WIRELESS POWER TRANSFER: A DEVELOPERS GUIDE

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Outline

PART I Momentum Dynamics Perspective

- Commercialization markets
- Installation
- Safety and standards
- Heavy duty vehicle focus

PART II FAQ’s about WPT

- Communications, alignment
- HD vs LD charging, FCC
- LOD, FOD, EMF

PART III Understanding the Physics

- Coupler design for high k
- Performance attributes, k, V, f, η
- Thermal performance of coupler

PART IV What Happens IF?

- Loss of communications, contactor trips

Wrap Up

AGENDA

PART I

Momentum Dynamics Perspective

MOMENTUM DYNAMICS
World-Leading Wireless Power Transmission Technology for Vehicle Electrification

- We provide the essential connection between the vehicle and the electric supply grid.
- Our technology is enabling and transformative.
- Fundamentally benefits transportation and material logistics across multiple vertical markets.
- It removes technical impediments which would slow the advancement of major industries (automotive, material handling, defense, others).

Fast Wireless Charging for all classes of vehicles

Momentum Dynamics has been developing high power WPT systems since 2009

Commercialization Markets

Essential Precursors

Low Speed Vehicles

Utility Vehicles – golf cars, airports, parks, campuses, police, neighborhood EV's

Industrial Lift Trucks

Many types, *existing EV market*, +$16B in vehicle sales/yr

Commercial Vehicles

Multiple classes, must save fuel, 33 million registered in US

Buses

Mandated to go to alternative fuel, must save fuel costs

Marine Applications

Commercial Marine and Defense Applications

Passenger Vehicles

Huge international market, will take time to develop

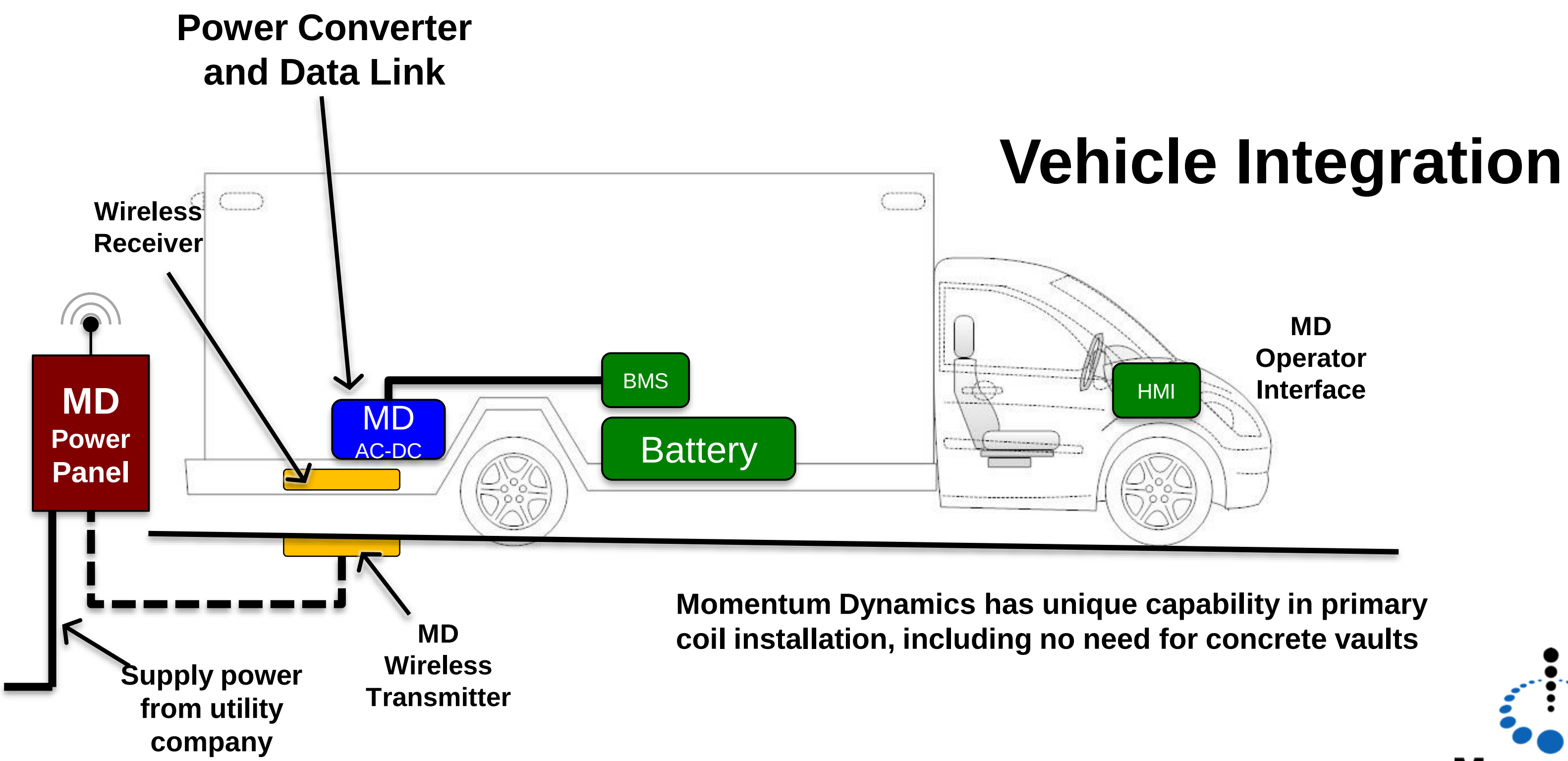
Opportunistic charging is as efficient as conductive

MD's Unique Wireless High-Power Leadership Technology

- High speed (high power) public charging can be done for partial charges in public locations now – where utility infrastructure supports it,
- The consumer can add, using a 25 kW wireless charger, 25 miles of driving range in a 15 minute stop at a local store,
- Or, considerably more when stopping at a restaurant, supermarket, or shopping center. Places where people normally park, and more drivers can access the spot each day and charge,
- "We think this is the future vision of stationary charging — it requires no penalty on the driver, and can support a growing population of EVs." Andrew Daga, CEO Momentum Dynamics Corp.

Installation

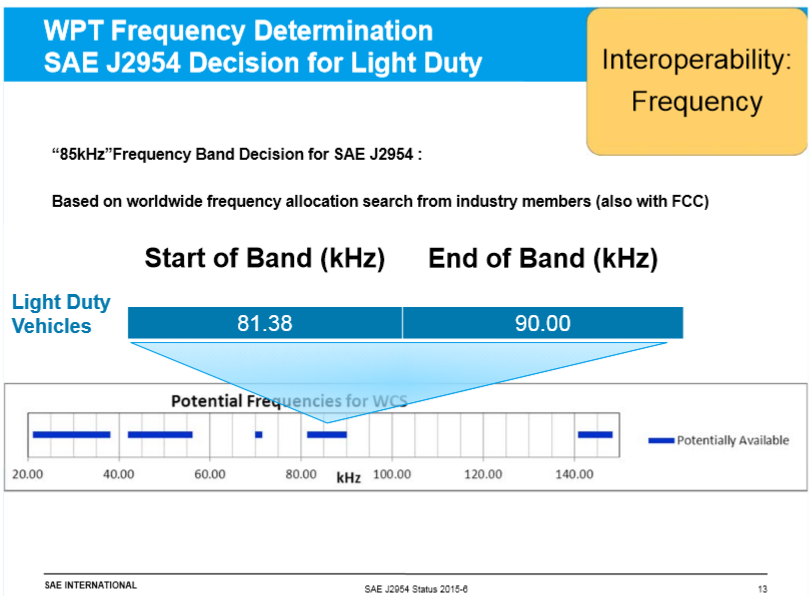
- Inductive charging is about much more than convenience, it is really about driving range extension
- Automatic charging allows the EV fueling experience to become a “background” operation in the same way that automatic toll collection has made toll collection a nearly unnoticed part of the driving experience

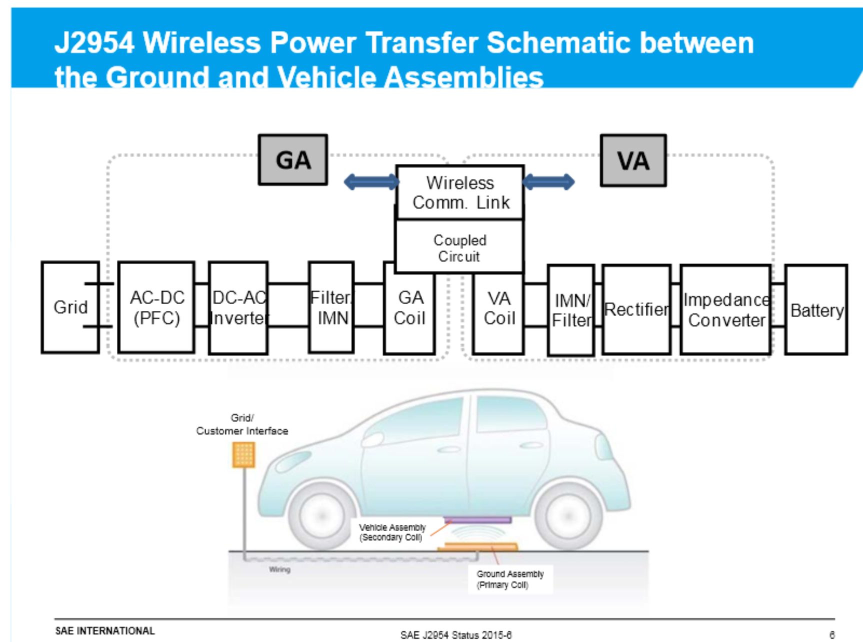


Momentum Dynamics has unique capability in primary coil installation, including no need for concrete vaults

WPT Safety & Standard

- SAE 2954-1:
  - Now published as a TIR – Technical Information Report, or guideline for wireless charging of LD vehicles. Power levels of 3.7, 7.7, 11, and 22 kW over z-gaps of 100mm to 250mm
  - Interoperable frequency specified as the 81.38 kHz to 90 kHz band
  - No recommendation at this point from SAE for HD vehicle charging at power levels >22 kW





Source: http://insideevs.com/chinas-zte-working-30-kw-wireless-charging/

Heavy Duty Vehicle Focus

- These vehicles routinely charge through a 12” z-gap
- MD technology supports modular 50 kW integration

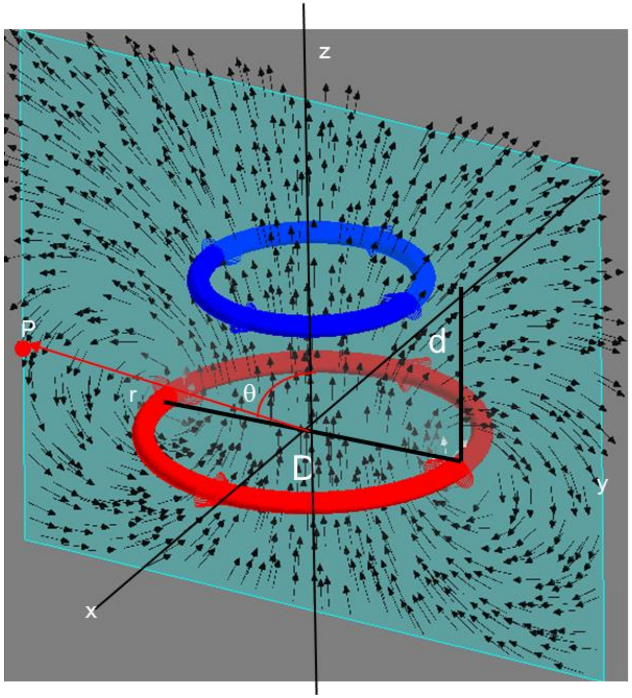
12” (31 cm) Air Gap

Wireless Transmitter

AGENDA

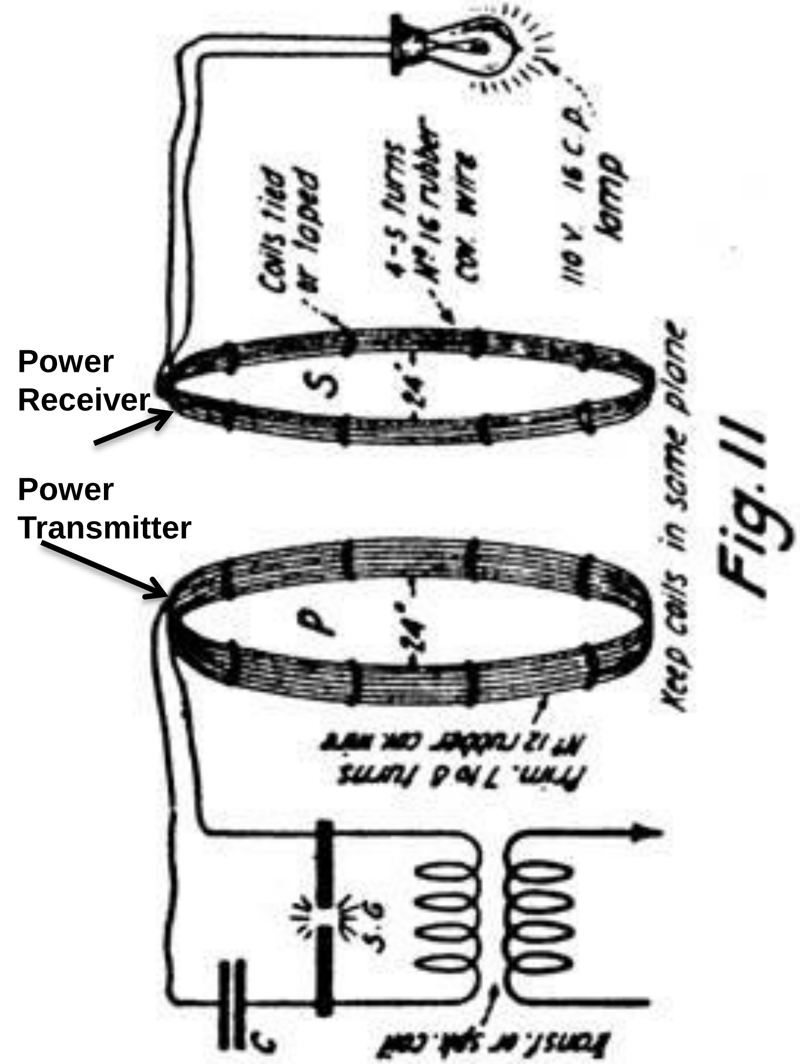
PART II

FAQ's about WPT



WPT Is Not New

- Wireless Power Transmitters and Receivers must be interoperable
- They must be able to work at various power levels – not just one
- They must work with multiple vehicle types
- They must work anywhere, automatically, in any weather



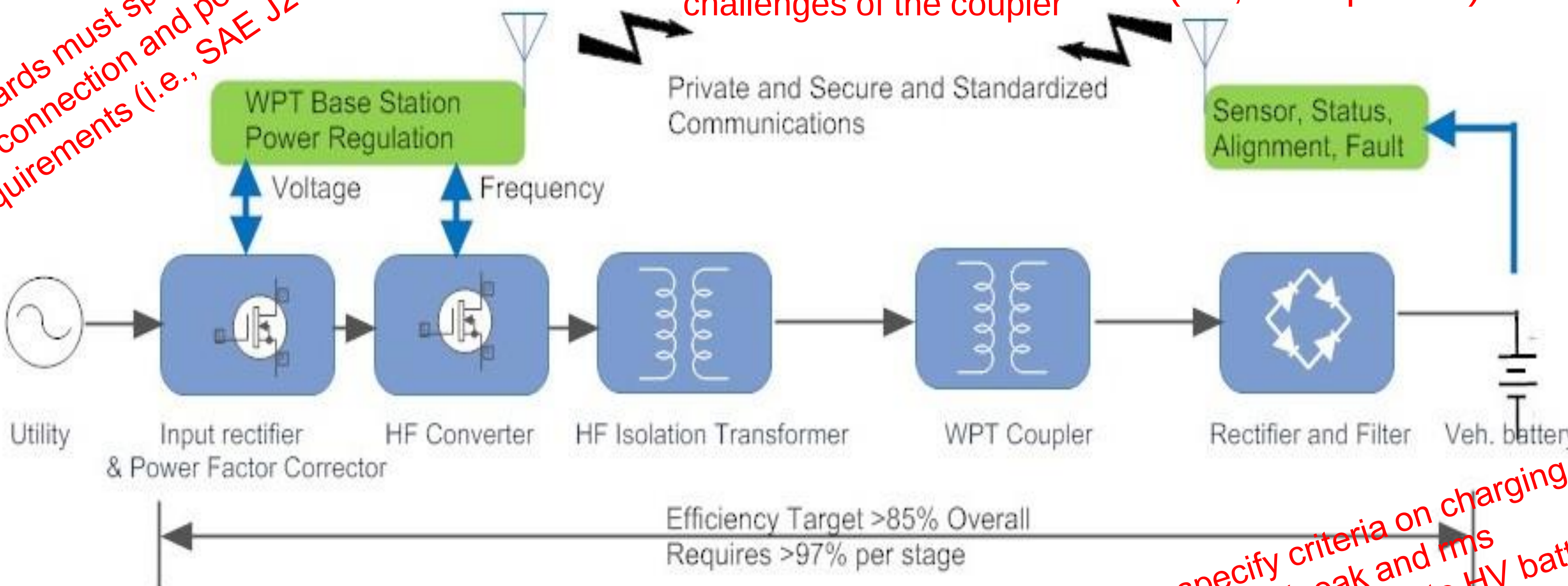
WPT Functional

- Power is coupled via transformer action, but the transformer is rendered very magnetically leaky due to physical separation of the primary from secondary portions.

Standards must specify utility interconnection and power quality requirements (i.e., SAE J2894)

Integration means dealing with bulk, thermal, and EMF challenges of the coupler

Communication channel is an intentional radiator (i.e., FCC part 18)



OEM's specify criteria on charging power quality (peak and rms current, voltage ripple) to HV battery

The WPT coupler is an unintentional radiator encumbered by variable leakage fields due to gap and misalignment

WPT Issues: Regulations

WPT chargers are non-intentional radiators (Title 47 CFR Part 15)

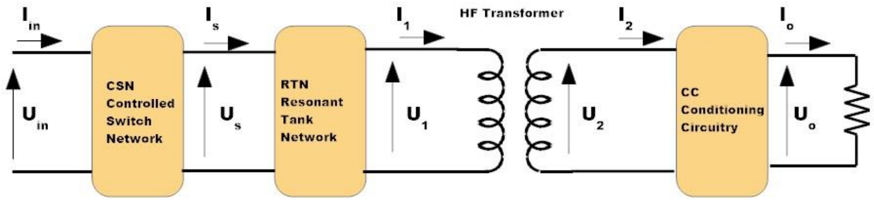
FCC Part 18 covers Consumer ISM Devices (Industrial, Scientific, Medical)

Commentary:

While a strict interpretation of the FCC rules does not demand an FCC license below 100 kHz, forward-looking WPT developers have been deploying systems with FCC experimental licenses in expectation of a rule change. Nevertheless, compliance with FCC Part 18 will unquestionably be required in any commercial system

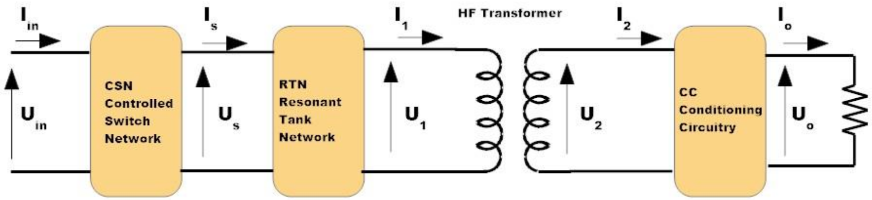
Licensing may not be required but type approval most likely will be (by or for the FCC).

FAQ on WPT



- From geometry the coupler mutual flux is optimized when VA and GA coils are same size
- Quality factor "Q" is often used in WPT analysis but developers must exercise care in dealing with definitions of series, parallel, loaded, or unloaded Q values
- Coupler alignment can be achieved using a variety of methods: camera, RFID, parking guides, sensing coils, and magnetic beacon. MD has developed positioning electronics that use existing GA coil and novel VA side electronics
- Charging regulation can be achieved through a variety of control methods such as GA side voltage control and/or duty ratio "d" control. Careful when $d<0.5$ since high reactive power must be handled on the GA side

FAQ on WPT



- Wireless communications forms the feedback channel for charging regulation. MD uses near field, full duplex, communications and encoding techniques that possess low latency and fast response
- Although a high power WPT charger can charge a LD passenger vehicle it will require harmonization of standards since LD chargers operate at 85 kHz and HD vehicle charging may settle on 20 kHz – interoperability is now an issue
- HD and LD chargers fortunately are interoperable in other areas: Communications for regulation, alignment sensing, payment, compatible messaging, LOD, FOD, and EMF
- If a metal object gets into the WPT active field (zone 1) the impact depends on its size and conductivity
- What if the family pet crawls into the active field? LOD=deactivate. Is a person with an implanted medical device (IMD) safe in proximity to a vehicle under charge? Yes, provided the EMF levels at vehicle perimeter (up to z=700mm) meet IEEE C95.1234(NATO).

FAQ on WPT

Graphic courtesy of ORNL

- If a fault occurs in the vehicle battery tray and the battery pack contactor opens or fuse blows during high rate WPT charging one method to avoid over voltage is to short the VA coil at its terminals
- Leakage fields are being dealt with through coupler design to the point that a person in a wheelchair (heart at ~ 70cm above plane of the GA) at the passenger door of a vehicle under charge would be safe. MD has their WPT technology validated by FCC and maintains close ties with J. Patrick Rielly, an international expert in human exposure to EMF, and with others

FAQ on WPT

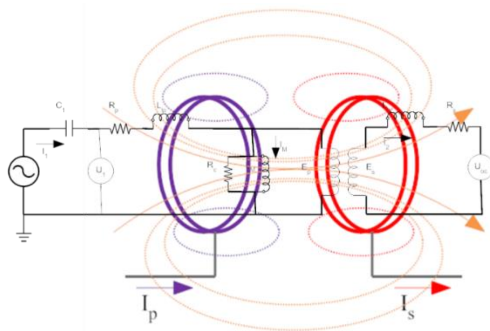
Graphic courtesy of ORNL

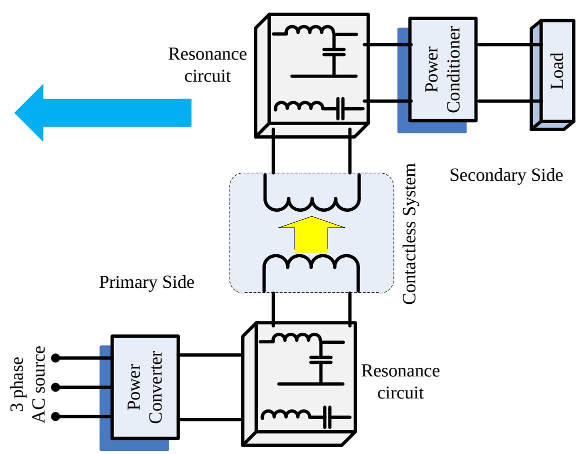
- The VA is environmentally sealed and bolted to chassis hard points. Installation is done so that ground clearance is not reduced and obstacle clearances are retained
- How is charging paid for? Many wireless providers are working on this, but most common is a cell phone app as “charge” for charge.
- What about cyber security and hacking? This is where MD’s NFC excels because:
  - it has a range of <3m, and
  - It uses secure encoding

AGENDA

PART III

Understanding the Physics

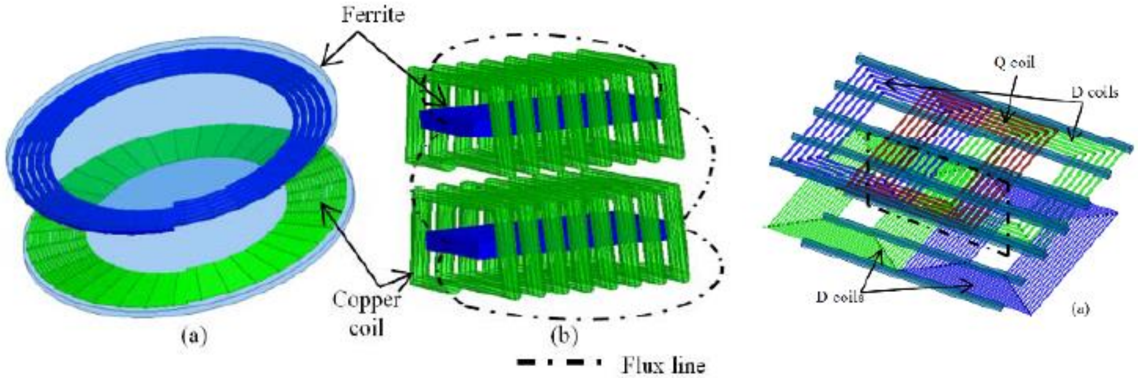




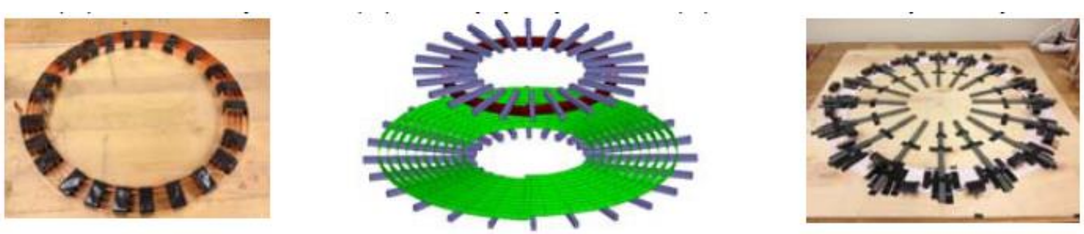
Graphic: Used with permission of UTD

Coupler Design for High k

- The industry underwent a period of competition between polarized and non-polarized couplers that was made more difficult by mis-matched pairing and the need for interoperability

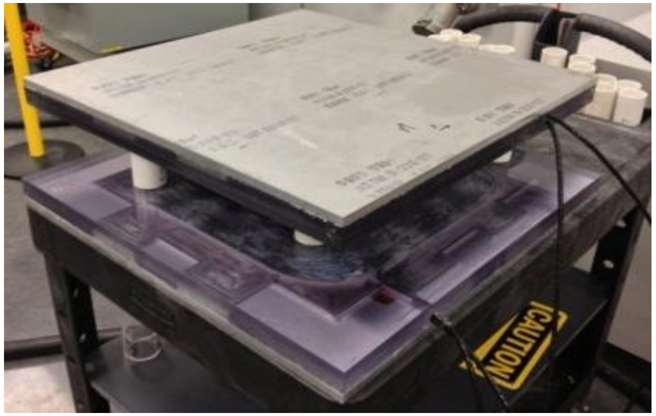


(a) Circular pads, (b) flux-pipe pads, (c) DD-DDQ bipolar pads



Trong-Duy Nguyen, Siqi Li, Weihan Li, Chunting Chris Mi, Feasibility Study on Bipolar Pads for Efficient Wireless Power Chargers, IEEE Applied Power Electronics Conference, Fort Worth, TX, USA, March16-20, 2014

Prototype WPT coupler: Courtesy of ORNL



Coupler geometry is circular to quasi-circular such as square to somewhat rectangular

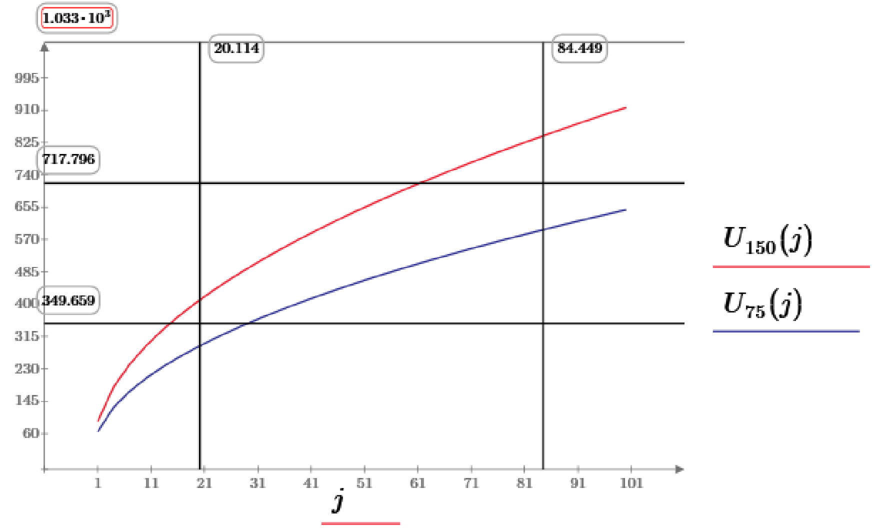
Performance Attributes, f and V

- Criteria: match mutual reactance to equivalent load
  - Example case: P_o=50 kW given k=0.22 and L_{s1} = 150µH, L_{s2} = 75 µH VA coil

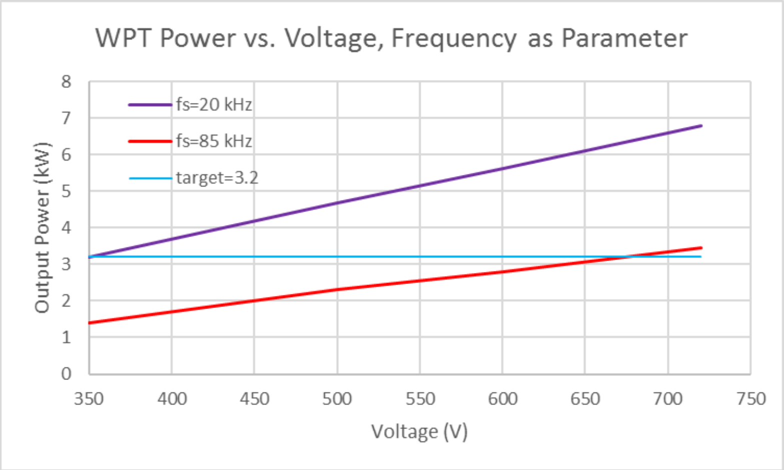
$$k\omega L_s = R_{eq}$$

$$2\pi k L_s f_s = \frac{\pi^2}{8}\frac{U_d^2}{P_o}$$

$$U_d(k, P_o, f_s) = \sqrt{\frac{16 k L_s P_o}{\pi} f_s}$$



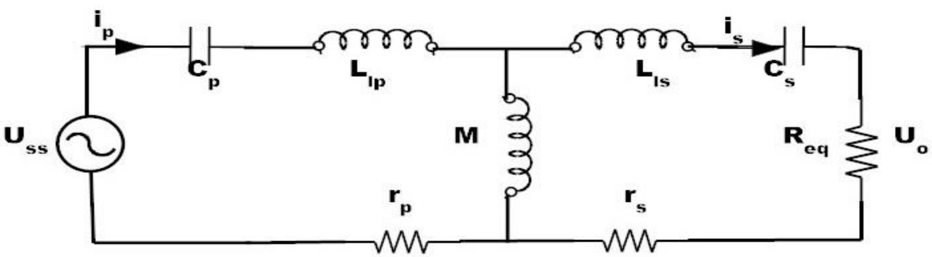
  - In the MathCAD plot j = f_s in kHz
  - Two cases shown L_s=150µH & 75µH
- Simulation reinforces $U_d(f_s)$
  - Plot P_o vs U_s to highlight trend
  - To realize P_o=3.2 kW @ fs=85kHz
  - U_s = 680Vdc, I_p =19.2 A_{rms}, I_s =17.7 A_{rms}
  - But, U_{pri} = 3.9 kV, 4X the 20 kHz value!



Performance Attributes, f & η

- It is true that WPT efficiency benefits from higher frequency, due in part to lower magnetizing current in the primary (Faraday's Law)
  - However, there is more afoot than that –
  - Consider the S-S compensated WPT where, $\omega_0 = \frac{1}{\sqrt{C_p L_{lp}}} = \frac{1}{\sqrt{C_s L_{ls}}}$

    And $\omega = \omega_0$



$P_{in} = U_{ss} i_p;$ $P_o = |i_s|^2 R_{eq}$

$$\begin{bmatrix} U_{ss} \\ 0 \end{bmatrix} = \begin{bmatrix} \left[r_p + j\left(\omega L_{lp} - \frac{1}{\omega C_p} + \omega M\right)\right] & -j\omega M \\ -j\omega M & \left[(r_s + R_{eq}) + j\left(\omega L_{ls} - \frac{1}{\omega C_s} + \omega M\right)\right] \end{bmatrix} \begin{bmatrix} i_p \\ i_s \end{bmatrix}$$

$$\begin{bmatrix} i_p \\ i_s \end{bmatrix} = \frac{\begin{bmatrix} (r_s + R_{eq}) & j\omega M \\ j\omega M & r_p \end{bmatrix} \begin{bmatrix} U_{ss} \\ 0 \end{bmatrix}}{r_p(r_s + R_{eq}) + \omega^2 M^2}$$

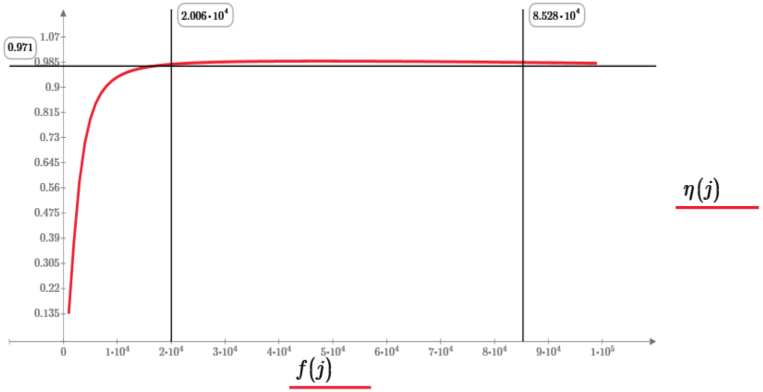
$$\eta(\omega) = \frac{1}{\left(1 + \frac{r_s}{R_{eq}}\right) + \frac{r_p}{R_{eq}}\left(\frac{r_s + R_{eq}}{\omega M}\right)^2}$$

Relationship for efficiency as f'cn ω given non-ideal coils, an equivalent load resistance R_{eq}, and mutual inductance, $M = k\sqrt{L_p L_s}$

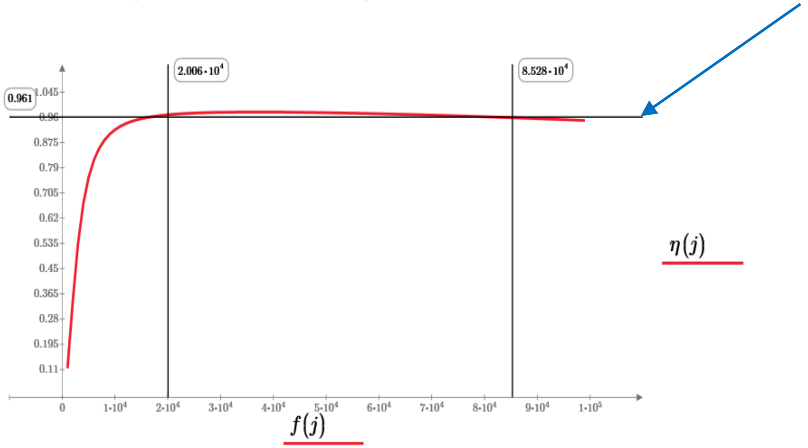
Performance Attributes, f & η

- For poorly designed couplers the efficiency at 20 kHz would be limited. However, appropriately rated Litz cable must be used or operation at 85 kHz will also suffer. Here, U_{in}=365V_{dc}, U_b=350V_{dc}, L_s = 150 μH, P_o = 25 kW, #8 Litz having R_{dc}=35mΩ,

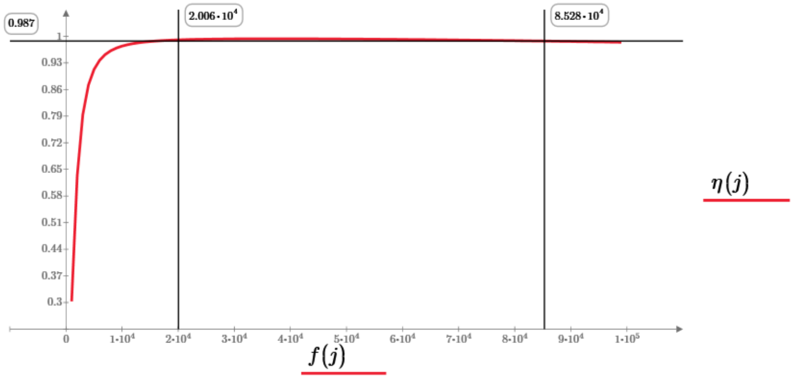
P_o = 25 kW, L_s=150 μH, k=0.18, η=0.971



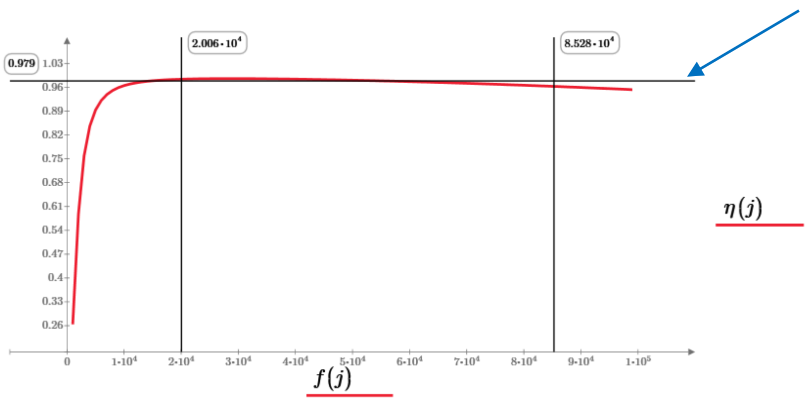
P_o = 50 kW, L_s=75 μH, k=0.18, η=0.961



P_o = 25 kW, L_s=150 μH, k=0.3, η=0.987



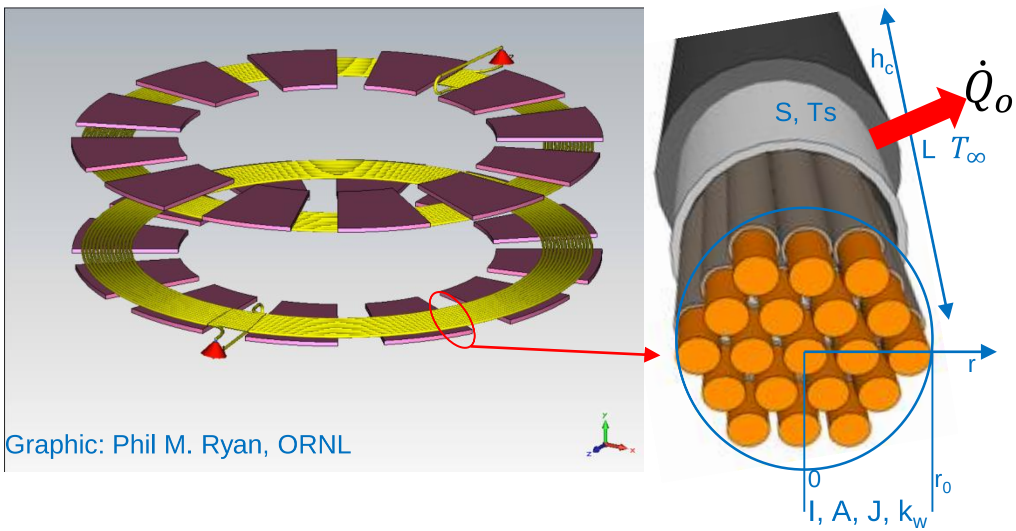
P_o = 50 kW, L_s=75 μH, k=0.3, η=0.979



Thermal Performance Considerations

Momentum Wireless Power

Joule heating of the coupler Litz cable, given mainly convection cooling (h_c), imposes a limit on current density (J=I/A) in the cable so that core temperature, T_o, does not exceed the wire thermal rating.



Graphic: Phil M. Ryan, ORNL

From Fourier's heat law and Newton's convection law in cylindrical coordinates, using:

Cable internal heat conductivity = k_w ~ 0.9 (W/mK)

k_w from work of Kevin Bennion & Gilbert Moreno, NREL for conductor bundle in a stator slot given 63% fill factor

Free air convection coefficient, h_c ~ 5 W/m²K

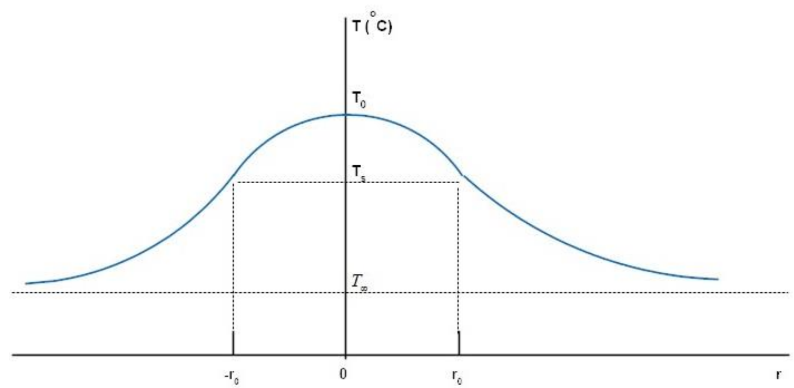
$$\dot{Q}_o = \dot{e}_{gen} V_{ol} = -k_w S \frac{dT}{dr} = h_c S [T_s - T_\infty]$$

$$\dot{e}_{gen} = \frac{J^2}{\sigma} \quad \left({}^{W}/_{m^3}\right)$$

Expect that cable core temperature, $T_0 > T_s > T_{air}$

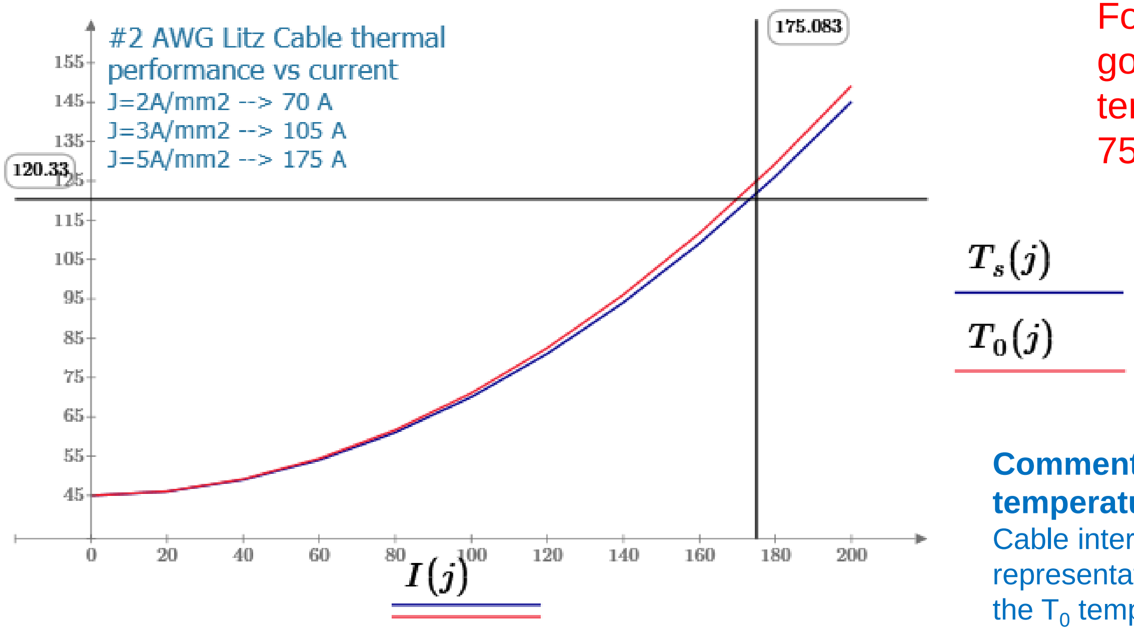
$$T_s = T_\infty + \frac{\dot{e}_{gen} r_o}{2h_c}$$

$$T_o = T_s + \frac{\dot{e}_{gen} r_0^2}{4k_w}$$



Thermal Performance Considerations

Consider a high power (25 – 50kW) WPT charger GA pad in Phoenix with air temperature 45^{o}C, and assuming the convection coefficient is reasonable, what would the Litz cable temperature be as a function of current?



For WPT 3 to 5 A/mm^2 represents a good working value and results in a temperature delta here of 25^{o}C to 75^{o}C for #2 AWG Litz.

Comments on Litz cable surface, T_s, and core, T_0, temperatures:

Cable internal heat conductivity = k_w ~ 0.9 (W/mK) is representative of tightly packed and potted motor winding so the T_0 temperature is optimistic.

Free air convection coefficient, h_c ~ 5 W/m^{2}K is representative of baseboard electric heater having vertical fins so the value of T_s here is optimistic.

AGENDA

PART IV

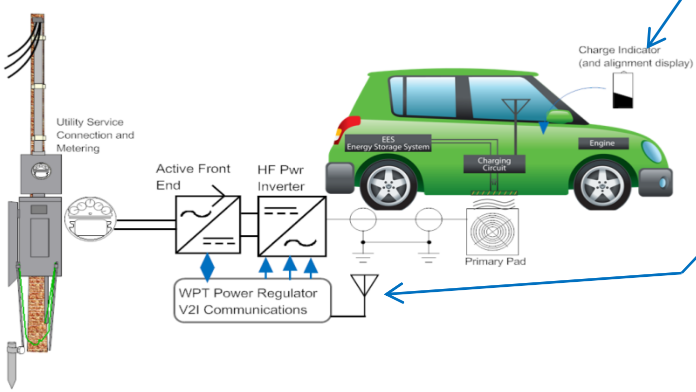
What Happens IF?

Managing Faults

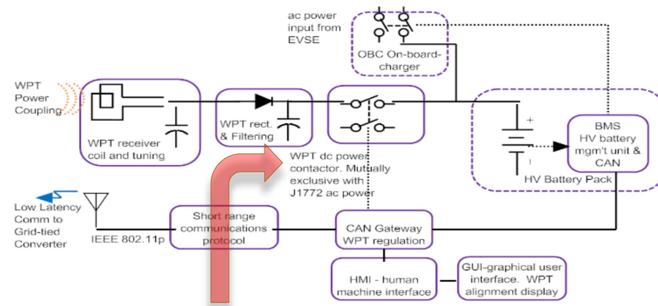
- How fast can a fault in the vehicle ESS trip the WPT charging to OFF?
- Communications channel may have >>1ms or more delay in message – latency

Fault detected by BMS

Response issued via comm channel



Graphic Courtesy of ORNL

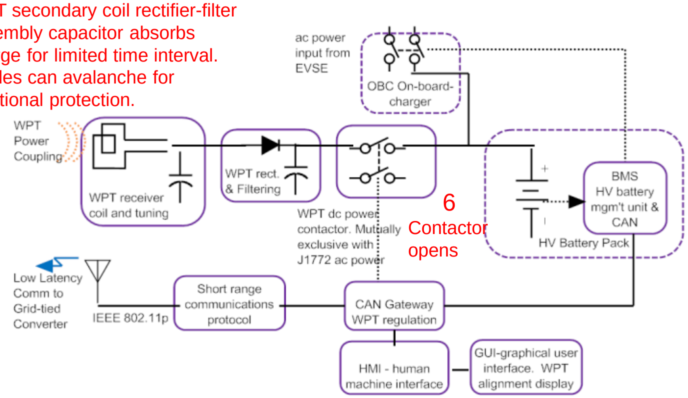


1 Time, $t=t_0$, BMS issues a STOP Charge message

2 $t=t_0+\varepsilon$, STOP CHARGE message to CAN Gateway results in disengage WPT power contactor signal

3 $t=t_1$, WPT power contactor responds, takes ~2-4ms, and wireless priority message sent to WPTB to inhibit HF power inverter

5 WPT secondary coil rectifier-filter assembly capacitor absorbs charge for limited time interval. Diodes can avalanche for additional protection.



4 At, $t=t_1+\delta$ the grid-tied power inverter inhibits and charging stops.

6 Contactor opens

Key Take-aways

- Coupler Design and Design Example Highlights
  - Use of ferrite spokes (or plates) as flux guides is essential in WPT to shape the coupled field (Litz cable loses effectiveness if too close to ferrite - proximity)
  - The VA coil is optimized when its diameter is nearly same as GA coil. For gap z > D/4 the VA coil should be somewhat larger than GA coil
  - Additional voltage matching may be realized by using unequal turns of the GA and VA coils, however, the impact is relatively low
  - Litz current density should be in the range 3 to 5 A/mm^2
- Plus, some interesting points regarding operating frequency & voltage
  - Voltage stress on the GA coil (and series compensating capacitor) are 4X higher at 85 kHz than at 20 kHz for a given coupler and at the same power level
  - Primary reactive power is 4X higher at 85 kHz than 20 kHz at same power level
  - Based on the optimization criteria operating at 85 kHz requires double the source voltage to realize the same throughput power as operating at 20 kHz
- Throughput efficiency is a function of frequency, but significant only when coupling coefficient k<0.15 and frequency <10 kHz.

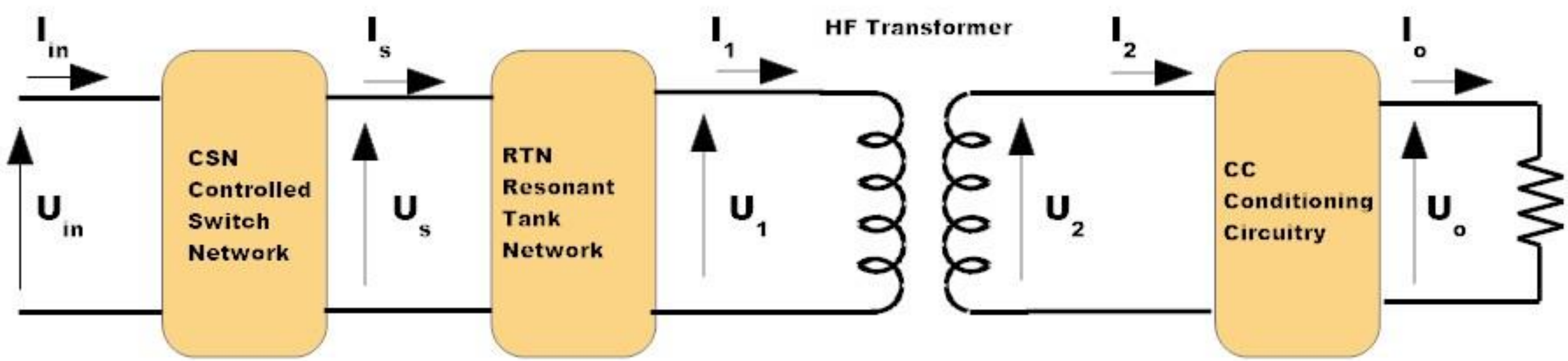
Momentum™ Wireless Power

Thank You

Backup Slides

Resonant Tank Networks

- Basic Architecture is similar to conductive (OBC), and many types of converters.



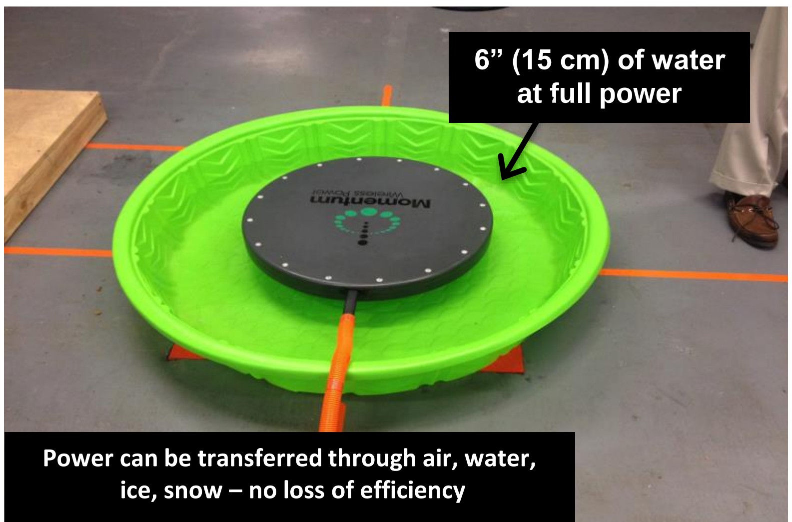
- dc Quasi-ac HF ac HF ac dc

- Input dc can be PS, rectified utility, or battery
- Generally input dc is the regulated output of a PFC stage that is required to meet utility power quality requirements of PF > |0.95| and THD < 5%
- Overall efficiency from dc input to dc output: 0.975*0.985*0.97*0.985 = 0.92

Ref: Maria Teresa Outeiro, Giuseppe Buja, Dariusz Czarkowski, "Resonant Power Converters: An Overview with Multiple Elements in the Resonant Tank Network," IEEE Industrial Electronics Magazine, pp. 21-45, June 2016

Coupler Submerged in Water

- WPT charging is not limited by submersion in water
- Contaminants that affect conductivity will have an effect, as would sea water
- Here again, operation at 20 kHz is a benefit since losses in the magnetic gap will increase with frequency
- Marine applications benefit from operation at 20 kHz or lower



Attenuation characteristics of materials

Material	Resistivity, ρ (Ωm)	Perm, μ_r (#)	X_D 20kHz (m)	X_D 85 kHz (m)
Sea Water	0.4	1	2.25	1.0
Wet earth	5	1	7.96	3.56
Aluminum	2.83E+8	1	6E-4	2.68E-4
Copper	1.75E+8	1	4.7E-4	2.1E-4
Iron	9.97E+8	150	9.17E-5	4.1E-5
Nickel	7.18E+8	220	6.43E-5	2.87E-5
Steel (1% C)	1.2E+7	200	8.7E-5	3.9E-5

Attenuation of -1 Np (Neper) at $x=X_D$ occurs in a material when the amplitude out (B or E) = e^{-1} (0.368) of the incident amplitude.

Bio:

Dr. John M. Miller is owner and founder of J-N-J Miller Design Services PLLC, which was established in 2002 to provide professional consulting in hybrid electric vehicle propulsion systems, electrochemical energy storage systems, vehicle electrification, and wireless charging. He has over 39 years of experience in electrical engineering across various industries that include automotive electrical systems, electric traction drive systems, aerospace-military guidance systems, white goods microprocessor control, and electrical practice in residential/commercial/industrial installations. In 2014 he joined Momentum Dynamics Technical Advisory Board as senior scientist working on wireless power transfer for heavy duty vehicles. His previous work experience includes Distinguished R&D Scientist at Oak Ridge National Laboratory (ORNL) where he held positions as Director of the Power Electronics and Electric Power Systems Research Center, and served as Program Manager of the DOE Vehicular Technologies subprogram APEEM. Prior to ORNL, Dr. Miller held various engineering and senior management positions at Maxwell Technologies, Ford Motor Company, and Texas Instruments. He has published several books and over 180 technical papers, with 59 U.S. patents awarded. He holds a B.S.E.E. from the University of Arkansas-Fayetteville, M.S.E.E. from Southern Methodist University, Dallas, TX, and Ph.D. from Michigan State University, East Lansing, MI. Dr. Miller is a Life Fellow of the IEEE and Fellow of the SAE and a registered professional engineer in Michigan and in Texas.

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