power rails and receiving pickups developed by KAIST (From generation 1 to 6).

3. Segment and power supply scheme

In order to overcome the issues of low transfer efficiency and high sensitivity to the changing parameters in a centralized power supply system, a new segmented scheme is proposed [14]. The voltage at the 50 Hz AC bus is first stepped up to reduce transmission loss. Then, before the segmented transmitters, the voltage is stepped down via the inverter. Constant current is also used at the transmitters. Efficient converter topologies are also reviewed for implementing a centralized power supply system.

(1) Centralized power supply scheme (**Figure 8**)

With the increasing length of the transmitter rail, the bandwidth of the primary side channel becomes narrower. Therefore, the system is more sensitive to the variations of parameters, and the robustness is decreased. The controller for the centralized power supply is relatively

a. High requirements of the components due to a single module supporting large power.

b. The whole rail is activated and causes high loss.

c. Low reliability due to any breakdown will affect the whole rail.

d. The efficiency is low when the load is small.

e. High self-inductance and therefore high voltage across capacitor.

f. Highly sensitive toward the variations in parameters, causing low stability.

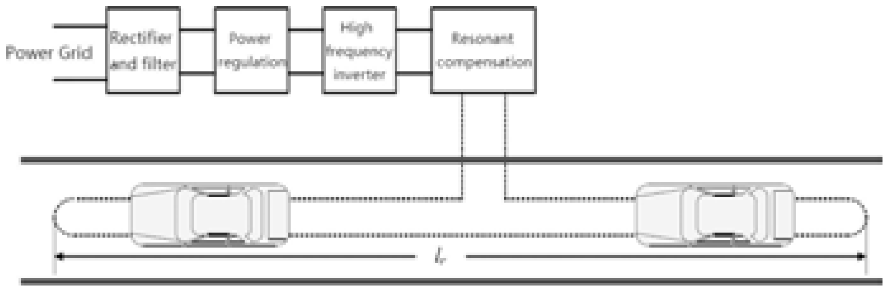


Figure 8. Centralized power supply scheme.

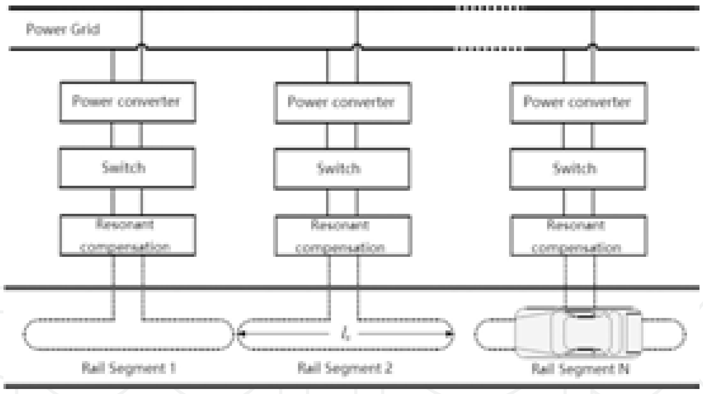


Figure 9. Power frequency scheme—segmented rail mode.

(2) Power frequency scheme—segmented rail mode (**Figure 9**)

The advantages of segmented rails are as follows:

a. Different segments can be turned on at different time periods, decreasing the power loss;

b. Smaller-sized power converters;

c. Higher reliability, when one of the segments breaks down, other segments will still be functioning normally;

d. Lower self-inductance, less sensitive to variations in parameters, and therefore increasing the system stability.

However, segmented rails also have the following disadvantages:

a. High number converters, difficult to control and high maintenance and construction cost;

b. High number of components is required and therefore low reliability of the whole system.

(3) High frequency scheme—segmented rail mode (**Figure 10**)

With segmented rails and centralized power supply, the advantages of this design are as follows:

a. Lesser power converter units, easier to maintain;

b. Different segments can be activated at different time periods, lesser power loss;

c. Lower self-inductance, less sensitive to variations in parameters, increases the system stability.

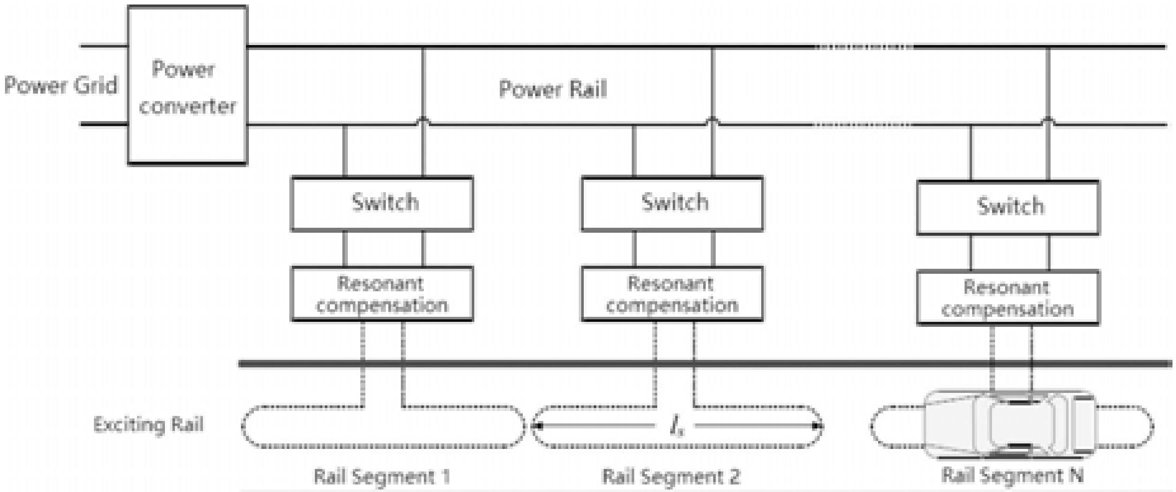


Figure 10. High frequency scheme—segmented rail mode.

However, this design has the following disadvantages:

a. When the power supply breaks down, all of the segmented rails will stop functioning, thus lowering the system reliability;

b. High loss in the cable connecting the power supply to the segmented rails;

c. High capacity power supply and therefore large requirements of the components;

(4) High frequency and high voltage scheme and low voltage and constant current rail mode (**Figure 11**).

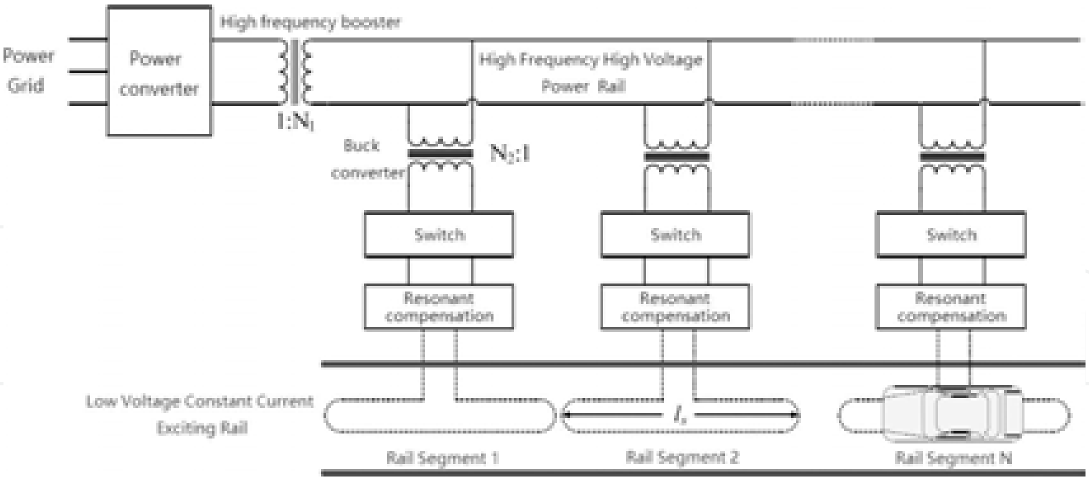


Figure 11. High frequency and high voltage scheme—low voltage and constant current rail mode.

(5) Combination scheme (**Figure 12**)

This type of rails combines the advantages of abovementioned rails; however, the system is complex and only suitable for a large-scale dynamic charging system.

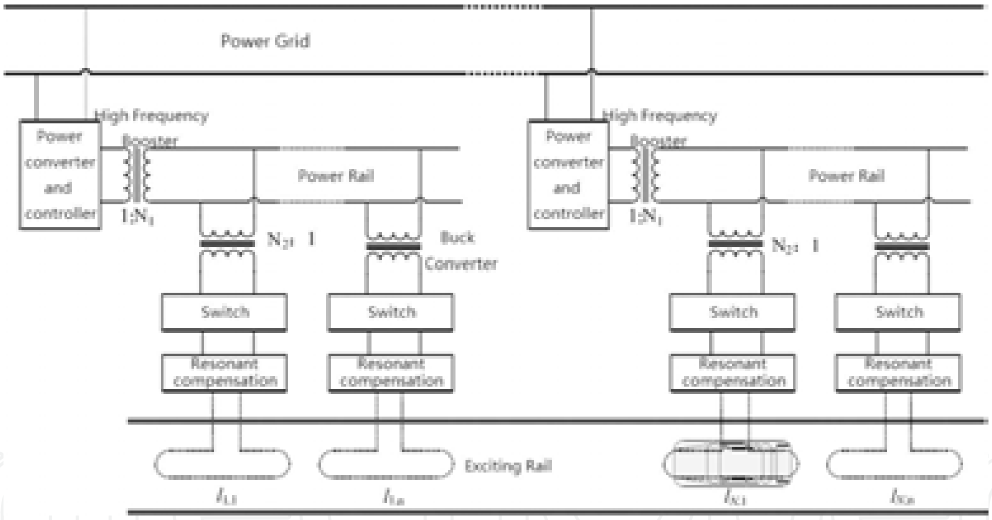


Figure 12. Combined type rail scheme.

4. Circuit topologies and impedance matching

In the DWPT system, the gap between the receiver and transmitter is always changing. Different cars have different heights with respect to the ground and the coupling coefficient will varies significantly. Coupling coefficient is an important parameter in WPT. If the value is too low, the efficiency may drop considerably. Contrarily, frequency splitting phenomena may occur if the coupling coefficient is too high, and the system functions in the unstable region. Therefore, the circuit topology should be designed to be insensitive to coupling changes.

In order to achieve a steady power supply with variations in coupling and to increase the system stability in the light-load region, an LCLC topology can be used. The current at the primary is kept constant and stress on switches is reduced during on-off. At the receiver side, a parallel-T configuration can increase the tolerance of the system toward coupling variation. The proposed topology is shown in **Figure 13**.

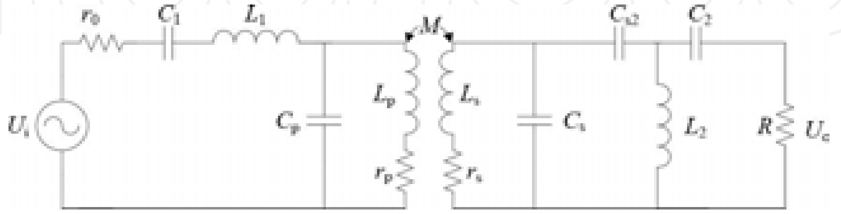


Figure 13. Circuit topology of double LCLC.

The transmitter current is written as follows:

$$i_p = (U_i - U_{r0}) / (\omega_0 L_p) \tag{1}$$

With $\lambda = L_s / L_2 < 1$ as the load coefficient, the receiver output voltage is as follows:

$$U_o = U_{oc} / \lambda = \omega_0 k \sqrt{L_p L_s} I_p / \lambda \tag{2}$$

The output voltage is 1/λ times the receiver voltage. A step-up voltage converter is used to provide sufficient power when coupling is low, therefore increasing the tolerance of the system against lateral displacement.

The voltage ratio and efficiency are given as follows:

$$\begin{cases} G = MR\lambda / L_0 (R\lambda^2 + r_s) + r_0 C_p (M^2 \omega_0^2 + r_p (R\lambda^2 + r_s)) \\ \eta = \omega_0^2 M^2 R \lambda^2 L_0 / (\omega_0^2 M^2 + r_p (R\lambda^2 + r_s))(L_0 (R\lambda^2 + r_s) + C_p r_0 (\omega_0^2 M^2 + r_p (R\lambda^2 + r_s))) \end{cases} \tag{3}$$

where r_0 is the internal resistance of the inverter circuit, r_p is the resistance of the transmitter, and r_p is the resistance of the receiver.

The power and efficiency curves are given in **Figure 14**. The efficiency is high at the low-coupling region which is particularly important for the DWPT application.

As shown by the curves in **Figure 15**, the efficiency and power are significantly improved for different loads and coupling coefficient compared to series topology.

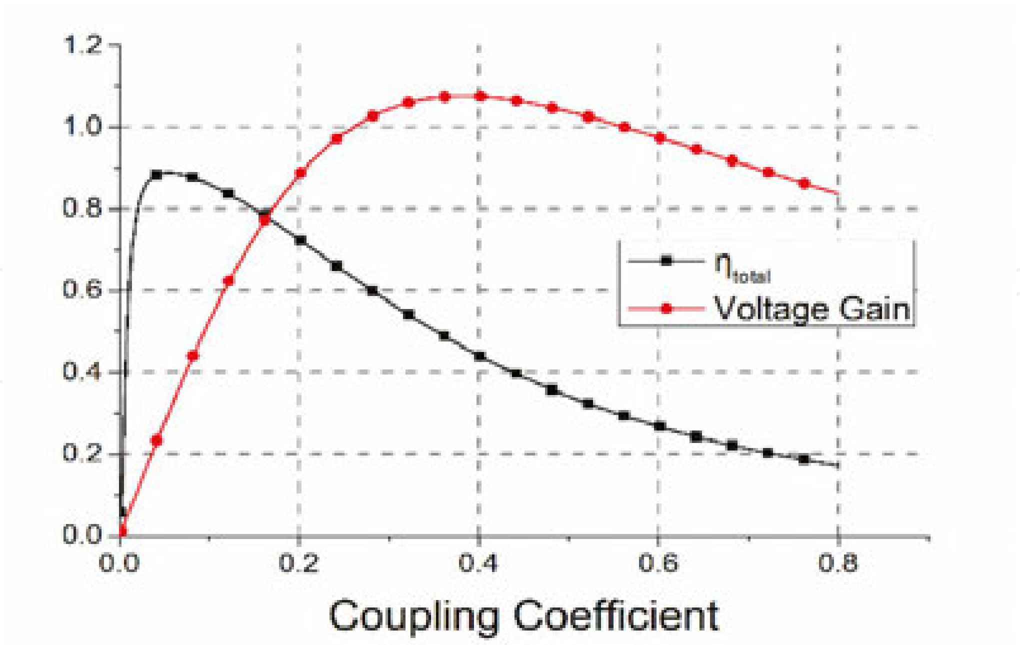
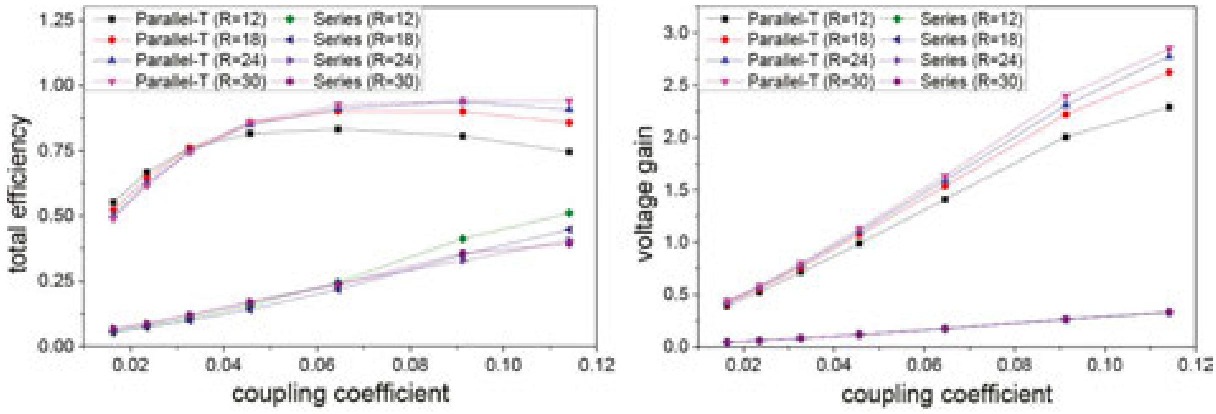


Figure 14. Efficiency and voltage gain vs. coupling coefficient.



(a) Efficiency (b) Voltage gain

Figure 15. Power and efficiency of the two kinds of structure vs. coupling coefficient.

While designing the circuit of WPT, the compensation is performed under no-load condition. In normal operating condition, frequency tracking is used to ensure resonance by keeping the same phase between primary voltage and primary current [12]. Besides, to ensure the EMC and system stability, control is used to achieve constant current. The magnetic field from the transmitter is in steady state. For example, in the WPT system developed by KAIST, the input voltage of the inverter is adjusted using a three-phase thyristor converter shown in **Figure 16** to achieve constant current at the transmitter.

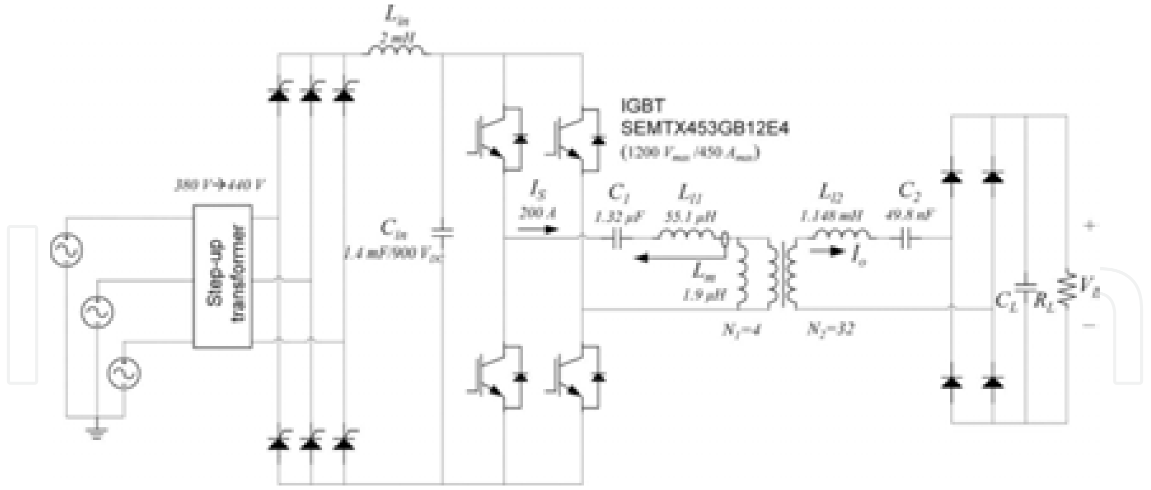


Figure 16. Diagram of the KAIST IPTS showing a power inverter, a power supply rail, and a pickup.

For the secondary side, in order to realize constant current, constant voltage, or constant power, a DC/DC converter is usually implemented. **Figures 17** and **18** show the DC/DC converters used in the WPT systems of the University of Auckland and KAIST [15, 16].

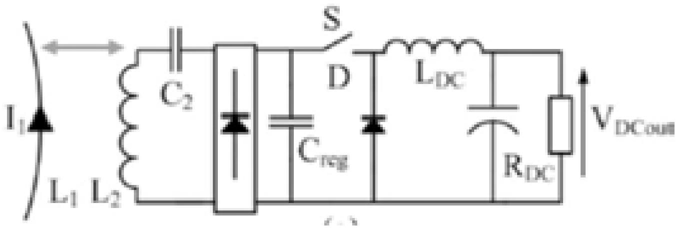


Figure 17. Secondary DC/DC converter.

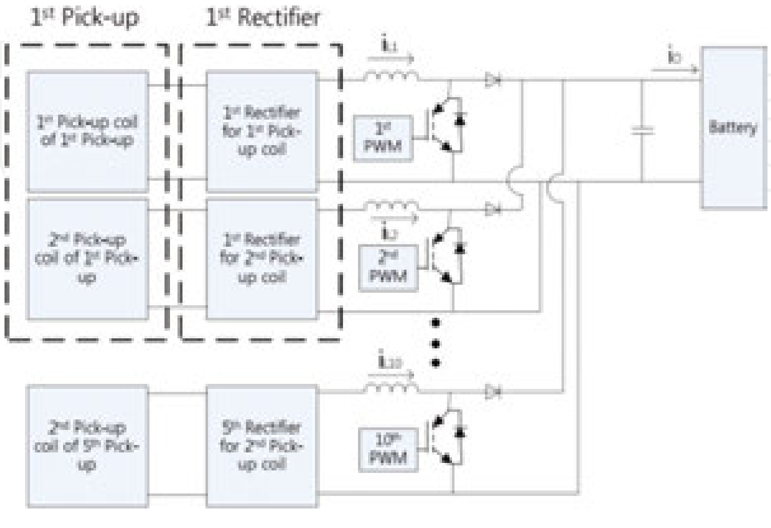


Figure 18. Functional diagram of OLEV power receiver system.

Figure 19 shows a secondary-side circuit which consists of both controllable rectifier and DC/DC converter. SPWM synchronous rectification is employed at the controllable rectifier. The duty cycle of the rectifier is regulated through SPWM; the effective resistance can be adjusted in the range of $R_{load} \sim \infty$. While for a boost converter, the effective resistance can be in the range of $0 \sim \infty$. Therefore, any desired values of the effective resistance can be realized to improve the system overall efficiency.

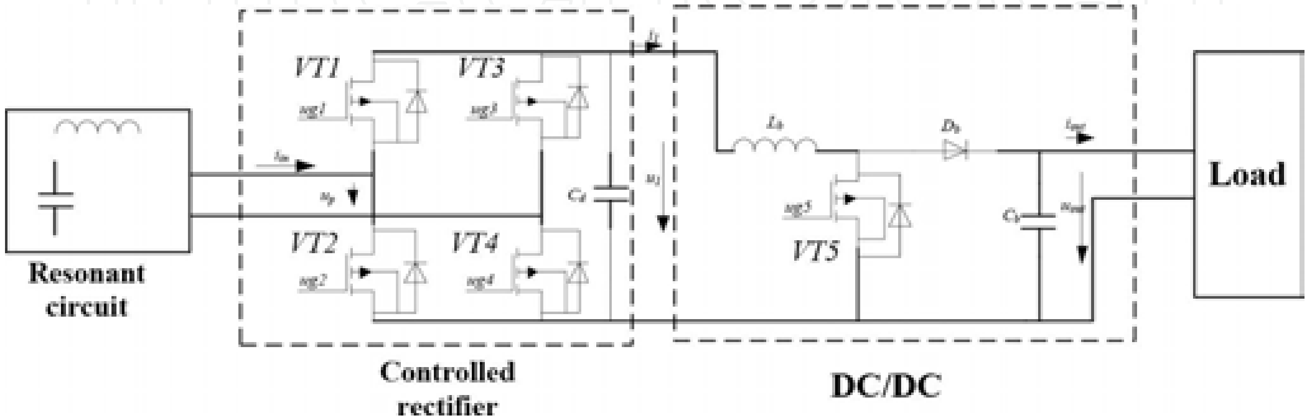


Figure 19. Dynamic impedance adjustment for secondary side pickups.

5. Control strategies

Three types of control were proposed for DWPT: primary control, secondary control, and double-side control. The University of Auckland proposed adjusting the duty cycle of the inverter to control primary resonant current, simplifying the system configuration [17]. KAIST designed constant current control at the primary. A DC/DC converter is added before the inverter, and the DC voltage from the main line is adjusted to achieve constant current for different loads [13]. The main objective of primary control is to produce constant magnetic field, then robust power control can be implemented. The University of Tokyo utilizes secondary control strategy. A buck converter is added after the rectifier [4]. General state space averaging (GSSA) is used to construct the small-signal model. Constant power or maximum efficiency is then realized using PI pole placement [18]. In addition, controllable rectifier and hysteresis comparator are also proposed for implementation at the secondary side to control the output power or maximum efficiency [19]. Double-side control can be with or without communication. ORNL combines the control of both sides, using a closed loop control and frequency adjustment with communication to realize wireless charging [3]. The Hong Kong University proposed simultaneous control of both power and maximum efficiency without communication. The smallest input power is searched to realize constant output power of the inverter [20] (**Table 3**).

Control strategy	**Primary control**	**Secondary control**	**Both side control**	
			With close-loop communication	**Without close-loop communication**
Merits	Constant current in transmitter, steady magnetic field, no need to consider reflected impedance	Constant charging current, constant charging voltage, or maximum efficiency	Both desired power and maximum efficiency are achievable simultaneously	Both desired power and maximum efficiency are achievable simultaneously
Demerits	Unable to control for maximum efficiency, limited control of output load, and constant current charging is not realizable	Adjustable range of the secondary side is limited, and accurate model is required	Additional wireless communication is required, lower the system reliability and real-time performance	Conflict control between primary side and secondary side

Table 3. Comparison of advantages and disadvantages of various control strategies.

The DWPT system is subject to disturbances such as variation of mutual inductance caused by movement of the vehicles. New robust control strategies, which are more superior to PID controllers [4,18,19] in disturbance suppression, are currently being studied.

6. Electromagnetic interference

The DWPT uses a high-frequency, strong magnetic field to transfer power wirelessly. The EMC is an important consideration as the DPWT system is surrounded by many sensitive electronic circuits. The requirements include shielding design, frequency allocation, and grounding design. According to the standard set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the current density exposed to the public is 200 mA/m^2, when the frequency is 100 kHz. The values may affect the nerve system of human body. The limit of specific absorption rate (SAR) is 2 W/kg and power density is 10 W/m^2; if the exposure to the human body is higher than these limits, heating of the human tissues may occur (**Table 4**).

Shielding method	**Metal conductor**	**Magnetic material**	**Active shielding**	**Resonant reactive shielding**
Merits	Fully enclosed metal conductor housing provide excellent shielding effect	Magnetic field shaping, increasing coupling coefficient and therefore low loss	Flexible placement, good shielding effect	Does not consume power from the system, controllable
Demerits	Eddy loss affecting the system efficiency	Limited shielding effect	Additional coil lower the system efficiency	Difficult to design, complex configuration

Table 4. Comparison of merit and demerit of various magnetic shielding methods.

The suppression of the leakage field can be divided into active shielding and passive shielding. In passive shielding, a magnetic path is created using magnetic material or canceling field using a low magnetic permeability metallic conductor [21–23]. The self-inductance and mutual inductance are increased when using magnetic material. The magnetic flux distribution is improved due to higher coupling coefficient, and transfer loss is decreased. However, the shielding effect is limited. Metallic shield is widely used in a high-frequency magnetic field to suppress electromagnetic interference. Both KAIST and ORNL utilize this kind of shielding method. The advantages include simple design and easy to use. However, metallic shielding cannot cover the transmitter and receiver completely. The exposed conductor is subject to friction and eddy current which will increase the heat loss. KAIST proposed a new active shielding method in 2015. A conventional ferrite plate is embedded in multiple metallic sheets as shown in **Figure 20**. Experimental results show that the magnetic interference is effectively reduced [24].

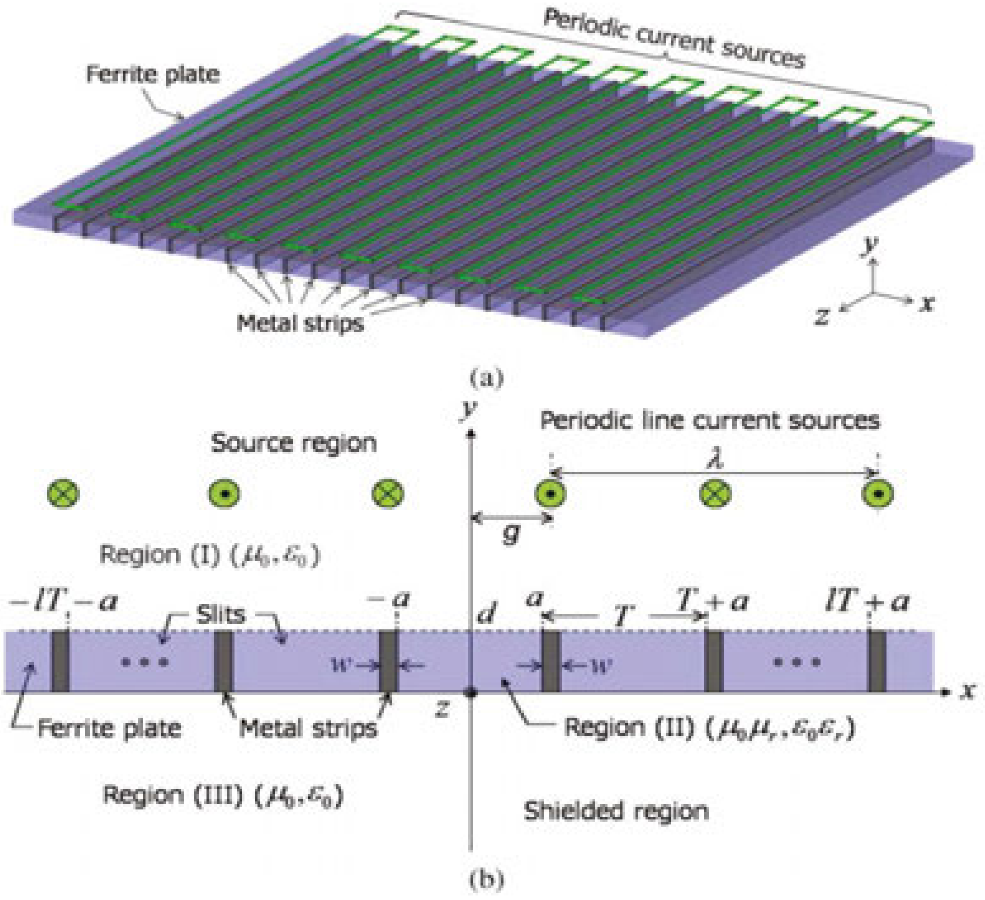


Figure 20. Ferrite shielding structure using an embedded metal sheet.

Regarding active shielding, additional coils with or without power supply are implemented at the WPT system to create a cancelling field as shown in **Figure 21**. Compared to metallic shielding, the space required is smaller.

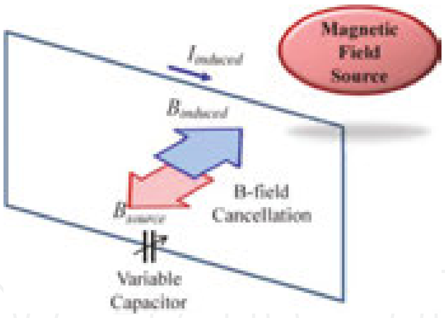


Figure 21. Magnetic field cancellation using a resonant coil.

KAIST published a paper in 2013, proposing an active shielding method using a resonant coil. A switching array is used to change the values of compensated capacitors, thereby controlling the amplitude and phase of the cancelling field. An experiment was performed using green public transportation [25]. In 2015, an improved version using double loop and phase adjustment to achieve resonance was proposed to achieve an active shielding without power supply. The shielding coils are placed at the side of the coupling mechanism as shown in **Figure 22**. The current induced by leakage field is then sensed. Magnetic field with the same amplitude but opposite polarity with the leakage is then created for field cancellation [26].

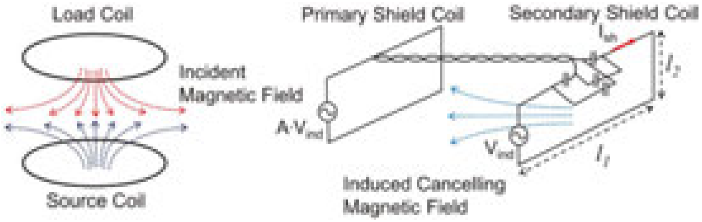


Figure 22. Resonant reactive power shielding with double coils and four capacitors.

In 2013, ORNL proposed using an aluminum board to reduce electromagnetic interference [27]. As shown in **Figure 23**, a 1-mm-thick aluminum shield is placed above the cables. The magnetic field measured at the passenger-side front tire is reduced from 18.72 μT to 3.22 μT.

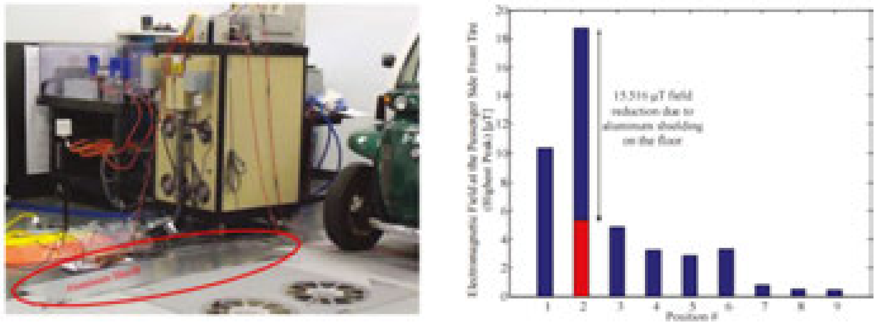


Figure 23. Suppression of magnetic field after adding aluminum plate and its effect.

7. Conclusions

With the advancement of EV and ET, the significance of DWPT has been consistently growing. Recent developments in DWPT for EV and ET have been presented throughout this chapter. Five different aspects of this technology, such as power rail and pickup design, power supply schemes, circuit topologies and impedance matching, control strategies, and EMC, are reviewed. Despite obtaining significant results post study in this field, some issues of concern are yet to be resolved. Previous results as well as the challenges in deployment of DWPT in real application have been highlighted in this chapter.

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