

In-depth perception of dynamic inductive wireless power transfer development: a review

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ABSTRACT

The emerging of inductive wireless power transfer (IWPT) technology provides more opportunities for the electric vehicle (EV) battery to have a better recharging process. With the development of IWPT technology, various way of wireless charging of the EV battery is proposed in order to find the best solution. To further understand the fundamentals of the IWPT system itself, an ample review is done. There are different ways of EV charging which are static charging (wired), static wireless charging (SWC) and dynamic wireless charging (DWC). The review starts with a brief comparison of static charging, SWC and DWC. Then, in detailed discussion on the fundamental concepts, related laws and equations that govern the IWPT principle are also included. In this review, the focus is more on the DWC with a little discussion on static charging and SWC to ensure in-depth understanding before one can do further research about the EV charging process. The in-depth perception regarding the development of DWC is elaborated together with the system architecture of the IWPT and DWC system and the different track versions of DWC, which is installable to the road lane.

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1. INTRODUCTION

For the past decades, electric vehicle (EV) invention resulting from the idea of moving the vehicle using electricity has already been proposed. In the case of the recent development in the automotive field, specifically EV, the growing interest is caused by the emission of greenhouse gas and fossil fuels depletion. It is hard to decide who or which country was the first to come out with this idea, but instead, it can be said that the invention of the EV was a series of breakthroughs. The introduction of inductive wireless power transfer (IWPT) technology was perpetrated by the well-known Nikola Tesla in 1891. He contributed the first remarkable innovation in IWPT technology by demonstrating the inductive coupling through Tesla coils. Tesla coils produced a high alternating current (AC) at suitable frequencies using highly resonant tuned coils that able to compensate the overall circuit in transmitting satisfactory power transmission efficiency (PTE) [1]. The frequency range starts from 10 kHz to 100 kHz [2]. However, regarding SAE J2954, the frequency for wireless power transfer of EV is limited to 85 kHz [2]. The inductively coupled coils were able to transmit an efficient power wirelessly since the coupled coils are placed with an air-gap between them (not physically connected).

Recently, public awareness of green technology has become the incentive of the Malaysian government to introduce EVs broadly [3]-[5]. Previously, the EV is only able to recharge with static wireless charging (SWC) system, as illustrated in Figure 1. The SWC charging method supplies the power from the charging station to the transmitter coil, which is embedded in the road. The receiver coil that is attached underneath the EV will receive the power from the transmitter coil. The IWPT is done when the receiver coil is in align position on top of the transmitter coil. However, this has led to uneasiness or commonly known as range anxiety, among the EV owners regarding the driving distance that their EV can last before they need to recharge again. Currently, the dynamic wireless charging (DWC) system has become the main focus for most researchers in this subject area. The ability to deliver the power produced by the electromagnetic coupling from the transmitter coils to the receiver coils is the benefit that IWPT can offer [6]-[8]. With no physical contact, it is highly resistant to dust environments and any weather conditions. And, with no physical contact, even in a moving state, the electromagnetic coupling could still recharge the EV batteries. This feature offers simultaneous energy transfer, which means that the energy transmission from the transmitter coil and energy acceptance by the receiver can be controlled to happen at the same time. Therefore, with DWC, the EV can travel with a longer mileage and shorter recharging time compared to the SWC system. In contrast to the existing petroleum-fueled car, EVs are equipped with a good energy storage unit that builds up from the battery packs that able to operate for a satisfactory distance [9]. The DWC system is currently being highlighted by most researchers and the transportation industry [10]-[12] because it uses the same principle of IWPT.

The main focus of this review is to explain the extensive works [7], [13]-[17] on improving the DWC system from the SWC system. The fundamental concepts which govern the IWPT, the overall concept of the DWC, significant components and parameters that affect the IWPT system are among the in-depth perceptions that are discussed in detail in this review. The advantages of the DWC of the EV battery are also explained and highlighted along with this review.

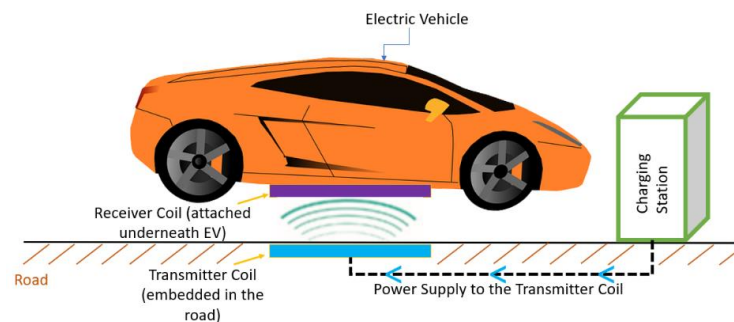


Figure 1. Static wireless charging (SWC) system

2. WIRELESS CHARGING BASIC CONCEPT

There are two categories of WPT, which is either capacitive WPT or inductive WPT (in this review, refers to IWPT). Even though the WPT may be in inductive or capacitive means, globally, most researchers acknowledge the inductive concept is much better in terms of PTE for EV implementation. This acknowledgement is due to the limited potential of capacitive coupling. The capacitive concept of transferring power from the transmitter coil to the receiver coil is achieved by using the electric field. Even though it may suggest a lower cost, regrettably, it has a small power density on behalf of low coupling capacitance [18]. Meanwhile, inductive WPT, which utilises the magnetic field, can have a high-power density where it is possible to have a large coupling coefficient. Thus, making the PTE of the inductively coupled concept has the ability to transfer energy up to 90% efficiency at distances of 100 mm from the grid to the vehicle's battery [6]. This condition is much suitable for EV considering the demand for high power transfer to recharge the vehicle in a short amount of time. The IWPT concept typically operates at a high-frequency range (10-100 kHz) to improve the power transfer.

The WPT ability is not limited to only improving the EV battery but also beneficial to the enhancement of the drone's battery capacity with the capacitive power transfer technique [19]-[21] and also inductive power transfer technique for much higher power transmission [22]-[38]. However, when looking at the maturity of the developed inductive concept, it shows that the capacitive concept has not yet been able to compete with the inductive concept in terms of high-power transmission. Not only that, the implementation

of the inductive power transfer technique has started to be used on automatic guided vehicles (AGVs) since several years back [39], [40]. Initially, although the battery charging concept for EVs is limited to wired charging, the development of IWPT that obeys Ampere's and Faraday's laws has contributed to the birth of wireless charging. It is characterised by couplers (transmitter and receiver coils) with good interoperability and gradually taking place in the EV industry as it promised a much pleasant and secure charging environment [41]-[43]. Most researchers have already tried to find out the way to charge the EV by using the wireless concept in order to enhance the mobility of the EV, which implements the IWPT technique. In the early development of the IWPT system, the finished product of assembled cars was expensive [44]-[48]. Therefore, tremendous efforts are taken to find ways to reduce the final cost of the assembled EV while having the same or improved PTE during the charging process. Figure 2 displays the wireless charging concept that involves electromagnetic coupling between the transmitter and receiver coils.

In Figure 2, the magnetic flux produced by the transmitter coil, which is embedded inside the road, is coupled with the receiver coil that is attached underneath the EV chassis. The magnetic flux is produced as the AC electrical power source from the power supply is injected into the transmitter coil after passing through the inverter. The magnetic flux received at the receiver coil indicates the amount of power that is received by the receiver coil, and the power is then passed to the rectifier before lastly accepted by the EV battery [49]. In practice, there will be flux leakage, and this flux leakage contributed to the power loss. However, the use of ferrite core rather than air core, together with the use of Litz wire instead of copper wire, contributes to reducing the flux leakage. These features can maximise the coupling between the coil windings of transmitter and receiver coils. For SWC, a provided area is needed for the EV to stop and park to charge the EV battery before starting any journey. Generally, the time taken to charge an EV can be a minimum of 30 minutes or more than 12 hours, depending on the battery size and charging point speed. For instance, only under 8 hours is needed for a typical EV of 60 kWh battery to charge from empty to full with a 7 kW charging point [50]. So, the charging process needs to occur quite a few times before arriving at the destination and this cause the lack of the ability to ensure long-range travel. Fortunately, this situation has urged the researchers to put on a vast effort to find a solution, and this is where dynamic wireless charging (DWC) comes into the picture [29]-[30].

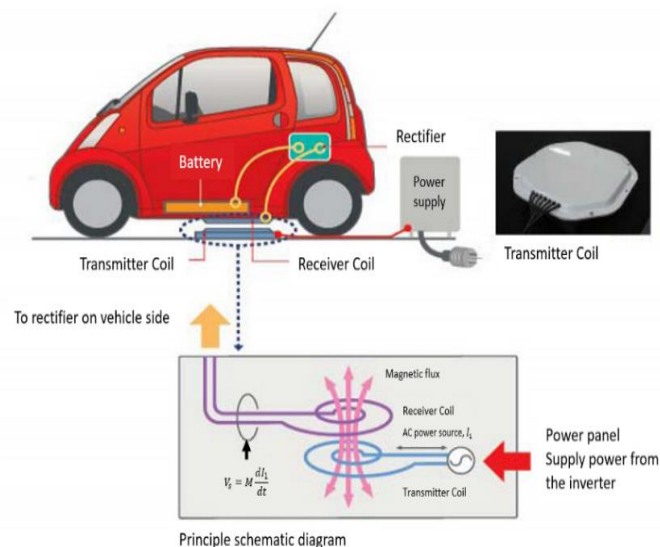


Figure 2. Wireless charging concept [10]

– Dynamic wireless charging (DWC) as the futuristic charging method

For a much convenient and time-saver charging process, the DWC approach has become a reliable system to recharge the EV battery [51]-[53]. DWC operation offers to recharge the EV battery while moving, and this means that the vehicle will not need to waste time to stop and park at the designated area just to wait for at least 4 hours of full charging before continuing the journey. In other words, the DWC can extend the EV range by applying the IWPT technique since it is able to recharge the in-motion EV [8], [54]-[59]. Several major components are required to ensure that the power is transferred sufficiently to the EV by using the electromagnetic induction principle. For a simple understanding, the magnetic field produced by the coil

from the grid (transmitter coil) to the vehicle battery (receiver coil) is made inductively to ensure that the power is transferred efficiently.

3. DYNAMIC WIRELESS CHARGING (DWC) FUNDAMENTAL CONCEPT

DWC is a viable means of charging the EV in an in-motion (dynamic) state. This concept used the fundamental concept of IWPT. As discussed previously, although power transmission is possible during the motion of the EV, it also requires a reasonable alignment and mutual inductance between the transmitter coil and receiver coil. In both SWC and DWC, there is no physical contact involved to transmit the electromagnetic induction to the receiver coil, which is produced by the electricity at the transmitter coil. Due to this, the same coil designs that are used for SWC may be further used to perform the DWC. The only exception when dealing with DWC is that it will include either an elongated transmitter coil or multiple transmitter coils that are to couple with the receiver coil on the EV.

3.1. Governing law for inductive wireless power transfer (IWPT)

Ampere and Faraday came out with their laws of physics which have become the underpinning laws for electrical engineering. The IWPT was then explored to achieve the advancement in EV transportation. Both of these essential laws govern the fundamental concept of the IWPT working principle. The most notable advances were made by Tesla, in which he demonstrated that high resonant tuned coils were able to create AC frequencies to achieve power transfer operation [11]-[12]. Dynamic IWPT concepts were initiated in the early 70s. Since then, it had received attention from car manufacturers to develop the SWC concepts by reinforcing this technology to improve it to DWC [54]. The future of EV depends on the promise held by the growth of the IWPT concept.

The IWPT concept is a result of the extension of the pioneering work of Prof. Heinrich Hertz from the 18th century to this current era [60]. Hertz demonstrated the development of his finding in the late 18th century, wherein free space, the electromagnetic wave propagation could generate high-frequency power [61]. An outcome from that finding contributed to Ampere and Faraday's laws which both laws are governing the IWPT fundamental concept. The Ampere and Faraday's laws are explained in brief as follows:

- a. Ampere's law: In free space, the electric current generates a magnetic field when it flows through a conductor. The magnetic field produced is proportional to the electric current (I) and permeability of free space (μ_o) [61].

$$\sum B_T \Delta l = \mu_o I N_1 \quad (1)$$

- b. Faraday's law: The time-varying magnetic flux induces a voltage in the conductor if it links a conductor. The voltage value (e) is proportional to the rate of change in magnetic flux and the number of turns in the conductor [61].

$$e = -N_2 \frac{d\phi_B}{dt} \quad (2)$$

where:

B_T = magnetic flux density in Tesla

Δl = length of conductor in meters

N_1 = number of transmitter coil turns

N_2 = number of receiver coil turns

ϕ_B = flux in the magnetic path in Wb

In the surrounding region of the transmitter coil, it will result in a time-varying magnetic flux of the same frequency as the operating frequency to produce when the time-varying current is applied to the transmitter coil through the AC power supply. The strength of the induced magnetic field (H) around a closed path is known to be directly proportional to the coil's current (J) that travel through the coil's wire, where the displacement current is neglected [15]. It is given by (3), which obeys Ampere's law:

$$\oint H \cdot dl = \int J \cdot ds \quad (3)$$

The (3) can be further simplified into (4) on the condition that the coil's wire consists of N turns:

$$\oint H \cdot dl = N_p I_p \quad (4)$$

From (4), N_p is transmitter coil turns number, I_p indicates the transmitter coil flow of current, and l is the closed path circumference. At this moment in time, it is already understood that the stronger transmitter coil magnetic field is the result of greater current magnitude in the transmitter coil. On the other hand, this is where the electromagnetic induction obeyed the principle of Faraday's law, which states that the time-varying magnetic flux that links with the receiver coil induced the electromagnetic force (EMF) to drive the current to the load (e.g. battery) when the circuit is closed. This condition is given by (5):

$$e_s = N_s \frac{d\phi_m}{dt} \quad (5)$$

- e_s : the receiver coil induced EMF that is produced by the flux linkage between the transmitter(s) and receiver coils
 N_s : the receiver coil turns number
 ϕ_m : is the flux linkage between transmitter and receiver coils or so-called mutual flux
 $\frac{d\phi_m}{dt}$: the rate of change of mutual flux

Now, it is understandable that the higher mutual flux rate of change results in the EMF induced magnitude of the receiver coil to be greater. Figure 3 demonstrates the discussion of this IWPT concept for a better understanding. In Figure 3, the fundamental concept of IWPT consists of two coils refers to the transmitter coil and receiver coil. These coils are coupled and separated by an air-gap. In EV charging application, the air-gap is the ground clearance between the road and the EV chassis. To minimise the proximity losses in enhancing the coupling between the two coils, the coils are intertwined around a magnetic material. However, recently, a single-sided coil is preferred [62]. The input DC which is then converted into high-frequency AC is used to energise the transmitter coil. The high-frequency AC, which obeys Ampere's laws shown in (1), generates a time-varying magnetic field [63]. The magnetic field is then linked to the receiver coil relying on the coupling coefficient, k , to induce a voltage at the receiver coil. The induced voltage created at the receiver coil is due to obeying Faraday's laws. Seeing the large air-gap indicates that the circuit is inductive. Hence, a large current (i.e. magneto-motive force) is obligatory to produce a sufficient magnetic field to link receiver coils [64]. It is essential to maximise coupling efficiency by tuning the transmitter and receiver coils to the same resonant frequency [65].

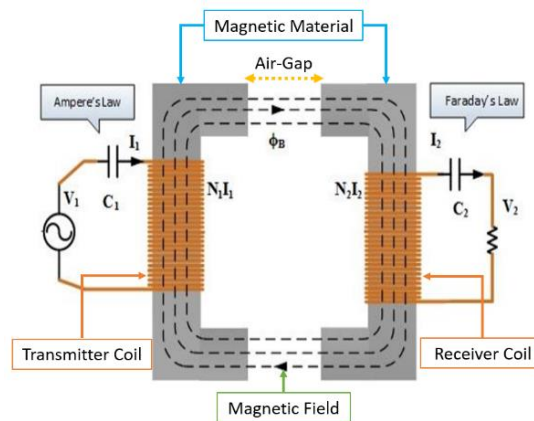


Figure 3. Fundamental concept of inductive wireless power transfer (IWPT) [61]

3.2. Characteristics of dynamic wireless charging (DWC)

A simple concept to understand the characteristics of the DWC is by imagining that there is a lineup of the transmitter coils embedded in the ground below the highway. Multiple transmitter coils are embedded along the road, as shown in Figure 4 (a), so that the power transmission is possible to be simultaneously received by the receiver coil attached underneath the EV chassis. The electromagnetic coupling has been studied to achieve wireless charging in order to transfer electricity to the EV without any cord. By implementing this technique, the EVs are now rechargeable without worrying about running out of battery even when facing traffic congestion or on a long journey that takes up to more than 4 hours. The proposition

of embedding the transmitter coils in the ground and connecting them to the public electric grids is an innovative effort to remove the worrisome plug-in and stationary charging [66]-[69].

Figure 4 (a) and Figure 4 (b) shows that the transmitter coil can be in two types of tracks for the DWC method, which is either lumped or elongated. For the lumped track, multiple transmitter coils are involved which each of them has its own compensation circuits. On the other hand, the elongated track consists of only one transmitter coil, and the length is longer than the receiver coil. The lumped track is quite complex compared to the elongated type of track in terms of building the charging coils and the overall system circuits. This complexity will lead to a higher cost to complete the charging system. However, the lumped track is much easier to be controlled to switch on the transmitter coil that is currently in use and to switch off the transmitter coil that is not in use. This ability can reduce the wastage of power throughout the DWC charging process. Therefore, each of them has its own advantages to offer, depending on the application.

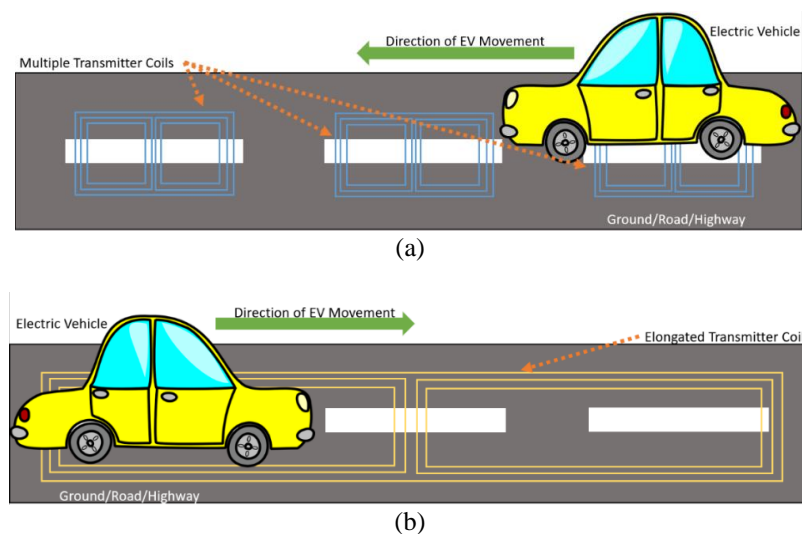


Figure 4. Types of dynamic wireless charging tracks: (a) lumped track, (b) elongated track

Recently, Sweden has implemented a 2 km length charging track to recharge the EV battery. This implementation has turned Sweden to have the world's first electrified road [70]. The track which acts as the transmitter coil with a length longer than the receiver coil to capture the energy transferred is known as the elongated track [71]. Nevertheless, since the elongated track will contribute to a constant coupling coefficient along the track, this type of track might lead to a decrease in PTE. Thus, the sizing of the coil itself is suggested to be built sufficiently big to encounter the problems [3], [4]. Meanwhile, a lumped track that acts as the transmitter coil is built with a length comparable with the receiver coil. Multiple transmitter coils are involved and commonly have a suitable distance between each other after a specific calculation [72]. However, with this type of transmitter track, the system might experience inconsistent and fluctuated PTE.

This situation is caused by the changes in the position, which also affect the coupling coefficient of the overall dynamic IWPT system [73]. This fluctuated output power pulsations still can be overcome by changing the distances between the transmitter coils, as suggested in [69]. The magnetic field produced by the electricity, which is caused by the resonance frequency, requires both coils at the transmitter and receiver sides to be in the same resonance frequency. Significant energy losses can be prevented if the operating resonance frequency is set in between 50% to 95% of the resonant circuit [74]. This technology suggests much convenient, flexible and safer ways to charge the EV. The PTE of more than 90% over a 10 inches air gap is possible to achieve if the resonance frequency energy is altered to be greater than almost 97% efficiency from the transmitter coil to the receiver coil.

3.3. System configuration of dynamic wireless charging (DWC)

In DWC, a long track consists of a transmitter coil (elongated track) or multiple transmitter coils (lumped track) is used to transmit the power to the receiver coil on the EV for recharging the EV battery throughout the journey. The battery of the EV gets charged while it is in-motion, and the power is transmitted

through the air with a certain air-gap from the stationary transmitter coil embedded underneath the road to the receiver coil that is moving together with the movement of the EV. Figure 5 shows a simple illustration of the DWC operation, and some important components involved in transmitting power dynamically.

Figure 5 illustrates the operation of the DWC system where it is obvious that in DWC, the transmitter coils are placed in-line, making its charging lane. The transmitter coil, which can be in elongated or lumped track version, are embedded underneath the road together with the compensation topology (CT) network to control the operation of energising the transmitter coil. In general, DWC adopts the long track execution to allow the receiver coil, which is the power receiver, to continuously pick up the electrical energy that is consumed during driving. In other words, the DWC aims to charge the EV while keeping the EV stay in-motion at the same time.

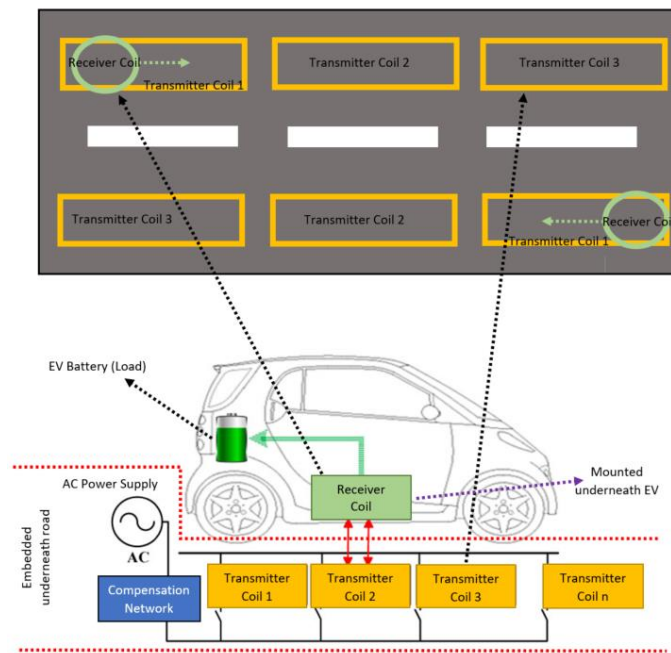


Figure 5. Simple illustration of DWC operation [2], [75]

Precisely, for the power transmission to occur, the transmitter coils, which are coupled with the receiver coil on the EV, are placed together with the power source and CT network inside the road. There is an air-gap for both coils to couple, and this air-gap will also include the EV ground clearance to decide the suitable depth to bury the transmitter coil circuit system underneath the road. The range of the air-gap is commonly from 100 mm to 200 mm, where this already includes the 120 mm, which is a standard ground clearance for most vehicles. An additional 30 mm to 80 mm is the suitable depth to cut the road surface to embed the transmitter coil circuit system to construct the DWC lane. For the construction of the DWC road, some researchers proposed to select a cement asphalt mortar (CAM) with the ratio of 1.4:1:1 of emulsified asphalt, cement and silica sand instead of using the hot mix asphalt concrete that is typically used to pave the road and 50 mm gap from the road surface is cut for burying the transmitter coil circuit system [76].

3.4. Significant components for inductive wireless power transfer (IWPT)

Moving to the next discussion, which is on the major components involved during the whole DWC process, these components are crucially needed to go through the process of transferring power dynamically. The utilised components for DWC are homogenous to the ones implemented for SWC. Regardless of having a similar concept and principle to recharge the EV battery, the overall DWC concept is much complex as it involves numerous transmitter coils to transmit the power. The overall calculation will also multiple as the system multiplied. Even though DWC may have complexity in terms of calculation, however, the calculation is still feasible.

Figure 6 encapsulates the overall flow of the IWPT from the transmitter coil to the receiver coil. The process of transferring power wirelessly started from the electric grid, which received the DC voltage around 230V to 240V and supplies to the system about 120 VAC generally. The voltage supply is quite similar to the

single-phase power received by houses, where the voltage is then converted to AC voltage by the DC to AC converter. The grid power system requires a boost converter (DC/HF AC converter) to produce an output voltage of 120VAC from the split single-phase [77].

DC/HF AC converter is used to convert the AC mains into high-frequency AC. This converter which is also known as the current-fed DC/AC converter, can operate in either buck or boost modes for enabling the conversion of power from low to high voltage [77]. This converter is a good solution that provides transformer balancing to be more accessible [78]. After that, the energy power flows through the CT network to filter any impurities so that the energy transfer to the receiver coil is reduced in losses [49]. A detailed discussion on different CTs can be found in section 2 of the article [2]. The inductive charging can only produce a magnetic field with the presence of alternating current at the coils of both transmitter and receiver sides. As the energy reached the transmitter coil, the air core transformers at both sides are now coupled and induced the inductive magnetic field. The receiving coil, which is attached underneath the EV chassis, then converts the oscillating magnetic fields received to a stable DC supply for the battery to recharge.

The major components that are explained are located in a dedicated space that is not easily accessible and protected by the materials that ensuring the induced magnetic field to be dissipated safely once the DWC process is accomplished. The DWC stations can be incorporated imperceptibly in any condition and environment regardless of the weather condition. Since a contactless DWC process is done, it implies that there is no mileage on parts involved, and there is no open door for vandalism. Thus, making the area compelling and safe. Throughout the charging process, various essential parameters need to be dealt with to ensure the PTE is at the maximum state possible. Among the parameters affecting the system performance are coupling coefficient, usually refers as k , self-inductance, mutual inductance, usually refers as M , misalignment, and air-gap. Different coil geometry also contributes to the PTE of the IWPT system [2]. In most literature, ferrite cores are used as the coil shielding to increase the PTE with its ability to reduce the inductance leakage when the transmitter and receiver coils are magnetically coupled [42]. Table 1 (in Appendix) summarises the advantages and limitations of the related works.

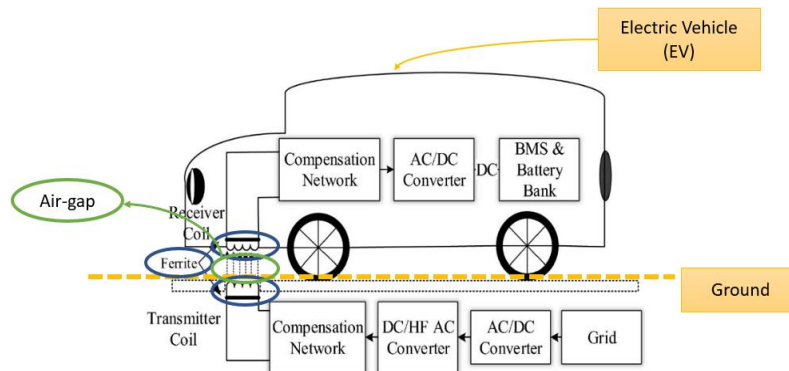


Figure 6. Block diagram of the IWPT flow [77]

4. CONCLUSION

This review is particularly discussing the inductive wireless power transfer (IWPT) system and dynamic wireless charging (DWC) for recharging the EV battery to offer an in-depth understanding before one can start to dig more into the EV charging process. The development of IWPT has contributed a lot to the DWC existence. The inductive charging has the ability to power up the EV stack of batteries as it is implementing the electromagnetic coupling strength that occurs between the inductive coils (transmitter and receiver coils) to convert it to the electrical charges. The EV DWC concept is discussed in-depth for its fundamental concept of wireless charging and the characteristics of the system. It can be concluded that various advantages are to be received by the consumer if the DWC has started to be widely implemented, such as 1) Battery capacity can be reduced thus, decreasing the weight of the EV and the price of EV itself. 2) More time and also space can be saved for charging as the recharging process of the battery occurs while in-motion. 3) No more range anxiety while travelling on a long journey. 4) Petroleum gas pollution is slowly avoided. 5) Enables automatic charging as soon as the EV cruising on the DWC lane available. 6) No more queuing for several hours at the charging stations. Thus, it is hoped that this review manages to offer a better understanding of the IWPT system and DWC process before one can further design the overall system itself.

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APPENDIX

Table 1. Summary table of related works

Ref.	Author(s), Year	Description	Advantages	Limitation	Type of Transmitter Track
[67]	Tan <i>et al.</i> (2020)	Proposed a method to select the length of the transmission coil while concerning speed limit and energy loss during charging	<ul style="list-style-type: none"> Using LCC-S compensation network Implement the IMN network for accurate control of each power received from different EVs Introduced 2 seconds principle to ensure effective braking 	<ul style="list-style-type: none"> The optimisation is done only for the transmitting coil 	Elongated Track
[68]	Li <i>et al.</i> (2019)	Developed a new coil structure that is inspired by the existing coil geometry to optimise a constant voltage and current as of the outputs	<ul style="list-style-type: none"> Implemented the separation of double-D quadrature (DDQ) where the double-D (DD) and Q geometry as the transmitter coils and DDQ as the receiver coil 	<ul style="list-style-type: none"> The feasibility of the proposed method is for a high-speed scenario 	Elongated Track
[69]	Mukhatov <i>et al.</i> (2018)	Suggested to observe the distance changes between the multiple transmitter coils on the power transfer efficiency (PTE)	<ul style="list-style-type: none"> The suggested idea can reduce the power pulsation between the transmitter coils as it changes from one transmitter coil to another transmitter coil 	<ul style="list-style-type: none"> The implementation of the suggested idea is only for circular geometry at both transmitter and receiver sides 	Lumped Track
[78]	Dashora <i>et al.</i> (2017)	Presented the in-depth analysis together with the hardware implementation of double-D (DD) coupler for the real EV size	<ul style="list-style-type: none"> Includes the planar magnetic cores to enhance the coupler performance 	<ul style="list-style-type: none"> Coupling properties are tested only at coaxial (no misalignment) condition 	Lumped Track
[66]	Zhang <i>et al.</i> (2016)	Suggested a selective dispersed coupling structure named grouped periodic series spiral coupler (GPSSC)	<ul style="list-style-type: none"> The GPSSC can avoid sudden power transfer energised by the transmitter coil The transmitter coils are controlled to be selectively ON or OFF Minimise the fluctuation of power transfer by improving the receiver coil by a ratio of R:H:D = 4:5:13 	<ul style="list-style-type: none"> The size of the transmitter and receiver coils are built on a tiny scale (only up to 75 mm) 	Lumped Track

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