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PAE

PAKISTAN ACADEMY OF ENGINEERING

KNOWLEDGE FORUM

LECTURE: WIRELESS POWER TRANSFER – Application in Hybrid – Electric Vehicles

by

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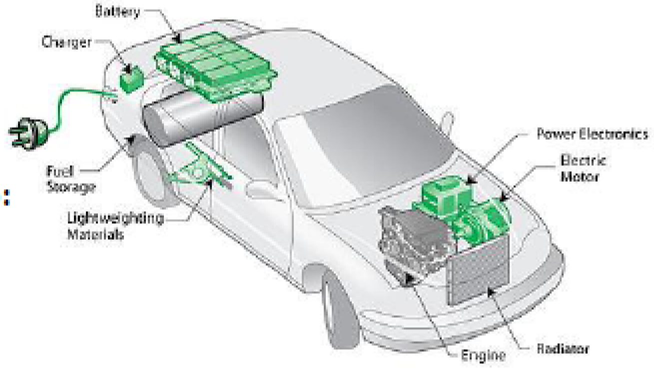
EXECUTIVE SECRETARY
PAE

Background

- **Plug-in Electric Vehicle (PEV) :**
  - Uses rechargeable battery packs that provides full or partial traction power for vehicle propulsion
  - The battery pack is chargeable from an **external** source of electricity
  - **Subsets include**
    - All-electric or Battery Electric Vehicles (BEV)
    - Plug-in Hybrid Electric Vehicles (PHEV)
- **Major advantages of (BEV / PHEV) include:**
  - Lower operating and maintenance costs
  - Little or no ***local*** air pollution
  - Reduced petroleum dependence
  - Reduced green house emissions
- **Market penetration less than expected due to:**
  - Initial Cost
  - Charging infrastructure
  - Range anxiety (BEV)
  - Time to recharge
  - Safety concerns
  - Drop in oil prices



Battery Charging Methods

- Wired electrical connection between utility power source (electrical outlet) and the vehicle – most common
- Battery swapping within 90 sec
- Supplemental charging methods including:
  - Photo voltaic cells on vehicle roof
  - Regenerative braking
  - Thermoelectric generators
- **Wireless charging**
  - Radio frequency -- Size, weight and cost
  - Laser -- Optical elements
  - Inductive – Most promising

Wireless Charging: Pros and Cons

Pros

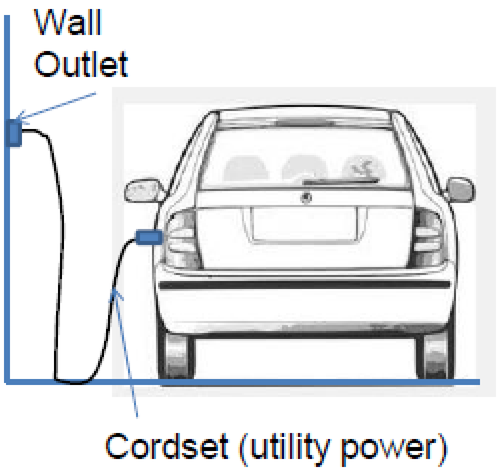
- Ease of use no cordsets to worry about
- Unaffected by rain / snow
- Well suited for vehicles operating on fixed routes (buses, trucks)
- Allows dynamic charging
- With wider future infrastructure implementation:
  - Smaller Battery => lower battery cost and weight
  - Increase in vehicle range

Cons

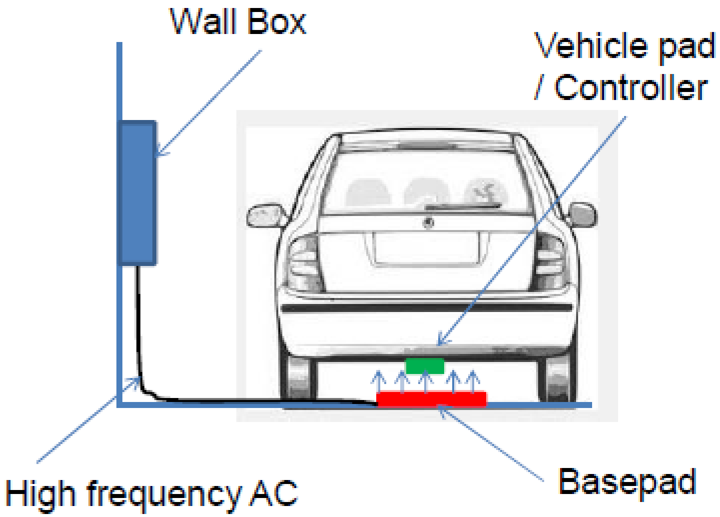
- At present higher cost and weight compared to OBC hardware
- Slightly lower efficiency
- System reliability yet to be proven
- Additional safety considerations
- Alignment between basepad and vehicle pad

Wired Vs Wireless

Wired



Wireless: magnetic resonance coupling



Developmental Wireless Charging Systems

- Milton-Keynes, UK, Bus, Jan 2014, 5 yr trial:
    - Two wireless stations
    - 10 minute charge @ stop => 2/3rd charge
- Scania / Royal Inst of Tech, Södertälje, Sweden, Bus, June 2016
    - Modified Bus Stations
    - 6 to7 min charge cycle
- Volvo C30 -- Proof of concept
- Daimler and Jaguar-Land Rover have active development programs
- Toyota has licensed technology from Witricity
- Waseda University, Tokyo: Electric Microbus
- Honda R&D is working on wireless charging system

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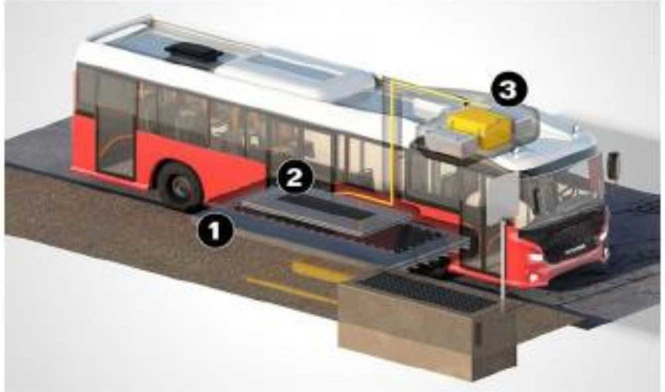
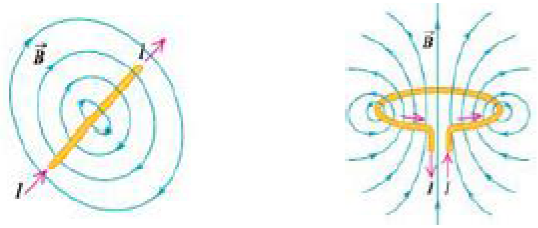
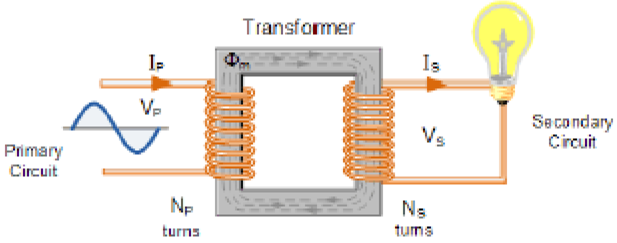


Principle of Operation

- A conductive loop is connected to an AC power source generates an oscillating magnetic field in the vicinity of the loop
- A second conducting loop, brought close enough to the first, "captures" some portion of that oscillating magnetic field, which in turn, generates or induces an electric current in the second coil
- This type of electrical power transfer from one loop or coil to another is well known and referred to as magnetic induction:
- Faraday-Maxwell Equations
  - **Magnetic flux density** (B) is defined as the force acting per unit current per unit length on a wire placed at right angles to the magnetic field. Unit Tesla



An oscillating magnetic field produces an electric field and an oscillating electric field produces a magnetic field

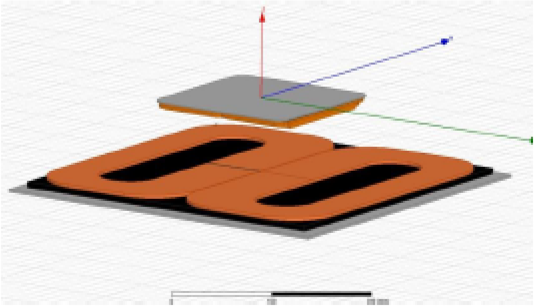


$$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

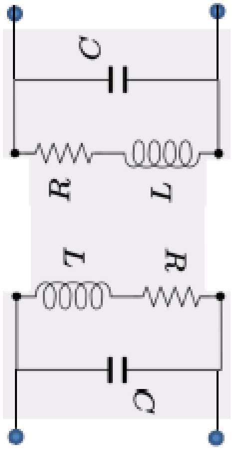
Magnetically Coupled Resonance

- Resonance: Natural frequency at which energy can be most efficiently added to an oscillating system (e.g. swing)
- Magnetic coupling occurs when two objects exchange energy through their varying or oscillating magnetic fields
- Resonant magnetic coupling occurs when the natural frequencies of the two magnetic circuits are approximately the same.



$$\omega_{n2} = \sqrt{\left(\frac{1}{L_2 C_2} - \left(\frac{R_2}{L_2}\right)^2\right)}$$

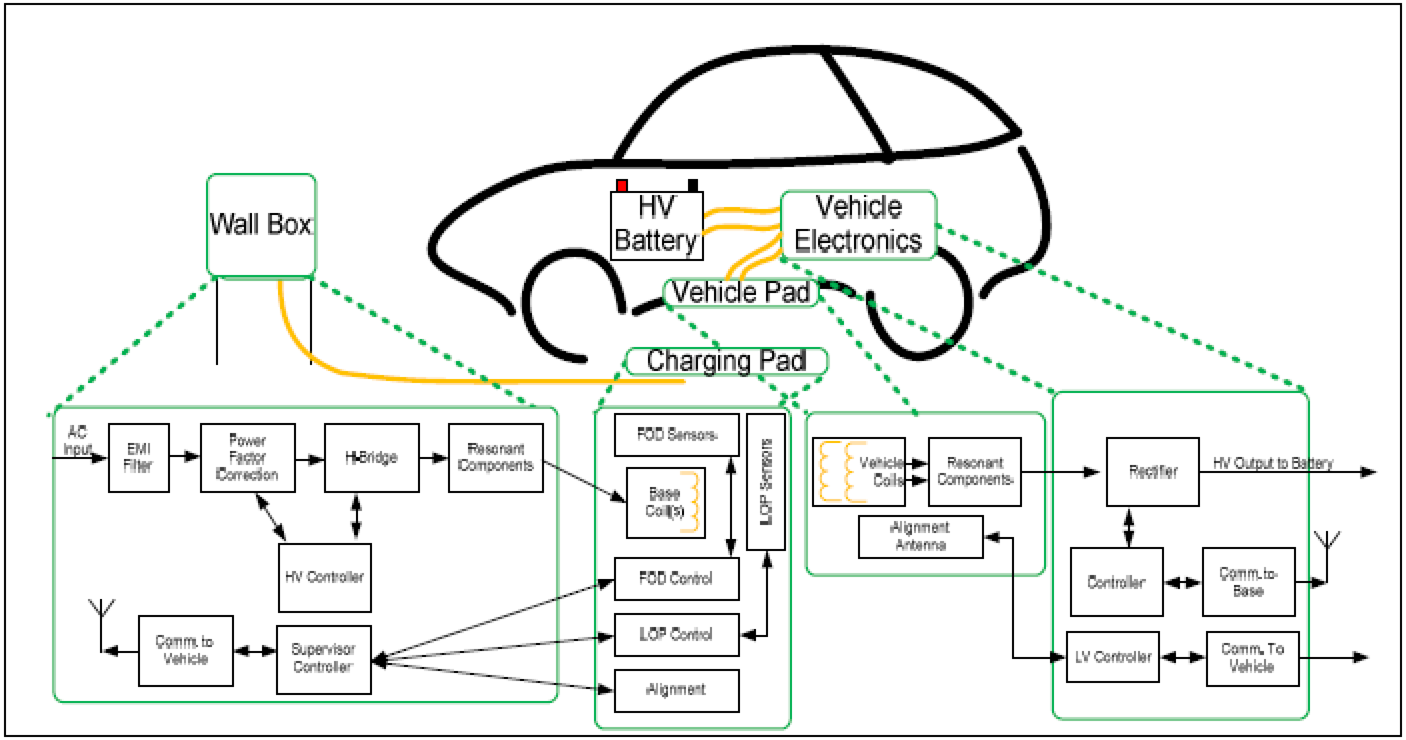
$$\omega_{n1} = \sqrt{\left(\frac{1}{L_1 C_1} - \left(\frac{R_1}{L_1}\right)^2\right)}$$



Wireless System Architecture

- The wireless charging architecture can be broken down to smaller subsystems
  - Wall box
  - Base pad or primary coupler
  - Vehicle pad
  - Vehicle Electronics - rectifier / controller

- Depending on the implementation scheme and objectives
  - Wall box and Base pad can be combined in one physical entity
  - Vehicle pad and Vehicle Electronics (rectifier / controller) can be combined in one physical entity


Wall Box
HV Battery
Vehicle Electronics
Vehicle Pad
Charging Pad
AC Input
EMI Filter
Power Factor Correction
H-Bridge
Resonant Components
HV Controller
Comm. to Vehicle
Supervisor Controller
FOD Sensors
Base Coil(s)
LOP Sensors
FOD Control
LOP Control
Alignment
Vehicle Coils
Resonant Components
Alignment Antenna
Rectifier
HV Output to Battery
Controller
Comm. to Base
LV Controller
Comm. To Vehicle

Standards

- SAE J2954: Work in Progress
  - Establishes minimum performance and safety criterion for wireless charging of electric and plug-in vehicles.
  - Interoperability
  - Better vehicle packaging, reduced cost, and ease of customer use
- ICNIRP

Health and Safety Aspects

- The exposure to electromagnetic radiation is limited by ICNIRP (INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION) guidelines
  http://www.icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf

Health Physics December 2010, Volume 99, Number 6

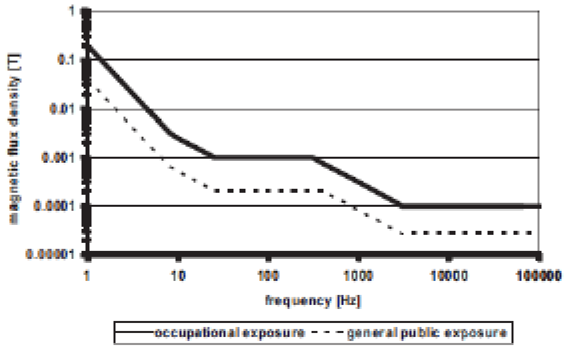


Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 3 and 4).

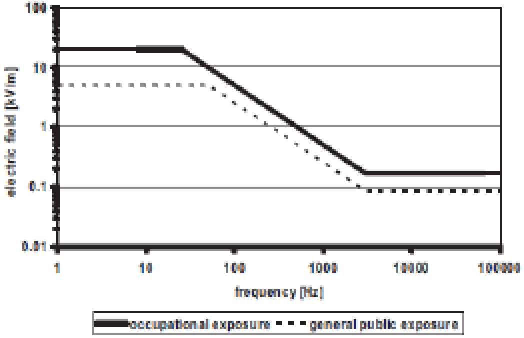
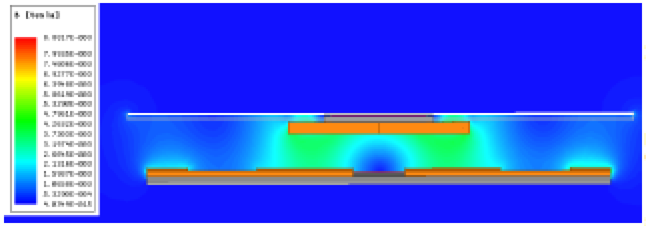


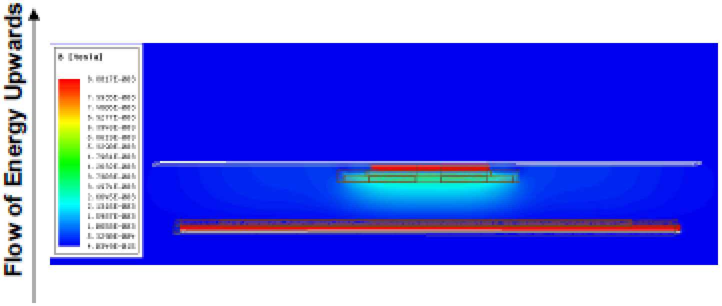
Fig. 3. Reference levels for exposure to time varying electric fields (compare Tables 3 and 4).

Magnetic Field in 52 mm Air gap

Side View



Front View at Coil Center

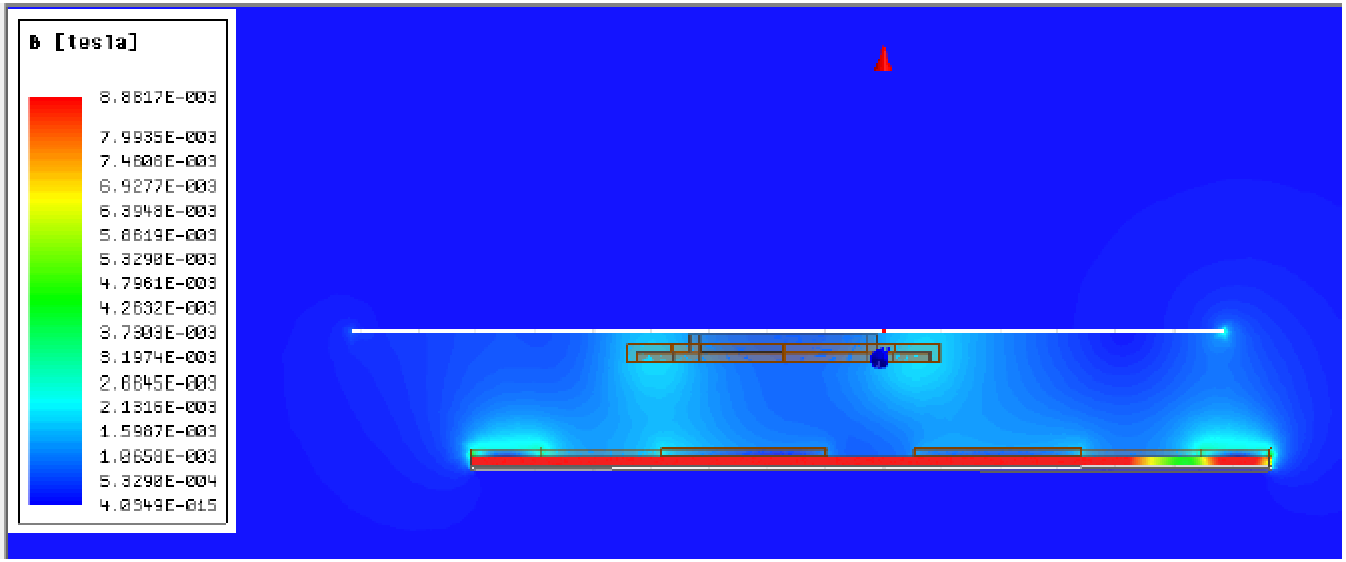


- The power transfer via the magnetic field is shown through front and side views taken through crossections of xy plane and yz plane.

Xoffset = 0, Yoffset = 0

Magnetic Field in 72 mm Airgap

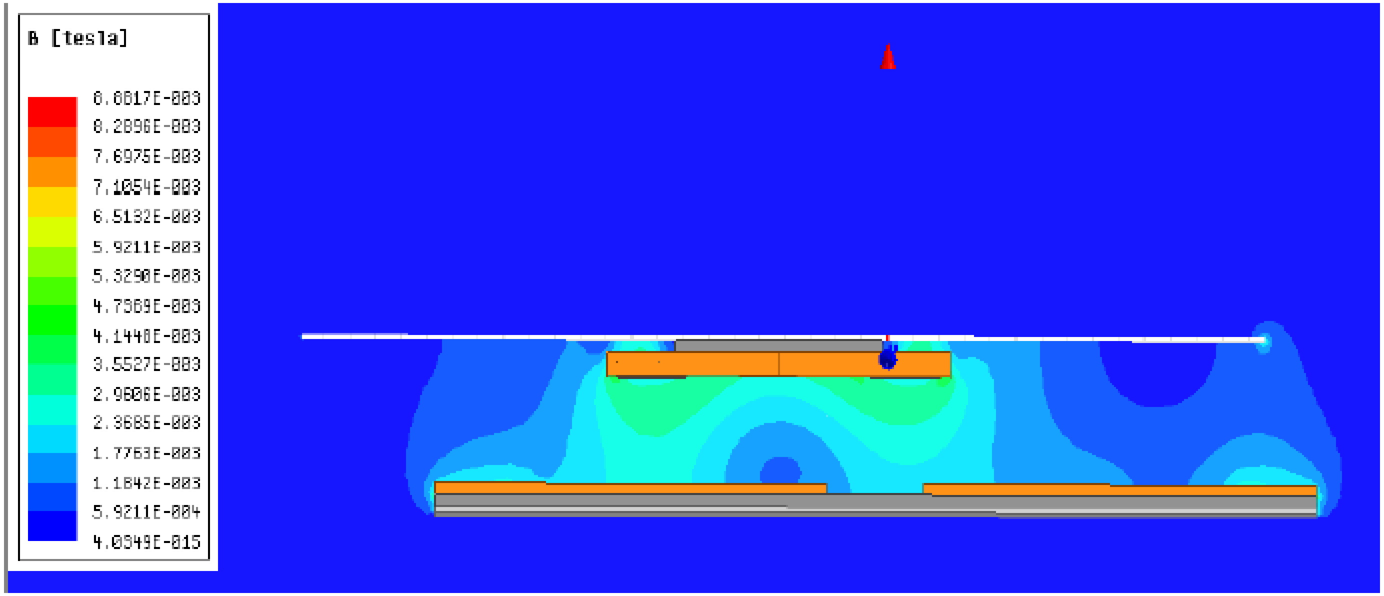
Side View at Coil Center - Xoffset = 75, Yoffset = 150



Y = 0 (Cross Sectional View)

Magnetic Field in 72 mm Airgap

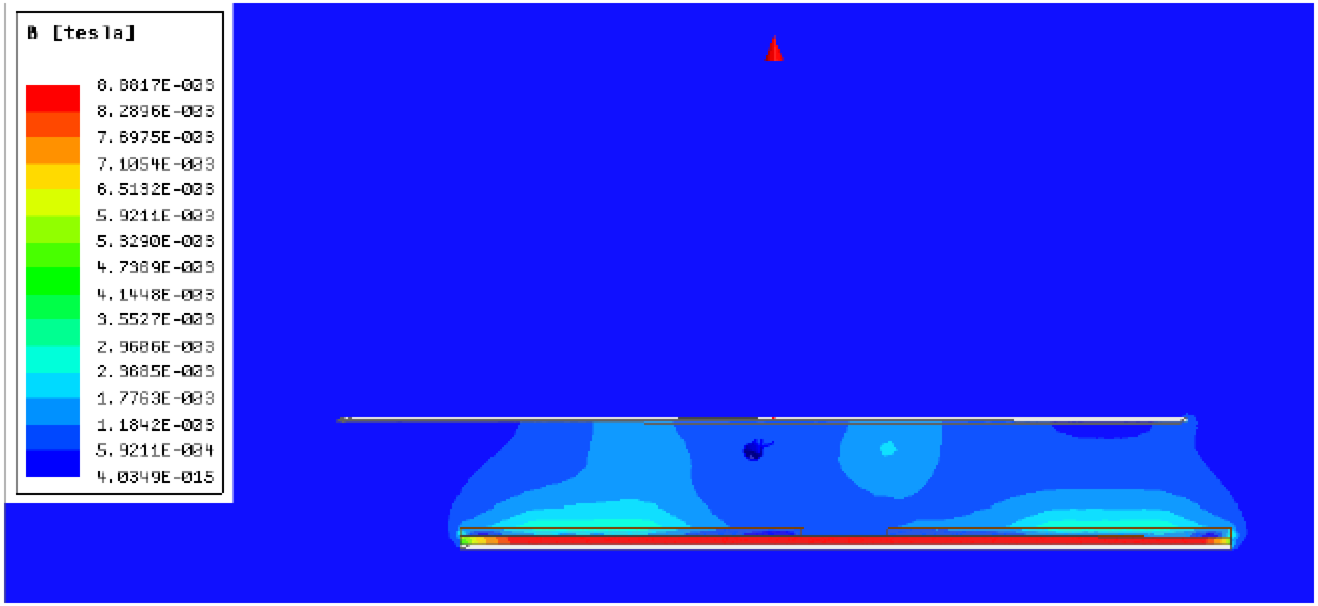
Side View at Coil Center - Xoffset = 75, Yoffset = 150



Y = 150 (Cross Sectional View)

Magnetic Field in Airgap (Dcc) of 72 mm

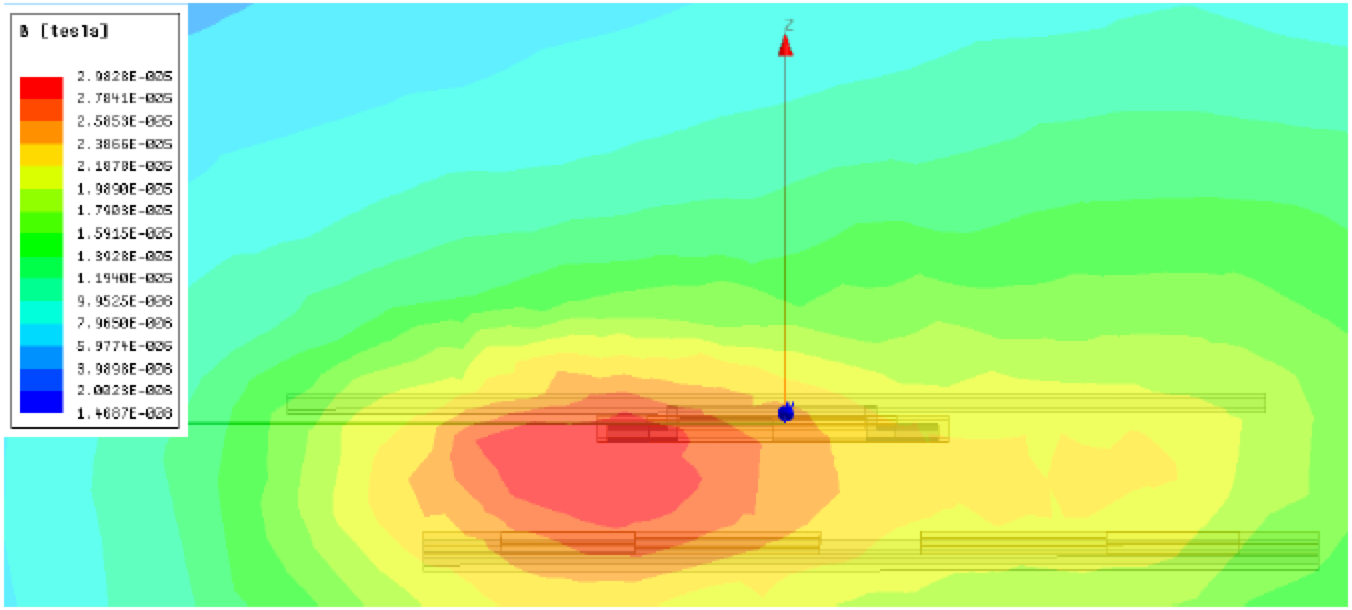
Side View at Coil Center - Xoffset = 75, Yoffset = 150



Y = 300 (Cross Sectional View)

Magnetic Field in 72 mm Airgap

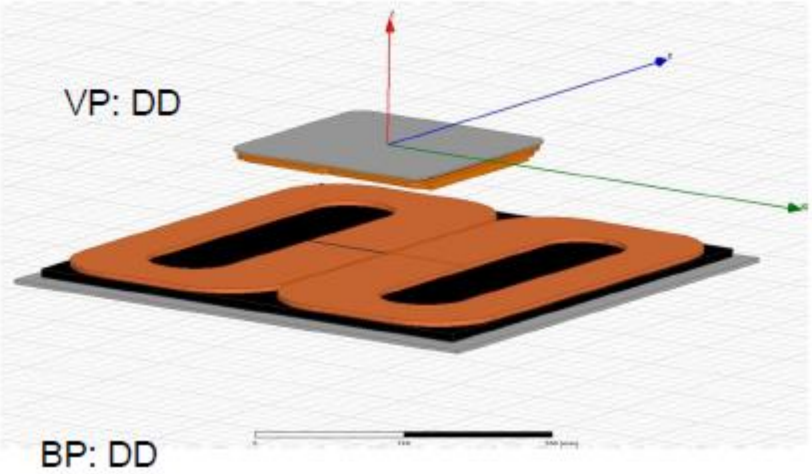
Side View at Coil Center - Xoffset = 75, Yoffset = 150

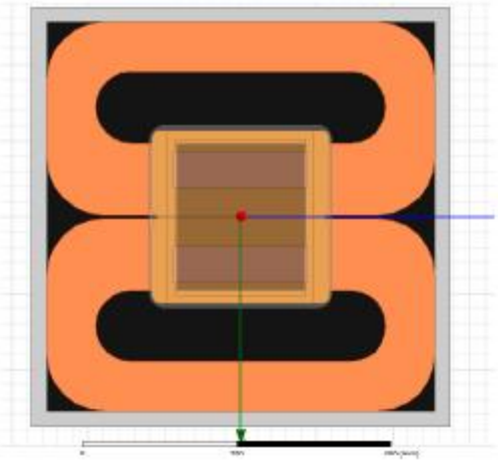


Y = 600 (Cross Sectional View - Lower Colorbar Scale)

Coil Arrangement

Basic Coil Architecture



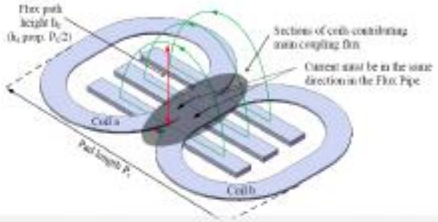


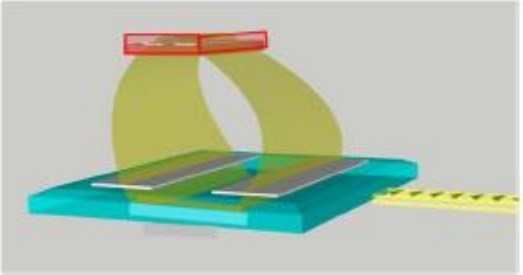
- Frequency of AC current through coil = 85 kHz
- High AC wire resistance due to skin and proximity effects
- Litz wire is necessar
- Litz wire consists of a bundle of individually insulated fine diameter wire strands weaved together and held by a outer jacket (serve)

Field Path Double D Coils vs Circular Coil

Double D Coil magnetic field path

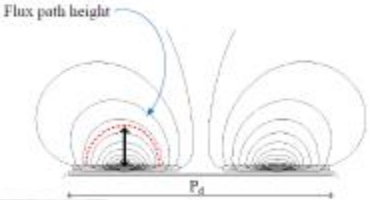
- Field travels in a closed loop from one side of the primary coil to one side of the secondary coil and back on the other side of the primary coil
- Both the source and return magnetic fields are contained above the Charging Pad
- Double D, usable flux height is P/3

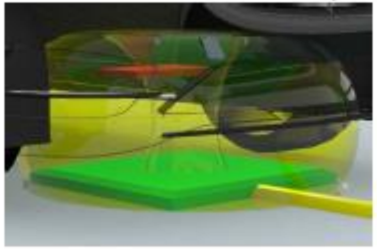




Circular Coil magnetic field path

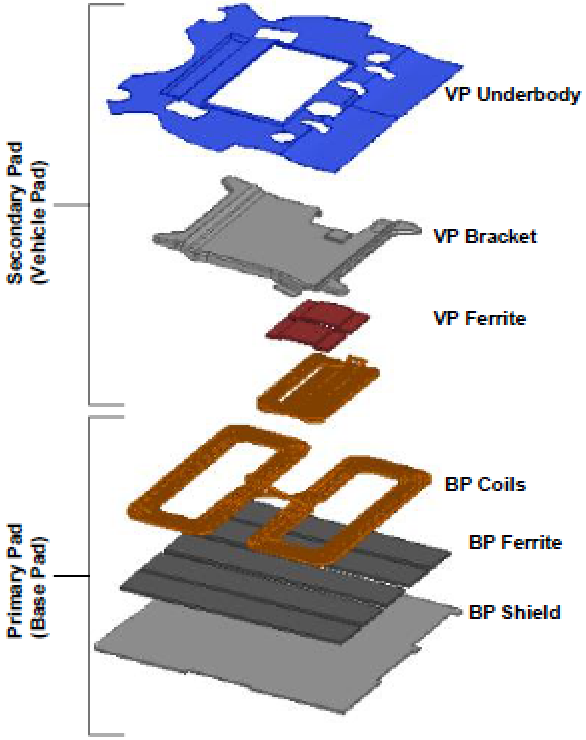
- Field travels from the center of the primary coil to the center of the secondary coil than back to the primary on the outside of the primary and secondary coils
- The source magnetic field is above the Charging Pad
- The return magnetic fields is on the outside of the Charging Pad
- Circular, usable flux height is P/4



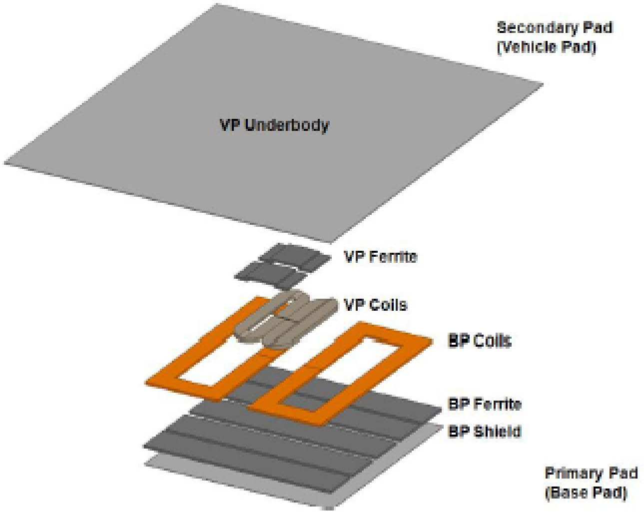


Exploded View of Real and Ideal Coil

Real Coil

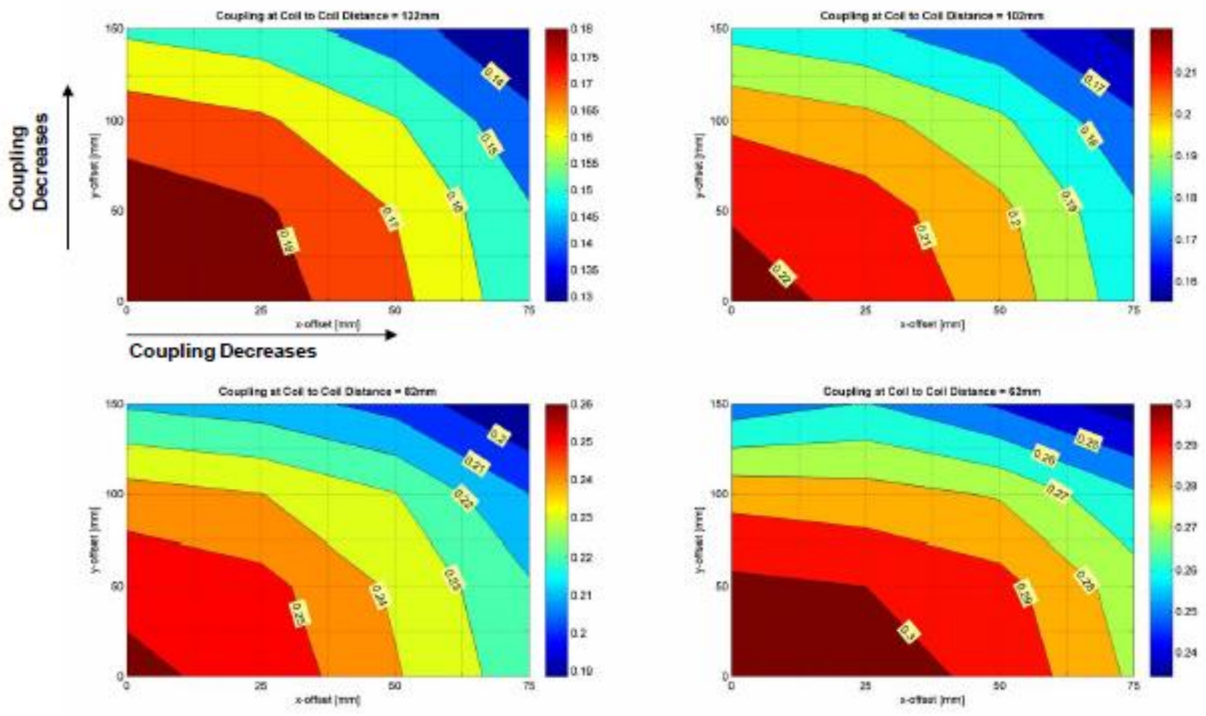


Ideal Coil



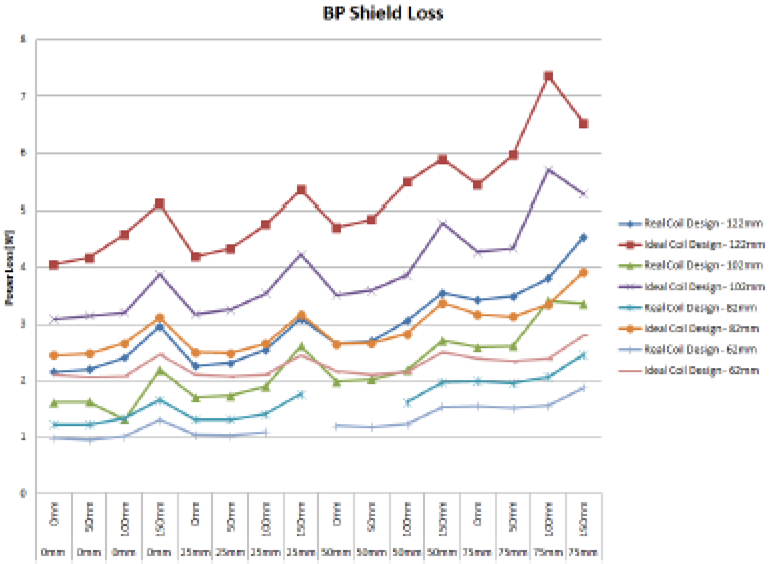
Coupling Coefficient (k12)

Coupling Coefficient Over 1st Quadrant (+X,+Y)

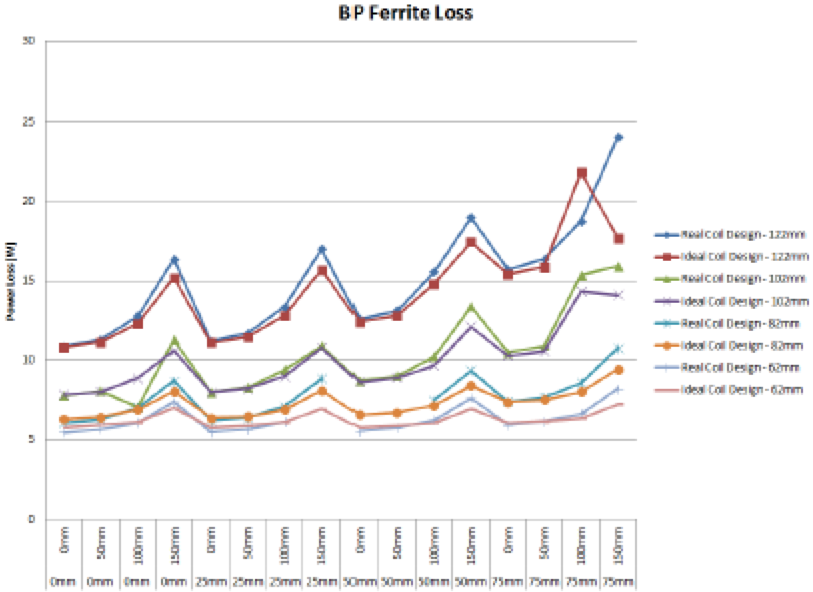

Coupling Decreases

Coupling Decreases

BP Shield Loss

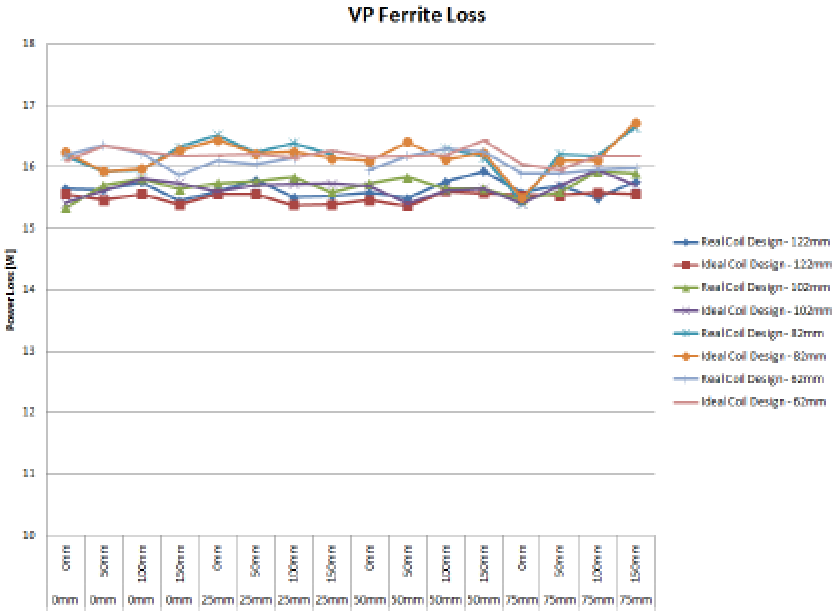


BP Ferrite Loss

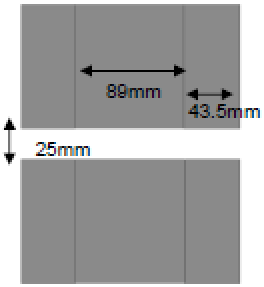


- There is a minor difference between BP ferrite losses between the original coil design and real coil design.

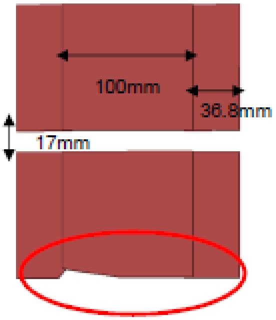
VP Ferrite Loss



Ideal Ferrite Design

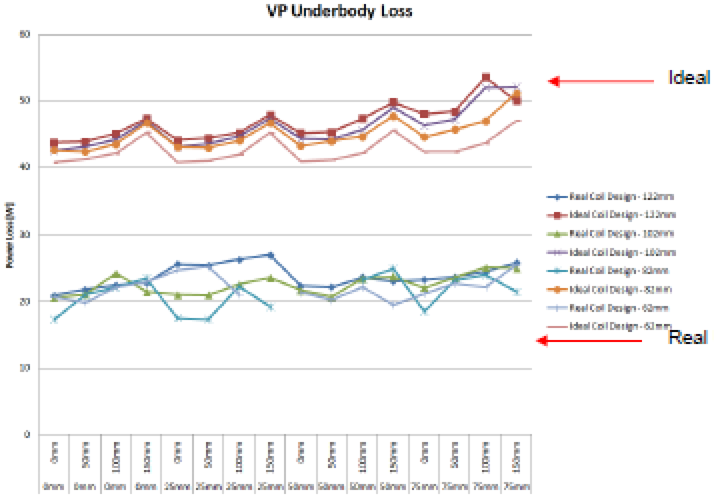


Real Ferrite Design



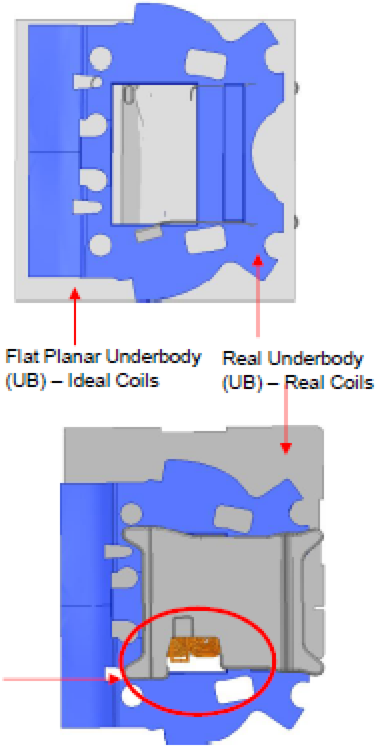
- There is a minor difference between BP ferrite losses between the original coil design and real coil design. The difference can be attributed to the cutout in the ferrite and minor geometrical changes to the ferrite to accommodate the exit of the coils in the real design and improve performance.

VP Underbody Loss



Ideal Underbody Losses

Real Underbody Losses



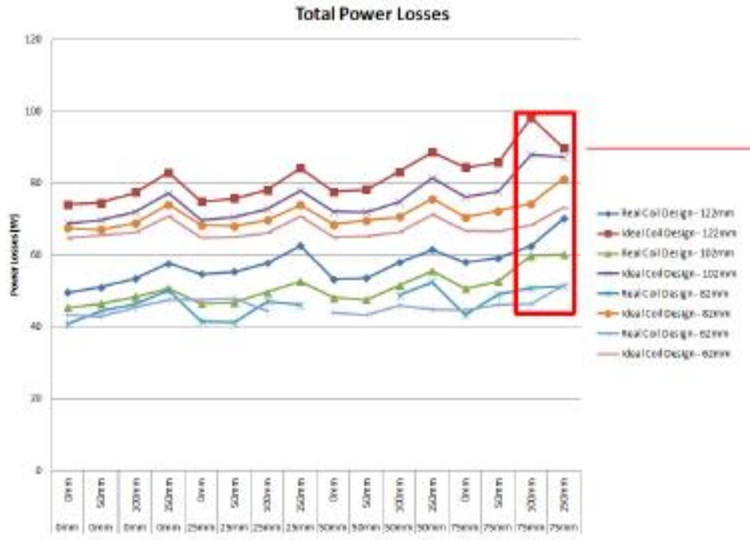
Flat Planar Underbody (UB) – Ideal Coils

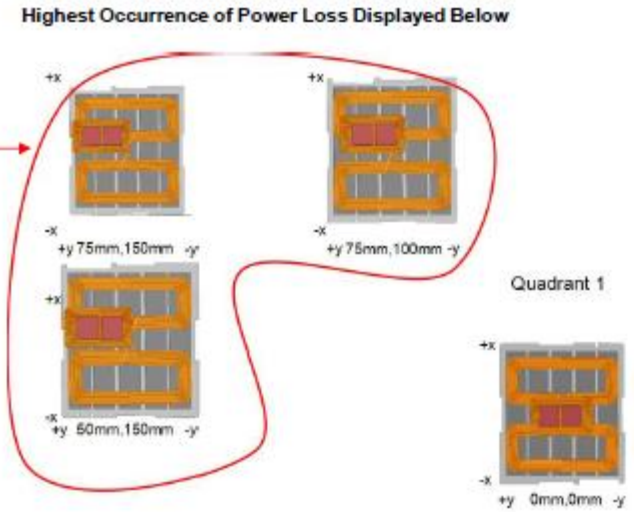
Real Underbody (UB) – Real Coils

Hole in VP Bracket
Over the VP Coils
(Real Coils)

- There is a large difference between real underbody loss and ideal underbody loss. The real underbody has significantly lower losses than ideal underbody losses due to the holes in the underbody and smaller size of the real underbody/bracket.

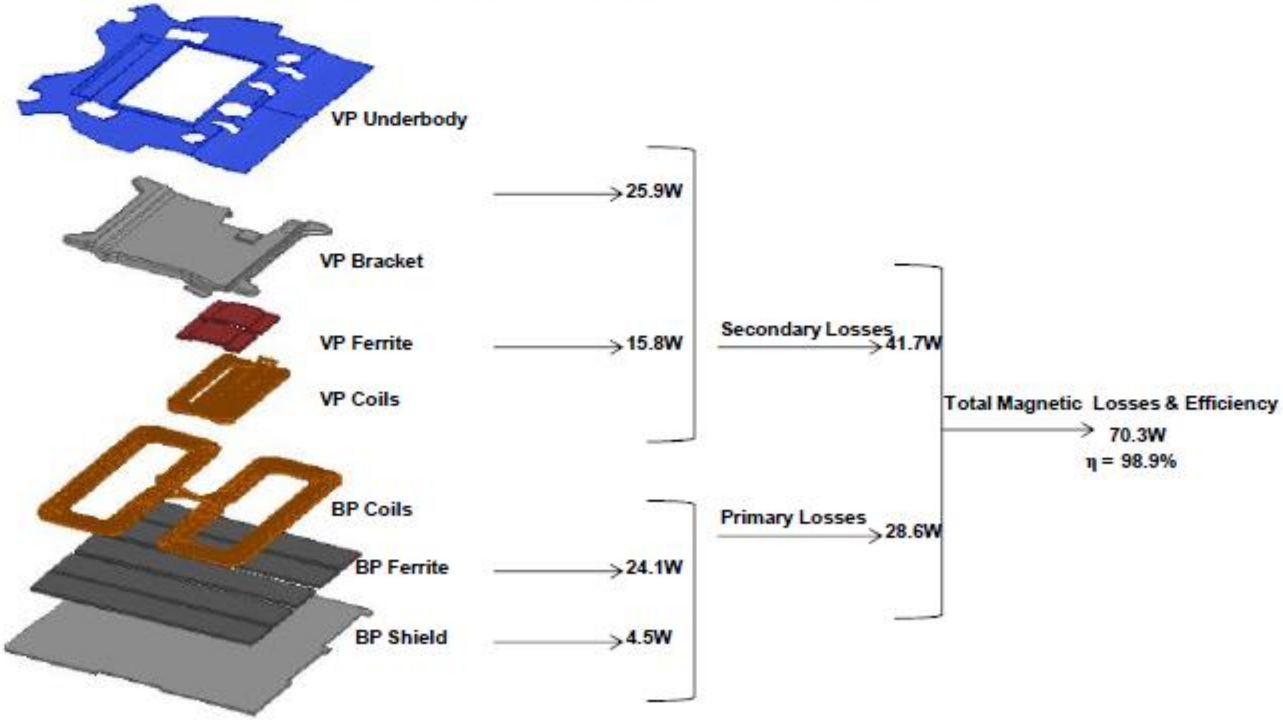
Total Power Losses





- Due to a decrease in power losses in the vehicle underbody the overall power losses have decreased from the ideal coil design to the real coil design.
- The highest occurrence of power losses is located near xoffset = 75mm, yoffset = 150mm and xoffset = 75mm, yoffset = 100mm for all z-heights.

Worst Case Power Losses at Dcc = 122mm/xoffset = 75mm / yoffset = 150mm



VP Underbody

VP Bracket

VP Ferrite

VP Coils

BP Coils

BP Ferrite

BP Shield

→ 25.9W

→ 15.8W

→ 24.1W

→ 4.5W

Secondary Losses → 41.7W

Primary Losses → 28.6W

Total Magnetic Losses & Efficiency → 70.3W

η = 98.9%

Summary

- The coupling difference between the real and ideal shield is present and the ideal shield contributes to a higher coupling difference .
- The coupling difference between the real and ideal ferrite losses was not significant, but in the VP Ferrite there was more of difference due to geometry changes to the VP Ferrite.
- The underbody loss was higher in the case with the ideal planar shield as the geometry in the real case has holes and is smaller.
- The BP shield loss is higher in the ideal coil case as the geometry of the ideal BP shield is thinner and the dimensions are smaller leading to more surface losses.
- The highest occurrence of power losses is located near xoffset = 75mm, yoffset = 150mm and xoffset = 75mm, yoffset = 100mm for all z-heights, while the lowest coupling is located at xoffset = 75mm, yoffset = 150mm.

Efficiency Estimation – without PFC

Hybrid Coil Design					
Vehcile Pad Coil Size		200 x 350			
Base Pad Magnetics Size		630 x 580			
	Best			Worst	
	Eff	Power		Eff	Power
PFC					
Inverter	98.0	144		96.5	180
Matching Transformer	99.6	29		99.4	40
Tuning caps	99.6	29		99.4	40
Base Pad leads 6m @ min A	99.9	6			
Base Pad leads 6m @ max A				99.8	18
Base Pad Coil @ min A	99.9	12			
Base Pad Coil @ max A				99.4	48
Base Pad Magnetics	99.9	7		99.4	25
Vehicle Pad Magnetics	99.8	25		99.7	27
Vehicle Pad leads @ min A	100.0	2			
Vehicle Pad leads @ max A				100.0	3
Vehicle Pad Coil @ min A	99.7	14			
Vehicle Pad Coil @ max A				99.6	14
Vehicle Body	99.4	49		99.2	69
Tuning Caps	99.8	14		99.8	14
Rectifier	98.7	90		98.2	130
Filter	99.7	20		99.7	24
Totals	93.8%	440		91.3%	631

630 x 580 Magnetics, 200 x 350 vehicle pad

Some conditions will not charge at full power; Z = 160mm & x >50mm & Y > 100 mm

Increase wire size in vehicle pad and base pad

Modified DD Structure to reduce locations that will not charge at full power

Tuning moved to the vehicle pad

Estimated vehicel Body losses - depends on the design of the vehicle sheild. Initially simulated with a flat vehicle shield

9/1/15 System Testing