

Chapter 2

Wireless Power Transfer (WPT) for Electric Vehicles (EVs)—Present and Future Trends

D.M. Vilathgamuwa and J.P.K. Sampath

Abstract 100 year old gasoline engine technology vehicles have now become one of the major contributors of greenhouse gases. Plug-in Electric Vehicles (PEVs) have been proposed to achieve environmental friendly transportation. Even though the PEV usage is currently increasing, a technology breakthrough would be required to overcome battery related drawbacks. Although battery technology is evolving, drawbacks inherited with batteries such as; cost, size, weight, slower charging characteristic and low energy density would still be dominating constraints for development of EVs. Furthermore, PEVs have not been accepted as preferred choice by many consumers due to charging related issues. To address battery related limitations, the concept of dynamic Wireless Power Transfer (WPT) enabled EVs have been proposed in which EV is being charged while it is in motion. WPT enabled infrastructure has to be employed to achieve dynamic EV charging concept. The weight of the battery pack can be reduced as the required energy storage is lower if the vehicle can be powered wirelessly while driving. Stationary WPT charging where EV is charged wirelessly when it is stopped, is simpler than dynamic WPT in terms of design complexity. However, stationary WPT does not increase vehicle range compared to wired-PEVs. State-of-art WPT technology for future transportation is discussed in this chapter. Analysis of the WPT system and its performance indices are introduced. Modelling the WPT system using different methods such as equivalent circuit theory, two port network theory and coupled mode theory is described illustrating their own merits in Sect. 2.3. Both stationary and dynamic WPT for EV applications are illustrated in Sect. 2.4. Design challenges and optimization directions are analysed in Sect. 2.5. Adaptive tuning techniques such as adaptive impedance matching and

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frequency tuning are also discussed. A case study for optimizing resonator design is presented in Sect. 2.6. Achievements by the research community is introduced highlighting directions for future research.

Keywords Wireless power transfer • Electric vehicles • Dynamic EV charging • Stationary EV charging

2.1 Introduction

PEVs have been proposed as the prospective mode of transportation to address environment, energy and many other issues. In spite of receiving many government subsidy and tax incentives, EVs have not become an attractive solution to consumers. Major drawback of EV is with the energy storage technology. Short comings of today's battery technology includes cost, size, weight, slower charging and low energy density. For example, energy density of commercial Lithium-Ion complete battery pack is around 100 Wh/kg [1]. This value is much smaller than that of gasoline engine. It would be infeasible to achieve range of a gasoline vehicle from a pure PEV with current battery technology. Long charging times and mechanical hassles with charging cables are main drawbacks of present PEV technology that impede the widespread proliferation of PEVs.

WPT technology can be used as a solution in eliminating many charging hazards and drawbacks related to cables. The concept of dynamic WPT enabled EVs, which means the EV could be charged while moving in a road will increase the effective driving range while reducing the volume of battery storage. Not only from the consumer perspective, but also from sustainable energy point of view WPT enabled EVs are greatly beneficial. For example, the concept of Vehicle-to-Grid [2] to enrich distributed energy generation model can be brought into next stage with WPT facilitated EVs [3]. Some futuristic concepts of motor/capacitor/WPT EVs have been proposed where EV is continuously charged and possible to run forever without batteries [4].

WPT technology is improving significantly covering aspects such as RF technology, near-field energy transfer, energy conversion and management, energy storage elements, novel materials and fabrication techniques EMC/EMI considerations. However, WPT is yet to fully mature in terms of power transfer efficiency, range, and power rating. Extensive research studies that have been carried out presently would bring the world closer to the futuristic concept of motor/capacitor/WPT EVs.

2.2 Basics of WPT Technology

WPT is the transmission of electrical power from the power source to an electrical load without the use of physical connectors. History of WPT began with the formulation of Maxwell's equations in 1862. Maxwell described phenomena of radio

waves in his equations. Later, in 1884 Henry Poynting illustrated electromagnetic waves as an energy flow and is used in his Poynting theorem. Nikola Tesla investigated the principle of WPT at the end of the 19th century [5]. Tesla's experiment was not exploited to a commercial level because of its seemingly unsafe nature, low efficiency, and financial constraints. After Tesla's initial experiments, electromagnetic waves are used for wireless communications and remote sensing applications.

With the advent of advanced semiconductor technologies, Tesla's proposition has now become a reality. The wireless nature of this transmission makes it useful in environments where implementation of physical connectors can be inconvenient, hazardous or impossible, particularly in EVs.

2.2.1 Wireless Energy Transfer Methods

Wireless power transfer methods encompass technologies such as Laser, photoelectric, radio waves (RF), microwaves, inductive coupling and magnetic resonance coupling. These technologies can be broadly categorized based on underlying mechanism, transmission range, and power rating. Based on the power transfer distance wireless energy transfer methods can be categorized into two types; near field and far field. If transfer distance is longer than the wavelength of electromagnetic wave, it is categorized in to far field technique. Laser, photoelectric, RF, microwave can be considered as far field energy transfer methods. Inductive coupling and magnetic resonance coupling based methods are regarded as near field approaches. Even though far field techniques have transmission range up to several kilometres, they suffer from the trade-off between directionality and efficiency. Frequency range of far field approaches are typically very high (GHz range) compared to near field (kHz–MHz). Inductively coupled near field approaches can be used to transmit high power efficiently in very near range (up to several centimetres). Efficiency of such systems deteriorates exponentially with the distance. The non-radiative WPT system demonstrated in 2007 by MIT [6] based on magnetic resonance coupling can be used in mid-range application with an acceptable efficiency. This MIT experiment has gained accentuating attention from the research community because many real world applications require longer transmission range.

2.2.2 Inductive Coupling Versus Magnetic Resonance Coupling

Traditional inductive power transfer (IPT) systems based on inductive coupling resulting from the Faraday's law of induction and Ampere's circuital law. The integrated magnetic field due to current carrying loop (transmitting coil) is defined by the Ampere's circuital law. According to Faraday's law of induction, time-varying

magnetic field induces electric field in receiving coil. Initial configurations of IPT systems used inductor in series with the coil [7]. This is analogous to loosely coupled transformer. Later, IPT based topologies are adopted with capacitor compensation [8]. Conversely, magnetic resonance technology originally used with self-resonance coils which resonates with its self-inductance and parasitic capacitance [6]. An external lumped capacitor is added to build the resonance coils when parasitic capacitance of coils are inadequate to make resonance at frequency of interest in later studies [9, 10]. Frequency selection for IPT based designs are limited to several kilohertz while magnetic resonance based systems can operate in frequencies up to a few Megahertz. Typical IPT schemes are limited to a few centimeters whereas magnetic resonance WPT can be used with larger range.

2.3 Modelling the WPT System

Modeling the WPT system is crucial in designing WPT system for EVs. Simplicity and the accuracy of the model are important. The modeling methodology needs to provide guide lines in the selection of system performance indices and design parameters.

The block diagram in Fig. 2.1a shows typical two resonator WPT system powered using high frequency (HF) power source. HF source can either be an inverter or combination of a power amplifier (PA) and a signal generator (SG). PA and SG based setups are commonly used in laboratory prototyping, but PA and SG combination has to be replaced with a high frequency inverter in real world implementation. Receiver resonator is connected to the load through a battery charging circuitry. In EV charging applications battery is connected through a rectifier and regulator circuit. Load impedance consists of the impedance of the charging circuit. Battery load can be approximated to a resistive AC load [11].

Equivalent source resistance represents output impedance of the power source. In case of PA and SG combination, source impedance is typically $50\ \Omega$. But in power converter based designs this value is much smaller than $50\ \Omega$. Therefore, source resistance must be chosen with careful attention in the design process based on the type of the source.

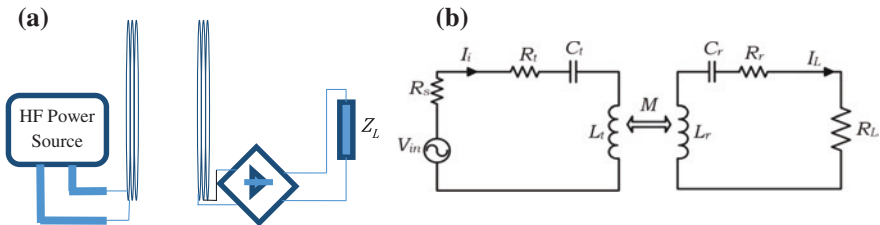


Fig. 2.1 a Two resonator WPT system. b The equivalent circuit

2.3.1 Equivalent Circuit Theory

As electrical lengths (ratio of cable lengths to operating wavelength) of cables and coils are very short, the system can be analysed in lumped parameter model. Lumped parameter circuit model is shown in Fig. 2.1b. Two types of resonant coils have been used in WPT; self-resonators and LC resonators. Self-resonators resonate with the self-inductance of coil and parasitic capacitance between turns, whereas LC type has an externally added lumped capacitor. Self-resonators have the advantage of low loss, but realization at low frequencies is challenging because the typical parasitic capacitance is very low. LC type is more controllable during the design process. Compensation capacitor of the LC resonator can either be Parallel (P) or Series (S) to the coil. Series compensation inherits voltage source characteristic while parallel compensation has current source characteristic. Based on the transmitting and the receiving resonator capacitor compensation, four topologies; Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS), and Parallel–Parallel (PP) can be realized. If parallel compensation is used at either side, the capacitance value depends on the coupling coefficient, which is a variable in a moving load application. Therefore SS compensation is preferred for EV applications.

Using Kirchhoff's voltage law, Eq. (2.1) can be obtained.

$$\begin{bmatrix} Z_t + R_s & j\omega M \\ j\omega M & Z_r + R_L \end{bmatrix} \begin{bmatrix} I_i \\ I_L \end{bmatrix} = \begin{bmatrix} V_i \\ 0 \end{bmatrix}$$

$$Z_{t,r} = R_{t,r} + j\omega L_{t,r} + \frac{1}{j\omega C_{t,r}} \quad (2.1)$$

$$M = k\sqrt{L_t L_r}$$

where V_i is the driving voltage applied on the transmitter resonator at carrier frequency ω , and Z_t and Z_r are the self-impedances of transmitter and receiver resonators respectively. These impedances are made up of $L_{t,r}$, $C_{t,r}$ and $R_{t,r}$ which are inductance, capacitance and resistance of the coils respectively. Capacitance includes both distributed capacitance of the coil and externally added lumped capacitance. The mutual inductance (M) between the transmitter and the receiver can be expressed in terms of coupling coefficient (k) and coil inductances.

Output power at the load and Power Transfer Efficiency (PTE) can be calculated as,

$$P_{out} = |I_L|^2 R_L$$

$$PTE = \frac{|I_L|^2 R_L}{|I_i|^2 (R_t) + |I_L|^2 (R_L + R_r)}$$

$$I_i = \frac{(R_L + Z_r) V_s}{(Z_t + R_s)(R_L + Z_r) + (\omega M)^2} \quad (2.2)$$

$$I_L = \frac{(j\omega M) V_s}{(Z_t + R_s)(R_L + Z_r) + (\omega M)^2}$$

At the resonance condition, reactive impedance of the coil becomes zero. Resonance frequencies of the transmitter and receiver coil becomes,

$$\begin{aligned} X_{t,r} &= j\omega_{t,r}L_{t,r} + \frac{1}{j\omega_{t,r}C_{t,r}} = 0 \\ \omega_{t,r} &= \frac{1}{\sqrt{L_{t,r}C_{t,r}}} \end{aligned} \quad (2.3)$$

Equivalent circuit method allows us to determine element parameters such as currents and voltage across coils, compensation capacitors. Therefore it is essential to use equivalent circuit based analysis to estimate component ratings in designing high power WPT system. Detailed analysis of design parameters and performance indices based on equivalent circuit is presented in Sect. 2.5.1.

2.3.2 Two Port Network Theory

Measurement of scattering parameters (S-parameter) is easier compared to voltage and current measurements in laboratory prototyping. In particular, S-parameter measurement is suitable at the initial stage of the design. S-parameter analysis of WPT system can be done using two port network modeling as shown in Fig. 2.2.

Using the definitions of two port network theory impedance parameter matrix (Z parameter matrix) and scattering parameter matrix (S parameter matrix) can be given as follows,

$$\begin{aligned} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} &= \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix} \\ \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} &= \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \end{aligned} \quad (2.4)$$

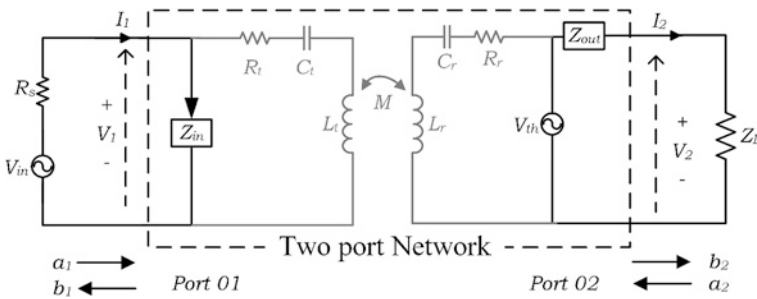


Fig. 2.2 Two port network modelling of the WPT system

Input and output impedances can be calculated using Z parameters;

$$\begin{aligned}
 Z_{in} &= \frac{V_1}{I_1} = Z_{11} - \frac{Z_{21}Z_{12}}{Z_{22} + Z_L} \\
 V_{th} &= \frac{Z_{21}}{Z_{22} + Z_L} V_{in} \\
 Z_{out} &= \frac{V_{th}}{I_{SC}} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11} + Z_s} \\
 R_{in} &= \text{real}(Z_{in}), R_L = \text{real}(Z_L)
 \end{aligned} \tag{2.5}$$

Input power, output power and the efficiency become,

$$\begin{aligned}
 P_{in} &= |I_1|^2 R_{in} = \frac{|V_{in}|^2}{|R_s + Z_{in}|^2} R_{in} \\
 P_{out} &= |I_2|^2 R_L = \frac{|V_{th}|^2}{|Z_{out} + R_L|^2} R_L = \frac{|Z_{21}|^2 |V_{in}|^2}{|(Z_{in} + Z_s)(Z_{22} + Z_L)|^2} R_L \\
 PTE &= \frac{P_{out}}{P_{in}} = \frac{|Z_{21}|^2 R_L}{|Z_L + Z_{22}|^2 R_{in}}
 \end{aligned} \tag{2.6}$$

S-parameters are convenient as they can be easily measured in laboratory experiments. Z parameters can be obtained by using the following conversion,

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \frac{Z_0}{\Delta} \begin{bmatrix} (1 + S_{11})(1 - S_{22}) + S_{12}S_{21} & 2S_{12} \\ 2S_{21} & (1 - S_{11})(1 + S_{22}) + S_{12}S_{21} \end{bmatrix} \tag{2.7}$$

where $\Delta = (1 - S_{11})(1 - S_{22}) - S_{12}S_{21}$.

When the source and load impedances are matched with characteristic impedance (Z_0) of the system ($R_s = Z_L = Z_0$), normalized output power (NOP) and PTE become,

$$\begin{aligned}
 NOP &= \frac{P_{out}}{|V_{in}|^2 / (4Z_0)} = |S_{12}|^2 \\
 PTE &= \frac{|S_{12}|^2}{1 - |S_{11}|^2}
 \end{aligned} \tag{2.8}$$

S-parameters can be measured connecting network analyzer to transmitting and receiving resonators. Power electronic converter or power amplifier is not needed in these experiments. S-parameter based analysis and measurement are recommended at the initial stage of the design process. Frequency characteristic of performance indices can be determined using this method at lower power level. It must be noted that source impedance is typically 50 Ω in network analyzer measurements. However, source impedance is much smaller if a power converter is used.

2.3.3 Coupled Mode Theory

Coupled mode theory (CMT) analyses energy exchange between resonant objects in time domain [12]. CMT analysis of WPT system is used to obtain more insight understanding of resonator behavior.

$$\begin{aligned}\frac{da_1(t)}{dt} &= -(j\omega + \Gamma_1)a_1(t) + jKa_2(t) + V_{in}(t) \\ \frac{da_2(t)}{dt} &= -(j\omega + \Gamma_2 + \Gamma_L)a_2(t) + jKa_1(t)\end{aligned}\quad (2.9)$$

where $a_{1,2}$ are time varying field amplitudes of two resonant objects (transmitting and receiving resonators) and ω is the eigen frequency. $\Gamma_{1,2}$ are intrinsic decay rates (or resonance widths) of sending and receiving coils due to losses, and Γ_L is the resonance width of the load. Resonance widths are inversely proportional to resistances in equivalent circuit approach. $V_{in}(t)$ is the excitation signal applied to sending coil. K is the coupling rate between resonators.

In steady state and pure sinusoidal excitation signal ($F_s(t) = A_s e^{-j\omega t}$), resulting field amplitudes are $a_1(t) = A_1 e^{-j\omega t}$ and $a_2(t) = A_2 e^{-j\omega t}$. Average power absorbed by the transmitting resonator and the power delivered to receiving resonator are $P_1 = 2\Gamma_1|A_1|^2$ and $P_2 = 2\Gamma_2|A_2|^2$ respectively. Input power from the source $P_{in} = P_1 + P_2 + P_{out}$ [13]. Output power delivered to the load and power transfer efficiency can be expressed as,

$$\begin{aligned}P_{out} &= 2\Gamma_L|A_2|^2 \\ PTE &= \frac{1}{1 + \frac{\Gamma_2}{\Gamma_L} + \left[1 + \frac{\Gamma_1\Gamma_2}{K^2} \left(1 + \frac{\Gamma_L}{\Gamma_2}\right)^2\right]}\end{aligned}\quad (2.10)$$

CMT is applicable for designs with high quality factor and low coupling coefficient.

2.4 WPT for EV Charging

WPT for EV charging has many advantages compared to wired-PEV charging. Inconveniences in wired PEV charging process are major impediments in gaining interest of consumers. Due to industrial requirements and advancements in technology, power transfer distance in WPT systems has increased from several millimeters to several centimeters. Although number of researchers working on the WPT technology, still there are numerous challenges to overcome in bringing it to commercial level. Acceptable power transfer efficiency at high transfer range, increasing power level, misalignment tolerance and safety considerations are major technical challenges. Demonstrated research works show promises that the WPT can be brought in to commercial level with a reasonable cost [14].

Stationary EV charging for PEVs and dynamic EV charging for moving vehicles have been studied and demonstrated in the literature. Although both stationary and dynamic WPT for EVs have been undergoing from laboratory demonstrations, to bring them to large scale commercialization, still there is significant work needs to be done on performance optimization, standardization, cost effectiveness and safety considerations. Charging process should be automated as much as possible.

2.4.1 Stationary WPT for EV Charging

Stationary WPT can replace the charging cable for PEVs. WPT system is activated when vehicle reaches to the charging area. Figure 2.3 illustrates typical stationary WPT platform for EV charging. High frequency power inverter converts low frequency utility power to high frequency AC power. Resonance electromagnetic field generated in the transmitting resonator transfers power to the receiving resonator. Received power at the secondary resonator is rectified to charge the battery pack. Power converters used for the WPT can mainly categorized in to two types, namely indirect power converters and direct power converters. Utility power is first converted to DC and then invert to high frequency AC power in indirect conversion method. Energy conversion undergoes two conversion stages AC-DC-AC in indirect method. Alternatively, direct conversion method converts energy directly from low frequency mains to high frequency in a single stage [15, 16]. The charging system can be implemented in urban areas such as parking lots and bus stops.

Stationary WPT for EV charging has better market acceptance and lower implementation cost compared to dynamic WPT. A few WPT enabled EVs have been introduced to market including “Leaf” by Nissan Motor Co., “2014 Volt” by Chevrolet, “Qualcomm HaloIPT” by Qualcomm Co., and “PUGLESS” by Evatran Co. Some of the commercial pilot projects have been successfully demonstrated recently. Automotive manufacturers such as Delphi, Magna, Maxwell and Panasonic have been working on developing WPT systems. The development kit, WiT-3,300 released by WiTricity Corporation is capable of delivering 3.3 kW power over

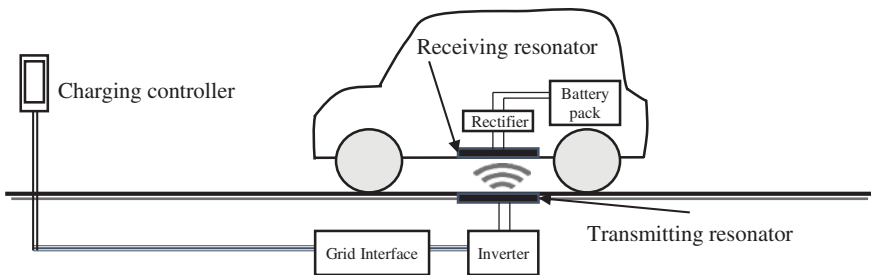


Fig. 2.3 Stationary WPT for EV

18 cm with 90 % efficiency. Size of WiT-3,300 transmitter and receiver resonators of are 50×50 cm [17]. University of Auckland has achieved 5 kW stationary IPT system with 90 % efficiency over 20 cm distance using 75 cm size coil design [18].

Stationary WPT solutions for EV charging has to be designed shifting the system complexity more towards the transmitting side infrastructure and keeping the vehicle component as simple as possible. Although mechanical and electrical hazards with plugged-in charger can be eliminated using stationary WPT for EV charging, driving range and slower charging time will still be a dominant issue.

2.4.2 Dynamic WPT for EV Charging

From the vehicle viewpoint, dynamic WPT enabled infrastructure where EVs can be charged continuously while in motion, theoretically solve the EV battery problem with unlimited driving range. However, employment of such system is reliant on the infrastructure development, which in turn limited by its cost. In addition, amount of the energy gained through WPT depends on the power level of the system, vehicle speed and duration that vehicle travel within the WPT enabled zone.

Dynamic EV charging approaches can be mainly categorized into two types based on transmitter array design; single transmitter track and segmented transmitter coil array. First type consists of a substantially long transmitter track connected to a power source. The receiver is noticeably smaller than the length of the track. Segmented coil array based designs have multiple coils connected to high frequency power sources as shown in Fig. 2.4a.

Transmitter track based systems are easier to control as the track is powered from a single source. Coupling coefficient along the track is nearly constant when the vehicle moves along the track. The transmitter track can be few meters to several tens of meters long. But this type of design suffers from several drawbacks. Firstly, the electromagnetic field emitted within the uncoupled region has to be suppressed to eliminate harmful exposure. Secondly, the compensation capacitor has to be distributed along the track to compensate large inductance. This brings additional constrain in construction. Thirdly, coupling coefficient is fairly low because of the smaller transmitter region covered by the receiver resulting lower efficiency. Usually ferromagnetic materials have been used to guide the magnetic flux and increase the efficiency. Relative range of track based systems are much smaller than unity.

On the other hand, segmented coil array eliminates field exposure and requirement for distributed compensation while lowering coupling issues. However, it introduces some other design challenges. It is necessary to track the receiver position and switch the appropriate power source as the load moves along the array. In addition, separation between transmitter coils needs to be carefully optimized. When coils are placed too apart, efficiency reduces steeply when the receiver moves away from the transmitter and power transfer will not be continuous. However, coils cannot be kept too close to each other due to two reasons. Firstly, negative mutual inductance between adjacent transmitter coils are significant generating negative

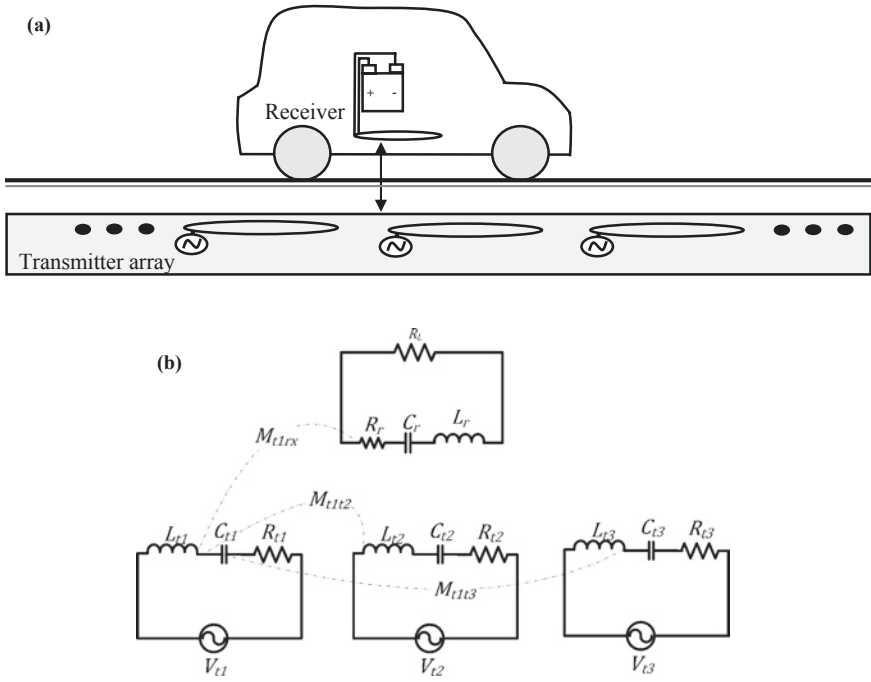


Fig. 2.4 **a** Dynamic EV charging with segmented coil array. **b** Equivalent circuit considering three nearby transmitters are powered simultaneously

current stress. Secondly, design cost will be increased with many transmitters in a given length of the track. Connecting source converters to multiple coils is also a design issue. Several transmitter coils can be connected to a single power converter in parallel, or there can be a converter connected to each coil. In both cases system complexity in terms of controlling the power flow is higher. Analysis of segmented coil based design can be carried out to derive most optimal design. Figure 2.4b shows equivalent circuit considering three nearby transmitters are powered simultaneously. Equation (2.11) can be used to study the system performance.

$$\begin{bmatrix} Z_{t1} & X_{t1t2} & X_{t1t3} & X_{t1r} \\ X_{t2t1} & Z_{t2} & X_{t2t3} & X_{t2r} \\ X_{t3t1} & X_{t3t2} & Z_{t3} & X_{t3r} \\ X_{rt1} & X_{rt2} & X_{rt3} & (Z_r + R_L) \end{bmatrix} \begin{bmatrix} I_{t1} \\ I_{t2} \\ I_{t3} \\ I_r \end{bmatrix} = \begin{bmatrix} V_{t1} \\ V_{t2} \\ V_{t3} \\ 0 \end{bmatrix} \quad (2.11)$$

$$P_{out} = |I_r|^2 R_L$$

$$PTE = \frac{P_{out}}{P_{in}} = \frac{|I_r|^2 R_L}{|I_{t1}|^2 R_{t1} + |I_{t2}|^2 R_{t2} + |I_{t3}|^2 R_{t3} + |I_r|^2 (R_L + R_r)}$$

$Z_m = R_m + j(\omega L_m - 1/\omega C_m)$, ($m = t_{1,2,3}, r$) are the self-impedances of transmitter and receiver coils where L_m , C_m , and R_m are inductance, capacitance and parasitic

resistance of the coil. Capacitance includes both distributed capacitance and externally added capacitance. $X_{mn} = X_{nm} = j\omega M_{mn} = j\omega M_{nm} (m = t_{1,2,3}, r)$ where $M_{mn} = M_{nm}$ is mutual inductance between m th coil and n th coil. ω is the operating frequency of the source. Subscripts $t_{1,2,3}$ represent three nearest transmitter coils to the receiver coil (represented by subscript r).

Some of the notable achievements in designing dynamic EV charging platforms can be identified as follows. UC Berkeley has conducted a test as a proof-of-concept of a dynamic WPT system for EV based on IPT in late 70s' [7]. They transferred a 60 kW of power through 7.6 cm distance to a passenger bus along 213 m long track. Due to limited semiconductor technologies, operating frequency of Berkeley system was 400 Hz and their efficiency was only 60 %. From there, researchers and industry have improved the performance of the dynamic EV charging systems. Korea Advanced Institute of Science and Technology (KAIST) is a leading research contributor in dynamic EV charging. The online electric vehicle (OLEV) centre of KAIST has demonstrated a transmitter track based roadway powered EV system. The OLEV has achieved 20 kW power transfer over 20 cm at 83 % efficiency with the use of Shaped Magnetic Field in Resonance (SMFIR) technology. SMFIR consists of current carrying transmitter rails of 5–60 m long and pickup module of 80 cm [19]. The relative transfer distance of KAIST-OLEV is still much smaller than unity. Oakridge National Lab (ORNL) has successfully demonstrated WPT system for moving EV using segmented coil array. ORNL has transferred 2 kW over 10 cm using 33 cm diameter coils with a maximum efficiency about 85 % [20]. But the efficiency of their setup tends to drop drastically with misalignment.

2.5 Design Challenges and Optimization Candidates

2.5.1 Analysis of WPT System

System performance indices can be analyzed using all three modeling approaches presented in Sect. 2.3. In this section we analyze performance indices for power transfer efficiency and transferred power with respect to design parameters. Equivalent circuit approach is chosen for the analysis. The efficiency term is not uniformly applied by the researchers in the literature. Both maximum power transfer operation and maximum efficiency condition are used as design goals. The maximum power transfer refers to the condition where maximum power is drawn from the source. The maximum power transfer occurs when the source impedance and the input impedance seen by the source are matched. Conversely, objective of the maximum efficiency operation is to optimize energy efficiency in the power transfer process.

As it can be seen in Fig. 2.5, the maximum PTE always occurs at the resonance frequency (f_0) for a two-coil system. Besides PTE declines with the coupling

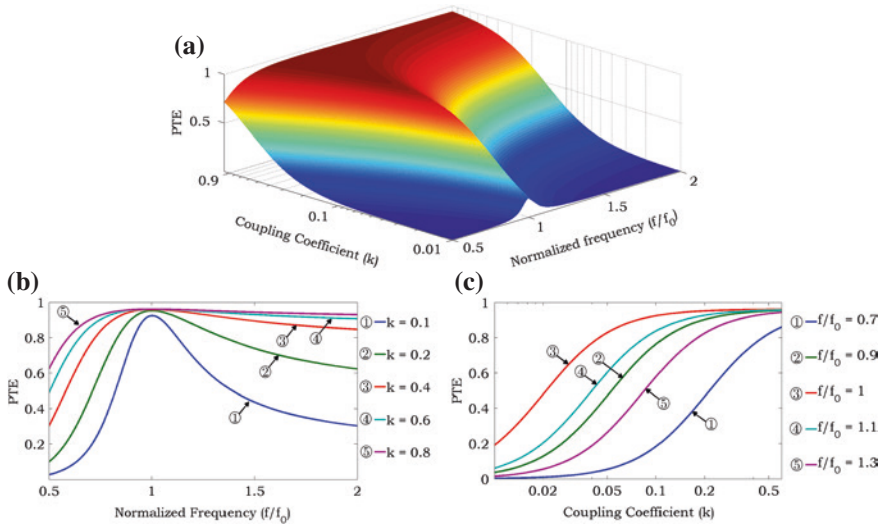


Fig. 2.5 **a** Power transfer efficiency (PTE) variation with respect to frequency (f) and coupling co-efficient (k). **b** PTE versus frequency. **c** PTE versus coupling coefficient. Frequency is normalized to resonance frequency (f_0)

coefficient between transmitter and receiver. On the other hand, output power is not always the maximum at the resonance frequency. When electromagnetic coupling between two coils is higher (strongly coupled), frequency at which maximum power transfer occurs is split. Transferred power to the load ($|S_{21}|^2$ or NOP) shows double peak behavior with respect to the frequency as can be seen in Fig. 2.6. This frequency splitting phenomenon [21] has led to various adaptive controlling efforts to maximize the power transfer, including frequency tuning [21, 22], impedance matching [23–25] and coupling manipulation [21, 26]. The point where the frequency splitting ends is referred to as the critical coupling point. Beyond the critical coupling point the transferred power to the load drops exponentially with increasing coil separation.

Both the transferred power to the load and the input to output efficiency have been used as the figure of merit in the literature. NOP can also be computed by modeling the system as two port network and using transfer scattering parameter, $|S_{21}|^2$ at impedance matched condition. It also should be noted that the maximum efficiency point shifts away from the resonance frequency in multi coil telemetry [9]. Based on the application, decision regarding optimization effort must be made between the transferable power and the efficiency. For low power applications where the importance of losses is not significant, the maximum power transfer operation is the main consideration. Energy efficiency is also a vital factor in high power applications.

At resonance condition, where $\omega_0 = 1/\sqrt{L_t C_t} = 1/\sqrt{L_r C_r}$ the power output and the efficiency can be expressed as,

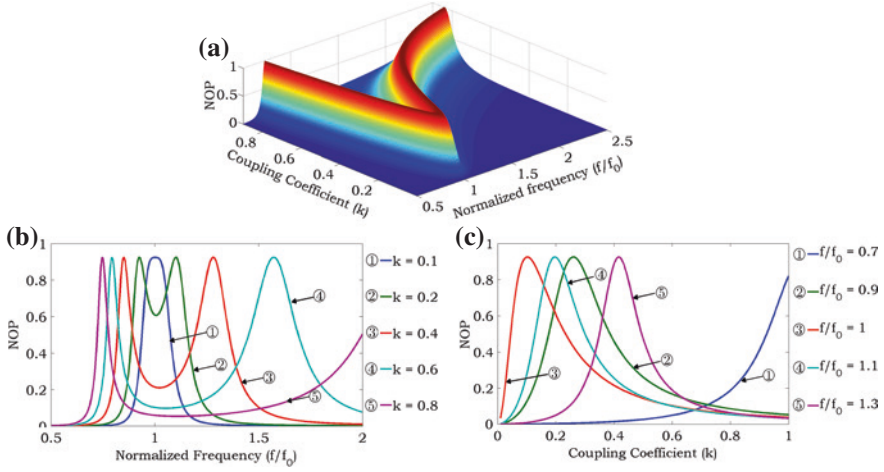


Fig. 2.6 a Normalized output power (NOP) variation with respect to frequency (f) and coupling co-efficient (k). b NOP versus frequency. c NOP versus coupling coefficient. Frequency is normalized to resonance frequency (f_0)

$$P_{out,\omega_0} = \frac{V_i^2 R_L (\omega_0 M)^2}{((R_s + R_t)(R_L + R_r) + (\omega_0 M)^2)^2} \quad (2.12)$$

$$PTE_{\omega_0} = \frac{R_L (\omega_0 M)^2}{((R_s + R_t)(R_L + R_r) + (\omega_0 M)^2)(R_L + R_r)}$$

Both PTE and the output power at the resonance depend on the value of load resistance as depicted in Fig. 2.7. Equation 2.13 gives values of load resistance for both maximum efficiency and maximum output power operating conditions. Impedance matching network can be used to make equivalent load resistance to its optimal value. Figure 2.8 shows the variation of optimal load resistance with respect to coupling coefficient.

$$R_{L,PTE_max} = \sqrt{\frac{(\omega_0 M)^2 R_r}{(R_s + R_t)} + R_r^2} \quad (2.13)$$

$$R_{L(max_Pout)} = \frac{(\omega M)^2}{(R_s + R_t)} + R_r$$

2.5.2 Designing the Figure-of-Merit of the System

Both PTE and transferred power cannot be optimized simultaneously. If transferred power is chosen as the first optimization goal, the maximum achievable efficiency can

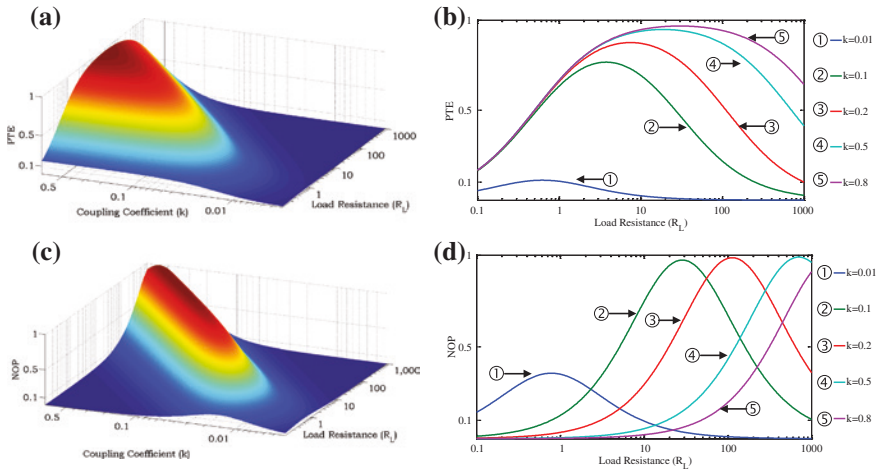


Fig. 2.7 a, b Power transfer efficiency (PTE), c, d Normalized output power (NOP) variation with respect to load resistance (R_L) and coupling co-efficient (k)

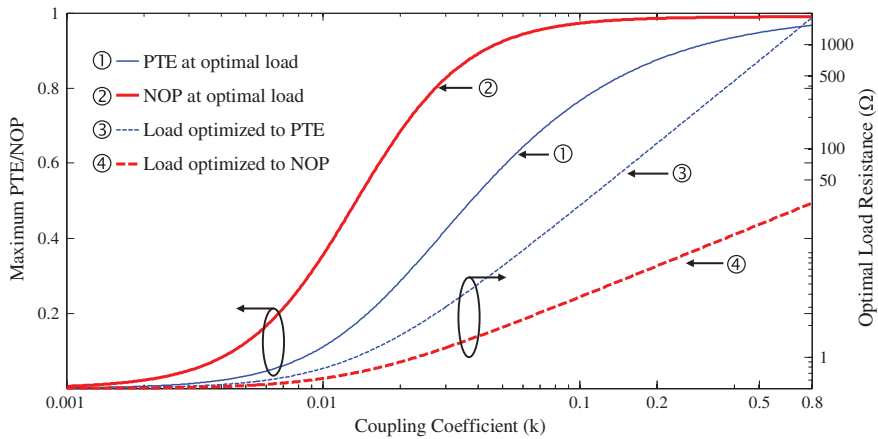


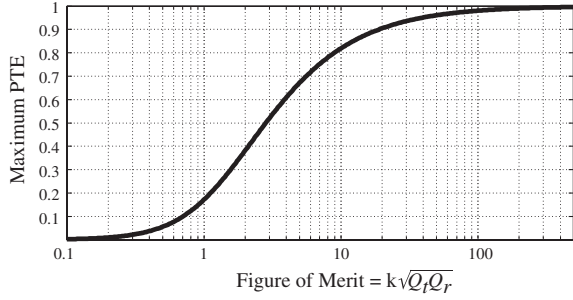
Fig. 2.8 Effect of load resistance on the power transfer efficiency (PTE) and normalized output power (NOP)

be limited. Which is not desirable for EV applications. On the other hand, if the first focus is on improving the efficiency of the system, other techniques such as adaptive impedance matching can be used to improve the transferred power. Therefore, it is recommended to focus on improving the efficiency in initial design stages.

2.5.2.1 Optimizing Power Transfer Efficiency

Maximum achievable efficiency when load resistance is optimized to $R_{L,PTE}$ can be expressed as [10, 27];

Fig. 2.9 Maximum achievable efficiency as a function of figure-of-merit (FOM), $k\sqrt{Q_t Q_r}$



$$\text{PTE}_{opt} = \frac{k^2 Q_t Q_r}{(1 + \sqrt{1 + k^2 Q_t Q_r})^2} \quad (2.14)$$

where $Q_{t,r} = \frac{\omega_0 L_{t,r}}{R_{t,r}}$ are unload quality factors of the transmitter and the receiver coils. As can be seen from Fig. 2.9, the maximum efficiency depends on the quality factors of the resonators, and the coupling coefficient between resonators. In order to achieve acceptable efficiency in a larger relative distance, (i.e. low coupling co-efficient) it is required to have resonator coils with high quality factor. Therefore, the operating frequency must be high enough and the AC resistance of resonators should be low. However, higher frequency operation leads to an increase in the complexity of the power electronic circuits. In initial demonstration done by MIT, team has achieved 40 % efficiency between sending and receiving resonators in 2 m distance [6].

2.5.2.2 Optimizing Transferred Power

Transferred power is also important to be considered because it determines VA ratings, thus the component ratings, especially ratings of the series capacitor and power converter switches. Transferred power becomes maximum when the maximum power is drawn from the source. This happens when the source impedance matches the input impedance of the coil system. Input impedance of the coil is varied with the coupling coefficient variation and operating frequency. When operating at self-resonance frequency, the maximum power transfer occurs at a particular coefficient value referred to as critical coupling point. Value of the critical coupling can be derived as in (2.15). Coupling coefficient equals to critical coupling at a particular distance. But in dynamic EV charging WPT distance and the coupling coefficient are continuously varying. Therefore, operating at critical coupling point is not desirable.

$$k_{critical} = \sqrt{\frac{(R_s + R_t)(R_L + R_r)}{\omega_0^2 L_t L_r}} = \sqrt{\frac{1}{Q_T Q_R}} \quad (2.15)$$

where Q_T and Q_R are loaded quality factors in transmitter and receiver resonators.

When operating out of critical coupling point, the reactive power of a transmitter can be 50 times larger than the transmitted active power [28]. Therefore, voltage and current in the coils can be very high without a proper design optimization. This high current could affect power rating of power converter switches and compensation capacitor. Voltage across the series capacitor and the inductor coil at the resonance operation can be expressed as in Eq. (2.16). The output power can be increased by increasing the voltage applied on the transmitter resonator, but it will also increase required capacitor rating. With high quality factor resonators (typically 400–1,000) this increase will be more significant.

$$V_{c_{t,r}} = V_{t,r} Q_{t,r} \quad (2.16)$$

Adaptive impedance matching networks can be used to match the source impedance to input impedance of WPT network [23–25]. Unlike PA based laboratory prototyping where source impedance is 50 Ω , in power converter based designs the source impedance can be a very small value. Therefore, the matching network should be capable of bringing input impedance of the WPT system close to source impedance.

2.5.3 Power Transfer Distance and Misalignment Tolerance

As identified in previous sections system performance is largely dependent on the electromagnetic coupling coefficient which has linear relationship with mutual inductance. In this section we analyze mutual inductance variation with respect to relative position of the receiver. Calculations are presented for a multi turn circular coil. Mutual inductance between circular resonators can be calculated using filament method [29] by modelling coil as a set of filamentary circular coils. Mutual inductance between misaligned filamentary circular coils with parallel axes shown in Fig. 2.10a can be computed using Eqs. (2.17), (2.18) and (2.19) [30, 31].

$$M = \frac{\mu_0}{\pi} \sqrt{r_t r_r} \int_0^\pi \frac{\left(1 - \frac{y_{tr}}{r_r} \cos \phi\right) \Phi(m)}{\sqrt{V^3}} d\phi$$

$$a = \frac{r_r}{r_t}, b = \frac{z_{tr}}{r_t}; m^2 = \frac{4aV}{((1 + aV)^2 + b^2)} \quad (2.17)$$

$$V = \sqrt{1 + \frac{y_{tr}^2}{r_r^2} - 2\frac{y_{tr}}{r_r} \cos \phi}; \Phi(k) = \left(\frac{2}{m} - m\right) K(m) - \frac{2}{m} E(m)$$

Complete Elliptic Integrals,

$$K(m) = \int_0^{\pi/2} \frac{1}{\sqrt{(1 - m^2 \sin^2 \gamma)}} d\gamma; E(m) = \int_0^{\pi/2} \sqrt{(1 - m^2 \sin^2 \gamma)} d\gamma$$

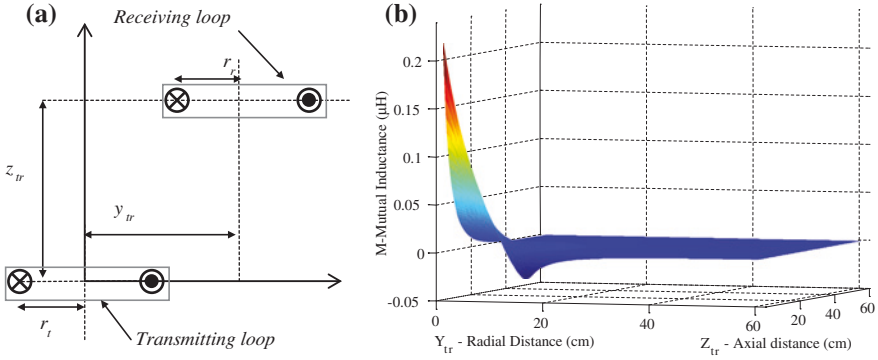


Fig. 2.10 **a** Filamentary circular coil arrangement. **b** Mutual inductance with respect to radial and lateral misalignment for elementary circular loops

Equation (2.17) becomes singular when $z_{tr} \neq 0$ and $r_r = y_{tr}$. In that case Eq. (2.18) needs to be used [30].

$$M = \frac{\mu_0}{2\pi} r_t \int_0^\pi \sqrt{((1 + aV)^2 + b^2)} \psi(m) d\phi$$

$$a = \frac{r_r}{r_t}, b = \frac{z_{tr}}{r_t}, m^2 = \frac{4aV}{((1 + aV)^2 + b^2)} \quad (2.18)$$

$$V = 2\sin\left(\frac{\phi}{2}\right) \text{ and } \psi(k) = \left(1 - \frac{m^2}{2}\right) K(m) - E(m)$$

The total mutual inductance between two multi turn coils will be,

$$M_{tot} = \sum_{i=1}^{N_t} \sum_{j=1}^{N_r} M_{ij} \quad (2.19)$$

where N_t and N_r are total number of turns in transmitter and receiver windings, and M_{ij} is mutual inductance between i th transmitter and j th receiver turns.

Mutual inductance for circular elementary coils with 890 mm radius is depicted in Fig. 2.10b. Mutual inductance reduces steeply with the increase of radial distance. For a given displacement, higher mutual inductance can be achieved by using larger coil size. Therefore, by increasing the dimensions higher efficiency can be achieved for a given distance. But this is not a good engineering approach. It would be appropriate if highest possible efficiency is achieved with minimum dimensions and cost. Therefore, power transfer distances need to be analysed by normalizing them to the coil dimension. A term relative range can be defined using the maximum dimension of transmitter and receiver as Eq. (2.20). In case of circular transmitter and receiver, relative range becomes geometric mean of radii.

$$d_{relative} = \frac{\sqrt{(D_t D_r)}}{2} \quad (2.20)$$

where D_t and D_r are maximum dimensions of transmitter and receiver coils.

It can be seen from Fig. 2.10b that mutual inductance drops to a negative value when axial distance is low. In case a transmitter array is used for dynamic EV charging, this negative mutual inductance causes a negative current stress on the adjacent transmitter reducing the efficiency of the system. If transmitter coils are kept very close to each other this negative mutual coupling can be even more significant.

2.5.4 Operating Frequency Selection

Operating frequency selection of the design has to be carried out with a number of technical and regulatory constraints. Considering maximum achievable efficiency for a WPT system in Eq. (2.14), highest possible quality factor is desirable. There are three options available in increasing quality factor; increasing inductance or frequency, and decreasing resistance. AC resistance increases with the increase of frequency due to skin effect losses. Usually inductance of a coil is determined by its shape and is independent on the operating frequency. Therefore, there is an optimum frequency for a given design type for highest possible quality factor. Typically, this optimum frequency is in MHz range for most designs. However, design of high power EV WPT system in MHz range frequencies is still beyond today's semiconductor technologies. Therefore, upper limit of the operating frequency is restricted by device constraints. There have been successful attempts to use frequencies ranges from 10 to 150 kHz for EV applications [32, 33]. With the advent of modern semiconductor technologies such as wide band gap devices, frequency limit of the devices are increasing rapidly. Therefore, cost effective, high power near MHz WPT for EV applications is not very far away.

2.5.5 Adaptive Tuning Methods

2.5.5.1 Adaptive Impedance Matching

Operating at maximum transferred power condition is important with regard to component rating. At a particular distance where coupling coefficient equals to critical coupling, transferred power becomes maximum. But in dynamic EV charging, WPT distance, thus the coupling coefficient is continuously varying. Adaptive impedance matching (AIM) network between source and the transmitter coils (Fig. 2.11) can be used in such a scenario [23–25]. On the other hand, the equivalent load impedance is dependent on the state of charge of the EV battery, which is varying with the charging. Adaptive impedance matching network can be used between receiver coil and EV battery charger to make equivalent load impedance to its optimal value.

Matching networks should be capable of adaptively changing the impedance of the network. Input impedance seen by the source has to be maintained at matched

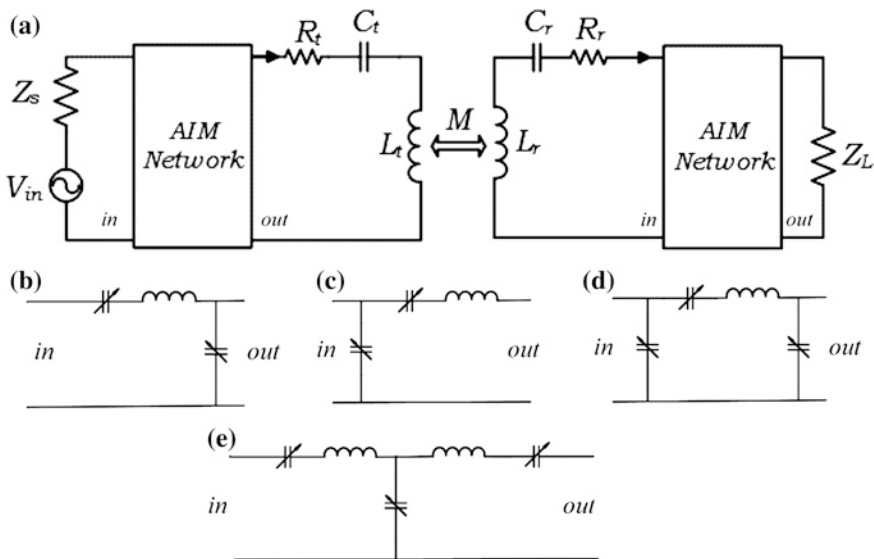


Fig. 2.11 a Transmitter and receiver side adaptive impedance matching (AIM). b L-type. c Inverted-L type. d Π type and e T-type matching networks

condition under dynamic changes in WPT system. Usually, a switched capacitor bank along with an inductor is used to change the impedance [23–25]. Current controlled inductor which has been used to control micro-inverter [34] can also be used as a variable inductor for the matching network. Based on the component arrangement of the matching network impedance, matching networks can be categorised into L-type, inverted L-type, T-type and Π -type. These matching networks are illustrated in Fig. 2.11. L-type and inverted L-type matching networks are simple but design freedom is higher in complicated T and Π types. Resistive losses in the components also become significant in complex matching networks with number of switching devices. Therefore, choice of matching network has to be carried out based on the design constraints such as coupling variation, number of components and switching devices.

2.5.5.2 Adaptive Frequency Tuning

Frequencies where maximum power transfer occurs at higher coupling coefficients can be determined by the Eq. (2.21). These two frequencies are known as electric resonance (f_e) and magnetic resonance (f_m) frequencies. It can be seen that both these frequencies are varying with the coupling coefficient. If the system operating frequency can be tuned to either of these frequencies maximum power transfer operation can be maintained. There have been attempts to use variable frequency techniques to adaptively tune frequency of power converters to maximum power

transfer condition [21, 22]. It must be noted that such frequency tuning approaches have to be used with compromised efficiency.

$$\begin{aligned} f_m &= \frac{\omega_0}{2\pi\sqrt{1+k}} \\ f_e &= \frac{\omega_0}{2\pi\sqrt{1-k}} \end{aligned} \quad (2.21)$$

2.5.6 Optimization of Resonator Design

Typical resonators used for stationary EV charging are in the form of a pad shape and built with the use of ferromagnetic materials in general. Such resonator coils with ferrite materials can be identified as two types based on the magnetic field distribution; double-sided and single sided. Magnetic flux propagate in both sides of the resonator in double sided resonator types [35]. This type of design needs additional shielding to prevent eddy current generated in EV chassis. Therefore, double sided resonator coil is not the optimal choice due to high shielding losses. Single sided resonator coils have a ferrite layer below the coil guiding the flux towards receiver [18, 36, 37]. Circular unipolar pad [36] and rectangular double D (DD) [18] shaped coil designs have achieved enhanced coupling in both radial and axial separations.

Resonator types used for dynamic WPT can be categorised based on the transmitter configuration. Transmitter track type configurations have long wires embedded in ferrite to shape the magnetic field. U-shape, W-shape and I-shape ferrite cores have also been used in this types of designs [32, 38]. One of the major challenges in transmitter track design is that receiver coil only covers a small part of the track resulting in a very poor coupling as identified in previous sections. When it comes to segmented transmitter array, coil design is similar to stationary EV charging. However, in dynamic charging coupling deterioration against lateral displacement is more significant than stationary charging case.

2.6 Optimization of Resonator Design

The coils play an imperative role in WPT design stages. For WPT coils, there are two performance indices: quality factor and electromagnetic coupling between transmitter and receiver. The quality factor can be improved by decreasing the AC resistance (skin and proximity losses) of the coil while maintaining high inductance. But, enhancement of the electromagnetic coupling is severely limited by the misalignment and distance between coils which cannot be compromised due to most application constrains. Instead, coupling variation can be optimized by choosing appropriate coil structure for a particular position displacement profile.

There have been a number of studies which addressed the losses related to resonators. Several optimized resonator designs have been proposed. For example, [39] presents a detailed optimization process for double layer printed

spiral coil. The authors have illustrated design procedure for optimal choice of number of turns, track width and turns separation. Reference [40] presents multi turn surface spiral for low AC resistance. But these designs can only be used in limited power levels as they are constructed in PCBs. Furthermore, substrate losses play considerable role in AC resistance. In order to address the issue of coupling deterioration with misalignment, inserting a negative current loop is considered in [41]. Although this approach reduces the coupling variation, it also reduces overall coupling due to its negative magnetic flux.

2.6.1 AC Resistance, Self-inductance and Parasitic Capacitance

Modeling WPT coils can be done using either analytical or simulation methods. For rectangular or circular coil shapes analytical optimization can be carried out using equations. But for complicated coil shapes with ferromagnetic materials, finite element analysis based simulations have to be carried out. AC resistance, inductance and parasitic capacitance of a circular multi-turn coil is discussed in this section.

Usually Litz wires are adopted to reduce the skin effect resistance of coil designs. AC resistance of circular Litz wire winding with N number of turns can be calculated using Eq. (2.22) [42, 43].

$$R_{ac} = R_{dc} \left(1 + \frac{f^2}{f_h^2} \right), f_h = \frac{2\sqrt{2}}{\pi r_s^2 \mu_0 \sigma \sqrt{N N_s \eta_a \beta}} \quad (2.22)$$

where R_{dc} , r_s , N_s and β represent the dc resistance of the coil, radius of each single strand number of strands per bunch and the area efficiency of the coil. The dc resistance is dependent on the manufacturing methods and type of the litz wire, usually available in the datasheet. The value of η_a is the area efficiency of the coil dependent on the height and width of the coil (Refer Fig. 2 in [43]).

Self-inductance of a multi-turn coil with N_t coaxial turns N_l concentric layers can be calculated using circular loop approximation as in Eq. (2.23).

$$L(R, r) = \mu_0 R \left(\ln \frac{8R}{r} - 2 \right) \quad (2.23)$$

$$L_{self} = N_t \sum_{i=1}^{N_l} L(R_i, r) + \sum_{i=1}^{N_l} \sum_{j=1}^{N_l} \sum_{k=1}^{N_t} \sum_{l=1}^{N_t} M_{ikjl} (1 - \delta_{ij}) (1 - \delta_{kl})$$

where δ_{ij} (or δ_{kl}) = 1 for $i = j$ (or $k = l$) and δ_{ij} (or δ_{kl}) = 0 otherwise. $L(R, r)$ is inductance of a circular loop with radius R formed using radius r wire. M_{ikjl} is the mutual inductance between two circular turns, i th layer k th turn and j th layer l th turn.

In general, self-capacitance of the coils used for WPT in kHz range is not significant compared to inductive reactance. But with the increase of the frequency, capacitive reactance also needs to be taken into account for accurate modelling. This stray capacitance between turns needs to be taken into account in designing the value of the lumped capacitor. Self-capacitance of a multi layered coil considered previously can be obtained using Eq. (2.24) [43].

$$C_{self} = \frac{1}{(N_t N_l)^2} \left[C_b N_l (N_t - 1) + C_m \sum_{i=1}^{N_l} (2i - 1)^2 (N_l - 1) \right]$$

$$C_b = \epsilon_0 \epsilon_r \int_0^{\pi/4} \frac{\pi D_i r_0}{\zeta + \epsilon_r r (1 - \cos \theta)} d\theta$$

$$C_m = \epsilon_0 \epsilon_r \int_0^{\pi/4} \frac{\pi D_i r_0}{\zeta + \epsilon_r r (1 - \cos \theta) + 0.5 \epsilon_r h} d\theta \quad (2.24)$$

C_b is parasitic capacitance between two nearby turns in the same layer, and C_m is that of nearby turns in adjacent layers. D_i , r , ζ , ϵ_r , h are the average diameter of the coil, wire radius, thickness and relative permittivity insulation and separation between two layers respectively. Quality factor of the coil can be determined based on the inductance and the resistance calculations.

2.6.2 Optimization of Resonator Design Parameters

In this section a case study of optimization process of a multi turn helical coil design is presented. The shape of the coil and design parameters are illustrated in Fig. 2.12. Number of layers (N_l), Number of turns (N_t), separation between layers (S_l) and separation between turns (S_t) are considered for the optimization process. A single turn with multiple layers results in a planar spiral coil shape whereas a single layer with multiple turns results in a helical shaped coil. Outermost radius (r_o) is kept at 9 cm and maximum height of the coil is restricted to 5 cm because most applications have to be designed within a given footprint area. The radius of the wire is fixed at 1 mm. AC resistance, inductance and quality factor are analysed using finite element analysis software Ansoft Maxwell® 2D. Each turn is approximated as a circular current loop in 2-D simulation as shown in Fig. 2.12b.

In order to analyse the effect of N_l and S_l , we choose single turn coil which represents a planar spiral. Simulation results presented in Fig. 2.13 show quality factor variation with respect to S_l and N_l . Both S_l and N_l affect AC resistance and inductance which ultimately determines the quality factor. It can be observed that both number of layers and separation have to be optimised to achieve a high quality factor. With the number of layers, coil inductance increases and consequently it affects the quality factor. In contrast, the physical effect of higher N_l increases the

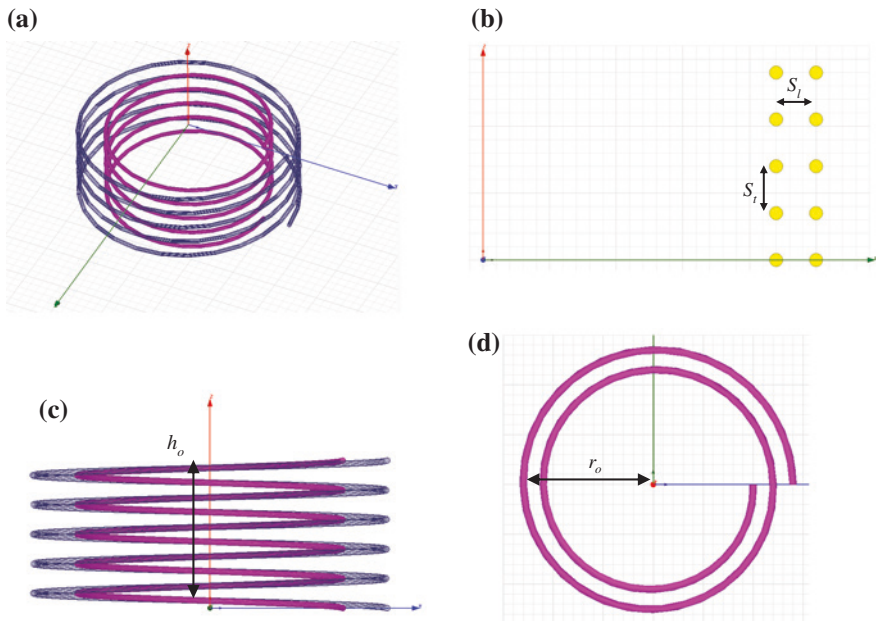


Fig. 2.12 Multi layered helical coil with two layers and 5 turns **a** 3-D view, **b** 2-D approximation, **c** side view, **d** top view

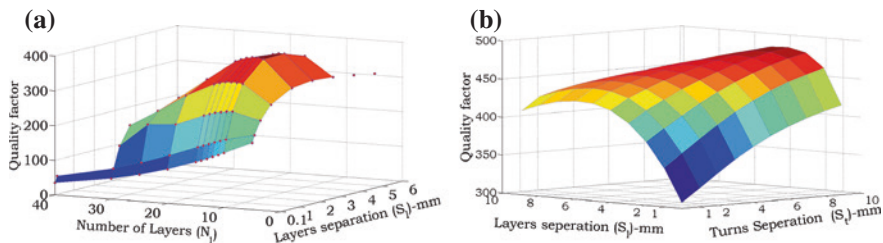


Fig. 2.13 **a** Quality factor versus number of layers and separation between layers at 1 MHz for planar spiral coil ($N_t = 1$). **b** Quality factor versus separation between layers and separation between turns at 1 MHz for multi layered spiral coil. (number of layers—5 and number of turns—3)

spiral coil length, thus the resistance, causing detrimental impact on the quality factor. On the other hand, lower S_l increases coil inductance as layers are confined to outer radius. However, when layers are very close to each other with low S_l , proximity losses are increased resulting a high AC resistance. This explains the steep dip in quality factor found in Fig. 2.13a for low S_l . The effect of the proximity losses with closer turns is more significant in higher frequencies. Therefore, separation between turns is a crucial design parameter with WPT operating at high frequency. Therefore, tightly wound coils with very small separation are not recommended for obtaining highest possible quality factor for WPT applications.

Next, impact of S_l and S_t is analysed for choosing a coil with 5-layers and 3-turns. Figure 2.13b shows quality factor variation with respect to S_l and S_t . Similar to planar spiral case, both lower and higher extremes of S_l results in a low quality factor. Previous explanation holds for this observation as well. Conversely, it can be seen that quality factor increases with S_t . Inductance of the coil is less dependent on S_t , because loop radius is independent of S_t . Larger turns separation reduces the proximity effect losses, leading to higher quality factor. This incremental effect of quality factor is less significant at higher S_t because influence of the proximity effect resistance becomes negligible. Increase of S_t is also limited by the coil height. It must also be noted that our circular current loop approximation becomes invalid at very high S_t .

Therefore, we next analyse the effect of number of layers and number of turns with a substantial separation between turns and layers (chosen as 3 mm). Results presented in Fig. 2.14a show that highest possible number of turns within the chosen footprint volume results in the best quality factors. Design with two layers shows the maximum quality factor with these parameters.

Figure 2.14b presents the quality factor variation of two layered coil with respect to separation between layers and turns. The maximum possible number of turns is chosen for the analysis. 11 number of turns with 3 mm turn separation result in best quality factor of 582. The maximum quality factors that can be obtained using planer spiral (at $N_t = 11$ and $S_t = 3$ mm) and helical (at $N_l = 12$ and $S_l = 2$ mm) coils are 400 and 530 respectively.

Based on the above analysis we can suggest recommendations for designing high quality factor coils for the WPT applications. Firstly, tightly wound coils with low separation between turns/layers is not recommended because proximity effect losses dominates the AC resistance. Secondly, multi layered helical coil can be used to increase the quality factor. Performance of multi layered helix is better than both planar spiral and the single layered helix. Third, design guideline for the multi layered helix can be derived as; 1. Choosing substantial value of separation between turns/layers, 2. Maximum possible turns with the given footprint area, 3. Optimizing the number of layers with the selected design.

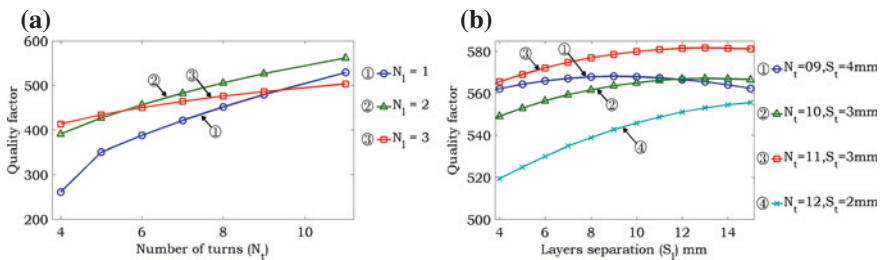


Fig. 2.14 a Quality factor vs number of turns and number of layers at 1 MHz for multi layered helical coil (separation between layers and separation between turns equals to 3 mm). b Quality factor vs separation between layers and number of turns with two layers

2.7 Future Directions and Trends

Dynamic WPT enabled EV charging is the ultimate objective of the current research activities. Dynamic WPT enabled infrastructure would allow power delivery while EV is in motion. Future EV equipped with such technology would not carry a large amount of energy storage.

However, substantial amount of research work has to be carried out to bring current technology to achieve such a scenario. Major design challenges are increasing the WPT range with acceptable efficiency level. Design and optimization of resonators plays a major role in improving the system performance in extended range. With the advent of modern semiconductor technologies such as wide band gap devices, frequency limit of the high power WPT system has been increasing in a rapid manner. Therefore, cost effective, high power, near MHz WPT would be next step of the WPT for EV charging. Ferromagnetic materials used for magnetic field shaping in kHz frequencies is not appropriate for high frequency applications. Materials amenable for near MHz WPT resonators have to be investigated for future solutions. Resonator arrangements such as use of repeaters or meta materials need to be investigated for EV applications. Tuning approaches such as adaptive impedance matching and frequency tuning techniques will have to be implemented to maintain system performance in dynamic moving conditions. Furthermore, investigations of appropriate matching networks have to be carried out. In addition, design of high frequency power converters for future WPT application would be another challenging aspect of future research. Reducing conduction and switching losses in power conversion is a vital factor in improving the efficiency. Direct power conversion topologies such as matrix converters can be identified as a potential direction for future WPT applications.

2.8 Conclusions

WPT technology for EV battery charging is discussed in this chapter. Efficiency, transferred power, range and misalignment tolerance are identified as the performance indices. A detailed analysis of WPT system is presented highlighting the contributions by the research community. Modeling methods and their own merits are presented. WPT methods for EV charging are elaborated with design challenges. Dynamic WPT for EV is identified as the next generation of transportation electrification. Recommendations for WPT coil designs are presented with case study.

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