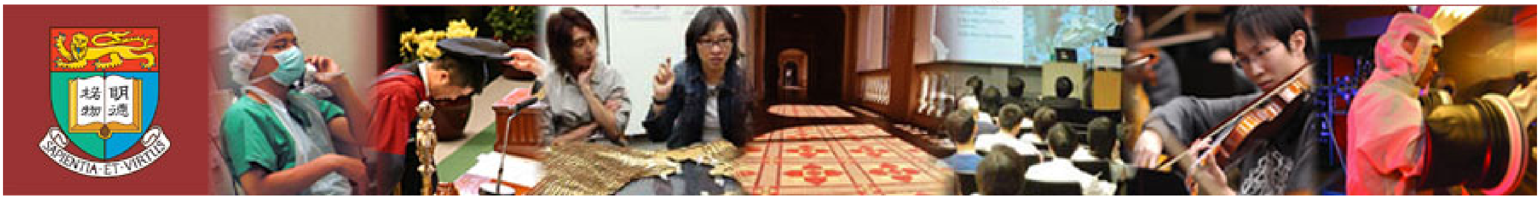

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Planar Wireless Charging Technology for Portable Electronic Products and Qi

This paper discusses the recent system platforms based on planar charging as well as its critical issues and related technologies. The information on the first wireless power standard "Qi" is then presented with future trend and development predictions.

By S. Y. Hui, *Fellow IEEE*

ABSTRACT | Starting from the basic principles of Tesla's wireless power transfer experiment in the 1890s, this review article addresses the key historical developments of wireless power and its modern applications up to formation of the world's first international wireless power standard "Qi" launched in 2010 for portable electronics. The scientific principles laid down by Nicolas Tesla for wireless power transfer, which still remain valid today, are first explained. Then, modern wireless power applications based on nonradiative (near-field) magnetic coupling for short-range applications are described. Some industrial application examples emerging since the 1960s are highlighted. The article then focuses on the comparison of the horizontal and vertical magnetic flux approaches developed in the early 1990s for low-power planar wireless charging pads. Several critical features such as localized charging, load identification, and freedom of positioning that are essential to wireless charging of portable electronic devices are explained. The core technologies adopted by the Wireless Power Consortium (WPC) for the "Qi" Standard in 2010 are summarized. Finally, the latest research and developments of wireless power transfer for midrange applications based on the domino-resonator concept and their future application potential are described.

KEYWORDS | Consumer electronics; contactless charging; wireless power standard Qi; wireless power transfer

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I. INTRODUCTION

The dawn of the portable battery-powered electronics and communication devices since the 1980s has brought huge benefits to human society. The invention of mobile phones, for example, has revolutionized the communication methods among people. However, each portable battery-powered electronic product comes with its own charger and, consequently, results in an increasing electronic waste issue [1], [2]. Table 1 shows the market size for a range of portable electronic products. Among them, the number of mobile phones alone reached about 1.7 billion in 2010 and is expected to exceed 2 billion by 2013. The emergence of new electronic products such as iPhones (with a sales volume of 244 million units in the period of April 2007–June 2012) [69] and iPads (with a sales volume of 84 million units from April 2010 to September 2012) [70] has accelerated the market expansion of portable electronic products.

The GSM Association has made efforts in promoting the use of micro-USB as a common standard to standardize the cord-based charging interface. According to [3], an annual reduction of about 51 000 tons of chargers would be achieved if a common charging protocol is adopted. Besides the standard cord-based charging option, nonradiative "short-range" wireless charging technology has emerged as an attractive and user-friendly solution to a common charging platform for a wide range of portable electronic products. Unlike traditional cord-based charging methods, wireless charging offers advantages such as the possibility of waterproof product designs and ease of use (e.g., cordless charging of mobile phones on a coffee table or inside a vehicle). Such advantageous features have already attracted over 130 companies to form a Wireless Power Consortium (WPC) [4], which launched the world's

Table 1 Market Size of Some Portable Devices (Excluding Medical and Personal Care Devices, Remote Controls, Industrial Portable Devices) Source: Databeans, Gartner, IMS, Morgan Stanley, Nintendo, Sony, TSR 2010

Market Size (Millions Units)	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Mobile Phones	**1421**	**1696**	**1841**	**1963**	**2069**	**2160**	**2236**	**2291**
2G phones	1133	1284	1305	1305	1301	1287	1261	1235
3G phones	287	409	534	648	745	825	890	836
4G phones	0	0	2	10	23	48	85	220
Tablets	**0**	**16.7**	**60**	**90**	**130**	**185**	**241**	**300**
Bluetooth Headset	**62**	**65**	**45**	**50**	**60**	**85**	**110**	**150**
Cordless Phones	**95**	**93**	**104**	**111**	**112**	**115**	**118**	**124**
Notebook Computers	**135**	**164**	**189**	**210**	**232**	**280**	**315**	**380**
Netbooks	**34**	**36**	**29**	**26**	**26**	**20**	**18**	**17**
Camcorder/Digital Recorder	**36**	**34**	**35**	**37**	**38**	**40**	**42**	**44**
Digital Camera	**120**	**118**	**127**	**131**	**140**	**145**	**159**	**169**
Portable DVD	**22**	**20**	**27**	**32**	**28**	**34**	**38**	**43**
Multimedia Player (incldg MP3/MP4)	**208**	**211**	**229**	**256**	**268**	**289**	**321**	**349**
Portable CD Audio	**45**	**44**	**46**	**46**	**50**	**51**	**51**	**52**
Nintendo DS	**31**	**27**	**17**	**14**	**12**	**10**	**10**	**10**
PSP	**16**	**14**	**9**	**15**	**18**	**18**	**18**	**18**
Total (Millions)	**2224**	**2535**	**2758**	**2981**	**3183**	**3432**	**3677**	**3947**

first Wireless Standard "Qi" in 2010 for wireless charging of portable electronic devices up to 5 W. An updated version of Part-1 of the Qi standard can be found in [5].

This paper starts with a brief review of the historical developments of wireless charging and their modern applications for portable electronic devices. (Medium and high power applications will not be included here as they are covered in other papers in this special issue.) It will highlight the parallel-flux and vertical-flux approaches that have been attempted for use in planar wireless charging pad systems for portable electronic products. Some essential safety and operating features that are often ignored in planar wireless power transfer research for consumer electronics are highlighted and their corresponding solutions are explained. Then, the basic charging methods adopted in the "Qi" standard are described. Finally, new challenges in foreign object detection and in increasing transmission length for future wireless power systems are addressed.

II. BRIEF REVIEW OF WIRELESS POWER TRANSFER

Over a century ago, early pioneers of wireless power such as M. Hutin and M. Leblanc showed that wireless power and resonance techniques could be applied to traction systems [71], and Nicola Tesla successfully demonstrated the use of a pair of coils for wireless power transfer. Fig. 1 shows a drawing of one experimental setup conducted by Tesla in which a lighting device is wirelessly powered via a pair of coils [6]. In fact, Tesla has pioneered both nonradiative wireless power [6], [7] via near-field magnetically coupled coils and radiative [8] wireless power transfer techniques via high-tension Tesla's coils. Nonradiative wireless power transfer relies on the near-field magnetic coupling of conductive loops. Energy is transferred over a

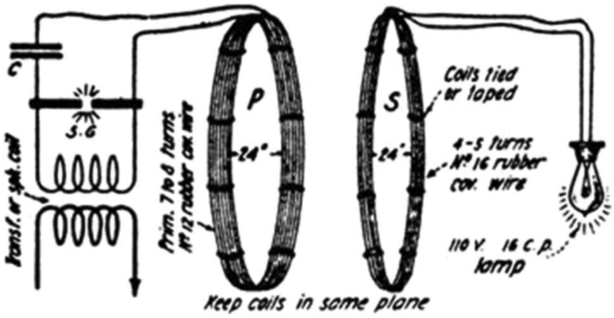

Fig. 1. *A diagram of one of Tesla's wireless power experiments [6].*

relatively short distance, which is of the order of the dimension (such as the radius or the diameter) of the coupled coils. Radiative power transfer relies on high-frequency excitation of a power source, and radiative power is emitted from an antenna and propagates through a medium (such as vacuum or air) over long distance (i.e., many times larger than the dimension of the antenna) in the form of electromagnetic wave. As radiative wireless power research is beyond the scope of this paper, only the principles of nonradiative wireless power research are discussed here.

According to [7], Tesla connected a coil in series with a Leyden jar (which is an early form of a capacitor) to form a loop resonator (i.e., an inductive-capacitive resonator). Through the near-field magnetic coupling between a pair of coils, he demonstrated that wireless power transfer could be achieved effectively at the natural resonance frequency of the loop resonator. According to a study on Tesla's contributions [72], it was stated in a 1943 article [73] that "Tesla is entitled to either distinct priority or independent discovery of:

1) the idea of inductive coupling between the driving and the working circuits;
2) the importance of tuning both circuits, that is, the idea of an "oscillation transformer";
3) the idea of a capacitance loaded open secondary circuit."

These three aspects of discovery have formed the founding principles for both nonradiative and radiative wireless transfer. In particular, the "oscillation transformer" concept goes beyond pure magnetic induction principle, and more precisely, refers to the use of magnetic resonance between two magnetically coupled coil resonators. The combined use of magnetic induction, tuned circuits, and resonance operating frequency has been a common theme in its wireless power and radio investigations [7].

It must be noted that these principles are still valid today for wireless power transfer. The use of resonance frequency is to compensate for the leakage impedance of the power flow path. The work reported in [9] demonstrated these principles in a four-coil system by adopting the impedance matching method for extending the transmission distance, at the expense of energy efficiency [74]. Energy transfer between coupled coils through small air gap has been the main operating mechanism in rotating electric machines [10], which is also a technology pioneered by Tesla. Despite Tesla's wireless power research, there was no widespread use of nonradiative wireless power transfer for mid- and long-range applications in the first half of the twentieth century. The main reason is the drastic reduction of transmission efficiency with distance as illustrated in Fig. 2 and highlighted in [11] and [12].

Since the 1960s, researchers in the biomedical fields have investigated the short-range wireless power transfer through body tissues [13]–[16] and radio-frequency (RF) powered coils for implant instruments [17]. Tesla's wireless power principles of the use of magnetically coupled coils and resonance techniques are followed [18]. Interestingly, the needs for both power and data transfer in the biomedical wireless power research [19] bear similarities with those in wireless charging of portable electronic products.

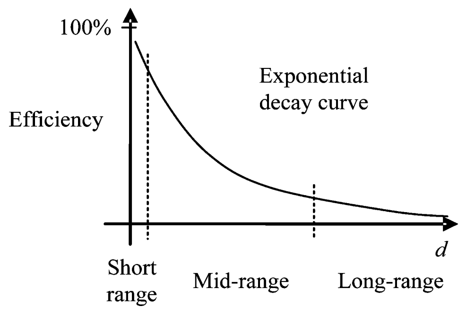

Fig. 2. ***Typical exponential decay curve of the efficiency as a function of transmission distance d for wireless power transfer.***

The advancement of modern power electronics in the 1980s enables easy control of power and frequency. Consequently, power-electronics-based transcutaneous energy transmission systems for bioimplants became possible [20], [21]. In the 1990s, medium- and high-power inductive pickup systems based on power electronics systems attracted much attention, particularly for applications in harsh environment [22], for charging electric vehicles [23], [24] and movable robotics [25] and industrial pickup systems [26]. On the consumer electronics front, wirelessly charged waterproof products such as electric toothbrushes and shavers have entered the consumer market. Such applications still adopt a "fixed-positioning" approach, meaning that the electric loads are placed in fixed locations such as the docking stations.

III. RECENT PROGRESS OF PLANAR CHARGING SYSTEM FOR PORTABLE ELECTRONICS PRODUCTS

The dawn of the age of mobile phones in the 1990s has undoubtedly increased the demand for chargers, as indicated in Table 1, in which a mobile phone is identified as the dominant portable electronic product type. Research into wireless charging for portable electronics, therefore, became an important topic in the late 1990s and throughout the 2000s.

A. Inductive Versus Capacitive Wireless Charging

Wireless charging can be achieved by either an inductive approach or a capacitive approach. So far, the inductive approach is the dominant means in the literature. Proposals of wireless charging of mobile phones based on magnetically (inductive) coupled windings, resonance technique, and power converters were reported in

[27]–[31]. Capacitive contactless power transfer up to several hundred watts has been reported for on-orbit applications [32] and has been considered for low-power wireless charging pad applications [33]–[35]. It should be noted that capacitive coupling requires a relatively large coupling area [33] (that may not be suitable for portable electronics with relatively small coupling surface) unless high operating frequency in the megahertz range is used [34]. In [35], the disadvantages of capacitive charging for portable electronics devices are identified as relatively small power density (due to small coupling capacitance) and lack of flexibility of the load locations. The main advantage of capacitive charging is that energy can be transferred through metal, while the inductive charging will induce eddy current in metal. However, the availability of very thin double-layer electromagnetic shields underneath the inductive charging pad and above the receiving coil [36], [37] has enabled the magnetic flux to be enclosed in a sandwich structure based on the inductive approach. The WPC, with over 130 company members, has adopted the inductive approach in the "Qi" Wireless Power Standard for portable electronics devices [5].

B. The Horizontal-Flux Approach Versus the Vertical-Flux Approach for Inductive Wireless Charging

Wireless charging platform (or pad) technologies refer to the specific use of a "planar wireless charging surface" on which one or more portable electronic devices can be placed and charged simultaneously. Two groups of patents that shaped the research and developments of inductive wireless charging platform (pad) technologies for portable electronic devices can be classified as: 1) the horizontal flux approach; and 2) the vertical flux approach.

1) The Horizontal Flux Approach: The horizontal flux approach [38]–[41] originated from the winding structure of a rotating machine in which rotating ac magnetic flux can be generated. By compressing a traditional cylindrical winding structure into a "pancake shape," alternating current (ac) magnetic flux can be generated in the flattened winding structure by exciting the windings with an ac. Because the lines of flux flow "horizontally" along the charging surface on which the loads are placed, as shown in Fig. 3, such method is termed the "horizontal-flux" approach [38]. In order to pick up the flux, the vertical surface area perpendicular to the lines of flux is needed. This imposes some restrictions on the orientation of the coils in the receiver module. If the plane of the vertical surface is in the same direction of the lines of flux, no energy can be transferred to the receiver coil. This problem can be mitigated by having a second set of winding perpendicular to the first set of winding. However, the vertical surface requirement (i.e., vertical with respect to the charging surface) does not fit well with the slim design of modern portable electronic products such as mobile phones. In addition, the horizontal-flux approach requires a relative thick layer of ferromagnetic material underneath the charging pad to guide the magnetic flux. Otherwise, the flux may induce eddy current and heat up metallic objects underneath the pad.

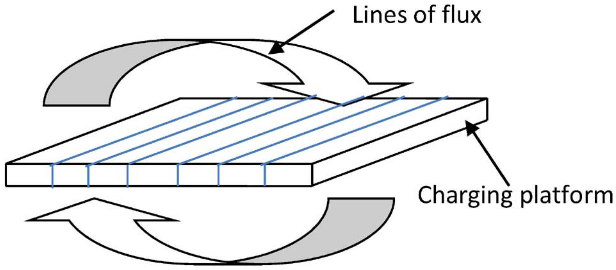

Fig. 3. ***Concept of an inductive charging pad based on the parallel-flux approach [38]–[41].***

2) The Vertical Flux Approach: The vertical flux approach [42]–[47] originated from the planar coreless transformer technology [48]. In the late 1990s, planar coreless transformers have been developed as new planar (2-D) devices for both power and signal transfer [49]. Such inventions have been successfully tested in isolated gate drives [50], [51] and offer a new solution to embed transformer in power integrated gate drive circuits [52], [53]. As an individual device, it was also tested by the Philips Research in wireless powering of lighting devices [54], used to wirelessly charge a Motorola mobile phone [55] and employed as a planar converter for power conversion up to over 90 W [56].

A wireless charging surface with free-positioning feature (i.e., allowing the electronic load to be placed freely within the charging area) can be formed by extending a single planar winding into a winding array structure. Because the lines of flux are perpendicular (vertical) to the charging surface, as shown in Fig. 4, such an approach is called the "vertical-flux" approach. It has been shown in [42] and [57] that a three-layer winding array structure can be used to generate uniform magnetic flux over the charging surface. Essentially, magnetic flux flows vertically out

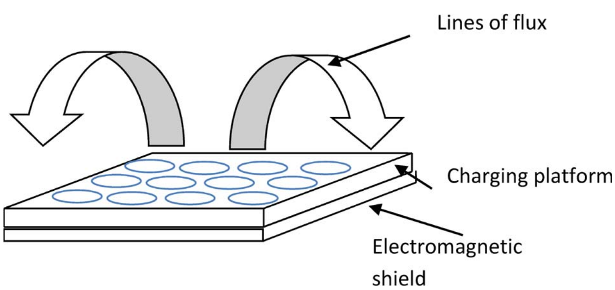

Fig. 4. ***Concept of a wireless charging pad based on the vertical-flux approach [42]–[47].***

of the charging surface like a water fountain. Therefore, the receiver coil can be placed anywhere on the charging surface and pick up the energy regardless of its position and orientation. This inherent free-positioning feature is user friendly and makes the vertical-flux approach a natural choice for wireless charging pad applications for portable electronic devices.

IV. CRITICAL ISSUES AND TECHNOLOGIES INVOLVED IN PLANAR WIRELESS CHARGING SYSTEMS

While many research proposals on planar wireless charging have been reported recently [58]–[62], the main focus point has been the technical aspects of the wireless power transfer. However, several critical issues that are essential to the success of such systems are often neglected. There are several do's and don'ts for a planar wireless charging system. For example, some planar power transfer systems neglect safety issues for domestic applications and contain emitted magnetic flux that is exposed not only to the loads, but also to the nearby objects. These critical issues are highlighted in the photograph shown in Fig. 5.

Besides power transfer, wireless charging pad systems should ensure several safety and regulatory requirements. For example, the magnetic flux emitted from the charging surface should be enclosed as much as possible and must not cause inflammable device such as a cigarette lighter to explode. It should not erase or corrupt data and information in smart cards and credit cards. It should not heat up metallic objects placed on or near the charging surface. Ideally, a good wireless charging pad should have a mechanism to totally enclose the flux path so as to eliminate flux leakage. The planar wireless charging systems should be able to locate the positions of the loads, identify their compatibility before allowing energy transfer, communicate with them bidirectionally, and monitor the battery conditions. Preferably, it should have functions for both power and data transfer.

Fig. 5. ***A photograph of a wireless charging pad with a variety of compatible and noncompatible items.***

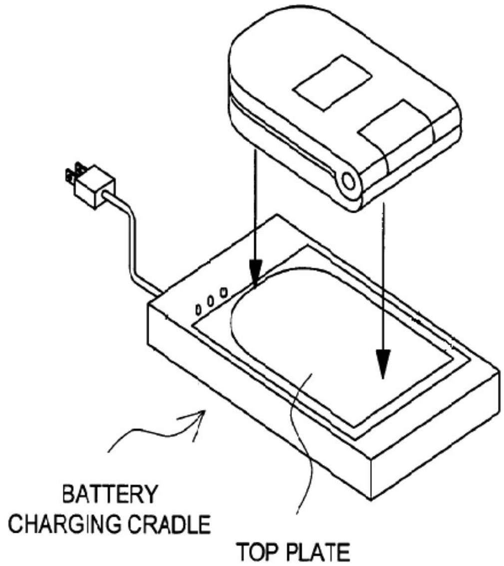

Fig. 6. ***An example of guided positioning method [63].***

A. International Regulatory Requirements

In view of these stringent requirements, researchers and designers of planar wireless power systems should consider issues such as safety, electromagnetic interference, and human exposure to radiation [83]. The following regulations that impose extra constraints on the research and development of planar wireless power technologies for portable electronic products should be taken into consideration:

- CISPR 11 or EN55011 class B group 2 conducted and radiated emissions;
- CISPR 22 or EN55022 class B conducted and radiated emissions;
- FCC part 15 class B conducted and radiated emissions;
- CISPR 14-2 immunity—Product family standard;
- EN62233:2008 measurement method for electromagnetic fields of household appliances and similar apparatus with regards to human exposure.

B. Important Features of Planar Wireless Charging Systems

1) Fixed or Guided Positioning Methods: As mentioned previously, wireless charging systems with fixed or guided positioning such as an electric tooth brush with a charging station have been commercially available. Methods that have been proposed include the use of:

- a standard socket or cradle [63] for accommodating the load in a fixed location (Fig. 6);
- magnet and magnetic attractor to guide the load to a fixed position [64].

2) Free-Positioning Methods: Free positioning is a user-friendly feature that allows a user to place and charge one

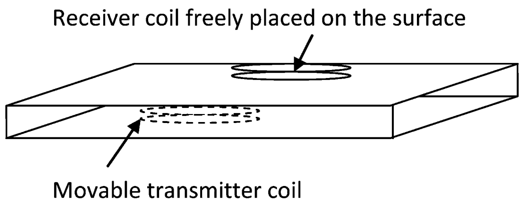

Fig. 7. ***Free-positioning method based on the movable transmitter coil (for a single-load system).***

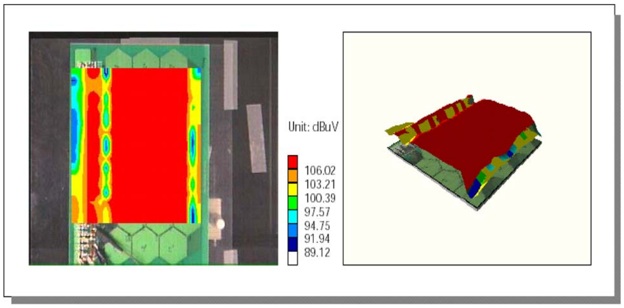

Fig. 9. ***Uniform vertical flux generated by a three-layer winding array for a free-positioning function (for multiple loads) [57].***

or more devices anywhere on the charging surface regardless of the position and orientation of the loads.

If the charging pad is designed for only one load, one solution is to provide a movable transmitter coil underneath the charging surface, as shown in Fig. 7. Usually with a mechanism to detect the location of the secondary coil, the charging station will move a transmitter coil in the x–y plane directly underneath the receiver coil so as to align the axes of the transmitter and receiver coils for maximum mutual coupling [5]. Such a method is, of course, suitable for a single load, but may not be applicable for multiple-load systems.

Another alternative for free positioning of a single load is to take advantage of the form factor of the charging system. Fig. 8 shows a wireless charging plate for a Nintendo game machine. The charging plate has a transmitter coil in the center. The circular form factor of the plate ensures that the machine can be placed with its receiver coil always kept in a straight coaxial position with the transmitter coil in any angular position.

For multiple-load systems, the multilayer winding array structure [57] can be used to generate uniform magnetic flux over the charging surface (Fig. 9). This means that multiple loads can be placed and charged on the charging surface simultaneously. However, the localized charging principle should be incorporated with the free-positioning feature in order to totally enclose the magnetic flux.

3) Localized Charging Principle: Local charging [47] refers to the conditions that the energy transfer (strictly speaking, the magnetic flux path between the transmitter and receiver coils) should be enclosed so as to avoid flux leakage that may affect other noncompatible objects. This principle can be achieved with the following methods.

- Instead of generating magnetic flux over the entire charging surface, only the appropriate transmitter coil (or coils) should be energized for both single- or multiple-load situations.
- The choice of transmitter coil(s) can be made in association with detection techniques for identifying the load position(s).
- There should be electromagnetic shields for enclosing the transmitter and receiver coils.

The objective of the localized charging principle is to ensure that the magnetic flux path is "sandwiched" within the covered area of the transmitter and receiver coils, as shown in Fig. 10. It is envisaged that the localized charging principle is an essential feature for domestic wireless charging pads. Based on the load detection and compatibility check, appropriate windings in the three-layer winding arrays can be selected for power transfer in order

Fig. 8. ***Free-positioning method based on form factors of the charging pad and load (for single load).***

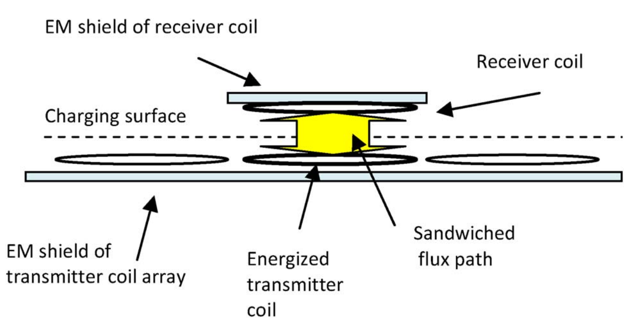

Fig. 10. ***Concept of localized charging principle essential to safety issues (for free-positioning and single- and multiple-load operations).***

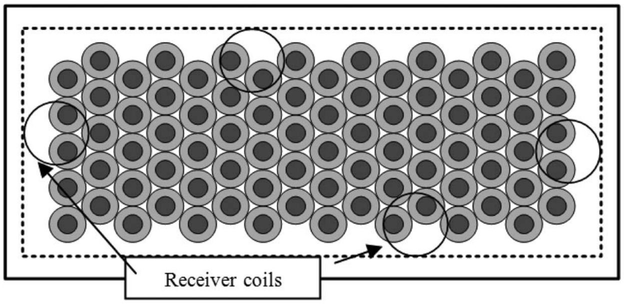

Fig. 11. ***A single layer of hexagonally packed primary winding array for multiple load, free-positioning, and localized charging [66].***

to achieve localized charging [65]. Recently, a new single-layer hexagonally packed winding array structure with free-positioning and localized features [47], [66] has been reported, as shown in Fig. 11. By ensuring that the receiver coil can totally enclose at least one transmitter coil in any position within the charging surface, the magnetic flux path can be totally enclosed within the coil pair for energy transfer and sandwiched by the EM shields of the receiver module and the charging pad.

4) Bidirectional Communications for Load Identification and Position, Compatibility Check, and Load Monitoring: To avoid the danger of unintended energy transfer to incompatible items, bidirectional communications between the loads and the charging pad is necessary. The purposes are to identify the load positions and compatibility, and to check the battery conditions. One simple solution is to send signals to the winding arrays. By sensing various signals such as the voltage across the transmitter coils and the mutual inductance or capacitance between the transmitter and receiver coils, the locations of the loads can be identified. Compatibility checks are needed to ensure that the loads are of the correct types. This can be done by sending signals from the loads after they receive the transmitter signals. Through such bidirectional communications channels, the load conditions such as the battery conditions can be monitored. When the loads are fully charged, the charging pad should be able to shut down or stay in the low-loss sleeping mode.

V. CHARGING METHODS IN THE "QI" STANDARD 1.0.3

The WPC launched the "Qi" standard in October 2010. The latest revised version includes three charging methods, covering both guided and free positioning. It should be noted that the following key features have been adopted by the WPC:

- inductive wireless charging;
- vertical-flux approach;
- guided or free positioning;
- localized charging;
- communications between loads and charging pad;
- load identification and compatibility checks.

The Qi standard includes three wireless charging approaches:

1) guided positioning charging based on magnetic attraction without movable mechanical part [Fig. 12(a)];

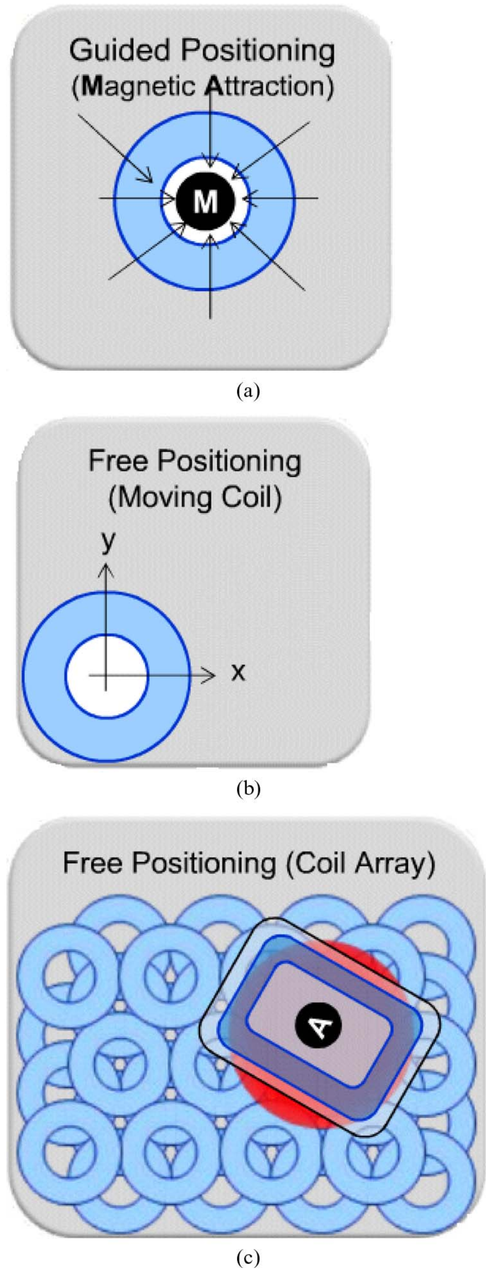

Fig. 12. ***(a) Approach 1: guided positioning charging [5]. (b) Approach 2: free positioning based on a mechanically moveable primary coil [5]. (c) Approach 3: free positioning based on the selective excitation of a coil array [5].***

2) free-positioning charging for a single device using a movable primary coil underneath the charging surface to locate the device [Fig. 12(b)];
3) free position for charging single or multiple devices using winding array without movable mechanical parts [Fig. 12(c)].

Approach 1 features "one-to-one" and "fixed-positioning" charging. If the load is not placed directly and precisely on top of the primary coil, the mutual coupling and energy transfer efficiency can deteriorate with misalignment of transmitter and receiver coils. Since it is essential to ensure that the primary coil of the charging pad and the secondary coil of the load are directly overlapped for maximum mutual coupling, some products based on this approach use magnets and/or visible marks on the charging pad and a piece of metal (magnetic attractor) inside the load for magnetic attraction in order to keep the load in the right location on the charging pad [Fig. 12(a)]. The advantage is its simplicity. The requirement of a piece of metallic magnetic attractor in the device implies some extra space requirement.

Approach 2 is a one-to-one charging method that relies on a mechanically movable primary coil underneath the charging surface, as shown in Fig. 12(b). This approach involves a search mechanism for the load position (i.e., the secondary coil in the load), either by inductive or capacitive means. The two motors underneath the charging surface will move the primary coil underneath the secondary coil of the load. This approach is simple if the charging pad is designed for only one device (i.e., single-device charging). For multiple-load charging, the motor control for multiple primary coils could be very complex and costly. In addition, systems with movable mechanical parts tend to be less reliable.

Approach 3 adopted in the Qi standard is based on the three-layer coil array structure [57]. It allows the users to place one or more portable electronic devices on the charging surface regardless of their positions and orientations. Approach 3 [Fig. 12(c)] offers "multiple," "free-positioning," and "localized" wireless charging features simultaneously. Compared with approaches 1 and 2, approach 3 offers more user friendliness, at the expense of a relatively more complex winding structure and control electronics. If the load is moved within the charging surface during charging, approaches 2 and 3 will continue to charge the load as they have the free-positioning feature.

VI. FUTURE TRENDS AND CHALLENGES

So far, this paper has addressed the "short-range" planar wireless charging technologies, with the emphasis on those adopted by the WPC in the "Qi" standard. Version 1.1 of the standard governs wireless charging for portable electronic devices up to 5 W, which makes it a suitable technology to cover planar wireless charging for a wide range of low-power products such as mobile phones, iPods, Bluetooth earpieces, etc. It is envisaged that future standards will extend the power capability to 120 W, so that more portable devices such as iPads and notebook computers can be covered. With the increasing amount of wireless power, several technical challenges will arise, namely the thermal, electromagnetic compatibility (EMC) and electromagnetic field (EMF) problems. Since the batteries are usually embedded inside the electronic devices with no or very limited ventilation, highly energy-efficient power conversion techniques are required in order to minimize the power losses in the receiver modules and, therefore, the temperature rise in the battery packages. The interactions of the ac charging flux and the signal transmission and reception of the electronic loads need special attention. The high charging flux means that it is probable for the ac flux to induce eddy currents in any unintentional metallic parts inside the electronic loads. Induced currents could lead to internal temperature rise and circuit failure. The requirements for slim designs in many modern electronic products could be conflicting with the dimensions of the EM shields.

Future challenges in planar wireless charging systems for 5-W applications include:

1) foreign object detection;
2) increased transmission distance.

A. Foreign Object Detection

Besides the power losses in the primary and secondary circuits, windings and magnetics, foreign objects in the proximity of the flux paths can also absorb power if such objects are of metallic or ferromagnetic nature. If these materials are in the midst of the ac magnetic flux, induced eddy currents would circulate within the materials, resulting in conduction losses and temperature rise. If the conduction loss is significant, the resultant temperature rise in the materials could be a safety concern [75] and a possible factor leading to the system failure and/or damage [76]. For example, it is mentioned in [77] that a power dissipation of 0.5–1 W in metallic objects such as a coin, metalized pharmaceutical wrapping, a paper clip, or a gold ring can raise the object temperature above 80 °C.

The secondary load usually refers to the secondary coil, the receiver circuit, and the battery load. Foreign objects can be classified as "friendly" parasitic objects and "unwanted" parasitic objects. Friendly parasitic objects generally refer to the metallic parts of the portable electronic devices that may absorb some power. Unwanted parasitic objects are those external ones that are not parts of the portable electronic devices.

Foreign object detection methods can be classified as: 1) the power difference method [76]–[79]; 2) the sensor method [80]; and 3) the transient energy decay method [81].

In [76]–[79], the transmitted power and the received power are monitored. The received power can be calculated based on the power loss model [76] or practically measured [77]–[79]. The power difference [76]–[78] or the ratio of the output and input power levels [79] is then calculated. If such power difference or power ratio is larger than a certain threshold, it indicates that foreign object(s) is present. Then, the transmitter will stop delivering power to the receiver circuit.

In [80], temperature and/or metal sensors adapted to detect anomaly in the power transmission path between the transmitter and the receiver are installed in the secondary circuits. Both the transmitted and received power levels are monitored. Any anomaly signal detected by the sensors on the secondary side is communicated with the primary circuit through the load modulation technique of the receiver circuit. If high temperature or presence of metal is detected, the control circuit will shut down the primary circuit.

In [81], the primary circuit is energized for a short duration and then disabled so that the transient energy decay time can be observed. If the rate of energy decay exceeds a certain threshold, it indicates the presence of a foreign object and the power transfer will be shut down.

B. Increased Transmission Distance

With the announcement of the WPC on extending the transmission range from 5 to 40 mm on April 20, 2012, new research efforts are expected to be devoted to new magnetic winding designs and arrangements. This new development in increasing the transmission distance range offers the possibility to design new planar wireless charging systems in tables and desks (such as coffee, kitchen, and bedside tables).

In order to overcome the poor efficiency problems of the use of a two-coil wireless power transfer systems for an extended air gap, as addressed in [11], [12], and [74], recent midrange wireless power transfer techniques, such as the four-coil systems [9], [81], [82] (Fig. 13), relay resonators [67], and wireless domino-resonator systems [68] (Fig. 14), can be considered and incorporated into future planar wireless chargers with increased air gaps.

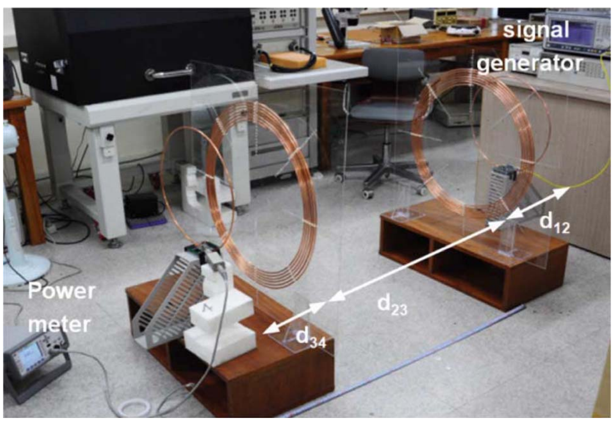

Fig. 13. ***A photograph of the setup of a four-coil wireless power transfer system [82].***

Fig. 14. ***Use of Tesla's loop resonators in a domino form for wireless power transfer. (The power flow path is bent and then split into two branches for powering two LED loads.)***

The four-coil system [9], [80]–[82] consists of two coupling loops and two coil resonators. It has been analyzed with basic circuit theory in [81] that the transmission distance between the two resonators can be maximized when the system is designed to obey the "maximum power transfer" theorem based on impedance matching of the source impedance and the input impedance of the four-coil system. The use of impedance matching implies that the system energy efficiency is limited to 50%. In practice, the four-coil system based on the impedance matching method reported in [9] has recorded a low system energy efficiency of 15%. On the other hand, the "maximum energy efficiency" principle does not have the 50% upper energy efficiency limit. Wireless power systems based on relay resonators or domino resonators can adopt such a principle to maximize the energy efficiency, making them a possible good compromise for maximizing the energy efficiency and transmission distance. The advantages and disadvantages of the "maximum power transfer" theorem and "maximum energy efficiency" principle for midrange wireless power transfer applications are explained in [74].

VII. CONCLUSION

The commercialization of mobile phones in the 1980s has clearly sped up the research and development activities in planar wireless charging systems. In this paper, the historical developments of short-range planar wireless power transfer technologies for portable electronic devices have been described. The choice of inductive charging over capacitive charging is addressed. The horizontal flux and vertical flux approaches are explained and compared. It is essential to design planar wireless charging systems with compliance with a range of international regulations including electromagnetic compatibility and human exposure to electromagnetic fields. Key user-friendly and safety features that are essential to domestic planar wireless charging systems are highlighted and explained. For low-power applications up to 5 W, foreign object detection and increased transmission distance will be new challenges in the near future.

With the formation of the WPC and its launch of the "Qi" wireless power standard, it is envisaged that the "Qi" standard will be expanded to cover applications of medium power levels (up to 120 W) in order to cover the wireless charging of portable products such as iPads and notebook computers. The initiatives by the WPC to increase transmission distance and power open new opportunities for wireless power research and development activities. In theory, planar wireless charging systems can be incorporated into office environment, coffee and bedside tables, and bathroom and kitchen desktops for powering a wide range of electric appliances from low-power devices, such as mobile phones and shavers, to high-power devices, such as electric kettles and inductive-cooking utensils. Therefore, more wireless power systems and products are expected to enter the consumer markets in the near future. ■

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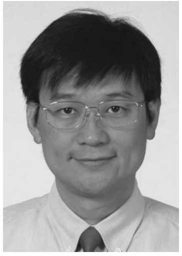

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