CONCEPTS, QUALITY FACTOR AND EFFICIENCY OF "WIRELESS POWER TRANSFER"

Dr. Pradeep Kumar Sharma[1]
Professor and Head, Department of Physics
University of Engineering & Management, Jaipur, Rajasthan (303807),
INDIA

Abstract— *The present text provides information regarding introductory concept of wireless power transfer through some of the existing technologies and evaluate its quality factor as well as deals with certain methods of improving the efficiency of wireless power transfer. Its figure of merit, transfer loss, quality factor and efficiency been calculated and analysed.*

Keywords—wireless network devices, power transfer devices.

I. INTRODUCTION

Since its inception by Nicolas Tesla in 1905, the idea of transfer of electrical power by using no wires has been a continuous effort worth doing for scientists and researchers. Many of them actually have succeeded for small distance transfer through coupling methods and some of them are trying to send electrical power to very large distance using methods involving electromagnetic radiations and LASERs. Here we will discuss some mid to high range power transfer techniques through performance enhancement and improved efficiency for radiative and non-radiative modes using resonance as the key factor to improve efficiency as well as power output.

At resonance, any isolated resonator can be identified by two parameters only i.e. its resonant frequency ω_0 and its intrinsic loss rate Γ. Quality factor, the parameter which tells us about energy storage is given by $Q = \frac{\omega_0}{2\Gamma}$ and it is evident that by reducing the loss of the system, energy storage can be improved. To get a highly resonant system, its Q-factor must be very high to transfer energy efficiently. For this purpose the resonating system must be made from components having very low absorptive and radiative losses along with very narrow resonant frequency width. The design of the resonating system should be such that it interacts very less with extraneous objects.

According to Dr. Morris P. Kesler2, it can be shown that for a coupled resonating system at resonance, the ratio of power delivered to power available from source is given by

$$\frac{P_L}{P_{g.max}} = \frac{4.U^2 \frac{R_g}{R_s} \frac{R_L}{R_d}}{\left(\left(1+\frac{R_g}{R_s}\right)\left(1+\frac{R_L}{R_d}\right)+U^2\right)^2}$$

Where Rg, Rs, RL, Rd are generator resistance, source resistance, load resistance and device resistance respectively and $U = k\sqrt{Q_s Q_d}$ is the figure of merit of the system. For maximum efficiency of the system parameters are chosen such that $\frac{R_g}{R_s} = \frac{R_L}{R_d} = \sqrt{1+U^2}$ and for this system maximum efficiency is given by, $\eta_{max} = \frac{U^2}{\left(1+\sqrt{1+U^2}\right)^2}$ with overall energy loss $\Gamma_d^{'} = \Gamma_d + \Gamma_w$. The efficiency of the power transfer is maximized when $\frac{\Gamma_w}{\Gamma_d} = \sqrt{1+U^2}$ and graphically it can be shown in fig. below.

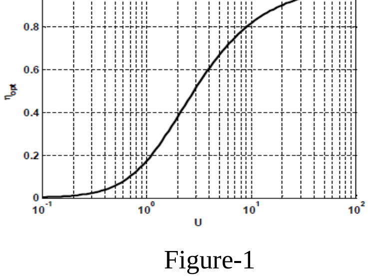

Figure-1

The figure of merit is the controlling parameter to decide the efficiency of the power transfer as can also be given as

$$U = k\sqrt{Q_s Q_d} \quad \text{.} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (0.1)$$

The above equations (1.1) and (1.2) give freedom about the precise positioning of the source and device, making almost free movement.2

Aristeidis Karalis, J.D. Joannopoulos, and Marin Soljačić4 worked out a series of experiments using Dielectric disks and Capacitively-loaded conducting loops to examine the effect of resonance widths, rate of coupling and figure of merit of the system. According to them coupling is strong when

$$\frac{k}{\sqrt{\Gamma_s \Gamma_d}} \gg 1$$

Using CMT they propose k value for dielectric disks as

$$\kappa = \frac{\omega_1}{2} \cdot \frac{\int d^3 r \varepsilon_2(r) E_2^*(r) E_1(r)}{\int d^3 r \varepsilon(r) \left|E_1(r)\right|^2} \quad \ldots\ldots\ldots\ldots \qquad (1.3)$$

which provide a just sufficient value for figure-of-merit that is not as required for strong coupling but even though can be used in various applications.

For Capacitively-loaded conducting loops of self inductances L1 and L2,

$$\kappa = \frac{\omega M}{2\sqrt{L_1 L_2}} \qquad (0.2)$$

With mutual inductance M as

$$M \approx \frac{\pi}{2} \cdot \frac{\mu_0 \left(r_1 r_2\right)^2}{D^3} \qquad (0.3)$$

They showed using CMT that by keeping fixed geometry and source energy stored, the resonant inductive mechanism allows for ~Q2 (~106) times more power delivered for work at the device in comparison to the traditional non-resonant mechanism. Capacitively-loaded conductive loops are also used as resonant antennas, but those operate in the far-field regime with D/r»1, r/λ~1, and the radiation Q's are intentionally designed to be small to make the antenna efficient, so they are not appropriate for energy transfer.

To make the system more environment-friendly and robust, it must show low energy losses to the interactions with random non-resonant extraneous objects. They4 analysed the sensitivity of the system with interactions of human and rigid wall. Using Perturbation Theory they proposed that when any extraneous object e is present then field amplitude inside the resonant object satisfies the equation

$$\frac{da_1}{dt} = -i\left(\omega_1 - i\Gamma_1\right)a_1 + i\left(\kappa_{11-e} + i\Gamma_{1-e}\right)a_1 \qquad (0.4)$$

Where ω_1 is frequency, Γ_1 is intrinsic loss rate, κ_{11-e} is induced frequency shift on 1 due to e and Γ_{1-e} is extrinsic loss rate due to e. Hence the total loss rate is $\Gamma_{1[e]} = \Gamma_1 + \Gamma_{1-e}$ with corresponding figure-of-merit $\frac{\kappa_{[e]}}{\sqrt{\Gamma_{1[e]}\Gamma_{2[e]}}}$ with $\kappa_{[e]}$ as perturbed coupling rate.

For dielectric disks, extrinsic loss can be quantified as

$$\Gamma_{1-e}^{rad} \propto \omega_1 \cdot \frac{\int d^3 r \left|\mathrm{Re}\left\{\varepsilon_e(r)\right\}\right|^2 \left|E_1(r)\right|^2}{E_{em}} \qquad (0.5)$$

And

$$\Gamma_{1-e}^{abs} = \frac{\omega_1}{4} \cdot \frac{\int d^3 r\, \mathrm{Im}\left\{\varepsilon_e(r)\right\} \left|E_1(r)\right|^2}{E_{em}} \qquad (0.6)$$

Where total resonant electromagnetic energy of the unperturbed mode is represented by

$$E_{em} = \frac{1}{2}.\int d^3 r \varepsilon(r) |E_1(r)|^2 \qquad (0.7)$$

And k is given as

$$\kappa = \frac{\omega_1}{4}.\frac{\int d^3 r \varepsilon_2(r) E_2^*(r) E_1(r)}{E_{em}} \qquad (0.8)$$

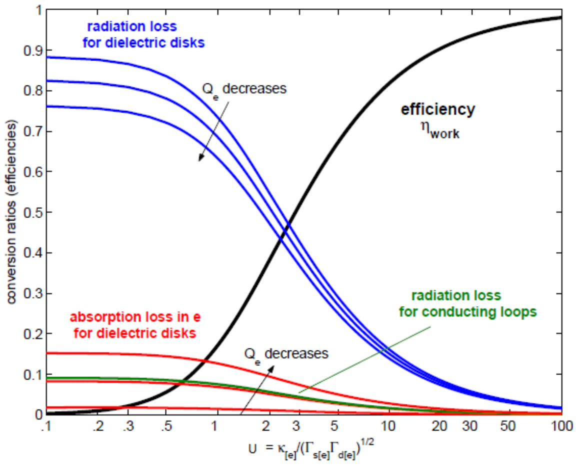

Figure-2

This depends linearly on field values of one into another. It suggests that energy transfer mechanism for this arrangement is quite sturdy and disk resonance is robust towards presence of extraneous objects with high-loss objects in close proximity as exception.

For Capacitively-loaded conducting loops, effect of extraneous objects was found to be negligible as all everyday objects are nearly non-magnetic and interacting with magnetic fields as with free space. Using PT formula (0.6) it is found that only close proximity of large metallic objects can affect these resonances. The overall efficiency graph can be plotted as in figure 2.

According to Brent Griffin and Carrick Detweiler14, two primary factors for the performance of the resonant coils are (i) they resonant at the same frequency and (ii) they have very high quality factor. To find the resonant frequency, its inductance is to be found using the relation

$$L = \mu_0 r N^2 \left(\ln \frac{8r}{c} - 1.75 \right) \qquad (0.9)$$

Where r is the radius of the coil, N is the total turns in coil and c is the wire bundle thickness.

Resonant frequency can be found using the formula

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (0.10)$$

Here C is the capacitance of in Farad. The quality factor of the resonant coils is calculated as

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad (0.11)$$

Here R is the resistance of the coil. They14 developed a control algorithm which was able to optimize the received power even with the dynamics of moving object prevented it from maintaining optimal position for power transmission. Static arrangement achieved more power transfer in comparison to aerial transmission in case of resonant coils.

II. CONCLUSION

Aristeidis Karalis, J.D. Joannopoulos, and Marin Soljačić4 In comparison of the two classes of resonant systems under examination4, the strong immunity to extraneous objects and the absence of risks for humans probably makes the conducting-wire loops the preferred choice for many real-world applications; on the other hand, systems of disks (or spheres) of high (effective) refractive index have the advantage that they are also applicable to much smaller length-scales (for example in the optical regime dielectrics prevail, since conductive materials are highly lossy).

In conclusion, we present a scheme based on “strongly-coupled” resonances for mid-range wireless non-radiative energy transfer. Although our consideration has been for a static geometry (namely κ and Γe were independent of time), all the results can be applied directly for the dynamic geometries of mobile objects, since the energy-transfer time (1κ−μ−∼1100s for microwave applications) is much shorter than any timescale associated with motions of macroscopic objects. Analyses of very simple implementation geometries provide encouraging performance characteristics and further improvement is expected with serious design optimization. Thus the proposed mechanism is promising for many modern applications. For example, in the macroscopic world, this scheme could potentially be used to deliver power to robots and/or computers in a factory room, or electric buses on a highway (source-cavity would in this case be a “pipe” running above the highway). In the microscopic world, where much smaller wavelengths would be used and smaller powers are needed, one could use it to implement optical inter-connects for CMOS electronics, or to transfer energy to autonomous nano-objects (e.g. MEMS or nano-robots) without worrying much about the relative alignment between the sources and the devices.

As a venue of future scientific research, enhanced performance should be pursued for electromagnetic systems either by exploring different materials, such as plasmonic or metallo-dielectric structures of large effective refractive index, or by fine-tuning the system design, for example by exploiting the earlier mentioned interference effects between the radiation fields of the coupled objects. Furthermore, the range of applicability could be extended to acoustic systems, where the source and device are connected via a common condensed-matter object.

REFERENCES

[1] Review and Evaluation of wireless Power Transfer (WPT) for Electric Transport Vehicles, FTA Report No. 0060 by Federal Transport Administration, prepared by Dr. Aviva Brecher and Mr. David Arthur, P.E., U. S. Department of Transportation, Volpe National Transportation Systems Center and references therein.

[2] Highly Resonant Wireless Power Transfer: Safe, Efficient, and over Distance, by Dr. Morris Kesler WiTricity Corporation©WiTricity Corporation, 2013.

[3] Wireless Power Transfer and Applications to Sensor Networks, Liguang Xie Yi Shi Y. Thomas Hou_ Wenjing Lou, Virginia Polytechnic Institute and State University, USA.

[4] Efficient wireless non-radiative mid-range energy transfer, Aristeidis Karalis*, J.D. Joannopoulos, and Marin Soljačić, Center for Materials Science and Engineering and Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.

[5] A Critical Review of Wireless Power Transfer via Strongly Coupled Magnetic Resonances, Xuezhe Wei 1,2,*, Zhenshi Wang 1,2 and Haifeng Dai 1,2 , 1 Clean Energy Automotive Engineering Center, Tongji University, Shanghai 201804, China; E-Mails: 1022wangzhenshi@tongji.edu.cn (Z.W.); tongjidai@tongji.edu.cn (H.D.) , 2 College of Automotive Studies, Tongji University, Shanghai 201804, China.

[6] Energy-Efficient Optimization for Wireless Information and Power Transfer in Large-Scale MIMO Systems Employing Energy Beamforming, Xiaoming Chen, Xiumin Wang, and Xianfu Chen, IEEE WIRELESS COMMUNICATIONS LETTERS, VOL. 2, NO. 6, DECEMBER 2013.

[7] Wireless Power Transmission using Resonance Induction Technique, Saravanan.A1, Subhashini.A2 , Dineshkumar.P3, Professor and Head, Department of EEE, Dhaanish Ahmed College of Engineering, padappai, Chennai, India 1, Assistant Professor, Department of ECE, Dhaanish Ahmed College of Engineering, padappai, Chennai, India 2, Assistant Professor Department of EEE, Dhaanish Ahmed College of Engineering, padappai, Chennai, India 3.

[8] Analysis of Wireless Power Transfer by Coupled Mode Theory (CMT) and Practical Considerations to Increase Power Transfer Efficiency, Alexey Bodrov and Seung-Ki Sul, IEEE Fellow, Republic of Korea.

[9] Transmission of Power through Wireless Systems Kilaru Kalyan, Shaik Avaes Mohsin, Angadi Suresh, International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-2, Issue-4, April 2013.

[10] Wireless power Transfer, Vikash Mishra1, Lavya Nigam2, Anand Mohan3 1,2Department of computer science & Engineering, HITM, Agra, 3BS-MS program IISER, Mohali, International Journal of Emerging Technology and Advanced Engineering Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 4, Issue 2, February 2014).

[11] Application of Wireless Power Transfer for Home Appliances using Inductive Resonance Coupling, Arjun Sharma, Senior Lecturer, Department of Mechatronics, Advanced Technical Training Centre (ATTC),Bardang, Sikkim, IndiaInternational Journal of Engineering Trends and Technology (IJETT) – Volume 16 Number 4 – Oct 2014.

[12] Understanding Low Frequency Non-Radiative Power Transfer, A. E. Umenei, Ph.D, Senior Research Scientist, June 2011, ©2011 Fulton Innovation, LLC.

[13] Brent Griffin and Carrick Detweiler, : Resonant Wireless Power Transfer to Ground Sensors from a UAV”.