Wireless Grid Integration of EVs: Recent Technological Advances

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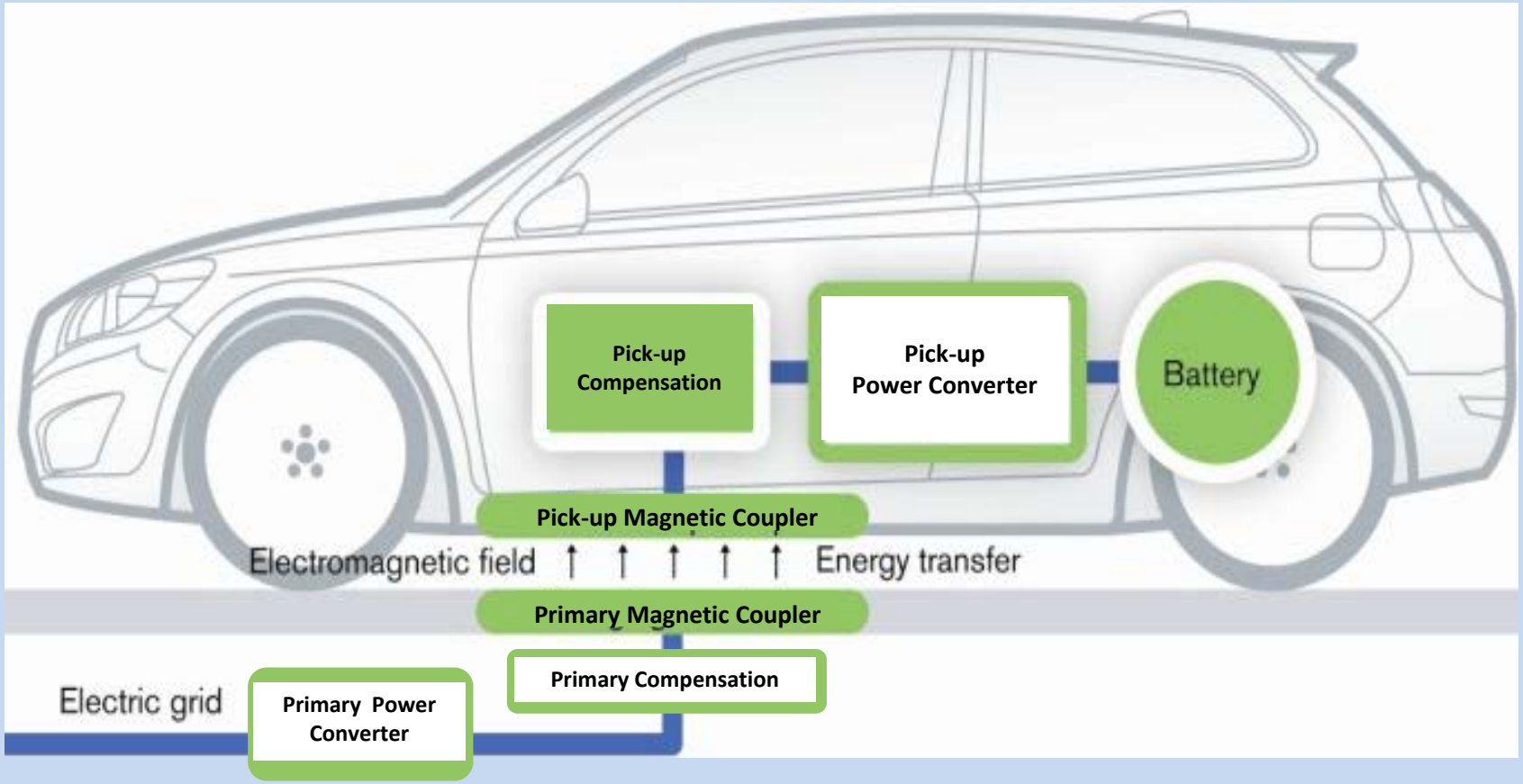
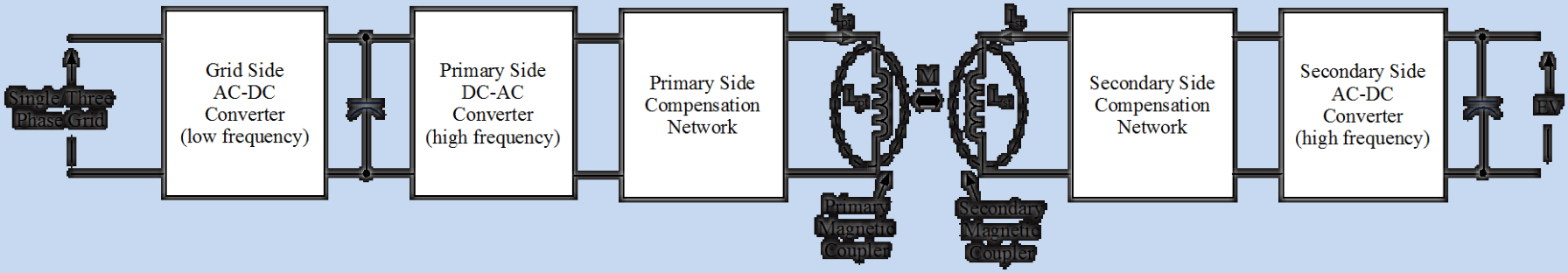
Background

Conventional IPT Solutions



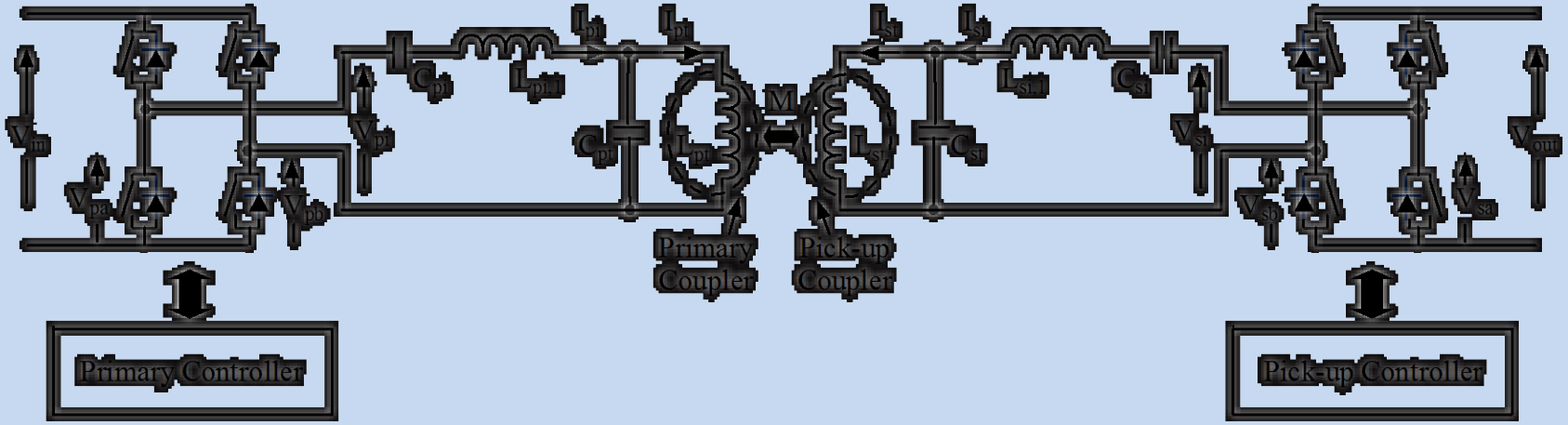
Conventional IPT Solutions



- Power transferred through a large air-gap between primary and secondary
  - Very weak magnetic coupling (less than 40% typically)
- Three stage conversion process
  - Grid to DC: PFC or soft-DC bus
  - DC to HF AC: Full-bridge, half-bridge or push-pull
  - HF AC to DC: Passive or AC controllers of buck or boost type
- Compensation networks improve power transfer
  - Reduce VA rating of the converters
- Uni-directional power flow
  - Allows for charging of EVs and limited ancillary services

Standard BD-IPT Systems

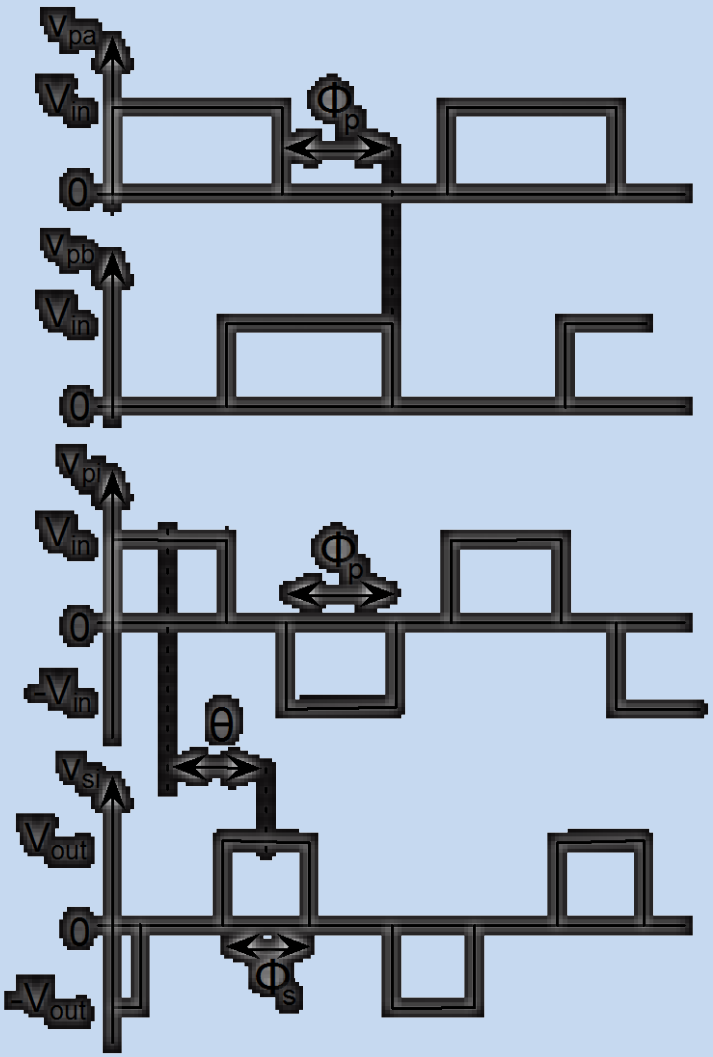
LCL-LCL BD-IPT System



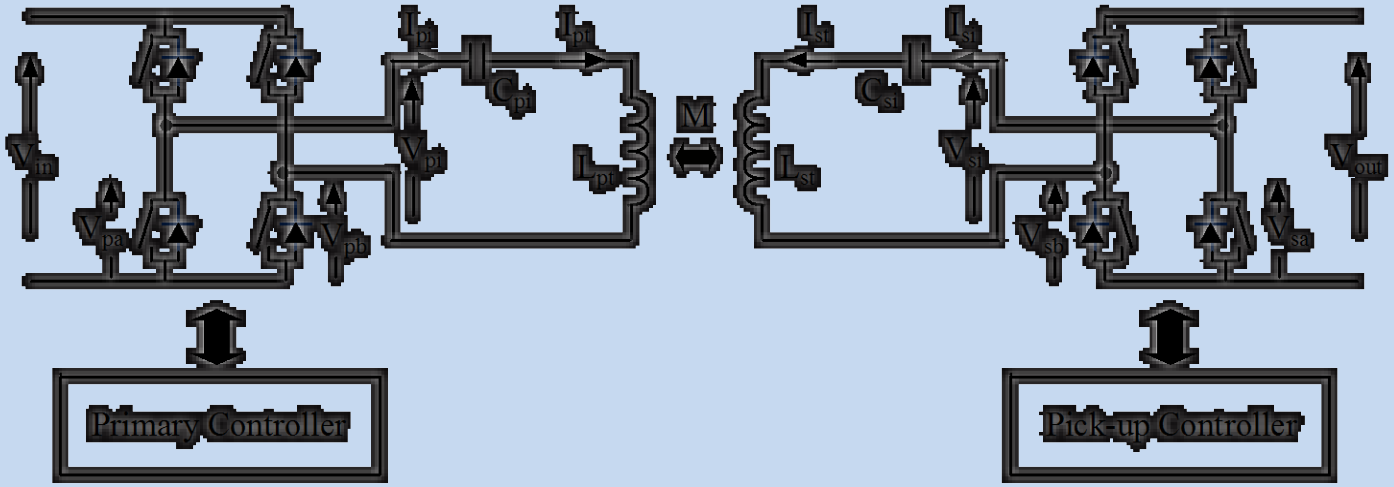
- Identical primary and pick-up circuits employing inductor-capacitor-inductor (LCL) T-resonant networks
  - Full-bridge converters operated as a frequency f_s to drive the resonant networks
  - LCL networks tuned to the fundamental switching frequency f_s
- Power flow
  - Phase-shift between converters
    - ✓ Regulates both the magnitude and direction of power flow
  - Phase-modulation applied to each converter
    - ✓ Regulates the magnitude of power flow
- Low-frequency inverter provides a bi-directional power interface with the grid

Control of Converters

- Output voltages, produced by converters, are controlled using phase-modulation
  - Each leg of the H-bridge operated at 50% duty-cycle
  - Both H-bridges are operated at same switching frequency, $f_s = \omega_s/2\pi$
  - Phase-modulation (Φ_p and Φ_s) between the two legs controls the output voltage
- Direction of Power flow is regulated by controlling phase-shift (θ) between the voltages produced by two converters
  - A lagging phase-shift corresponds to power transfer from input to output
  - A leading phase-shift corresponds to power transfer from output to input

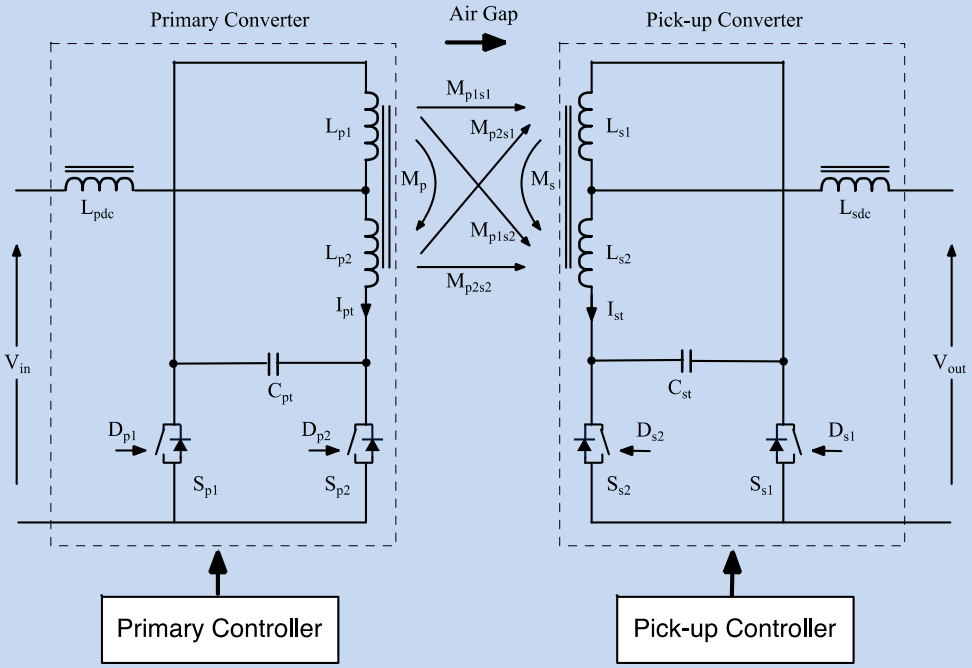


Series-Series BD-IPT Systems



- Identical primary and pick-up circuits employing series-tuned networks
  - Full-bridge converters operated at a frequency f_s to drive the resonant networks
  - Capacitors and pads inductances tuned to the fundamental switching frequency f_s
- Power flow
  - Phase-shift between converters
    - ✓ Regulates both the magnitude and direction of power flow
  - Phase-modulation applied to each converter
    - ✓ Regulates the magnitude of power flow
- A low-frequency inverter provides bi-directional power interface with the grid

PPRC based BD-IPT



- Identical primary and pick-up circuits each employing a PPRC
  - Switches operated below the natural resonant frequency to achieve ZVS
- Power flow
  - Phase-shift between converters
    - ✓ Regulates both the magnitude and direction of power flow
  - On-off control applied to each converter
    - ✓ Regulates the magnitude of power flow

A Comparison of BD-IPT

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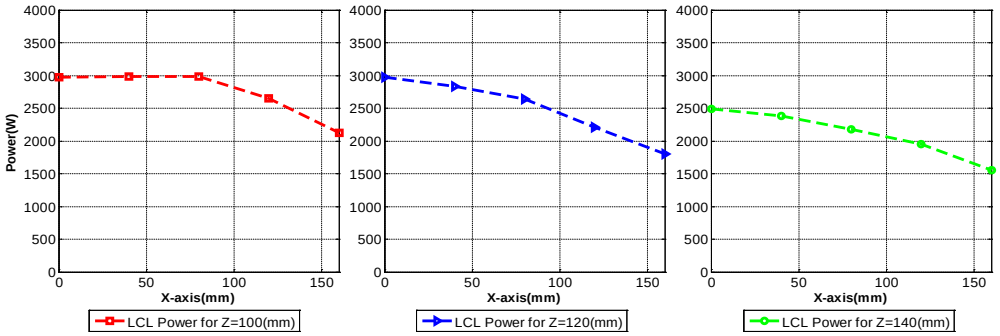
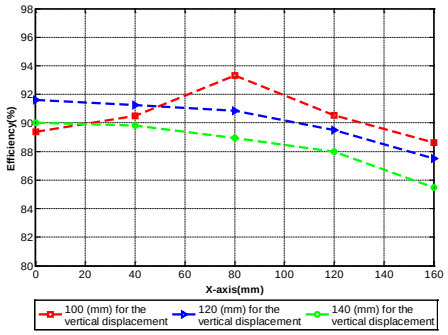
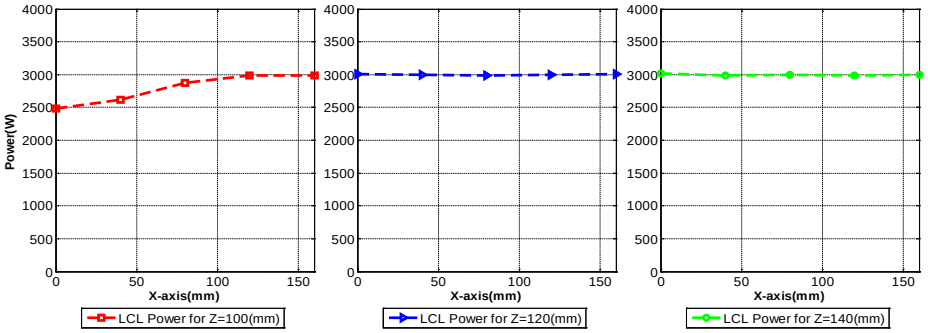
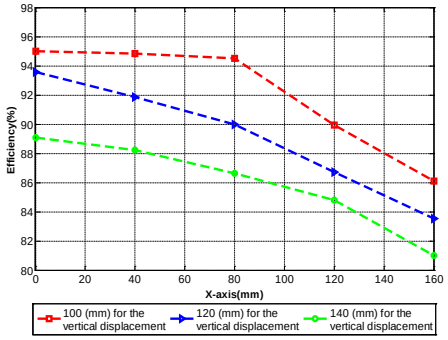
LCL-LCL BD-IPT



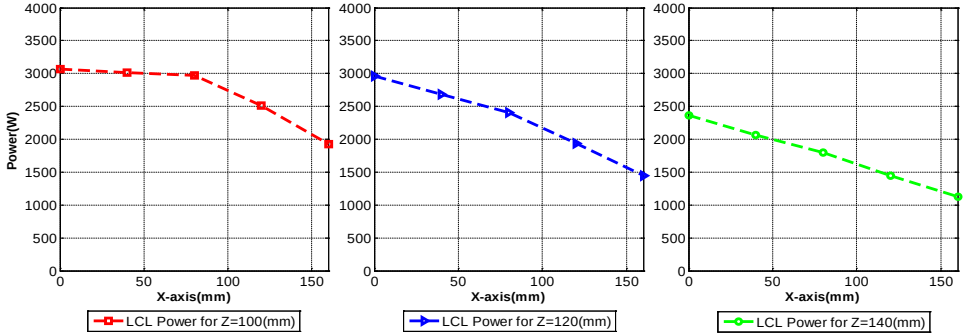


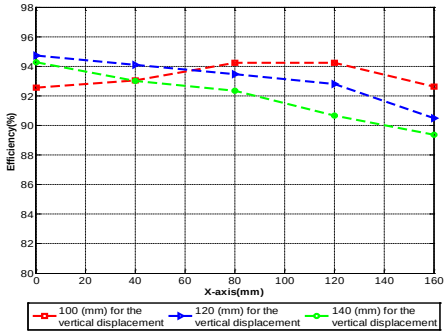
Series BD-IPT





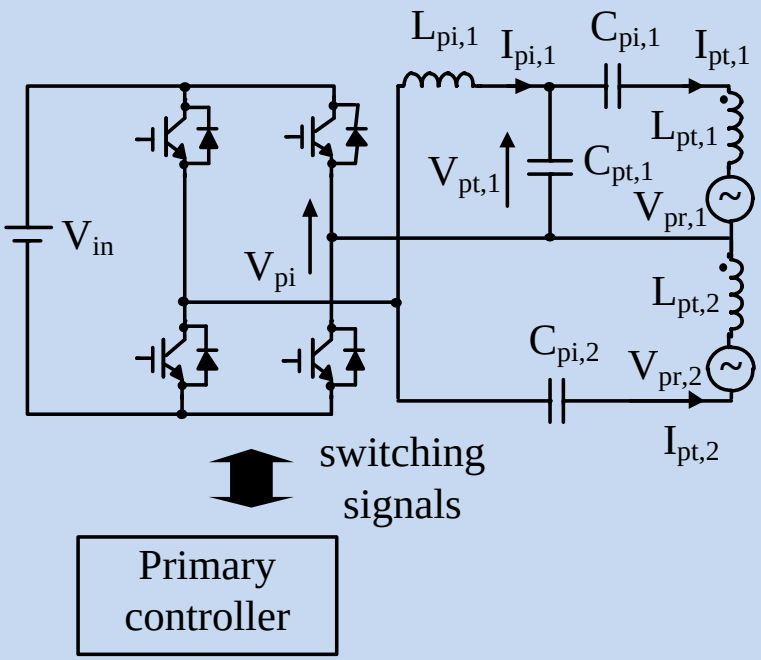
PPRC BD-IPT

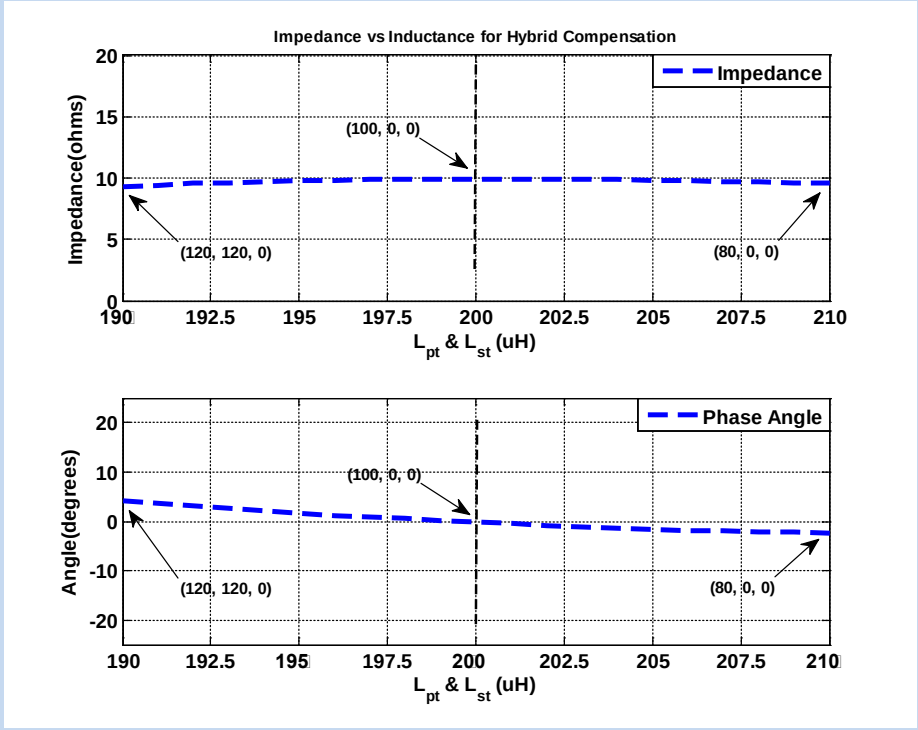




Spatial Tolerance

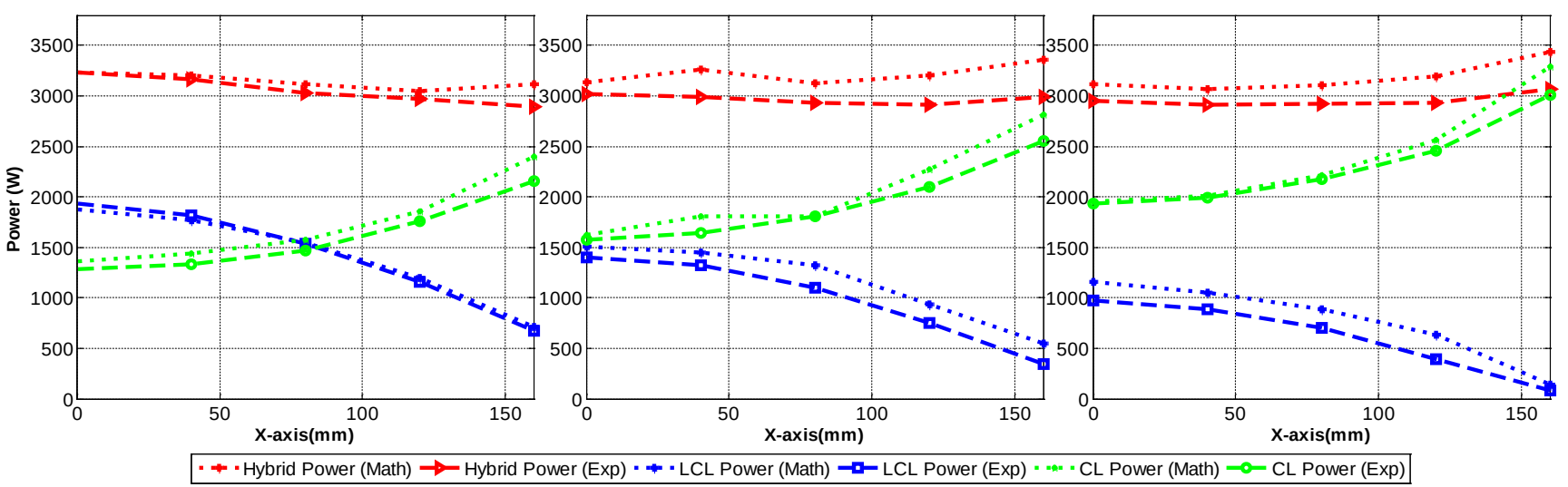
A Hybrid BD-IPT System



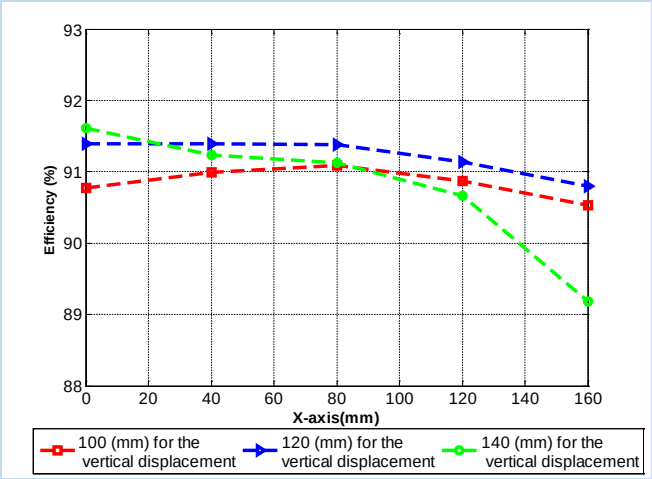


- Properties of LCL and CL tuning combined to achieve a system immune to misalignment
  - Maintains a near constant output power with near 0 VAR loading
- Simplify control and improves efficiency

Simulation results

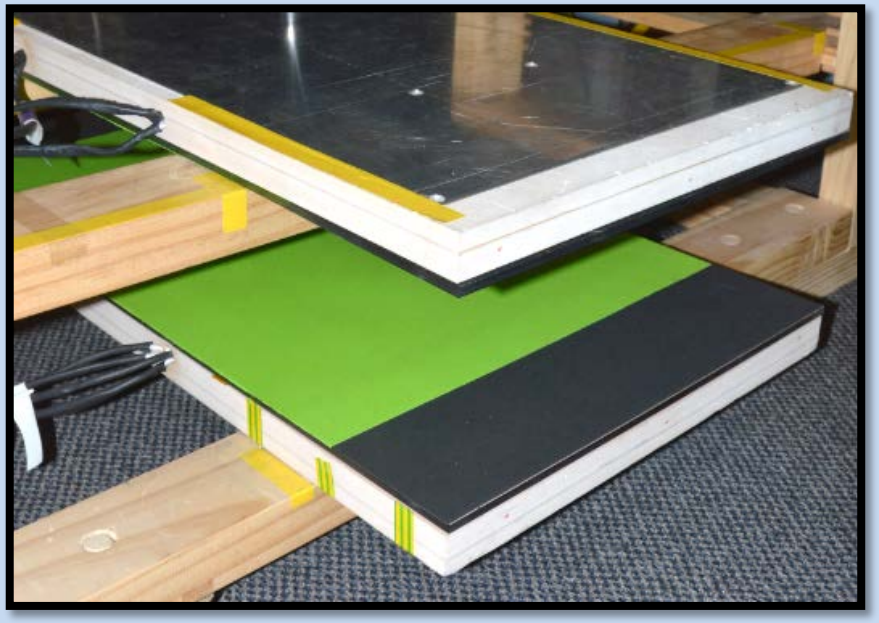


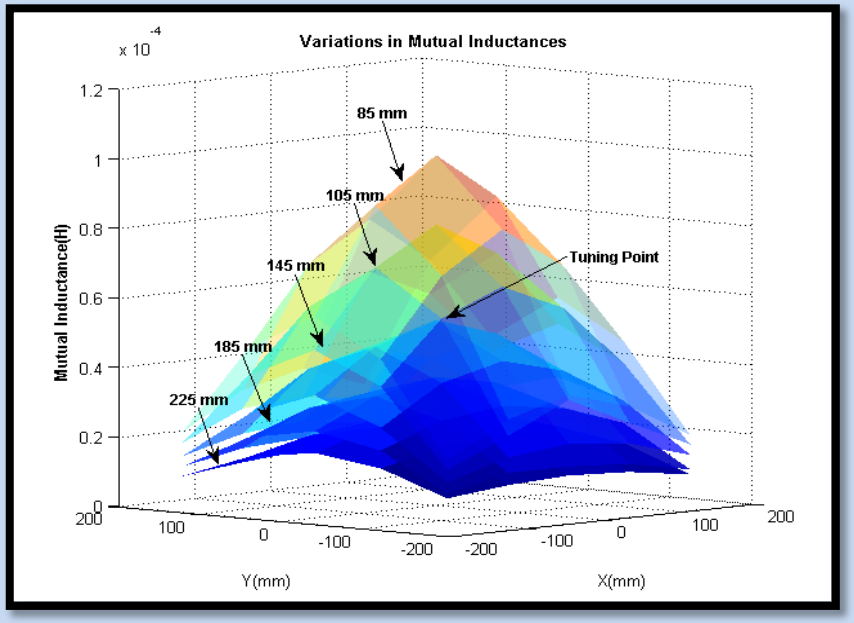
- Output power maintained with +/- 5% for 40 mm Z-displacement and 150 mm X-displacement
  - Open loop control at 100% modulation index
  - Power can be further regulated through modulating the switches
- High efficiency as the LCL-LC system facilitate ZVS over a wide range of displacements



Optimum Control

Optimization





- Self & mutual inductances vary over a 3-D space of misalignment
  - Detunes the system increasing losses and reducing power throughput
- Relative phase-angle, operating frequency, phase-modulation and dead-time can be varied to improve performance
  - Ex: System can be retuned by changing the relative phase-angle
  - Evaluation of optimum control parameters and close-loop control

Re-Tuning Through Theta

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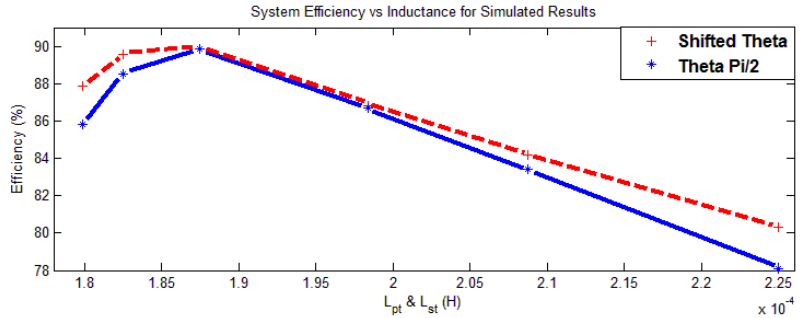
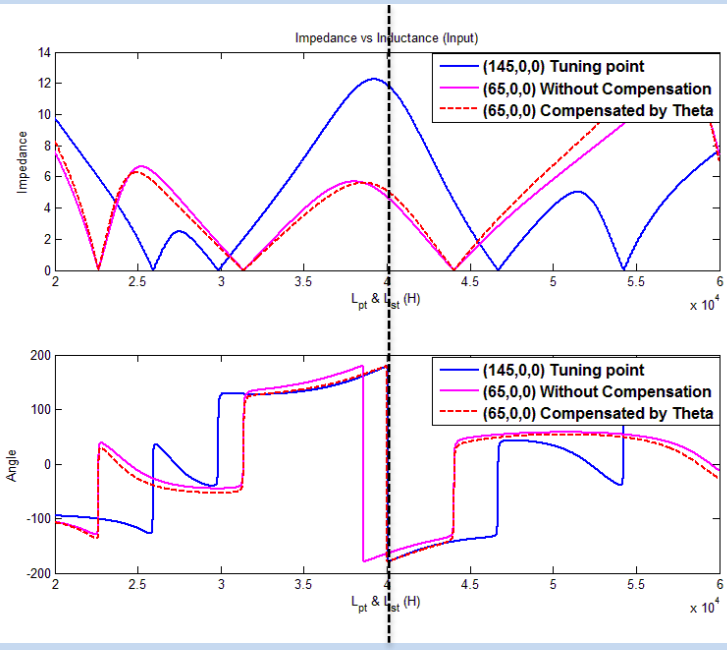
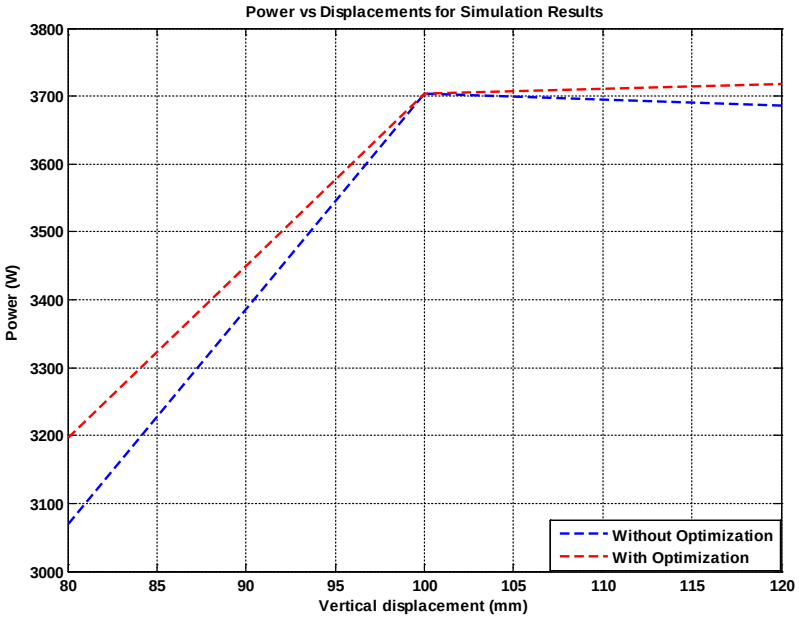


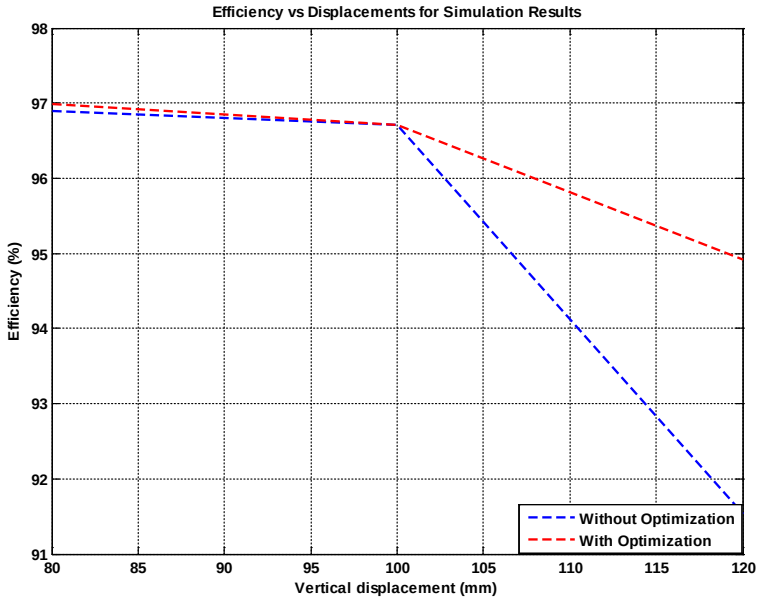
Theta between inverters regulated to negate the reflected VAR load due to misalignment



Facilitates ZVS over a wide range of X, Y and Z displacement

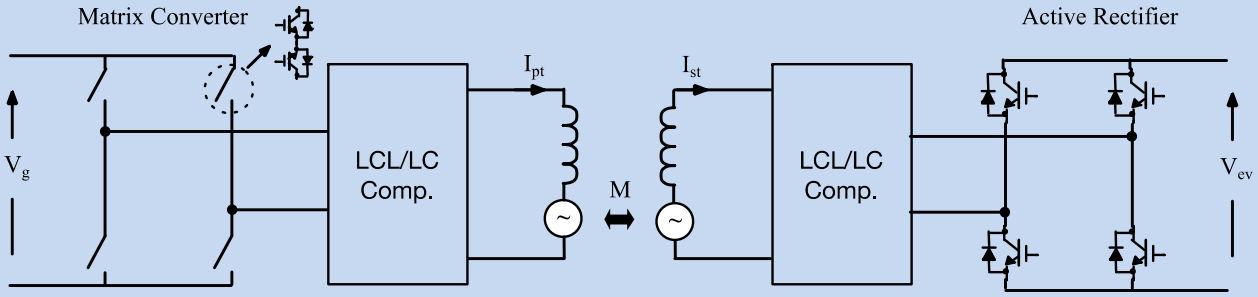
Frequency & Angle Control

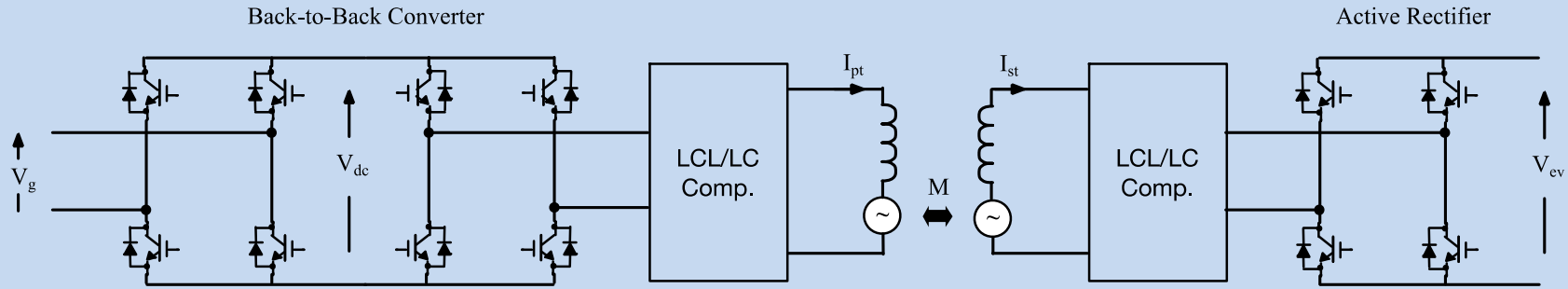




Ancillary Services

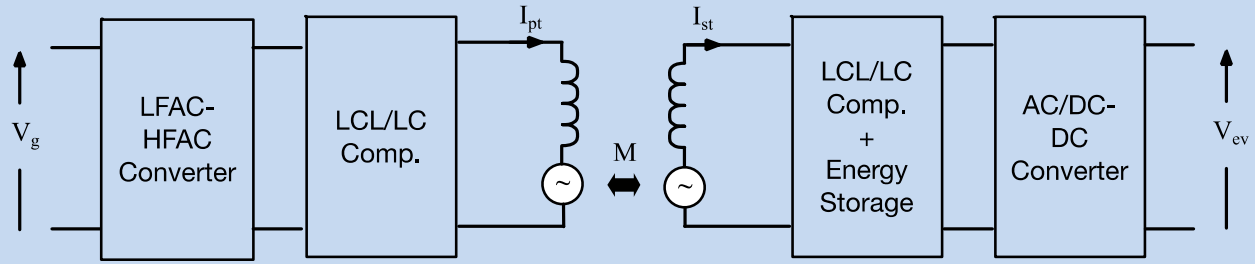
Direct LFAC to HFAC

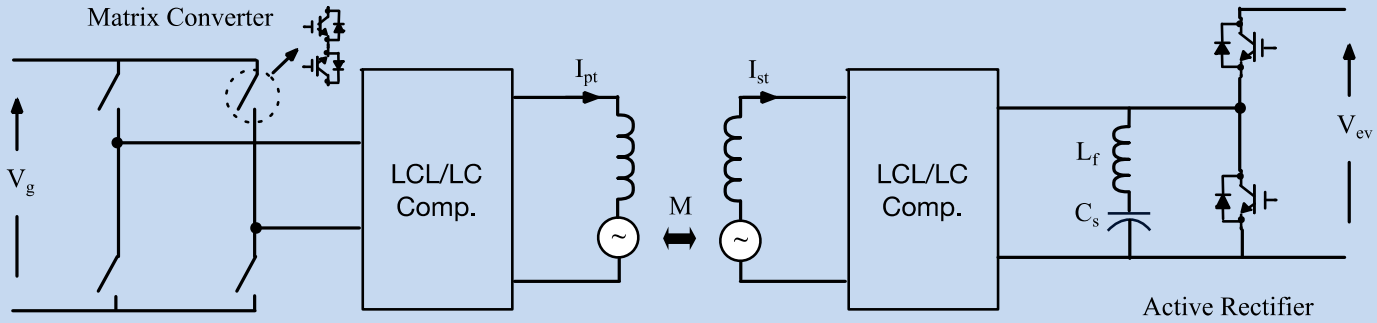




- Employs a matrix or back-back converter for direct grid integration
  - Does not require a large filter inductor or DC-link capacitors
  - Reduced number of conversion stages
- Complicated control strategies required to ensure reliable operation

VAR & Harmonic Control





- Energy storage integrated with the HF IPT system
  - Reduced number of stages and size of energy storage
    - ✓ Can be the super-capacitor of a hybrid-storage system
- Can provide ancillary grid services
  - PF correction and VARs through AC side storage