Wireless Power Transmission for Power Supply: State of Art

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Abstract. *The wireless power supply is motivated by simple and comfortable use of many small electric appliances with low power input. This paper reviews the concepts that are suitable for wireless power transmission with respect to power supply of such appliances in small areas. The categorization of the concepts is made. The efficiency of the concepts is discussed on general base. The reference levels for exposure to electric and magnetic fields are mentioned, and maximal power delivered to an appliance by fulfillment of these levels is considered.*

Keywords

Wireless power transmission, wireless power supply.

1. Introduction

The topic, this paper deals with, is known in literature namely as "wireless power supply" or "contactless power supply". The problem can be exactly expressed as power transmission between its source and its appliance where in a certain part of a transmission chain transmission is mediated without a connection of wires which are associated with the source and appliance. In addition, the appliance can be freely moved in certain bounds.

The concepts of wireless power transmission (WPT) differ according to a distance between the source and appliance, which is to overcome without the connection of wires, their mutual arrangement, degree of freedom of the appliance movement with respect to the source, frequency, electromagnetic field character, and power transmission efficiency. The general block scheme of a WPT chain is depicted in Fig. 1. There is a "wireless" transmission medium between a side of source and a side of appliance. This medium is separated from the source and appliance by adaptors, which ensure efficient transmission. The adaptors in part form electromagnetic field with the help of suitable coupling elements, further contain matching networks, and often include frequency converters because suitable frequencies for transmission through the medium differ from suitable frequencies for the source and appliance.

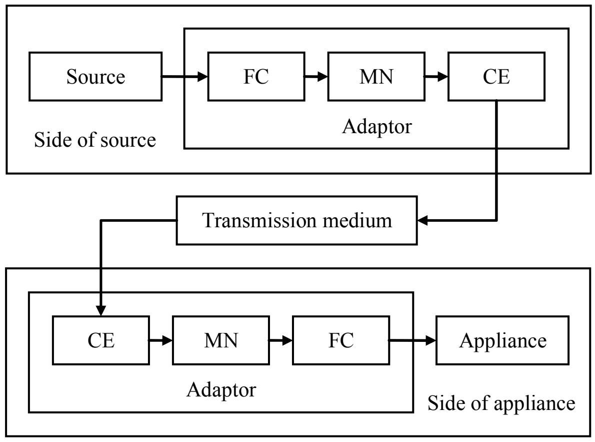

Fig. 1. General scheme of WPT chain (FC – Frequency Converter, MN – Matching Network, CE – Coupling Element).

The further text is aimed to the concepts of WPT suitable for power supply of appliances with low power input (from a few microwatts up to a few watts) which are located in small areas (transmission distance is from a few millimeters up to a few meters).

The concepts of WPT for power supply of the appliances with low power input in the small areas can be divided according to the two main criteria:

- Degree of freedom of the appliance movement with respect to the source.
- Character of electromagnetic field – type of power transmission.

According to the degree of freedom of the appliance movement with respect to the source, the concepts can be divided in two-dimensional (2D) and three-dimensional (3D). In case of 2D concept, the appliance is restricted to movement along any determined surface which has different properties from the free space and serves for power transmission from the source to the appliance. In case of 3D concept, the appliance can be moved in the determined free space through which power is transmitted from the source to the appliance.

With respect to the electromagnetic field character (or power transmission type), the concepts can be classified in two groups. A wave for WPT is formed in the first group and is not formed in the second group. In other words, the electromagnetic field has wave and non-wave character. Thus, the transmission by the electromagnetic wave (TEW) is used for the wave character, and the transmission by the electromagnetic induction (TEI) is exploited for the non-wave character usually.

2. Concepts

In this section, basic concepts of WPT for purposes of power supply are particularly described as exemplification of the above-mentioned categorization. For a brief overview of their properties with respect to the categorization, transmission distance, frequency, and power transmission efficiency, see Tab. 1.

Concept	Deg. of free.	Transm. type	Transm. distance
PSSIC	2D	TEI	A few mm – a few cm
PSSSW	2D	TEW	A few mm – a few cm
PSISIC	3D	TEI	Tens of cm – a few m
PSSA	3D	TEW	Tens of cm – a few m
Concept	Frequency		Pow. transm. efficiency
PSSIC	Tens of kHz – a few MHz		Tens of %
PSSSW	A few GHz		A few %
PSISIC	Hundreds of kHz – a few MHz		A few % – tens of %
PSSA	A few GHz		Hundredths of %

Tab. 1. Overview of properties of basic concepts of WPT for purposes of power supply.

2.1 Power Supply Surface with the Use of Inductive Coils (PSSIC)

This 2D concept [1] uses TEI. The coupling elements are represented by inductive coils, see Fig. 2. On the side of source, transceiving coils which are arranged to create a surface excite magnetic field. On the side of appliance, which can be moved along this surface, power is delivered to the load with the help of a receiving coil which is coupled in this field. The transmission medium is a dielectric gap between the transceiving and receiving coils.

The transceiving and receiving coils mostly have flat shape. A wire is either coiled only in the peripheral line or filling the surface of the coil. For better homogeneity of magnetic field, the transceiving coils are arranged in several layers.

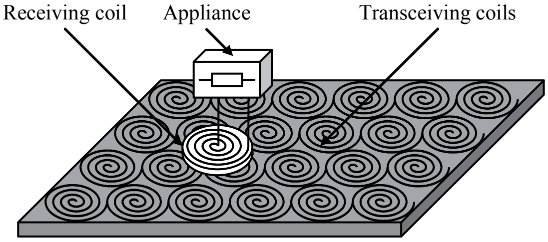

Fig. 2. Scheme of concept of power supply surface with the use of inductive coils.

2.2 Power Supply Surface with the Use of Slab Waveguide (PSSSW)

This 2D concept [2] uses TEW. The transmission medium is a slab waveguide. The coupling elements are represented by transitions between the slab waveguide and waveguides which are associated with the sides of source and appliance, see Fig. 3. The waveguide is created by a dielectric slab with an all-metal bottom wall and a top wall represented by a metal grid. On the side of source, power of electromagnetic wave is coupled by a transceiving transition through the metal grid to the slab waveguide. From this place, cylindrical wave propagates through the slab waveguide. On the side of appliance, which can be moved along the surface created by the slab waveguide, a part of wave power is extracted from the slab waveguide by a receiving transition and delivered to the load.

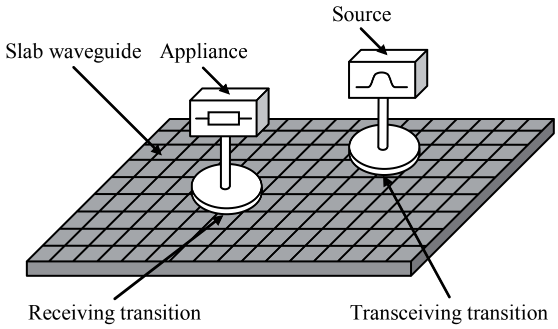

Fig. 3. Scheme of concept of power supply surface with the use of slab waveguide.

2.3 Power Supply in Space with the Use of Inductive Coils (PSISIC)

This 3D concept [3] uses TEI. The transmission medium is the free space. The coupling elements are represented by inductive coils, see Fig. 4. On the side of source, a transceiving coil excites magnetic field in the determined space. On the side of appliance, which can be moved in this space, power is delivered to the load with the help of a receiving coil which is coupled in this field.

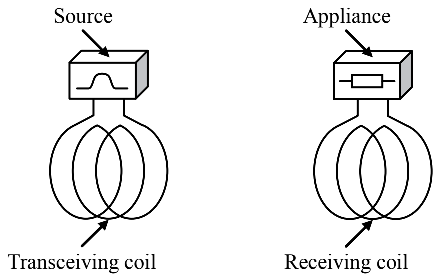

Fig. 4. Scheme of concept of power supply in space with the use of inductive coils.

In a more complex configuration [4], the transceiving coil is arranged as three orthogonal Helmholtz's coils, which enclose the determined space. The receiving coil is created from three orthogonal coils to decrease the dependence on arrangement with respect to the transceiving coil. The receiving coil has a core with high permeability for higher coupling with the transceiving coil.

2.4 Power Supply in Space with the Use of Antennas (PSSA)

This 3D concept [5] uses TEW. The transmission medium is the free space. The coupling elements are represented by antennas, see Fig. 5. On the side of source, a transceiving antenna radiates power of electromagnetic wave to the determined space. On the side of appliance, which can be moved in this space, a part of wave power is received by a receiving antenna and delivered to the load.

The directive properties of the transceiving antenna are optimized for coverage of the determined space [6]. The receiving antenna is usually omnidirectional for easier receiving of incoming wave from different directions [7] or designed for circular polarization of wave to decrease the dependence on arrangement with respect to the transceiving antenna [8].

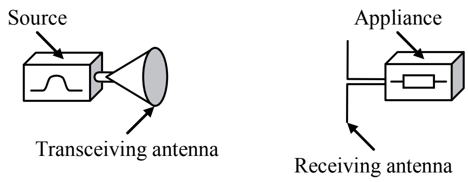

Fig. 5. Scheme of concept of power supply in space with the use of antennas.

3. Comparison of Concepts

3.1 Efficiency

In this section, quantitative and qualitative comparison of the above-mentioned basic concepts of WPT is made. The assessment of the concepts from efficiency point of view is complex because it depends on distance, mutual arrangement, and degree of freedom of the coupling elements on the sides of source and appliance, frequency, electromagnetic field character, and extraneous objects in the transmission medium (namely for 3D concepts).

Here defined efficiency η of power transmission is related to active power P_L delivered to the effective load represented by the appliance and to total active power P_T entering the coupling element on the side of source. This definition comprises the main causes of losses adherent to a certain type of WPT and has formula:

$$\eta = \frac{P_L}{P_T}. \quad (1)$$

In case of TEI, the losses are predominately represented by ohmic resistances of the transceiving and receiving coils. On the other hand, transmission is not too much influenced by the transmission medium and for 3D concept by extraneous objects in it because the medium and most of objects in the room have dielectric character.

In case of TEW, the losses are predominately represented by decrease of power density on the wave-front with the increasing distance from the transceiving transition/ antenna. In consequence of this phenomenon, a portion of transmitted power reaches the appliance only. The transmission is influenced by reflections and multipath propagation in the transmission medium and for 3D concept by extraneous objects in it.

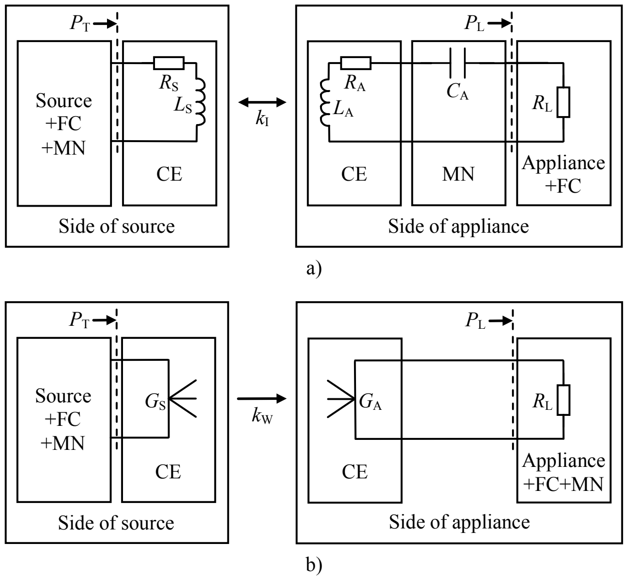

Fig. 6. Models for power transmission efficiency determination of concepts with a) TEI and b) TEW.

In Fig. 6 a) and b) respectively, the simplified models for efficiency determination of the concepts with TEI and TEW are depicted. The symbols in Fig. 6 a) mean:

C_A – capacitance of matching capacitor,
L_A – self-inductance of receiving coil,
L_S – self-inductance of transceiving coil,
R_A – ohmic resistance of receiving coil,
R_L – effective resistance of appliance including frequency converter,
R_S – ohmic resistance of transceiving coil,
k_I – coupling coefficient of transceiving and receiving coils.

The symbols in Fig. 6 b) mean:

G_A – gain of receiving transition (2D concept)/ antenna (3D concept),
G_S – gain of transceiving transition (2D concept)/ antenna (3D concept),
R_L – effective resistance of appliance including frequency converter and matching network,
k_W – transmission coefficient between transceiving and receiving transitions (2D concept)/antennas (3D concept).

The transitions/antennas losses can be respected with the help of efficiencies ζ_A, ζ_S and directivities D_A, D_S of the transitions/antennas by relations [9]:

$$G_A = \zeta_A D_A \,,\; G_S = \zeta_S D_S \,. \tag{2}$$

The efficiencies η_I and η_W for TEI and TEW according to the models in Fig. 6 a) and b) respectively are given by the formulas [9], [10]:

$$\eta_I = \frac{(k_I Q)^2}{\left(1+\sqrt{1+(k_I Q)^2}\right)^2} \,, \tag{3}$$

$$\eta_W = \left(\frac{k_W G}{2^n \pi}\right)^2 \tag{4}$$

where

$$Q = \sqrt{Q_A Q_S} \,,\; Q_A = \frac{\omega L_A}{R_A} \,,\; Q_S = \frac{\omega L_S}{R_S} \,, \tag{5}$$

$$G = \sqrt{G_A G_S} \,, \tag{6}$$

$$k_I = \frac{M}{\sqrt{L_A L_S}} \,,\; k_W = \left(\frac{\lambda}{r}\right)^{\frac{n}{2}} . \tag{7}$$

Q_A and Q_S are quality factors of the receiving and transceiving coils, ω is angular frequency ($\omega = 2\pi f$, f is frequency), M is mutual inductance of the transceiving and receiving coils, λ is wavelength in the transmission medium, r is distance between the transceiving and receiving transitions/antennas, $n = 1$ for 2D concept and $n = 2$ for 3D concept. In addition, the following conditions of optimal transmission for the model according to Fig. 6 a) are valid:

$$R_L = \sqrt{R_A^2 + \omega^2 k_I^2 L_A L_S \frac{R_A}{R_S}} \wedge \omega L_A = \frac{1}{\omega C_A} \,. \tag{8}$$

In other words, the second condition means resonance of the receiving coil and matching capacitor reactances. In case of the model according to Fig. 6 b), the impedance and polarization matchings of the transitions/antennas are considered, and reflections and multipath propagation in the transmission medium are not taken into account.

Fig. 7 a) and b) show the curves of efficiencies η_I and η_W based on equations (3) and (4). It is apparent that required efficiency η_I or η_W can be reached as a proper combination of parameters k_I and Q or k_W and G. It means that decrease of transceiving and receiving coils coupling, which is respected by k_I, (increase of transceiving and receiving coils distance, improper mutual arrangement of transceiving and receiving coils) can be compensated by increase of coils quality factors Q_A, Q_S (increase of angular frequency ω, decrease of coils resistances R_A, R_S). The resistances R_A, R_S depend on frequency roughly proportionally to $\omega^{1/2}$. Thus, the increase of ω really increases Q_A, Q_S. Similarly, decrease of transmission between the transceiving and receiving transitions/antennas, which is respected by k_W, (increase of distance r, decrease of wave length λ) can be compensated by increase of transitions/antennas gains G_A, G_S. The efficiency η_I or η_W tends to increase with increasing product $k_I Q$ or $k_W G$, thus, with one increasing product component at least. The efficiency η_I limits with increasing product $k_I Q$ to 100 % whereas the efficiency η_W seems to go over 100 % with increasing product $k_W G$. This incorrectness is caused by invalidity of (4) for the near-field region of the transitions/antennas. When it is considered that Q tends to infinity because ω tends to infinity the following explanation can be given for $\eta_I = 100$ %. The optimal appliance resistance R_L is equal to infinity according to (8) as well. Thus, it is incomparable bigger than the coils resistances R_A, R_S. However, the deeper analysis shows that the power P_L tends to zero in this case.

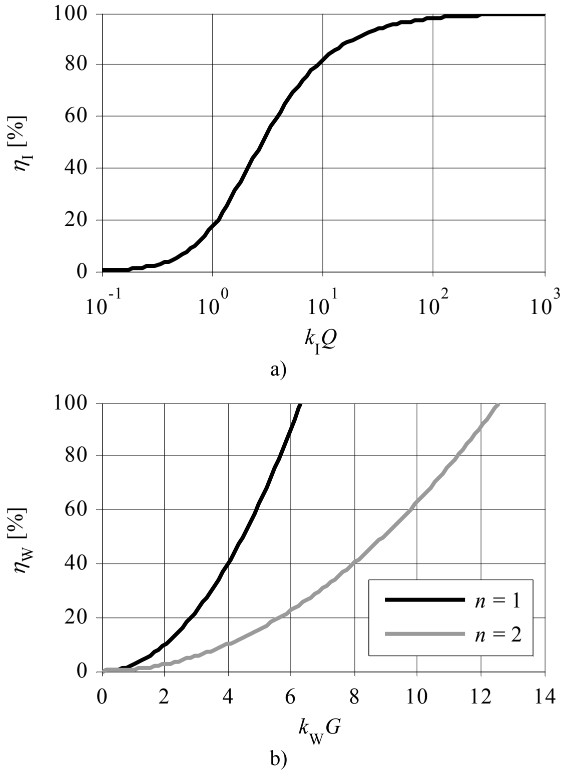

Fig. 7. Power transmission efficiency of a) TEI and b) TEW ($n = 1$ for 2D concept, $n = 2$ for 3D concept).

Only weak dependence of efficiency on mutual arrangement of the coupling elements is desirable. With the increasing distance between the coupling elements, the coefficients k_I and k_W decrease. To maintain the efficiency by conservation of weak dependence on coupling elements mutual arrangement is better possible for TEI by increase of coils quality factors Q_A, Q_S. Of course, for TEW, the efficiency can be maintained by increase of transitions/antennas gains G_A, G_S. However, it is in contradiction with weak dependence on mutual arrangement of the coupling elements. It can be said that the coupling elements represented by the inductive coils can afford isotropic character even by higher quality factors, however, the coupling elements represented by the transitions/antennas become by higher gains directive.

Considering parameters k_I and Q or k_W and G, it is difficult to give typical values because these are strongly dependant on the concept implementation. The raw estimation of value of product $k_I Q$ or $k_W G$ can be obtained with the help of the curve in Fig. 7 a) or b) and typical expected power transmission efficiency for the certain concept, which is mentioned in Tab. 1.

3.2 Reference Levels

For using wireless power supply in areas where humans are present, it is necessary to keep the reference levels for general public exposure to electric and magnetic fields [11], see Fig. 8. It is especially important for 3D concepts where transmission is accomplished through the free space. Further, with the help of certain simple examples of 3D concepts for TEI and TEW, the maximal achievable values of power that can be delivered to the appliance by fulfillment of the reference levels are calculated. For calculation, the models of the sides of appliance according to Fig. 6 a) and b) are used. It especially deals with characterization of the receiving coupling elements. It means determination of self-inductance L_A and resistance R_A of the receiving coil for TEI and gain G_A of the receiving antenna for TEW respectively. In the space, we assume the existence of homogenous magnetic field for TEI or electromagnetic field for TEW that is harmonically time-varying with angular frequency ω and has maximal acceptable rms value of magnetic field strength H_{max} or power density S_{max} with respect to the reference levels.

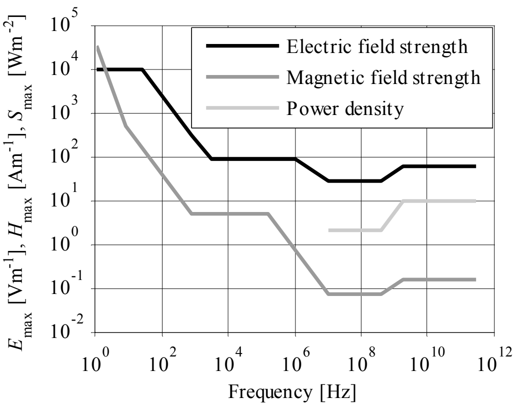

Fig. 8. Reference levels for general public exposure to time-varying electric and magnetic fields (rms values).

In case of TEI, a single-layer cylindrical coil is considered as the coupling element (receiving coil). The coil has diameter D_C and is created by N turns wound closely one by other by a copper wire with conductivity σ and diameter D_W. The power $P_{L,I}$ delivered to the appliance can be calculated with the help of the model in Fig. 9 a) and b). The voltage source responds to voltage u induced by magnetic inductive flux Φ that belongs to the receiving coil. For calculation of flux Φ, the homogenous magnetic field with strength H whose vector $\boldsymbol{H}$ is perpendicular to the turns area A_C of the receiving coil is assumed. The voltage u implies from induction law by the equation [12]:

$$\begin{aligned} u &= -\frac{\partial \Phi}{\partial t} = -\frac{\partial}{\partial t}\left(\iint_{A_C} \mu_0 \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{A}_C \right) \\ &= -\frac{\partial}{\partial t}\left(\underbrace{\mu_0 \sqrt{2} H_{max} \cos(\omega t)}_{H} \underbrace{\frac{\pi D_C^2 N}{4}}_{A_C} \right) \\ &= \omega \mu_0 \sqrt{2} H_{max} \sin(\omega t) \frac{\pi D_C^2 N}{4} \end{aligned} \tag{9}$$

where μ_0 is permeability of vacuum. The high frequency resistance R_A of the receiving coil is estimated by the formula [9]:

$$R_A = \frac{N D_C}{D_W} \sqrt{\frac{\omega \mu_0}{2\sigma}} \,. \tag{10}$$

For calculation on working frequency, it is not necessary to determine the self-inductance L_A of the receiving coil because its reactance ωL_A is compensated by reactance $-1/\omega C_A$ of the matching capacitor according to (8). The power $P_{L,I}$ is then determined with the help of the circuit model in Fig. 9 b) by equation:

$$P_{L,I} = \left(\frac{\omega \mu_0 H_{max} \pi D_C^2 N}{4(R_A + R_L)} \right)^2 R_L \,. \tag{11}$$

In case of TEW, a half-wave dipole is considered as the coupling element (receiving antenna). The power $P_{L,W}$ delivered to the appliance can be calculated with the help of the model in Fig. 9 c). For calculation, the electromagnetic plane wave with power density S which is coming in the maximum of antenna reception and is polarization-matched (vector $\boldsymbol{E}$ of electric field strength is parallel to dipole axis) is assumed. The power $P_{L,W}$ is then determined with the help of antenna effective aperture A_A by the equation [9]:

$$P_{L,W} = S A_A = S_{max} \frac{\pi c^2 G_A}{\omega^2} \tag{12}$$

where c is speed of light.

For evaluation of power calculation for selected values of parameters of the sides of appliance with the help of (11) and (12), see Tab. 2. From results, it is apparent that, in case of TEI, maximal power delivered to the appliance by fulfillment of the reference levels can be about orders higher than in case of TEW. The calculated values are, of course, only estimations. In the nearer places to the transceiving coupling element, the values of electric and magnetic fields are usually higher than in the further places. However, the reference levels have to be fulfilled in all considered space. Thus, the values in the further places have to be necessarily lower than the reference levels allow.

Although these are only certain simple examples of the above-mentioned concepts, the similar results can be generally expected for comparison of concepts with TEI and concepts with TEW by fulfillment of the reference levels.

TEI		TEW	
Selected values			
D_C [m]	0.1	c [ms^{-1}]	$3\cdot10^8$
D_W [m]	0.001	G_A [-]	1.5
f [Hz]	$1\cdot10^6$	f [Hz]	$5\cdot10^9$
N [-]	100		
R_L [Ω]	50		
μ_0 [Hm^{-1}]	$4\pi\cdot10^{-7}$		
σ [Sm^{-1}]	$5.96\cdot10^8$		
Reference levels			
H_{max} [Am^{-1}] @f	0.73	S_{max} [Wm^{-2}] @f	10
Evaluation			
$P_{L,I}$ [W]	0.37	$P_{L,W}$ [W]	$4.3\cdot10^{-3}$

Tab. 2. Evaluation of calculation of maximal power delivered to appliance by fulfillment of reference levels for examples of 3D concepts with TEI and TEW.

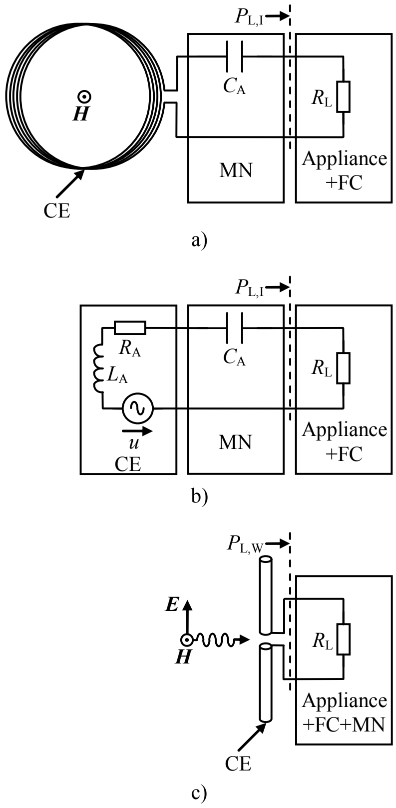

Fig. 9. Models for calculation of maximal power delivered to appliance by fulfillment of reference levels for examples of 3D concepts with a), b) TEI and c) TEW.

4. Conclusion

The review of concepts that are suitable for wireless power transmission with respect to power supply of appliances with low power input in small areas was presented. The concepts categorization according to degree of freedom of the appliance movement with respect to the source and character of electromagnetic field was made. The basic concepts were described as exemplification of performed categorization. The power transmission efficiency of the concepts was discussed on the general base. The simple models for efficiency determination which especially follow from the type of power transmission were shown. The reference levels for general public exposure to time-varying electric and magnetic fields were mentioned. With the help of two simple examples, the estimation of maximal power which can be delivered to the appliance by fulfillment of these levels was calculated.

The future of wireless power supply has two trends which should ensure its higher usability. The first is increase of power transmission efficiency and freedom of appliance movement, and decrease of dependence on mutual arrangement of the source and appliance. The second is decrease of appliance power consumption.

Acknowledgements

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