3rd year annual report
24th October, 2016

Dynamic wireless charging of Electric Vehicles

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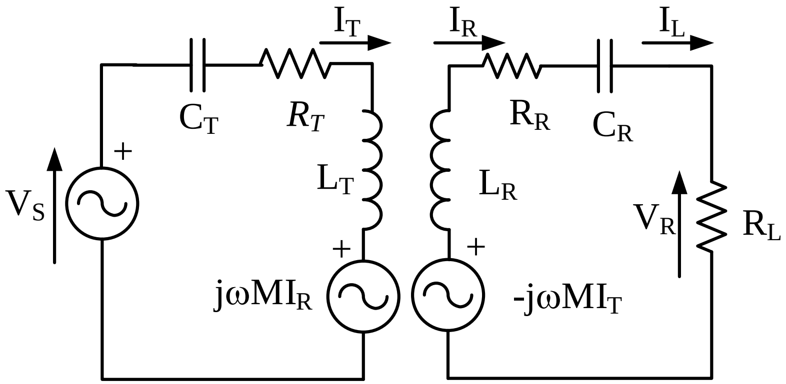
Containts

- Wireless battery charging (WBC)
- WPT coils and coupling
- WPT track segmentation
- Reflexive Segmentation
- DD coil for dynamic WBC
- Energy Analysis in Motion
- Unequal DD coil for dynamic WBC

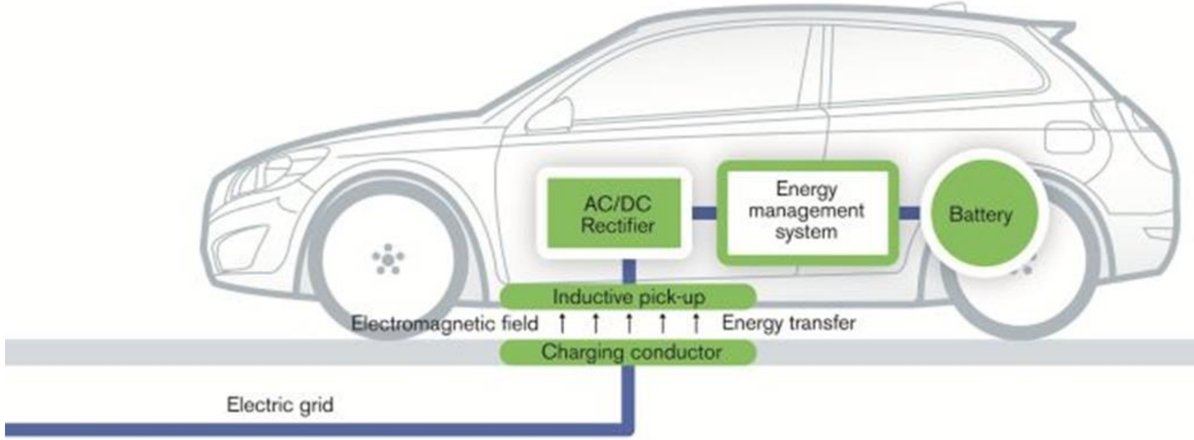
Wireless battery charging (WBC)

- Inductive power transfer is the most convenient.
- Power transfer efficiency

$$\eta = \frac{1}{1+\frac{R_T R_{R1}}{\omega_0^2 M^2}}$$



- Higher M and ω_o improves the efficiency.
- M depends upon coil structure and airgap.
- Resonance (using C_T and C_R) improves efficiency.

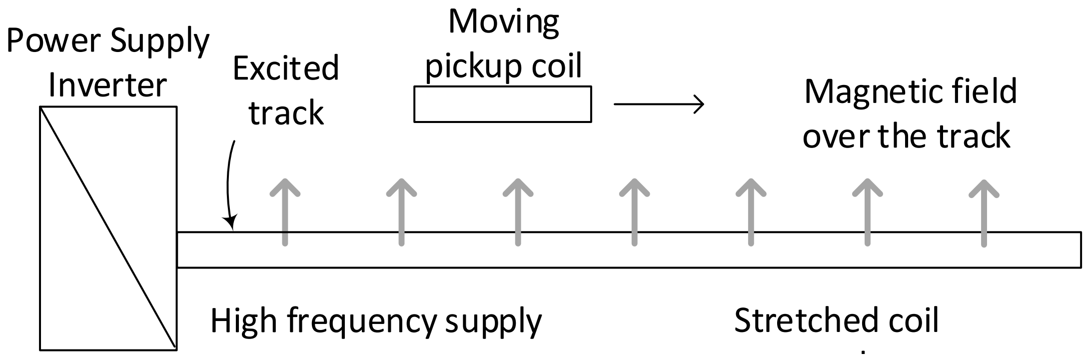


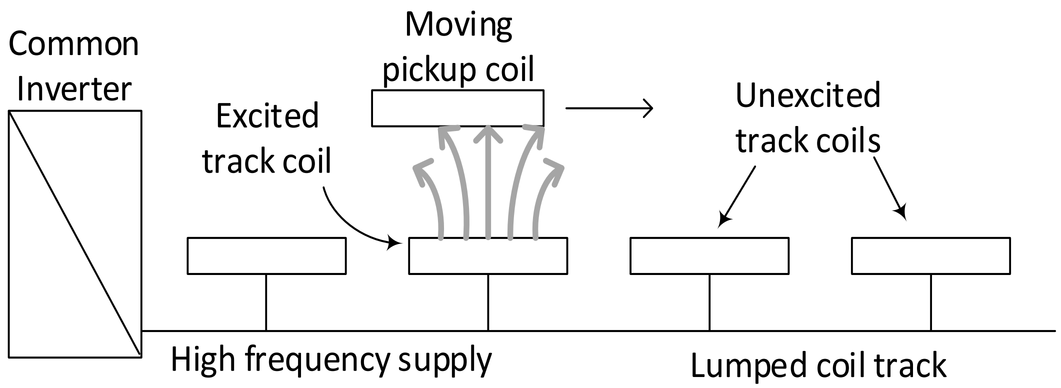
Dynamic Wireless Charging (DWC)

- WPT track is buried under road surface.
- Track configurations-
  - Stretched coil track
  - Lumped coil track
- Coupling Coefficient:

$$M = k\sqrt{L_T L_R}$$

- Attributes of comparison
  - Power transfer efficiency
  - Segmentation capability
- Lumped coil track has been chosen for further research.





WPT track segmentation

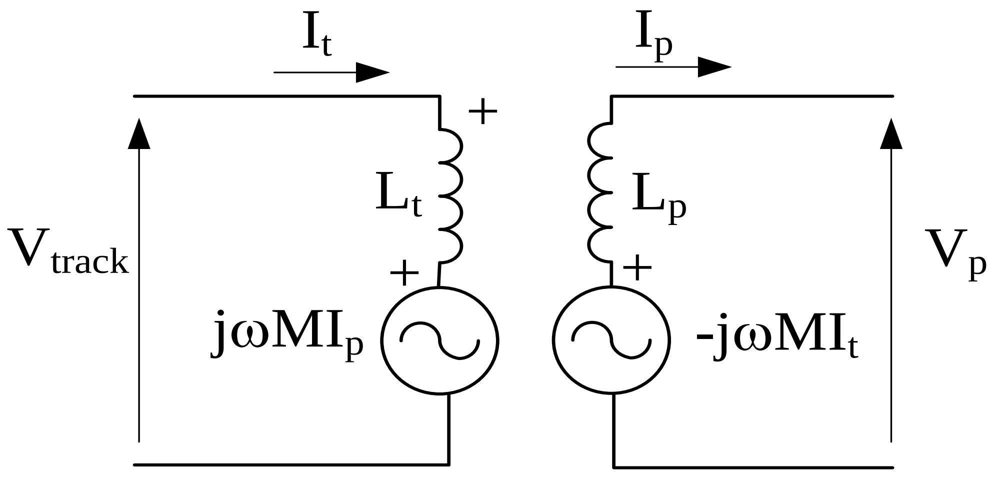
- WPT track is divided in segments for safety purpose.
- Flux density over OFF segments must be < 6.25 μT. (ICNIRP guideline)
- Sensing and switching arrangement makes it operational.
- Reflected impedance from pickup coil can be used for segmentation.
- Reflexive method is inherently automatic and switches free.

Reflexive Segmentation

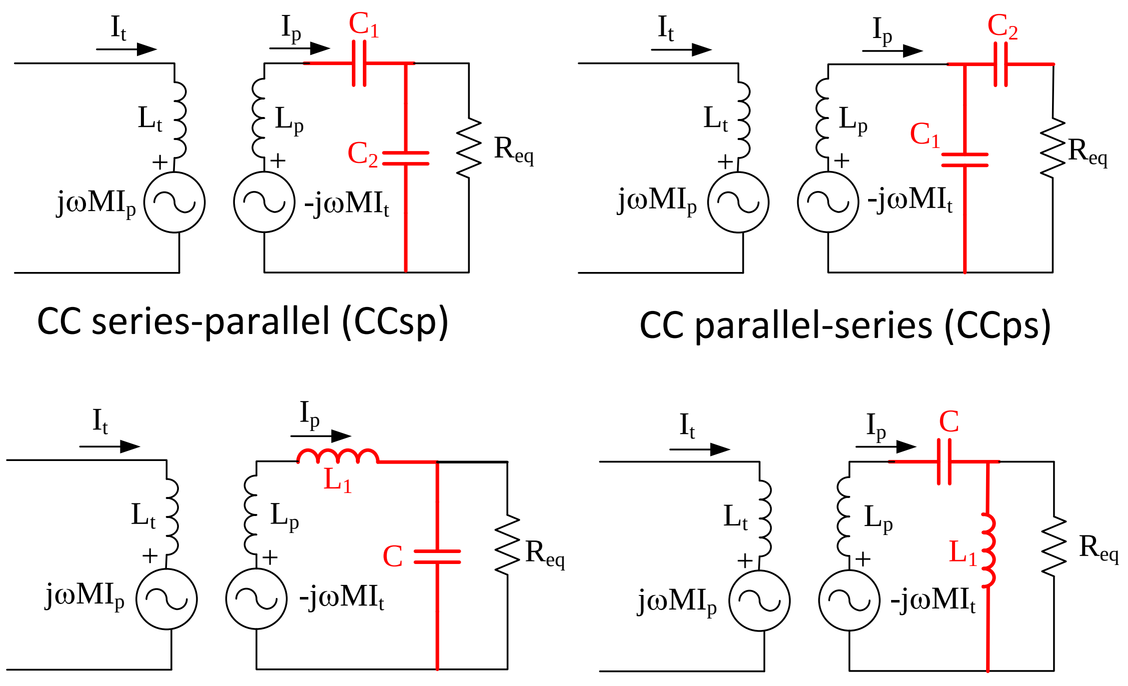
- Pickup reflects impedance into the coupled track coil.

$$Z_r = \frac{j\omega M I_p}{I_t} = \frac{\omega^2 M^2}{Z_p}$$

- Compensation in pickup can define the behaviour of Z_p and Z_r.
- Commonly used single capacitor compensation is not adequate.
- Two element topologies have been considered and analysed.



Two Element Compensation



CC series-parallel (CCsp)

CC parallel-series (CCps)

LC series-parallel (LCsp)

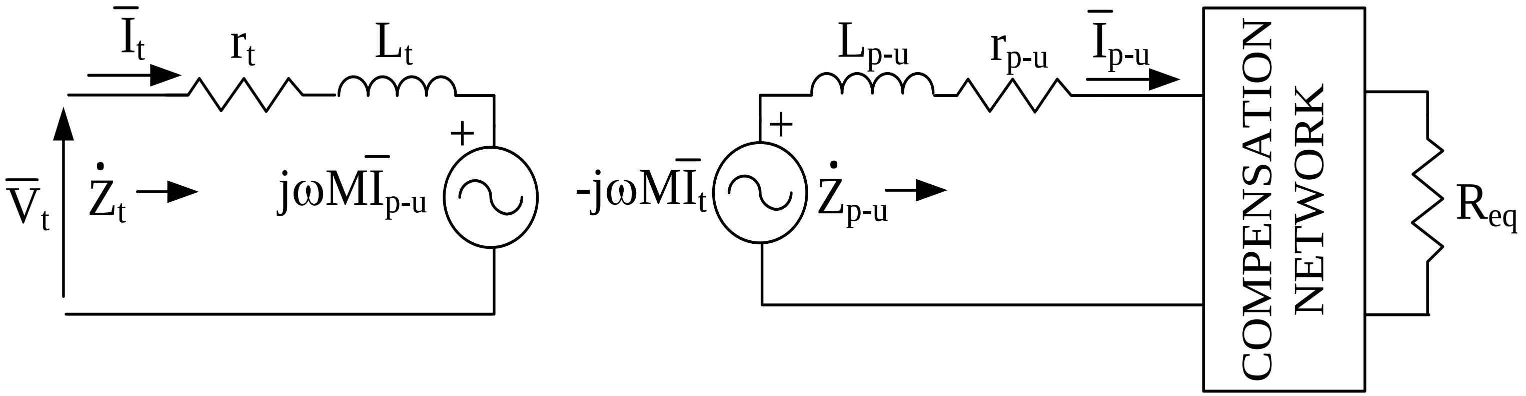
CL series-parallel (CLsp)

- Desired reflected impedance can
  - Fully compensates the track reactance
  - Prevent the resistance rise.

Factors	CCsp	CCps	LCsp	CLsp
Segmentation ability	✓	✓	✗	✓
Reflected R_{eq} is limited	✓	✓	✗	✗

- Current gain in coupled state is prime factor of selection.
- Nature of reflected real load affect the current gain.
- CCsp and CCps have candidature for application.

Performance Figures



- Performance is analyzed with different compensation network.
- Segmentation ration

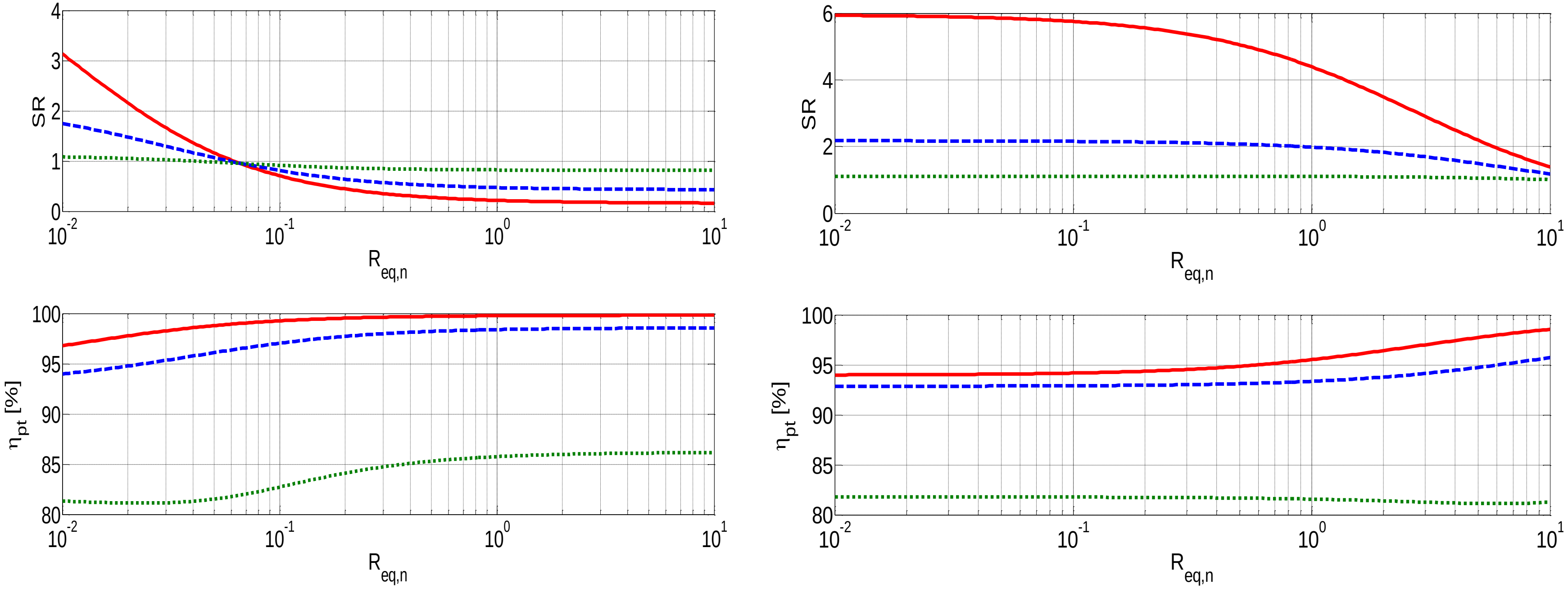
$$SR \triangleq \frac{|\bar{I}_{t,c}|}{|\bar{I}_{t,nc}|}$$

- Efficiency

$$\eta_{pt} = \frac{P_{p-u}}{P_s} = \frac{R_{ref}}{r_t + R_{ref}}$$

Performance Figures

CC_{SP} topology CC_{PS} topology

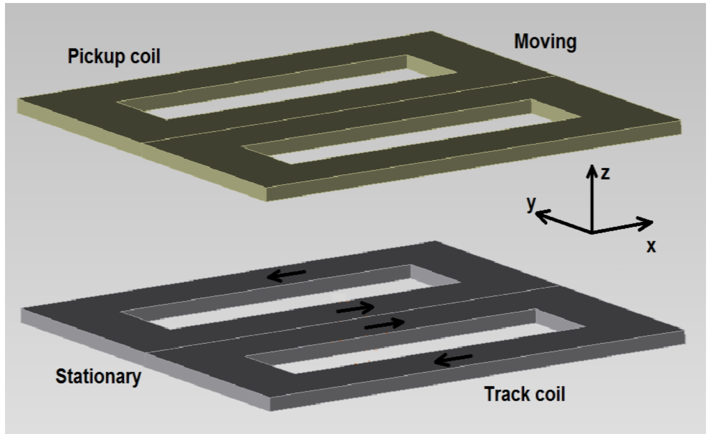


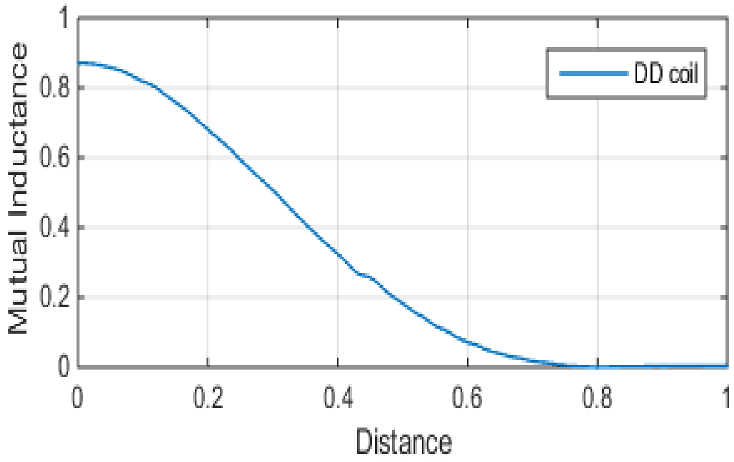
Curves are treced for normalized track coil resistance ($r_{t,n}$) 0.01 (red), 0.03 (blue) and 0.1 (green)

Parameters are normalized with respective coil reactance ($\omega L_{p\text{-}u}$ for pickup and ωL_t for track).

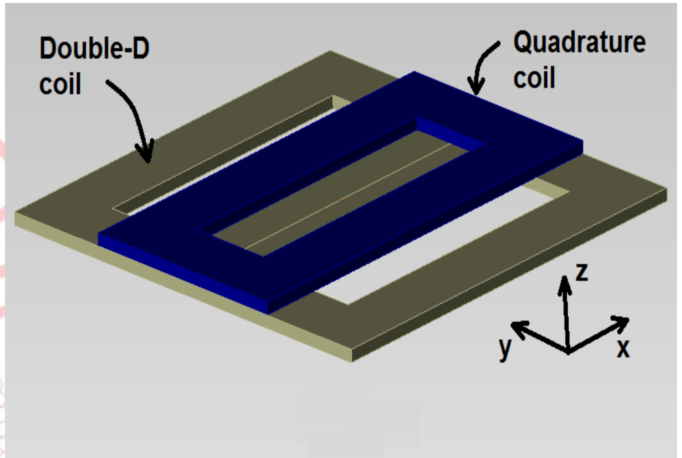
- Reflected resistance in CC_{PS} topology is much lower than CC_{SP}.
- Lower R_{ref} resistance reduces η_{pt} but makes high Segmentation Ratio (SR).
- Parasitic resistance significantly deteriorates the performance.

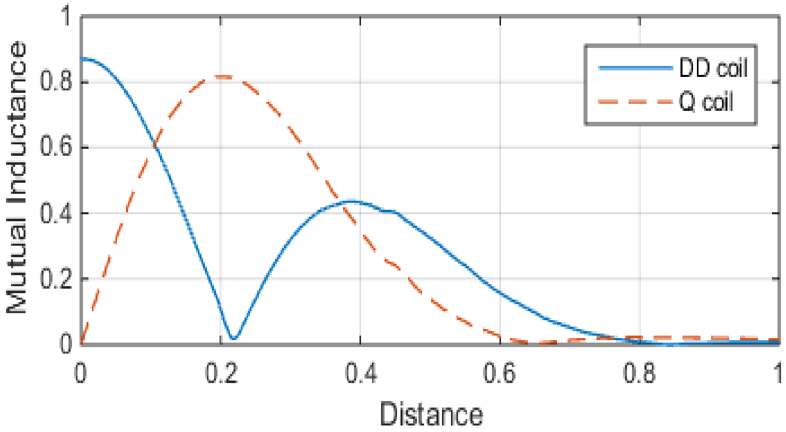
DD coil for Dynamic WBC



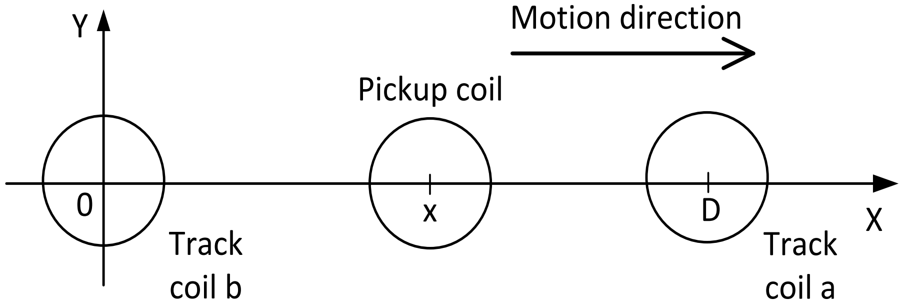


- Opposite poles are in same face of the coil.
- Behaviour of mutual inductance depends upon the direction of misalignment.
- Quadrature coil (Q-coil) can compensate the null power effect.
- JMAG data is plotted.

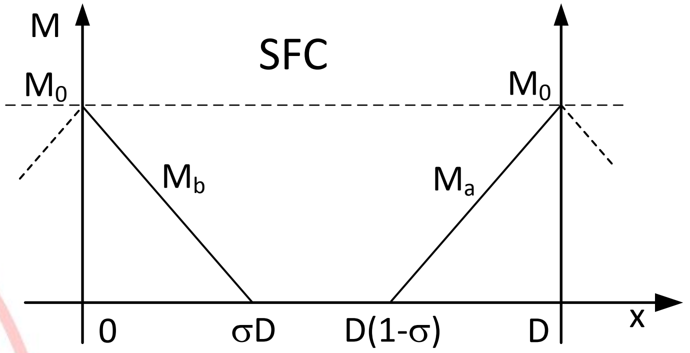




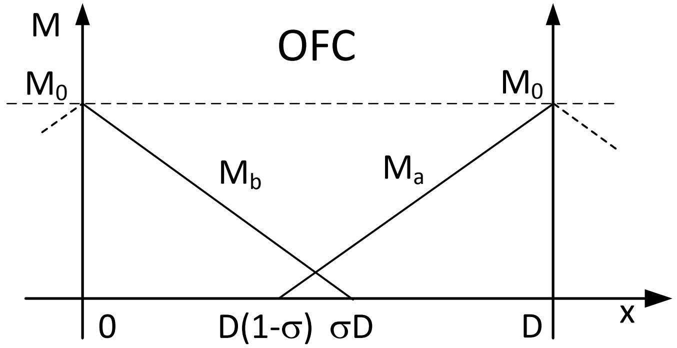
- Energy analysis while pickup is moving b/w two track coils.
- Induced voltage in pickup $V_I = \omega_s I_t [M_b(x) + M_a(x)]$
- Two analysis conditions
  - Separate flux coverage (SFC)
  - Overlapped flux coverage (OFC)



- σ is the coefficient to define SFC (σ <0.5) and OFC (σ >0.5) .



$$E_{SFC} = 2\sigma D \frac{KM_0^2}{3U}$$



$$E_{OFC} = 2\sigma D \frac{KM_0^2}{3U}\left(5 + \frac{3}{\sigma^2} - \frac{1}{2\sigma^3} - \frac{6}{\sigma}\right)$$

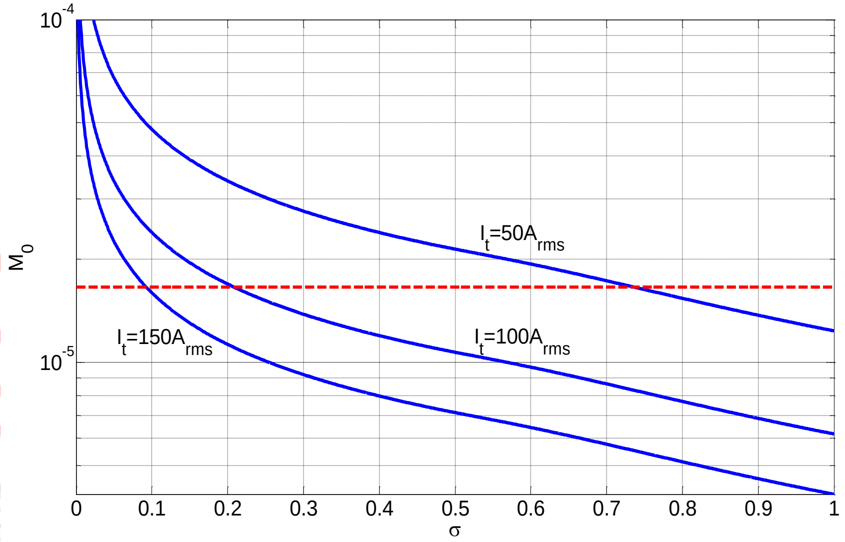
Track Layout Design

- Per km energy transfer (E_{km}) can be written as

$$E_{km\_SFC} = \frac{1000}{3U} \frac{\omega_s^2 I_t^2 M_0^2}{R_L} \sigma$$

$$E_{km\_OFC} = \frac{1000}{3U} \frac{\omega_s^2 I_t^2 M_0^2}{R_L} \sigma \left(5 + \frac{3}{\sigma^2} - \frac{1}{2\sigma^3} - \frac{6}{\sigma}\right)$$

- For a fixed E_{km}, relation among M_0, I_t and σ is plotted.
- This diagram gives a guidline to design a track layout.
- Considering 4 pairs of coils, track design is reported in the table.



Coil pair	M_0 (μH)	Current [A_{rms}]	σ	n [coil/km]
#1	16.6	50	0.736	294
		100	0.208	83
		150	0.093	37
#2	9.7	50	n.a.	n.a.
		100	0.595	397
		150	0.269	179
#3	6.3	50	n.a.	n.a.
		100	0.981	981
		150	0.623	623
#4	5.8	50	n.a.	n.a.
		100	n.a.	n.a.
		150	0.683	455

DWC System Case Study

- The power needed to run a car at constant speed U on a horizontal road is

$$P_{tract} = (F_d + F_{roll})U$$

- The power supplied by the battery or DC link can be written as

$$P_{DC} = \frac{P_{tract}}{\eta_{PT}} + P_{aux}$$

- Requisite energy per km can be written as

$$E_{tract} = \frac{1000\, P_{tract}}{U}$$

- Peak power transfer in WPT is

$$P_0 = \frac{\omega_s^2 I_t^2 M_0^2}{2R_L}$$

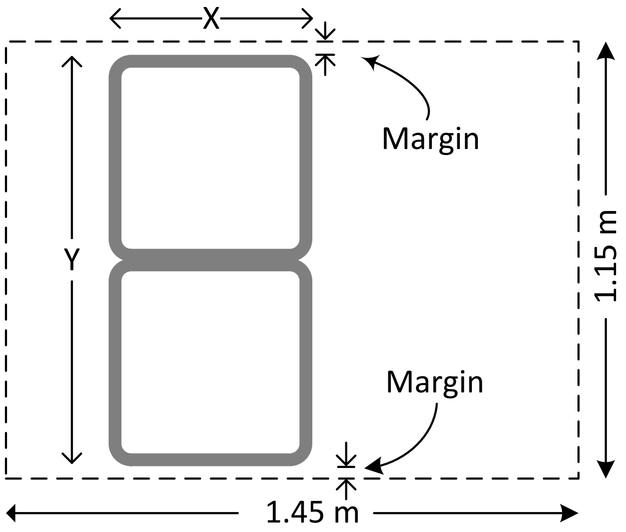
- An overall efficiency of 80% is assumed for the EV powertrain,

$$R_L = \frac{8}{\pi^2}\frac{V_B^2}{P_{avg}}$$

Case Study Vehicle

- Electric vehicle: ENEA Urbe.
- DD coil set is designed for DWC.
- System power rating is 5 kw.
- Requisite energy per km is 207 kJ.
- Under body space is available for pickup coil.

Quantity	Values
Mass	756 kg
Maximum speed	50 km/h
Air drag coefficient	0.28
Front area	2.1 m^2
Rolling friction coefficient	0.01
Ground Clearance	17 cm

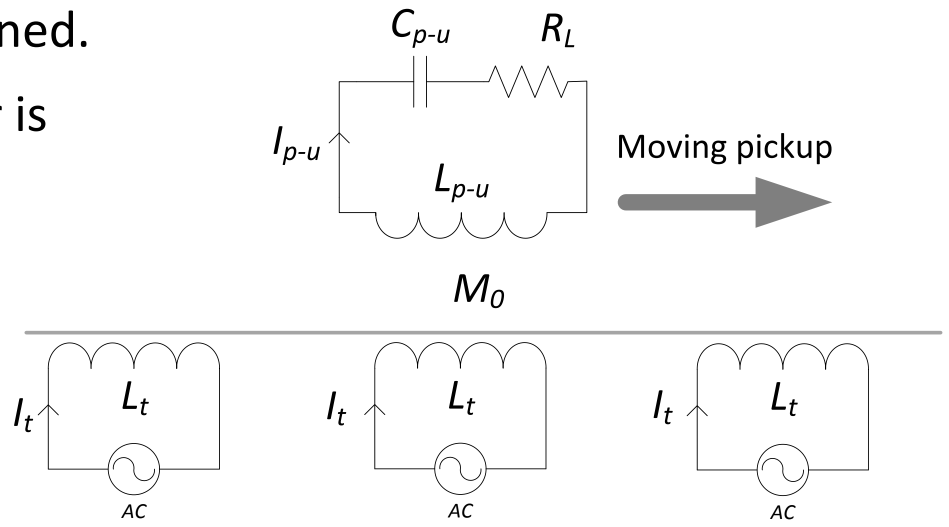


Coil Design

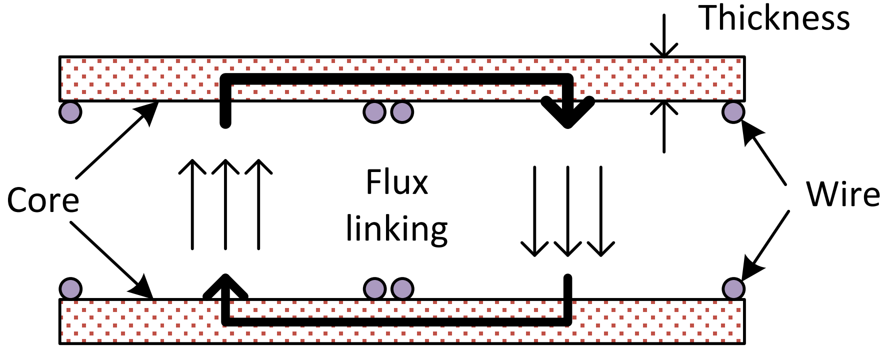
- Peak power is achieved when coils are perfectly aligned.
- Desired mutual inductance for requisite peak power is

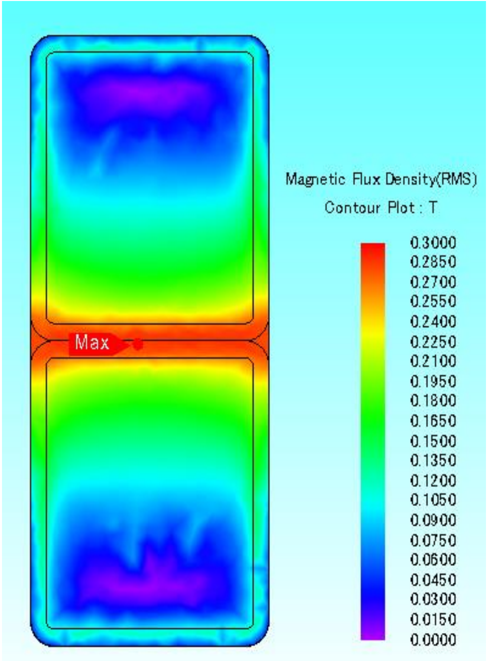
$$M_0 = 15\ \mu H$$

- Load equivalent resistance in pickup side is
- $R_L = \frac{8}{\pi^2}\frac{V_B^2}{P_{av}} \cong 0.65\Omega$
- Increasing coil turns, reduces coil area.
- For fixed M_0, various coils have been designed.

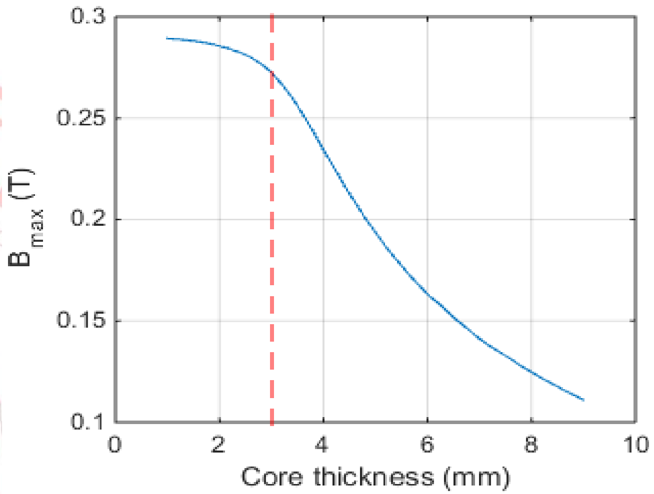


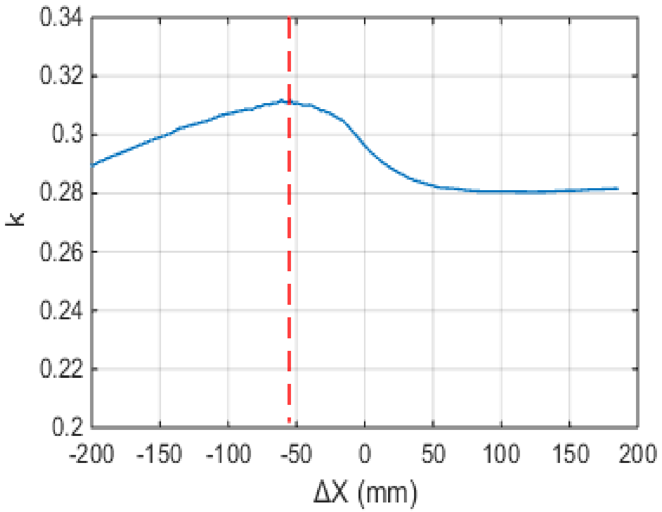
#turns	X (mm)	Y (mm)	L (µH)	M (µH)	k
1	1450	950	19,66	8,91	0,45
2	820	950	41.53	15.11	0.36
3	415	950	49.33	15.15	0.31
4	275	950	59.24	15.15	0.26
5	211	950	70.45	15.11	0.21



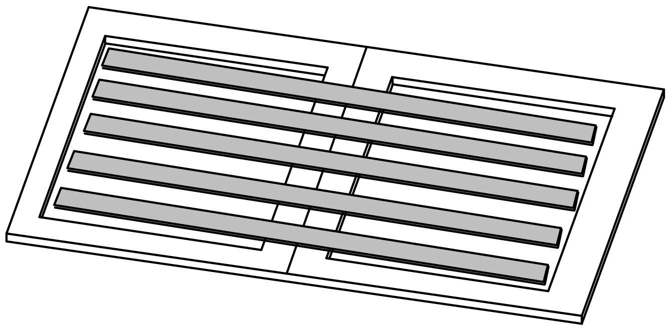


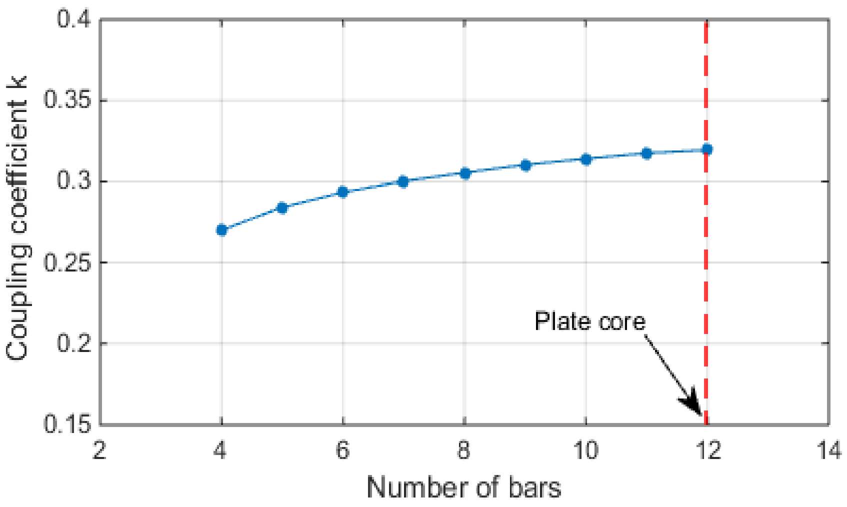
- Ferrite plates are used for flux path.
- Core thickness is designed by FEM results.
- Core plate area is optimized.

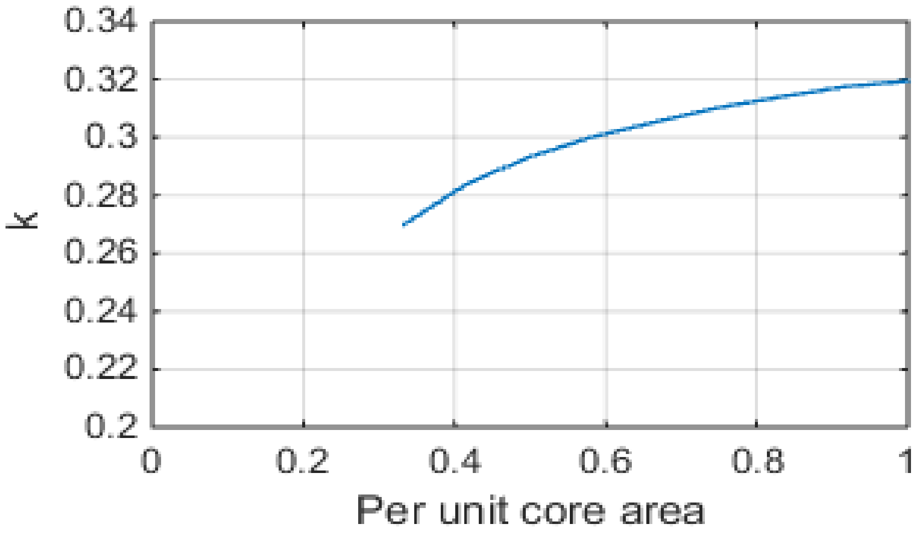




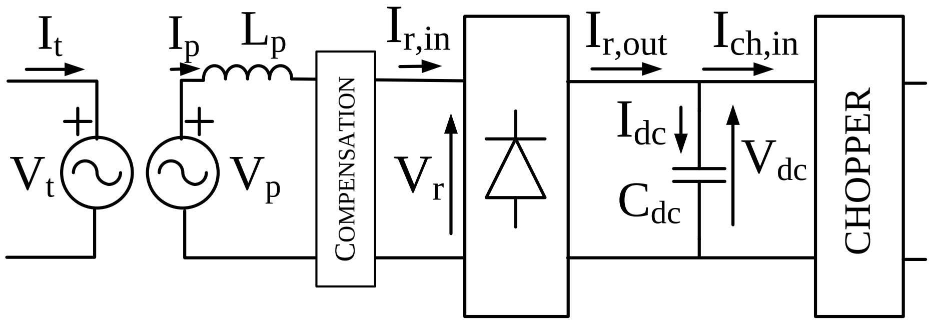
- The core plate is divided into 12 bars.
- One by one bars are removed with keeping equal spacing.
- Change in coupling coefficient is plotted.
- Material can be saved by paying reduction in coupling



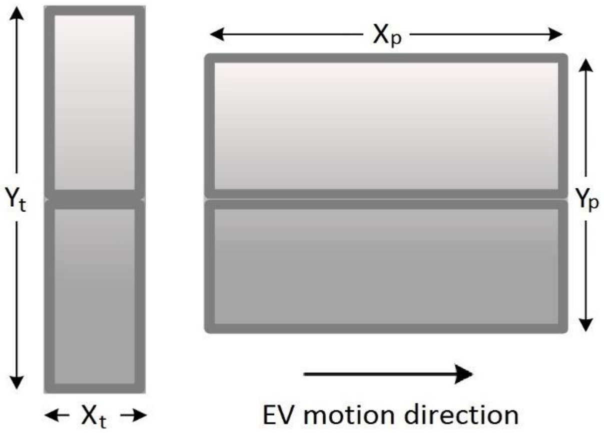




Concept of Unequal DD-coil (UDD)



- Triangular waveform with the DD coil set.
- V_m corresponds to minimum DC link voltage.
- Higher peak voltage makes larger charging span.



UDD Coil Set and Inductance

- M_0 increases by lengthening pickup.
- Unequal DD coil set shows flat-topped M-profile.
- Taking fixed track coil size, four pickup are analysed.
  - Track X-dimension= 0.40 m.
  - Track Y-dimension= 0.95 m.
- Pickup dimensions are chosen such that M_0 remains same for comparison.

Power and Energy Analysis of UDD Coil

- Separate flux coverage (SFC) and overlapped flux coverage (OFC) are defined based on σ_2.
- Wider charging span.

DD and UDD Comparison

- Coil length ration $\lambda = \frac{X_p}{X_t}$, where X_p=1.2 m fixed.
- λ>1 for UDD and λ=1 for DD coil set.
- Both DD and UDD coils have SFC, OFC_1 and OFC_2 arrangements.
- UDD coils allows higher V_m/V_0 and shorter track coils for all the three cases.
- Table shows that UDD coils reduce the cost of the track to less than half without impairing the performances of DWC system.

Conclusion of the Thesis

- Wireless charging of moving electric vehicles is discussed.
- WPT track and automatic track segmentation analysed.
- Power and energy analysis is explained to built a track layout.
- Special coil configuration is proposed and analysed.

Publications

- G. Buja, M. Bertoluzzo, and **H.K. Dashora**, “Lumped Track Layout Design for Dynamic Wireless Charging of Electric Vehicles,” IEEE Trans. on Industrial Electronics, Vol. 63, No. 10, pp. 6631-6640, Oct. 2016.
- **H.K. Dashora**, S. Giacomuzzi, M. Bertoluzzo, and G. Buja, “Performance Analysis of Reflexive Segmentation Topologies in DWC systems”, accepted for IEEE Industrial Electronics International Conference (IECON), 2016.
- **H.K. Dashora**, M. Bertoluzzo, G. Buja, “Reflexive properties for different pick-up circuit topologies in a distributed IPT track,” In proc. of IEEE International Conference on Industrial Informatics (INDIN), 2015, pp. 69-75.
- K.N. Mude, **H.K. Dashora**, M. Bertoluzzo, and G. Buja, “From wired to in-moving charging of the electric vehicles,” In Proc. of International Conference on Development, Energy, Environment and Economics, 2014, pp. 33-42.

Personal Training Plan

ATTIVITA' DIDATTICHE ATTIVATE DALLA SCUOLA							
Corso/Seminario (Periodo/Data)	**Docente**	**Durata (ore) del corso / seminario**	**Crediti ECTS acquisibili**	**Frequenza (SI/NO)**	**Accertamento (SI/NO e tipo)***	**Sessione di accertamento****	**Crediti ECTS acquisiti**
Fundamentals of measurements for engineering	Prof. Debei	10	2.4	Si	SI (Write-up)	Nov, 2014	2.4
Space Optics and detectors	Prof. Naletto	20	4.8	Si	SI (Exam)	Nov, 2015	4.8
Spaceflight mechanics and control	Prof. Lorenzini	10	2.4	Si	SI (Write-up+interview)	Nov, 2014	2.4
Measuring instruments for diagnostics and control	Prof. Rossi	10	2.4	Si	SI (Write-up)	Nov, 2014	2.4
Preparation of a research proposal	Prof. G. Naletto	10	2.4	Si	SI (Write-up proposal)	Nov, 2014	2.4
PC-based measurement system development	Prof. M. Lancini	20	4.8	Si	SI (Project)	June, 2015	4.8
Electric Road Vehicles	Prof. G. Buja	48	6.0	Si	SI (Exam)	Nov, 2015	6.0
Technological Advancement in Electro mobility	Prof. G. Buja	6	1.2	Si	Seminar & discussion	June, 2014	1.2
Design, realization & calibration of the Stereo Camera	Prof. Dadeppo	4	0.4	Si	Seminar & discussion	May, 2016	0.4
Danno da radiazione in dispositivi elettronici	Prof. D. Bisello	4	0.4	Si	Seminar & discussion	Mar, 2016	0.4
Recenti sviluppi nella navigazione satellitare	Prof. A. Caporali	4	0.4	Si	Seminar & discussion	Mar, 2016	0.4
Dispersed Multiphase flows: intro. & adv. aspects	Prof. F. Picano	4	0.4	Si	Seminar & discussion	June, 2016	0.4
Tidal evolution in the solar system	Prof. Christos	4	0.4	Si	Seminar & discussion	Oct, 2016	0.4

ALTRE ATTIVITA' DIDATTICHE							
Corso/Seminario (Periodo/Data)	**Docente**	**Durata (ore) del corso / seminario**	**Crediti ECTS acquisibili**	**Frequenza (SI/NO)**	**Accertamento (SI/NO e tipo)***	**Sessione di accertamento****	**Crediti ECTS Acquisiti**
Presentation research program and attendance	Prof. G. Naletto	2	0.5	Si	Si	May, 2014	0.5
Presentation of the activities done during 1st year	Prof. G. Naletto	2	0.5	Si	Si	Nov, 2014	0.5
Presentation of the activities done during 2nd year	Prof. G. Naletto	2	0.5	Si	Si	Nov, 2015	0.5
CISAS annual presentation	Prof. G. Naletto	2	0.5	Si	Si	Sept, 2016	0.5
Presentation of the activities done during Ph.D. course	Prof. G. Naletto	2	0.5	Si	Si	Oct, 2016	0.5
Attendance to Conference	Various	75	3	Si	Si	Oct, 2016	3
Totale crediti ECTS acquisibili in attività didattiche (>30):			33.9	**Totale crediti ECTS acquisiti in attività didattiche alla data 04/11/2016:**			**33.9**

Thanks!!