# New Challenges in Transportation Electrification, Powertrain Drives & New Power Electronics Architectures


## Osama A. Mohammed

Distinguished Professor
Director, Energy Systems Research Laboratory
College of Engineering and Computing
Florida International University
Miami, Florida USA


**3D-PEIM Keynote Presentation**
The 4th International Symposium on
3D Power Electronics Integration and Manufacturing
FIU-Graham Center
February 1st, 2023

# Overview

- **PHYSICS-BASED MODELING for Electric Machines and Drives**
- **Condition Monitoring and Diagnostics in Machines Drives for Transportation Electrification**
- **Wide Band Gap Devices and the Modeling of Power Electronic Converter Architectures for Transportation Electrification.**
- **EMI in PCB Designs and Circuit Optimization**
- **Component Signature Source Recognition**

# We Need Detailed Models Through Computational Electromagnetics Tools

***Physics-Based Modeling For Electric Machines And Drives***

# Operational Level

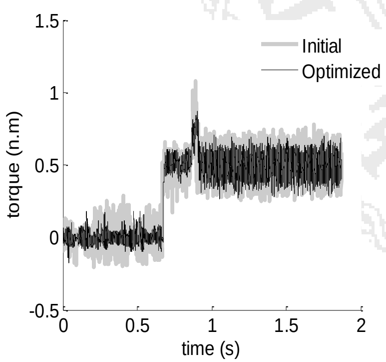
**Low Freq. Modeling**
**Control**
**Diagnosis**
**Prognostics**
**Design**
**Optimization**
**Monitoring**
**HIL optimization**

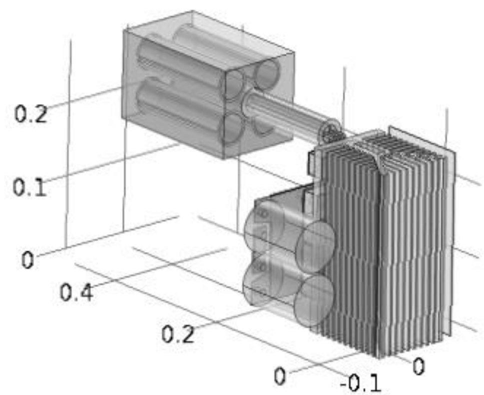
# Signature

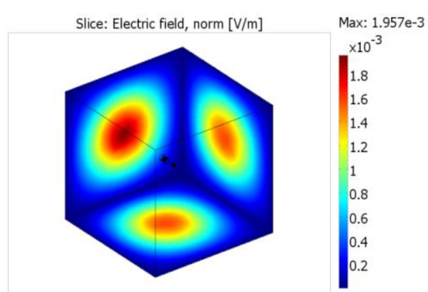
**Model verification**
**Heavy computation**
**Equivalent source modeling**
**Environmental design**
**Device arrangement**
**Monitoring**

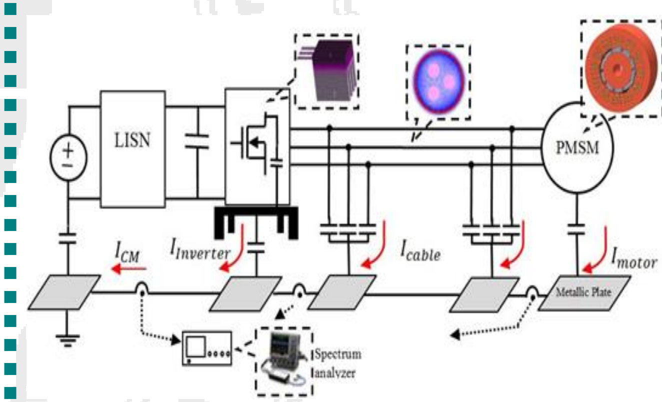
# Propagation level

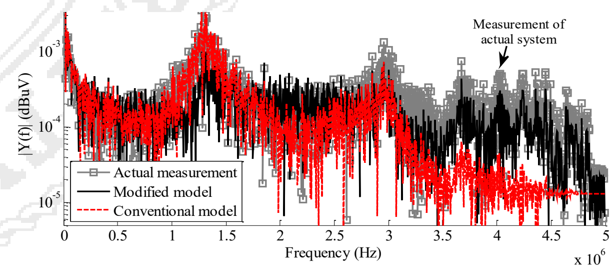
**Identification of Propagation path & Noise sources**
**High frequency phenomena**
**EMC mitigation**
**EMC Filter design**
**Active Filtering technique**
**Heat sink design**
**Switching Devices**

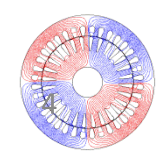


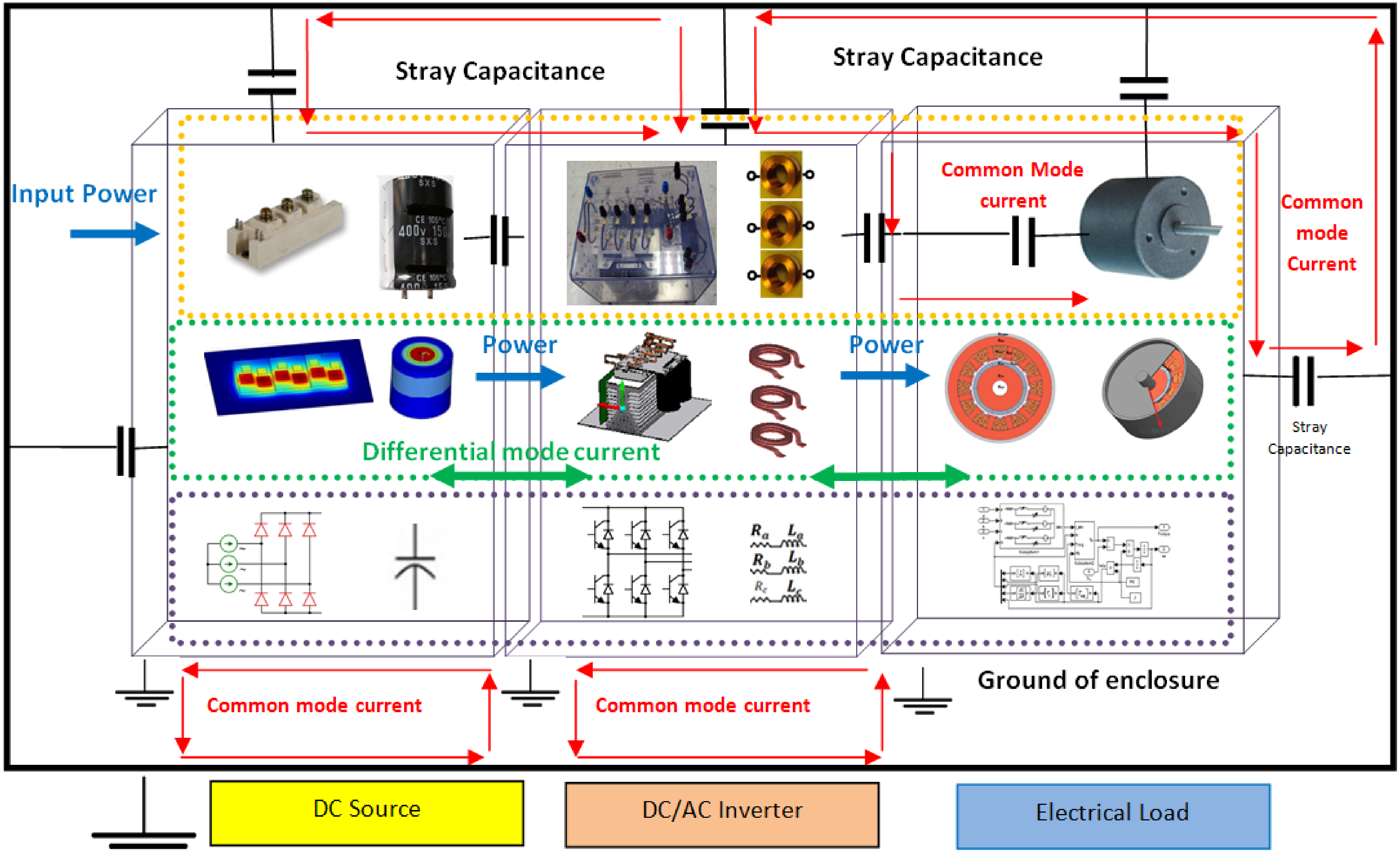



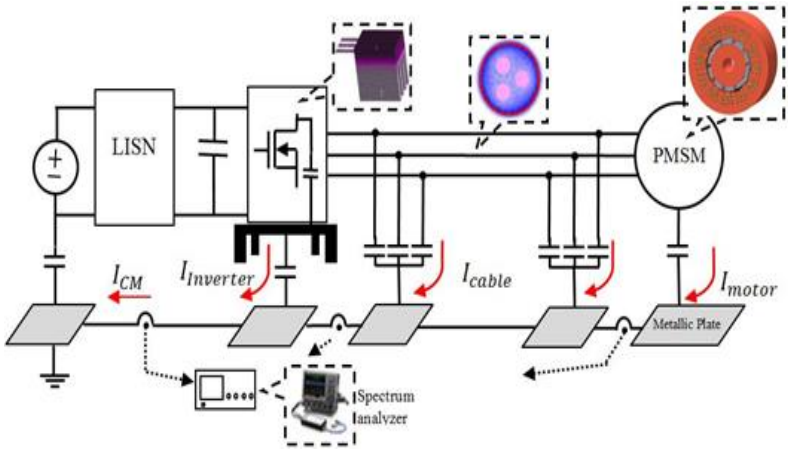



# From Device to Enclosure Levels:



# From Device to Enclosure Levels:

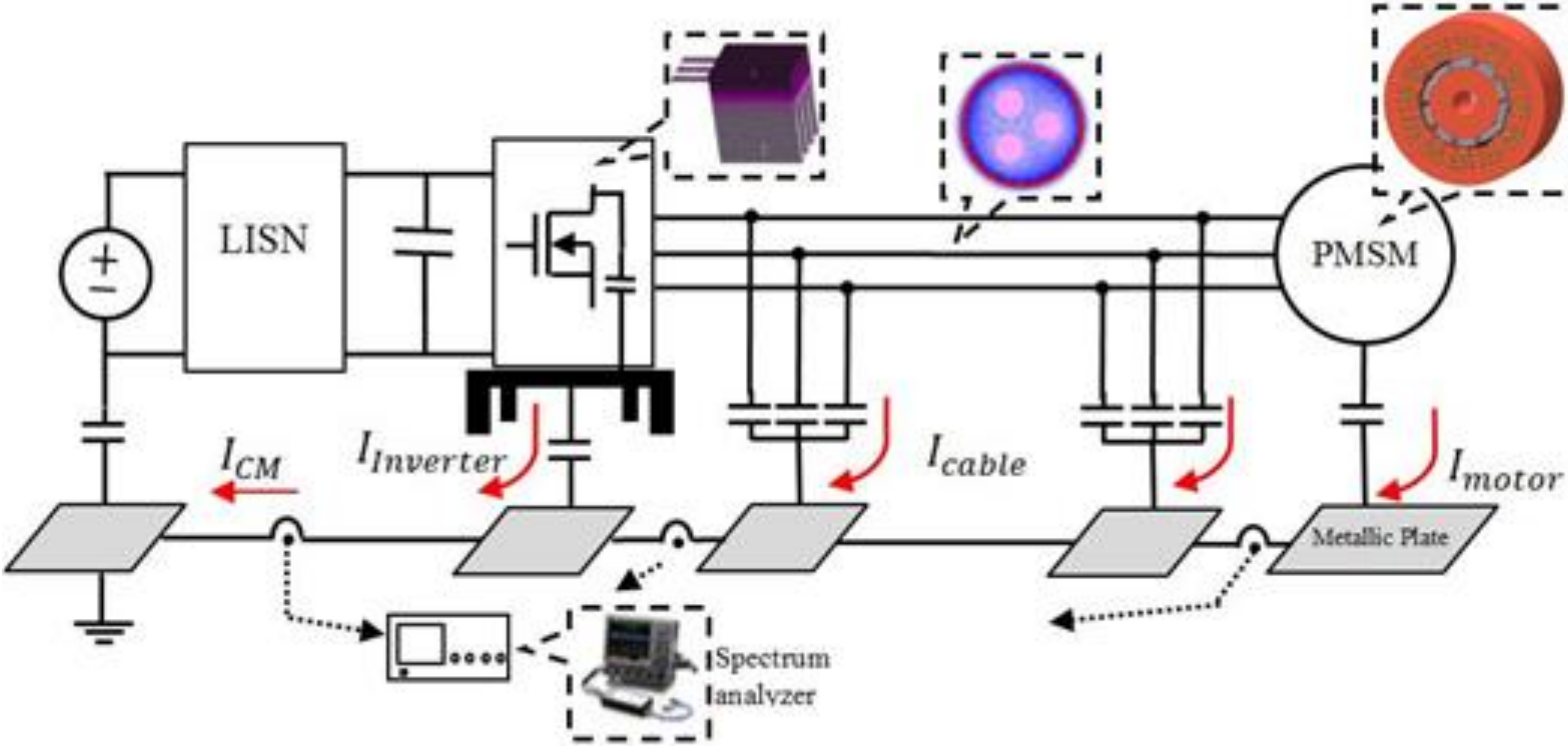
| Device level | Interface level | Encloser level |
|---|---|---|
| Electrical Machines | Cable harness between components | Outer enclose with air and each of the enclosures inside |
| Speed controllers | Capacitive current paths between enclosures and between each enclosure to the floating ground | |
| IGBT Modules | | |
| Inverter & Converter | | |
| Integrated circuits | Decoupling Capacitors | |
| Internal cables | | |
| Enclosures | | |
| Power Bus | | |
| AC and DC choke | | |
| EMI Filter | | |



# Application of physics-based modeling approach in development of machine drive systems

- **Physics-based machine-drive design optimization**
  - Full software based optimization
  - Hardware in the loop FE based design optimization
- **Physics-based sensorless position estimation**
  - High frequency signal injection
  - Physics-based EMF estimation
- **Physics-based design of Fault diagnostic and prognostic**
  - Signal-based
  - Model-based EMF/current /voltage estimation
- **Physics-based Reliability assessment**
  - Offline demagnetization assessment
  - Online demagnetization assessment

# High Frequency modeling of Machine-drives




1-Converter model including switches & passive elements

2-cable model

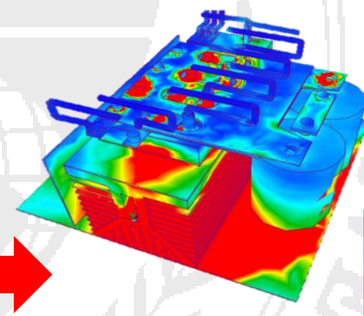
3-machine model

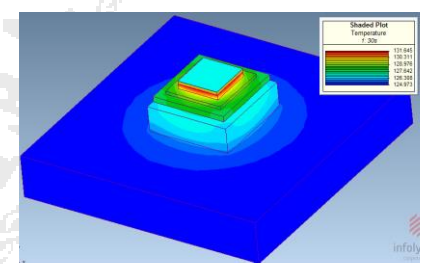
# Physics-based Modeling in WBG Devices

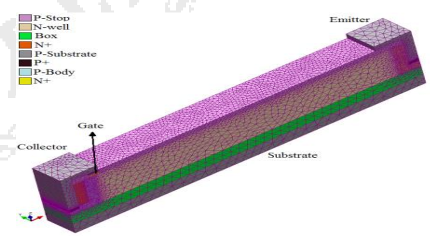
Physics-Based Modeling is a way to simulate the real behavior and characteristics of a system considering its material properties, structures, geometry, packaging, switching activities, etc.

It is based on being able to solve the partial differential equations (PDE) that models the real-dynamic behavior of physical systems

- **Multi-physics PDE can be used for modeling different characteristics:**
  - Electromagnetic
    - Electric Fields
    - Magnetic Field
  - Thermo-dynamics
    - Heat Transfer (Temperature)
  - Solid State dynamics
    - Carrier concentration







# Creating the Models

- Solve general heat transfer, magnetic and electric fields and the solid-state dynamics.

## Eqs1.: Magnetic and electric field PDE:

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \nabla \times B = \mu.\epsilon.\frac{\partial E}{\partial t} + \mu\left[J + \frac{\partial P}{\partial t} + \nabla \times M\right] \qquad \nabla.E = \frac{1}{\epsilon}(\rho + \nabla.P)$$

$$\nabla.B = 0 \qquad D = \epsilon E + P \qquad B = \mu(H + M) \qquad J = J_{ext.} + \frac{\partial P}{\partial t} \qquad \rho = \rho_{int} - \nabla.P$$

## Eq.s2: General Heat Transfer PDE and ODE:

$$c.\frac{dT}{dt} + \nabla.(K_c.\nabla T) = P_{loss} \qquad \frac{dP_{loss}}{dt} = \mathrm{h.A.(T - T_{ambient})}$$

## Eqs.3: Solid State Dynamic PDE:

$$-\nabla.(\varepsilon\nabla\psi) = q(p - n + N)$$
$$-\nabla.J_n = qR_{SRH}$$
$$-\nabla.J_p = qR_{SRH}$$

$$J_n = qn\mu_n\nabla\psi + qD_n\nabla n$$
$$J_p = qp\mu_p\nabla\psi + qD_p\nabla p$$

$$R_{SRH} = \frac{np - {n_i}^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

# The Multiphysics Approach Involving Solid State and GaN Based Devices

Solving magnetic and electric fields  after computing the Solid-State Dynamics.

Constitutive Relationships

Coupling

**Magnetic and electric field PDE in COMSOL FEA Eqs 1.**

**Solid State Dynamic PDE in COMSOL FEA Eqs 3**

Information about Materials and Geometry

- FDI of GaN devices
- FDI of Power Converters
- Fault Tolerant Applications.

$$-\nabla.(\varepsilon\nabla\psi) = q(p - n + N)$$

Poisson Relationship

- Silvaco Software FEA
- Research Group
- Laboratory Research
- Company

**Final Goal**

**Initial Point**

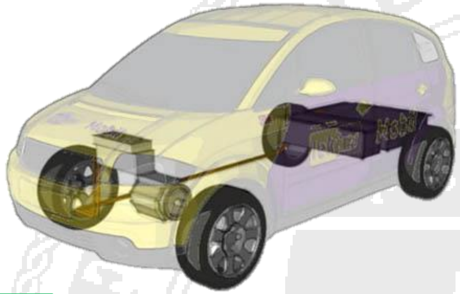
# Physics-Based Optimization of EMI Performance in Machines & Power Converters:

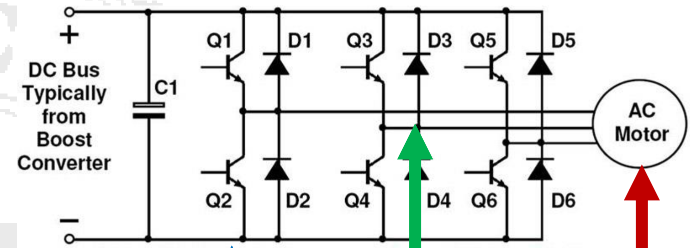
- The IEC defines electromagnetic compatibility as "the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment".

- Types of disturbances:
  - ✓ Low Frequency, f < 9 kHz
  - ✓ High Frequency, f > 9 kHz
- Principal electromagnetic conducted phenomena:

| ✓ Conducted low-frequency phenomena: | ✓ Conducted high-frequency phenomena: |
| --- | --- |
| ❖ Harmonics, inter-harmonics | ❖ Induced voltage or current |
| ❖ Signals superimposed on power lines | ❖ Unidirectional transients |
| ❖ Voltage fluctuations | ❖ Oscillatory transients |
| ❖ Voltage dips and interruptions | |
| ❖ Voltage unbalance | |
| ❖ Power frequency variations | |
| ❖ Induced low-frequency voltages | |
| ❖ DC components in AC networks | |

# Physics-Based Model of Motor Drive system



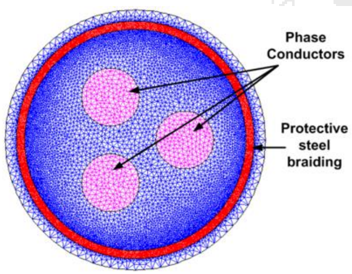


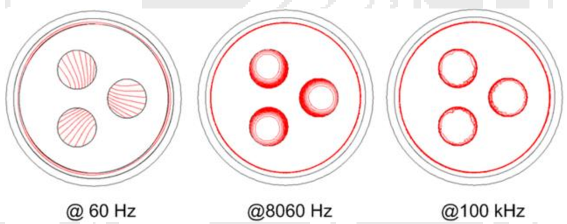

Inverter

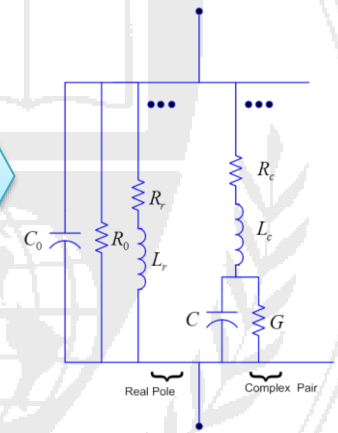
Cable

Motor

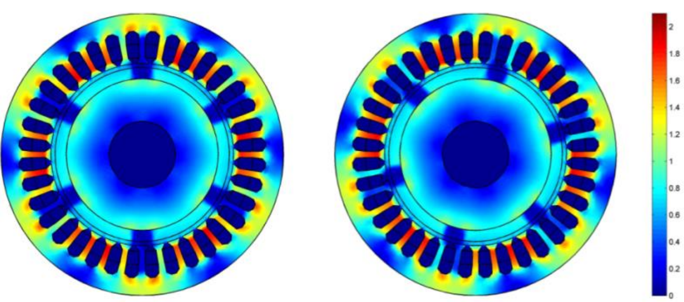
Cable Model

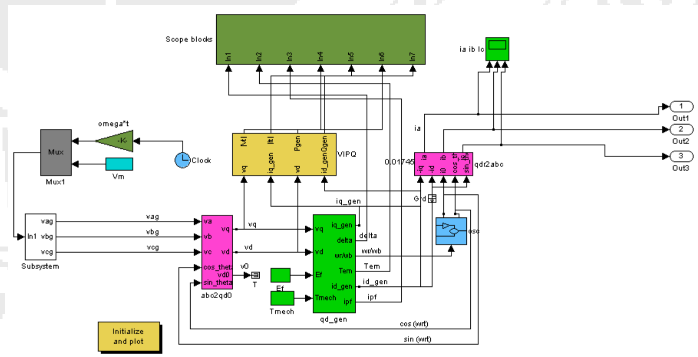


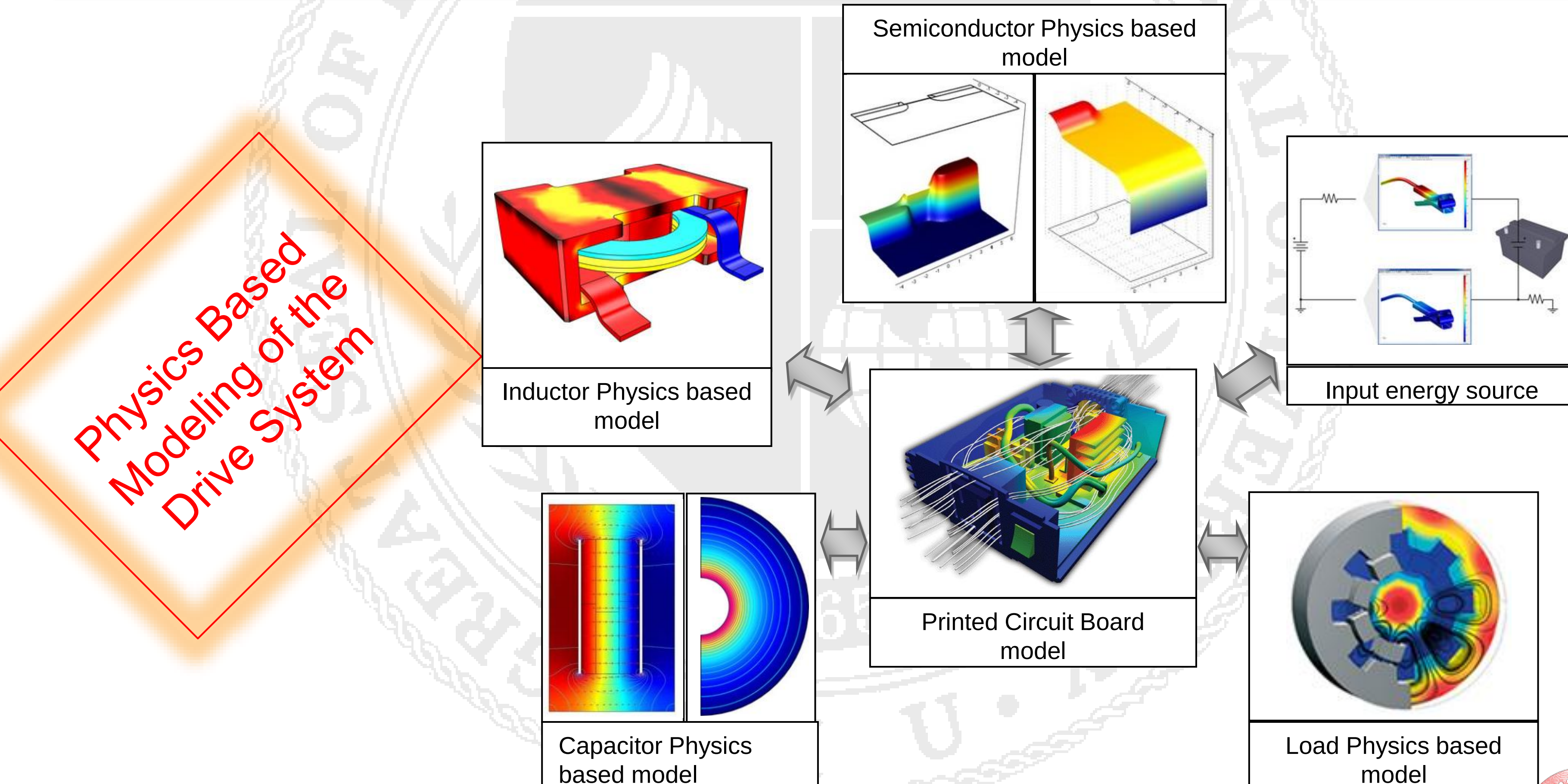

Machine Model



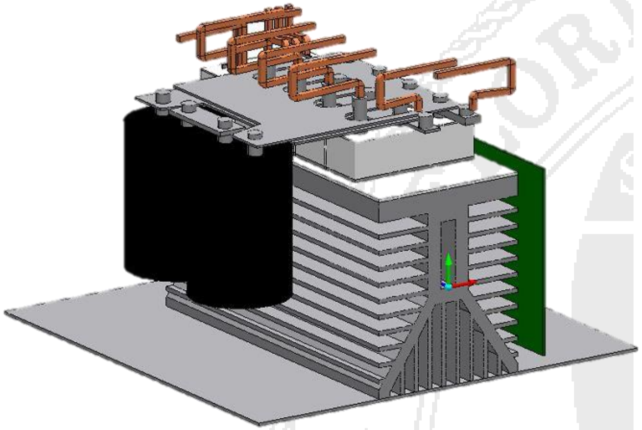


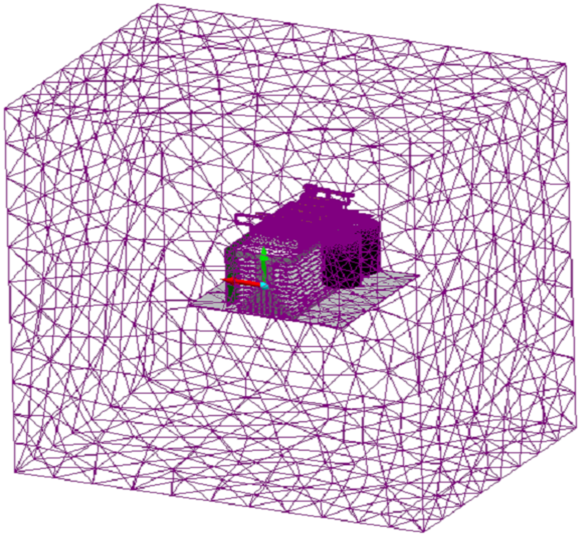

Inverter Model

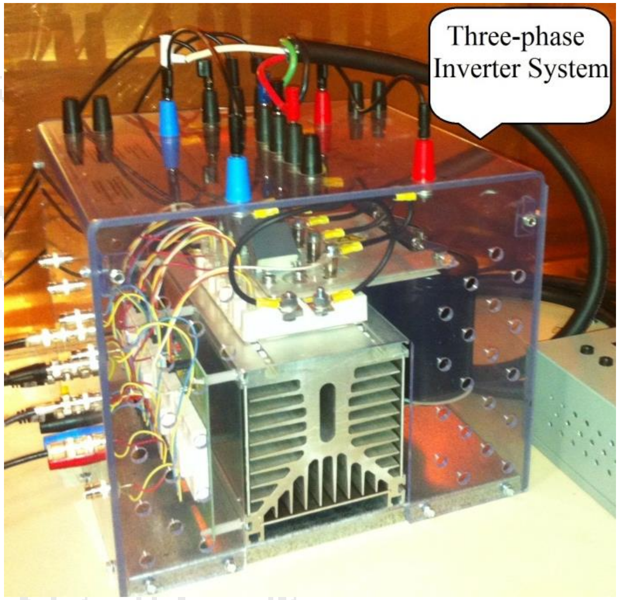
- To design the whole converter with respect to physical and operational constraints.
- The system components are modeled numerically and then combined to achieve a model for the converter.

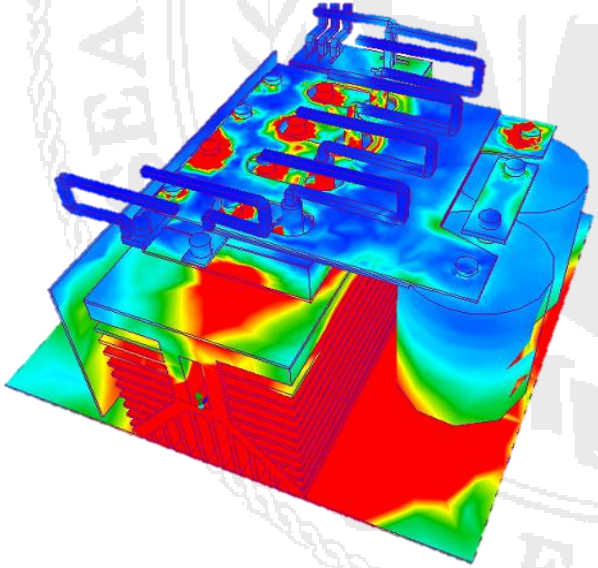


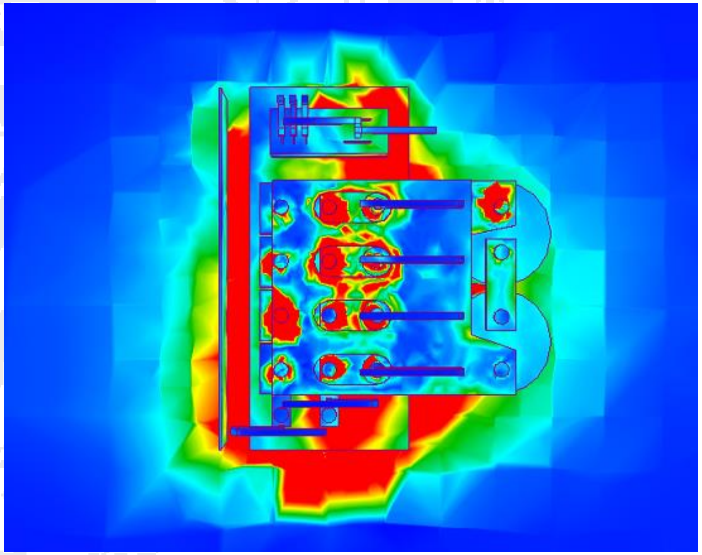
# Whole Inverter Model in Finite element:







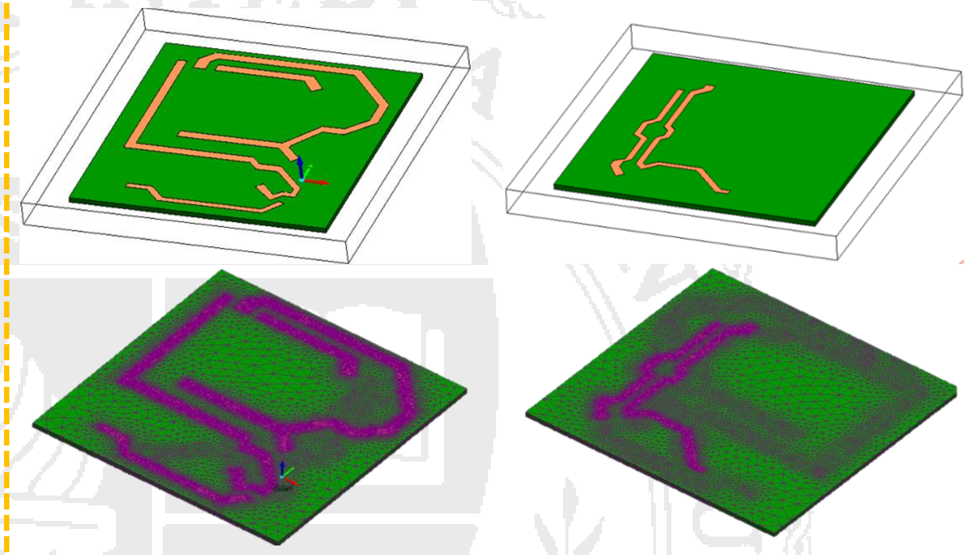


# Inverter Physics-Based Modeling:

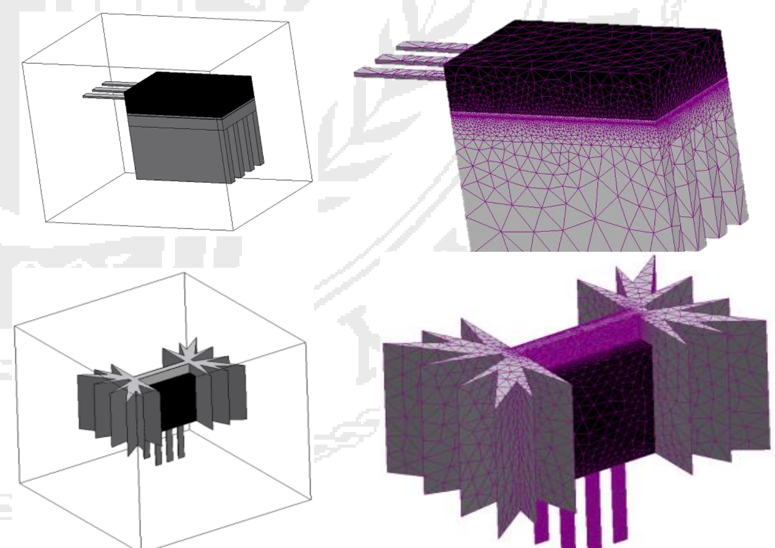
Inverter

- 1-PCB
- 2-Heat Sink
- 3-Semiconductor Switches

## 1-PCB Model



## 2- Heat Sink Model

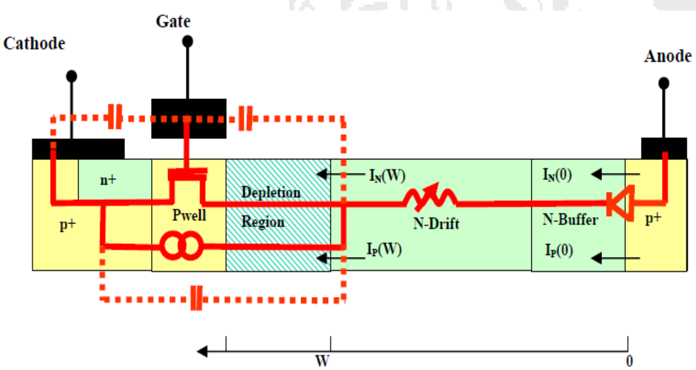


# Semiconductor devices Modeling: IGBT Example

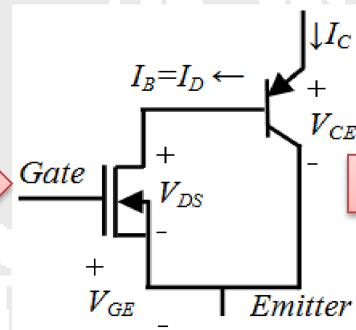
## IGBT PHYSICS-BASED MODELING for high frequency modeling of machine drive

Analytical model of the IGBT based on semiconductor physics using Hefner's Algorithm + High-frequency parasitic elements calculation using FE → IGBT physics based model

- Physics-based analytical model of the IGBT based on Hefner's Algorithm:

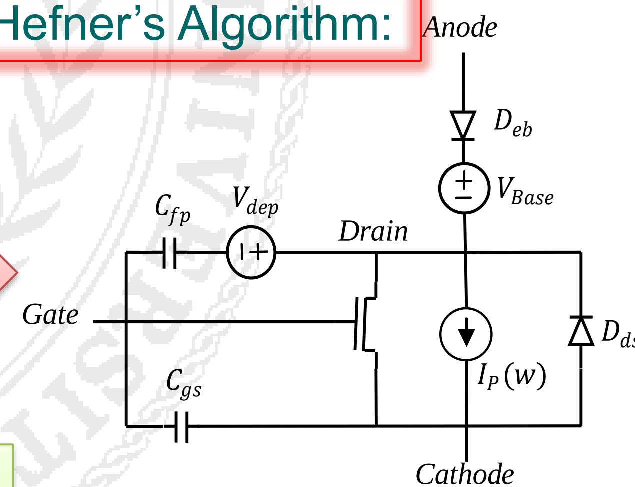



Schematic of the LIGBT structure




Darlington representation of IGBT

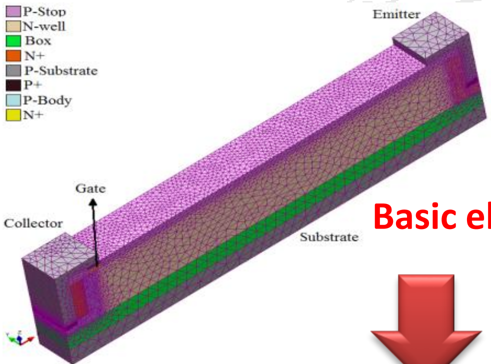
Darlington connection of a BJT and a MOSFET



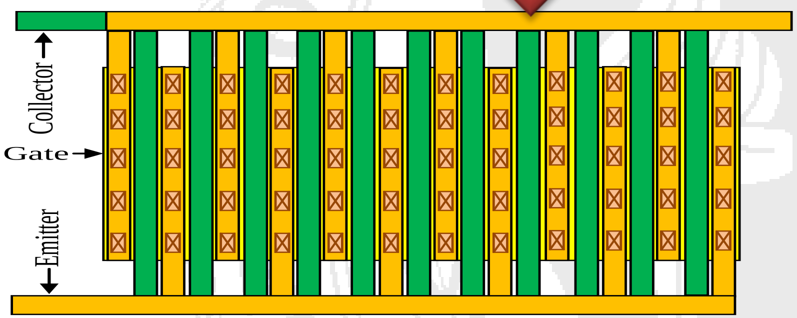

Hefner's IGBT model

# Construction of IGBT fast and accurate model using FE

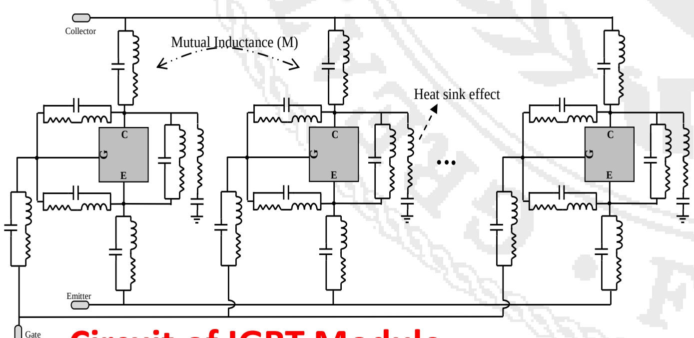
**The IGBT cell within the presented IGBT module, has the width of 36 μm, therefore, in a device with the width of 560x4 μm, it is considered that 62 of these unit cells are in parallel**




Basic element

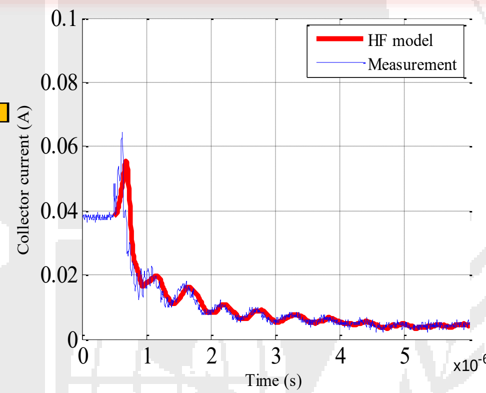


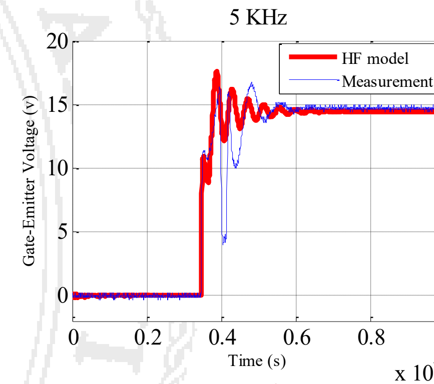

IGBT Module

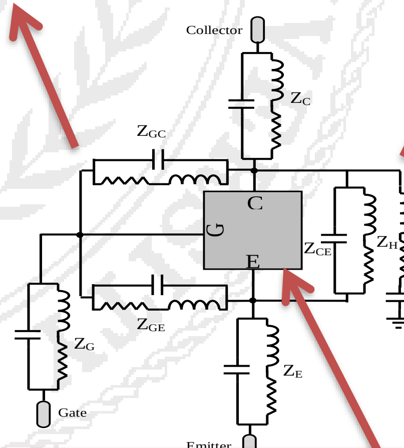



Circuit of IGBT Module

Model Reduction

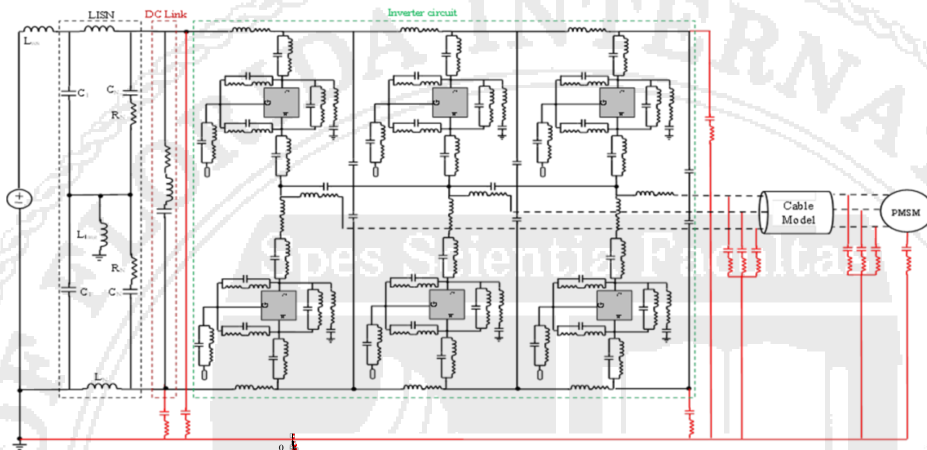


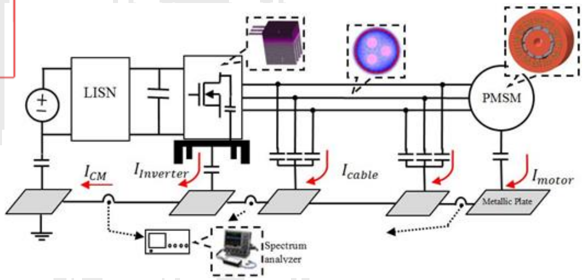




**The Hefner's model is utilized as a block in the IGBT model**

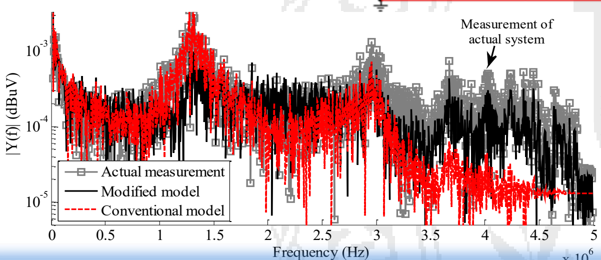
# Test and Verification of high frequency model of machine drive



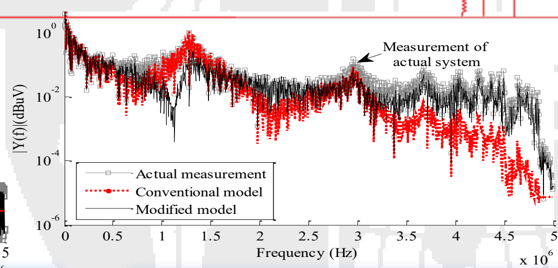

**a motor-drive system**



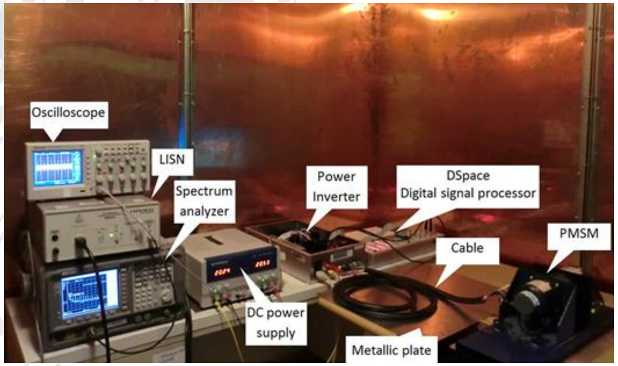

**Simulation of high frequency model of machine drive**



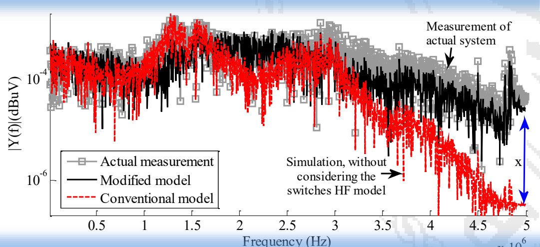

**Frequency spectrum of synchronous machine's input current in Matlab.**



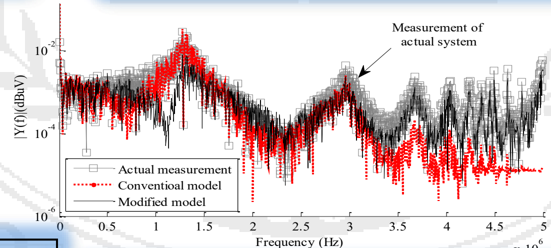

**Frequency spectrum of the common mode current.**




**Measurement of high frequency model of machine drive**




**Frequency spectrum of the synchronous machine's input voltage**




**Frequency spectrum of the converter's output voltage**

# Physics-based Modeling of Power Electronics Converters

*Physics-based Modeling of Power Electronics Converters*

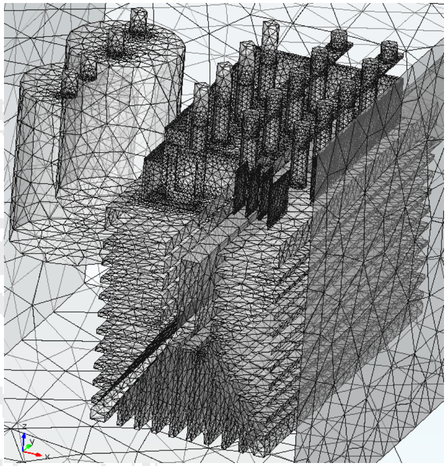
Understand the intrinsic properties of the component

Electromagnetic Emissions can be predicted and reduced through optimization algorithms

Design of the Power Converter considering parasitic components: switching frequency, placement of devices, dimensions

Study efficiency, power losses , performance of Power Converter, robustness and reliability

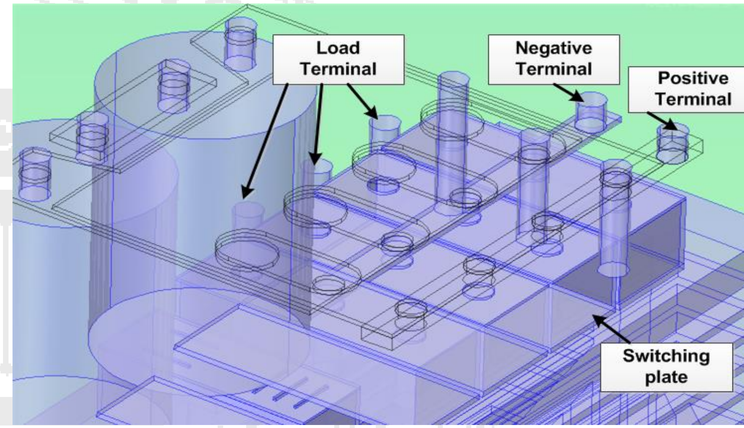
Conditioning Monitoring, Fault Detection and Diagnosis

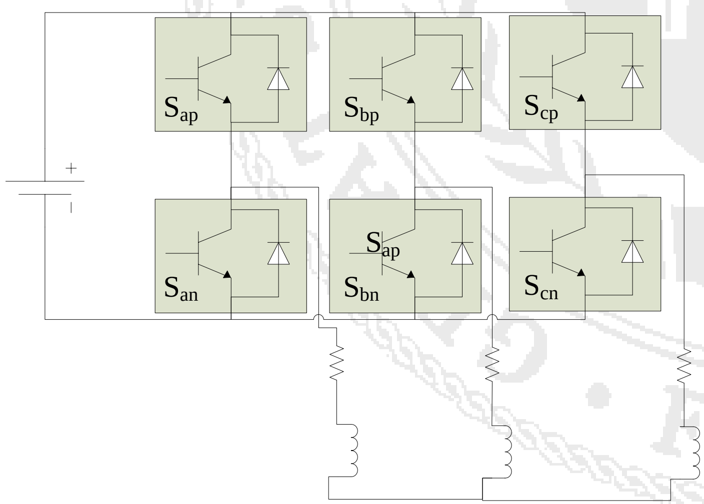


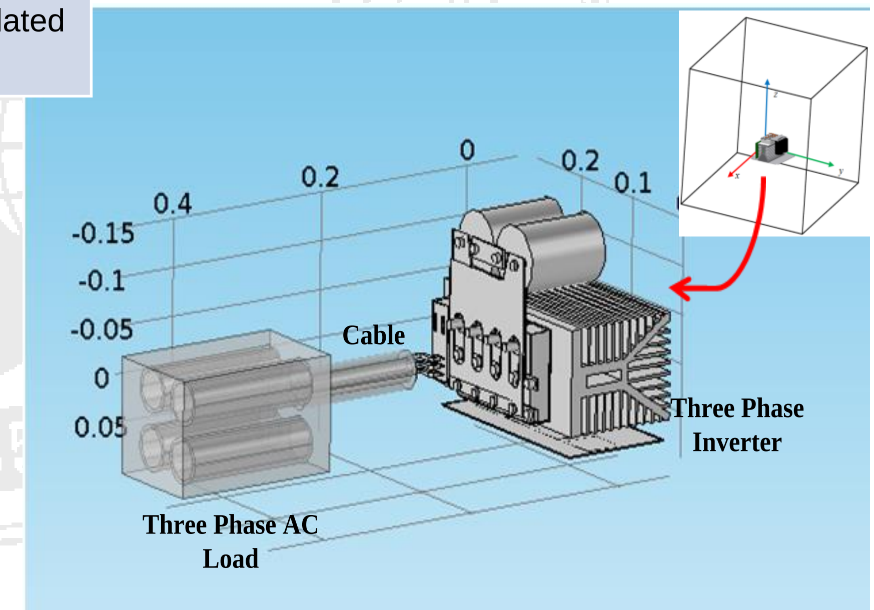
3D Full Finite Element Model of the inverter

# Power Train Modeling in Electric Transportation Systems

| Component | Characteristics |
|---|---|
| **Inverter** | Three-phase, 5.5 kW, Switching frequency: 5-kHz, Switching algorithm: SVM, Length: 30-cm, Width: 30-cm, Height: 25-cm, Nominal voltage: 320-V, Amp: 20-A |
| **Electric Load** | 3-kW AC load |
| **Connection cable** | XLPE, Diameters: Cross-sectional area: 1000mm$^2$, Thickness of insulation: 2.8mm, Nominal thickness of pvc sheath: 2.4mm, Overall diameter: 51mm, insulated and armored PVC sheathed cable |

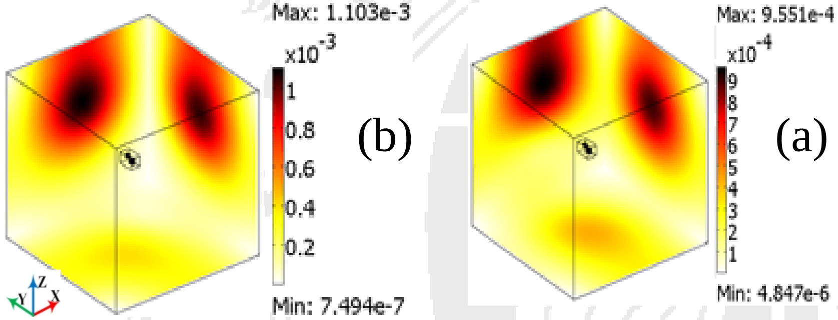


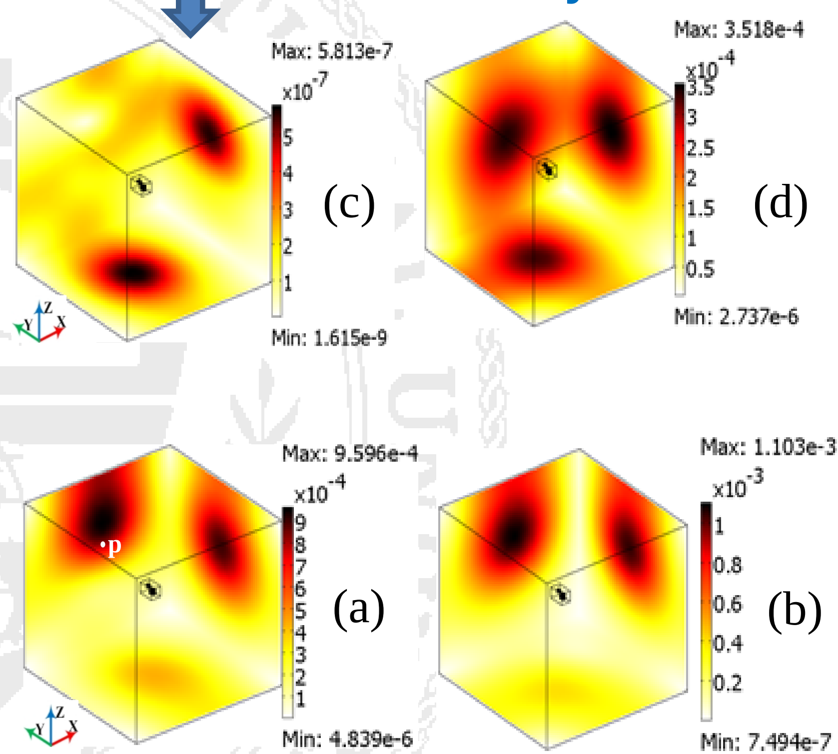
# Power Train Modeling in Electric Transportation Systems

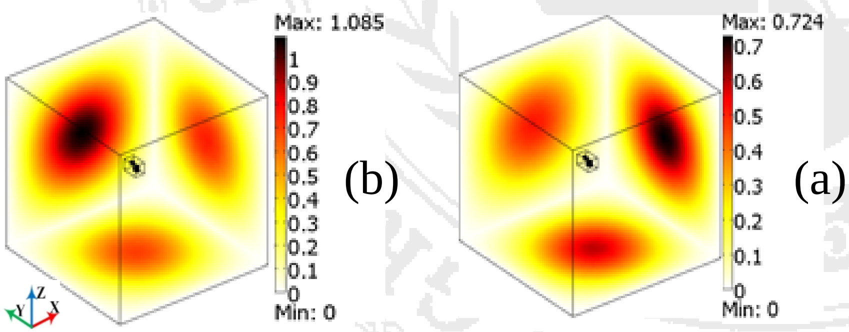
**Case 1: Converter connected to the Load**




Stray magnetic field density of the system:
(a) IGBT switched on (b) IGBT switched off (µT)

**In the Whole System**



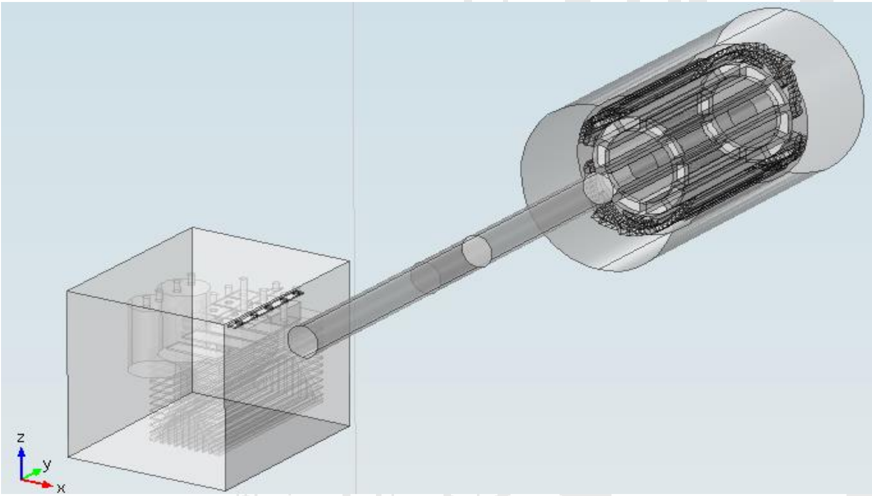

Stray magnetic field density of the system (µT):
(a) only the cable is switched on,
(b) only the inverter is switched on,
(c) only the load is switched on,
(d) the whole system is switched on

Stray electric field of the system: (a) IGBT switched on (b) IGBT switched off (µV/m)

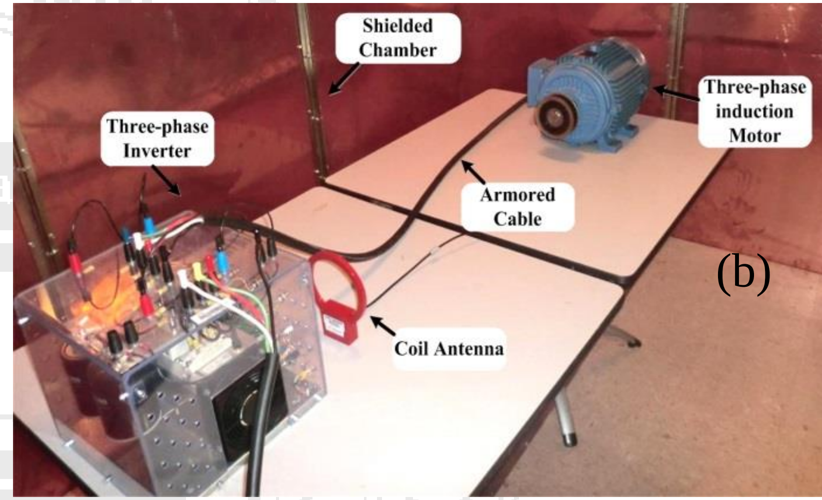
# Power Train Modeling Results

The scheme of the setup of case 2
(a) FE simulation (b) measurement

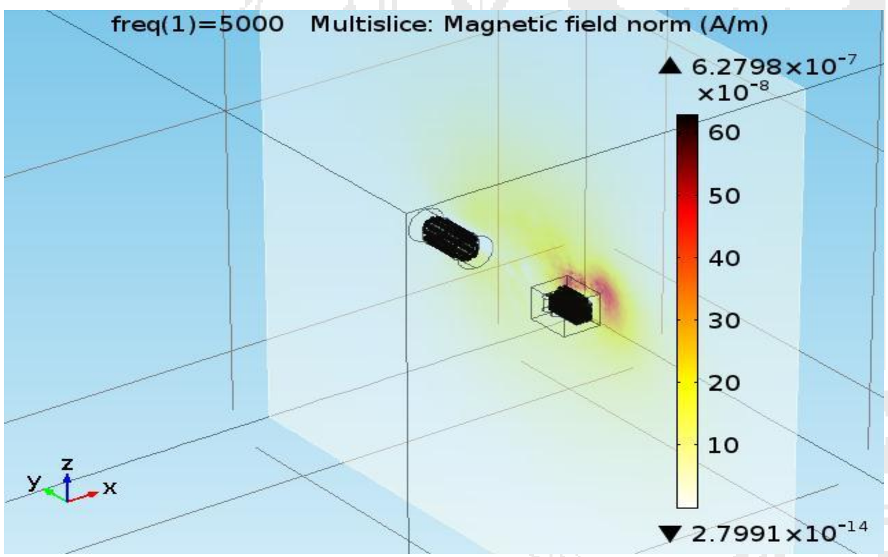
Case 2: Converter connected to the Motor

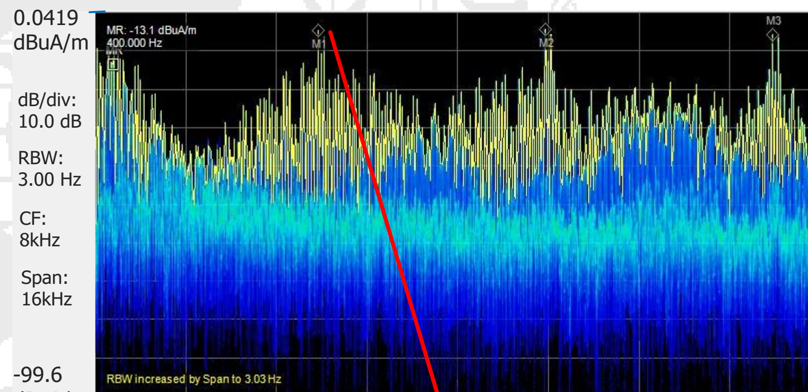



(a)




(b)



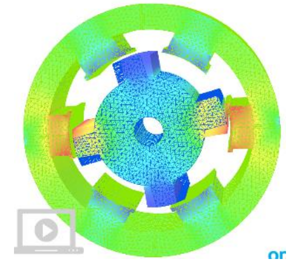




| Marker | Frequency | Δ Frequency | DPX |
|---|---|---|---|
| MR | 400.000 Hz | | -13.1 dBuA/m |
| M1 | 4.925 kHz | 4.525 kHz | -4.37 dBuA/m |
| M2 | 9.925 kHz | 9.525 kHz | -3.94 dBuA/m |
| M3 | 14.950 kHz | 14.550 kHz | -5.48 dBuA/m |

Stray magnetic field intensity of the setup case2 at 5 kHz simulated in FE (μA/m)

Measured frequency response of the stray magnetic field intensity of the setup case2

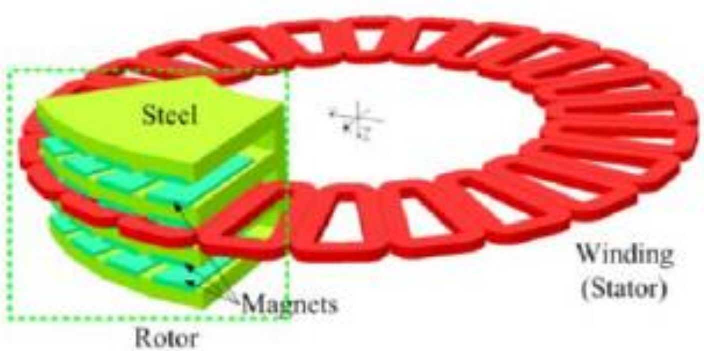
# PHYSICS-BASED MODELING IN ELECTRIC MACHINES



- The physics-based model is:

  A FE data-based model that can predict the machine operational and internal conditions at different working points.

- It can be utilized in the development of:
  - Physics-based observers,
  - The physics-based design optimization system.
  - The physics-based fault diagnosis and prognostic system.

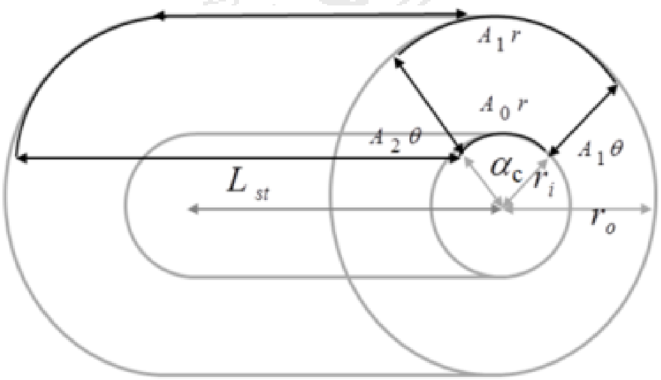


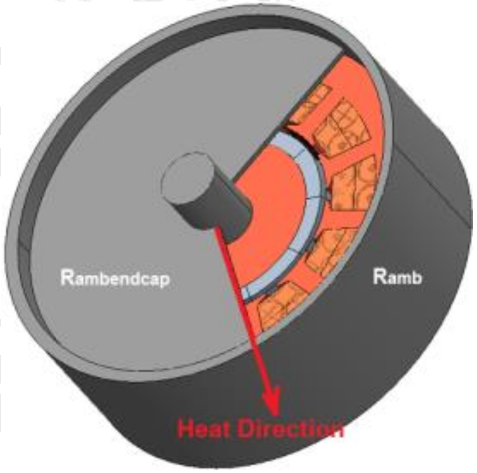
# Elements of the Physics-based Model

- Look up tables
- Permanent magnet modeling
- The model of magnet model in the machine
- Thermal modeling of the machine
- Electrical modeling of the machine
- Connecting the drive into the machine

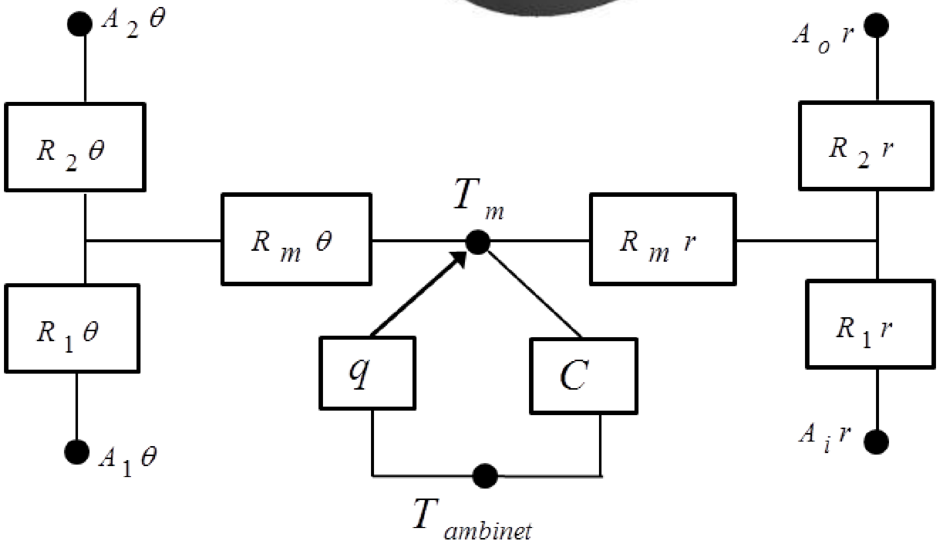
# Thermal modeling

Break down the machine into small cylindrical components:




The equivalent T model for each cylinder is calculated as



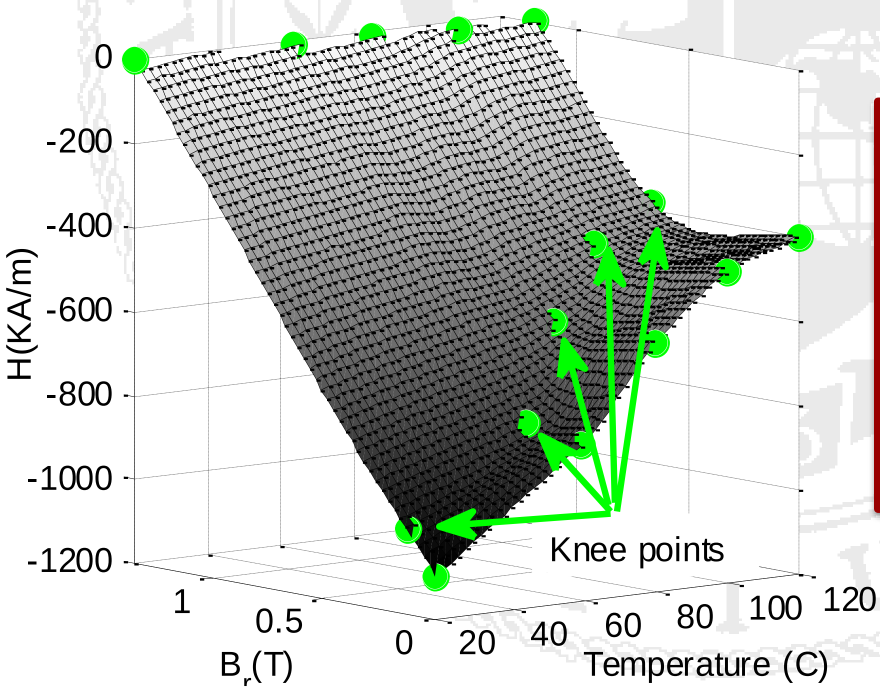

**Normally heat transfer in the $\theta$ direction is neglected.**

# Modeling of the magnets:

- In general B-H curve magnets can be modeled as:

$$H = p_{00} + p_{10}.T + p_{01}.B_r + p_{11}.T.\,B_r + p_{02}.\,B_r^2$$

$B_r$ is the remnant flux density, $T$ is average temperature of the magnet

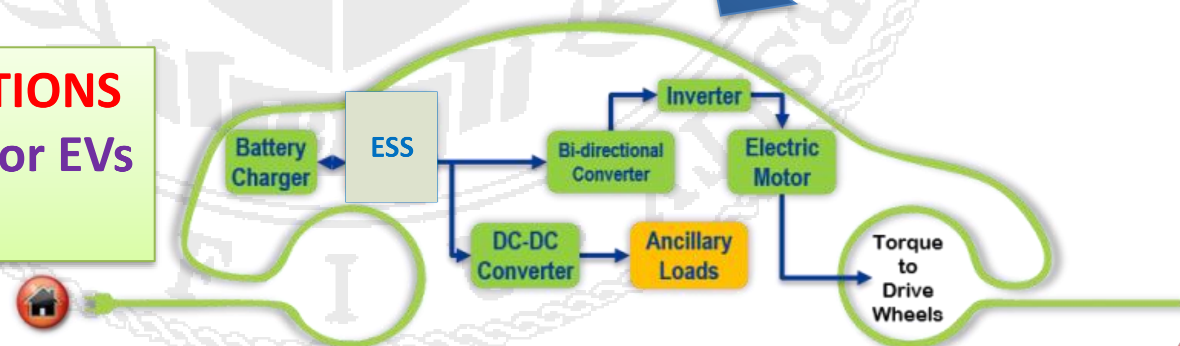



Typical demagnetization surface for sintered magnet on a Nd-Fe-B base, B (H) at different temperatures

# Fault Detection and Machine Control

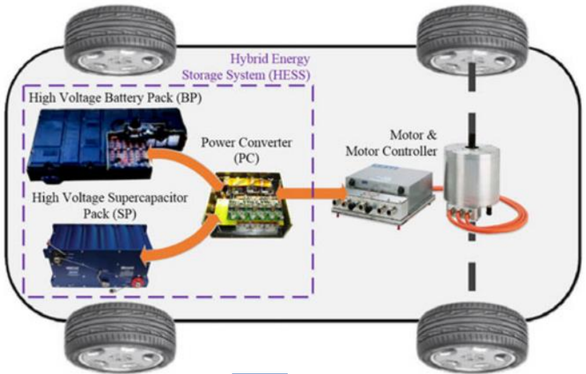
- In plug-in electric vehicles (PEVs), the motor is closed-loop driven (FOC or DTC)
- In urban cities, the vehicle is subjected to multiple stops, acceleration and deceleration
- Consequently, for in-city EVs, the drive system is subjected to several transient in the operation mode.
- Due to the high switching frequency of the DC-AC converter and the transient operation, the stator's windings are subjected to *Inter-turn short circuit (ITSC) faults*.
- How to detect that fault in DTC driven motors in EV powertrains? That is the question we are trying to answer

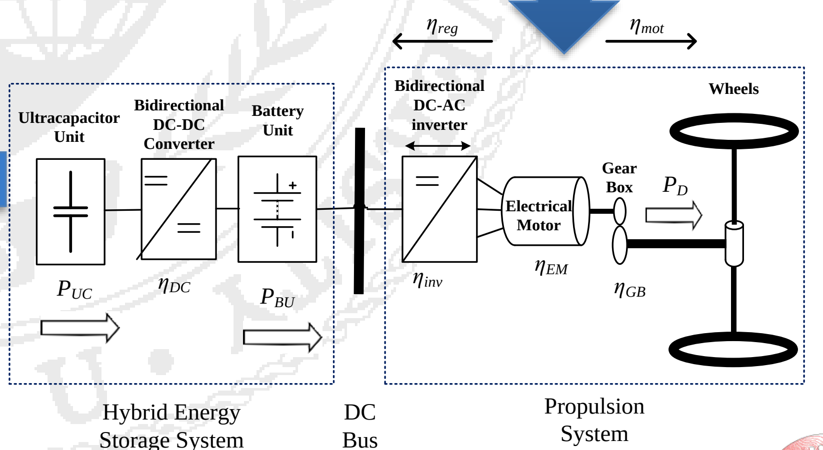
**We can use COMPUTATIONS to develop FD process for EVs and PHEVs**

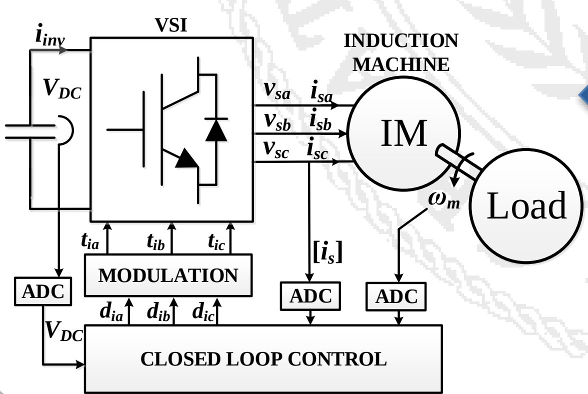


# Condition Monitoring

- To perform online condition monitoring to detect the ITSC for DTC driven induction motors.
- WHY? Stator winding insulation accounts for about 30~40% of induction machine failures in industrial applications.
- The condition monitoring technique will be based on:
  - Current
  - Sequence components Impedance
- The fault detection (FD) technique should be applied on board (DSP or FPGA) to fit the EV powertrain requirements



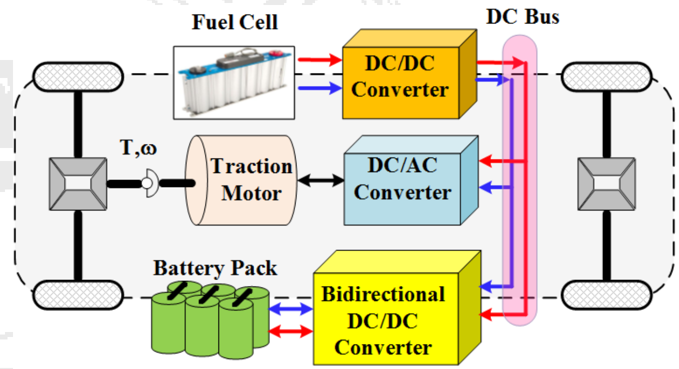



# Wide Band Gap Devices and Modeling of Power Electronic Converters and Architectures for Transportation Electrification

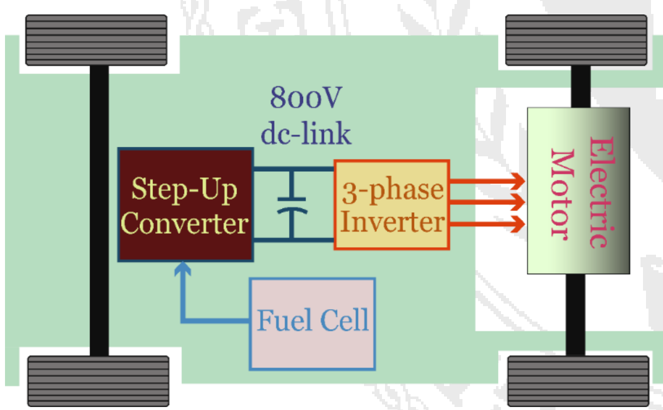
# Power Electronic Challenges

**Key Components of an EV powertrain:**
- ❖ Electric machines
- ❖ Power electronics converters
- ❖ Energy management System
- ❖ Energy storage system

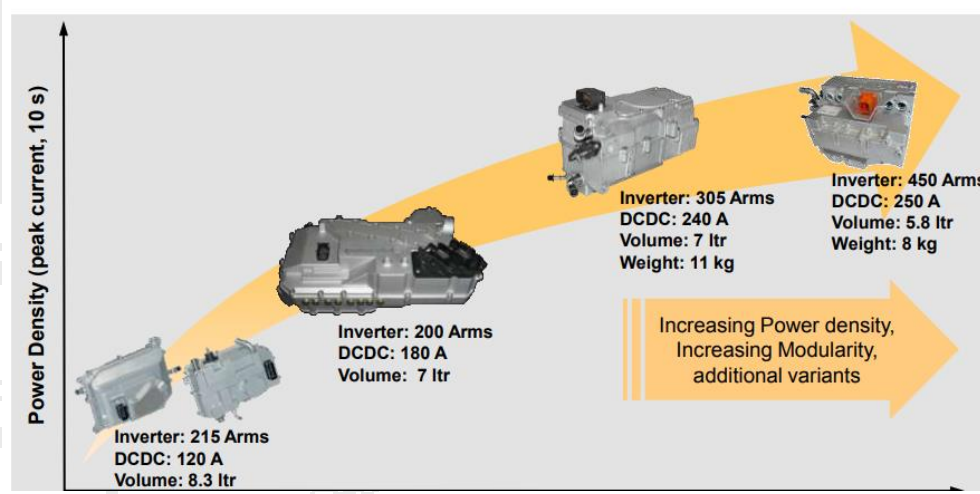
- Ultra-fast chargers using 800 V bus systems
- Fuel-cell powered EV powertrains




**General configuration of battery-based EV powertrain**




**General configuration of fuel cell-based EV powertrain**




**Power Density over the Years**

# Transformerless Architectures

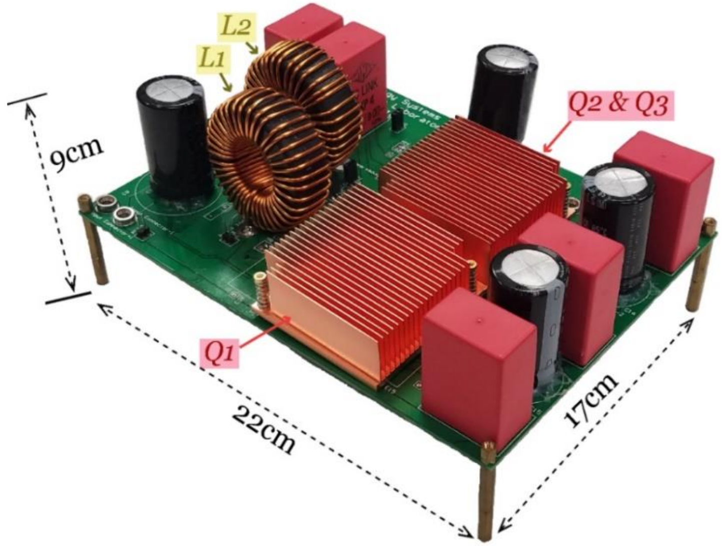
What are the Transformerless architectures ?

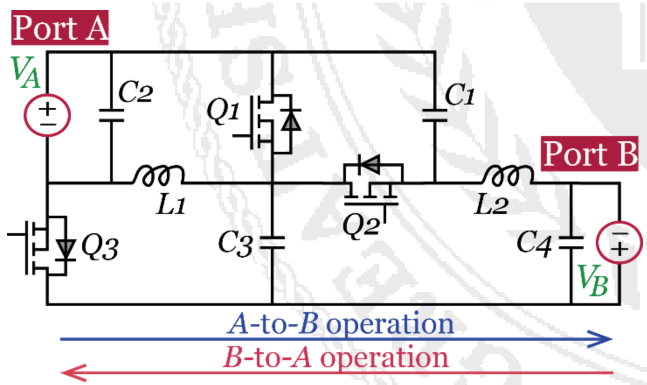
Transformerless power electronic architectures are power converters with high voltage gain/reduced voltage stress without magnetic coupling components, usually with integrated canonical-switching-cell, switched inductor, switched capacitor, voltage multiplier, …. etc. networks.

The advantages of these architectures

- High voltage gain.
- Reduced voltage stress on the semiconductor devices.
- High power density.
- High specific power.

# Transformerless Bidirectional DC-DC Converter with Wide Conversion Ratios



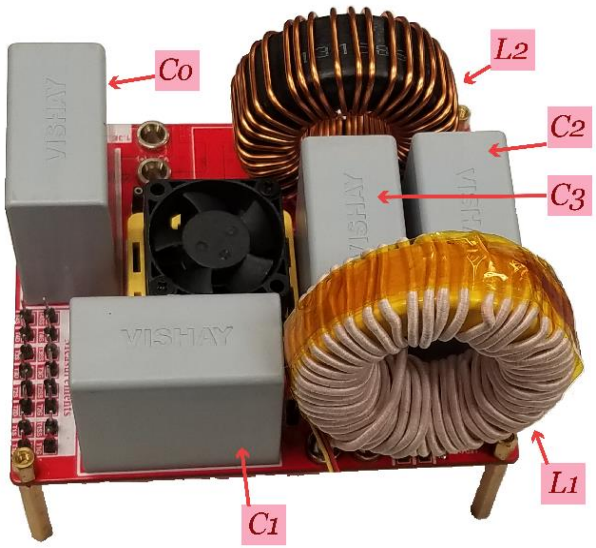

**Recently published by our research group in IEEE Transactions on Industrial Electronics**

- Power: 1.6 kW
- Switching frequency: 100 kHz
- Input Voltage: 50-100 V
- Output voltage : 400 V
- SiC MOSFETs

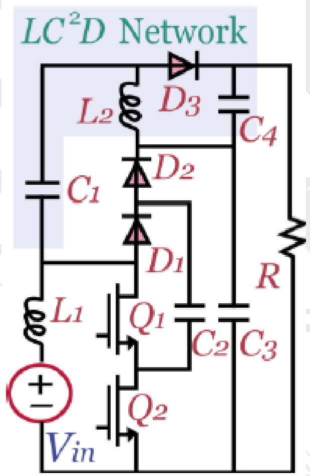
- The setup is implemented using **Silicon Carbide (SiC)** MOSFETs.
- This bidirectional dc-dc converter has low voltage stress on the semiconductor devices, wide voltage gain range, low number of components and fast dynamic response.
- It is suitable for energy storage systems, electric vehicles, microgrids and uninterruptible power supply systems.

# A New Three-Level Boost Converter With An Integrated $LC^2D$ Output Network

This converter is based on a 3-level flying capacitor boost converter



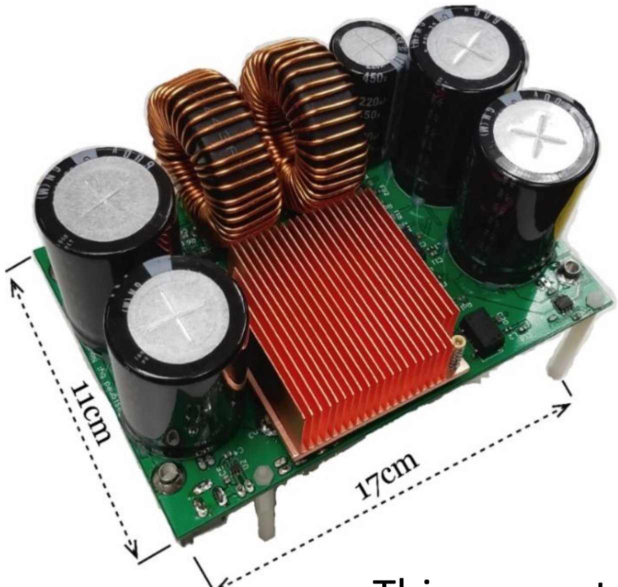

an extra $LC^2D$ output network is used to enhance the voltage gain and reduce the voltage stress on the switches and diodes



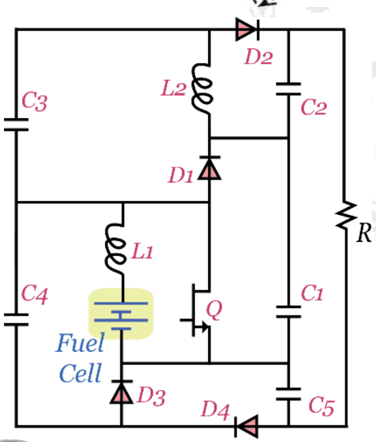

- Power: 1.3 kW
- Switching frequency: 100 kHz
- Input Voltage: 50-100 V
- Output voltage : 800 V
- GaN HEMTs and SiC Diodes

- The setup is implemented using Gallium Nitride (GaN) enhancement high electron mobility transistors **(E-HEMTs) and SiC diodes.**
- This converter has lower voltage stress on the semiconductor devices and higher voltage gain compared to the conventional three-level boost converter.
- It is suitable for renewable energy systems and fuel cell vehicles.

# A New Single-Switch DC-DC Converter with Wide Voltage Gain for Fuel Cell Vehicles



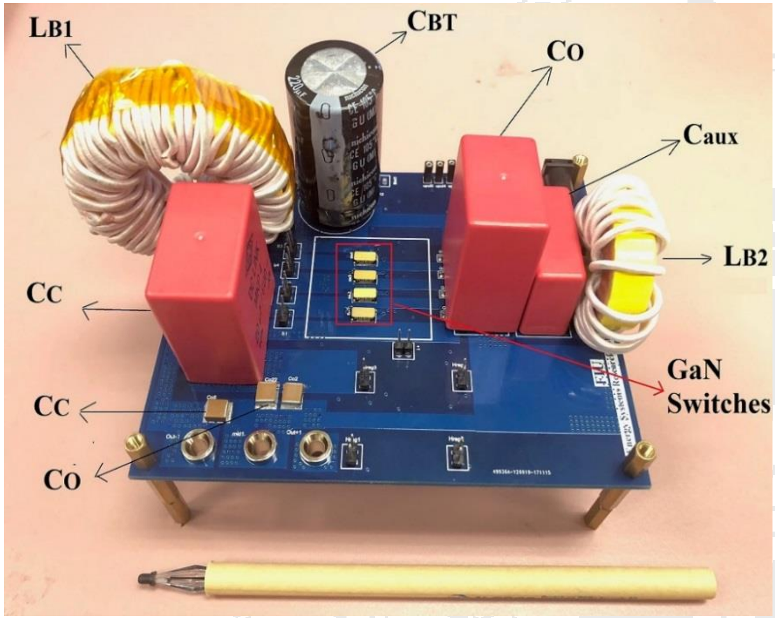

- Power: 2 kW
- Switching frequency: 100 kHz
- Input Voltage: 50-100 V
- Output voltage : 800 V
- GaN Switches and SiC Diodes



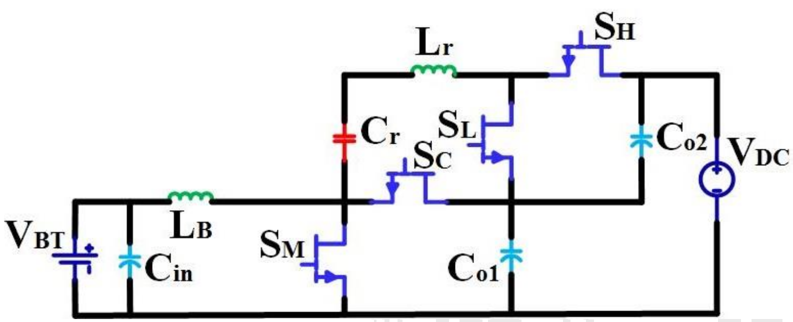

This converter has one switch and has a wide input voltage, low voltage stress on the semiconductor devices, and high voltage gain without any sort of magnetic coupling

- The setup is implemented using GaN HEMTs and SiC diodes.
- **This converter has low voltage stress on the semiconductor devices, wide voltage gain range, low number of components and fast dynamic response.**
- It is suitable for fuel cell electric vehicles, and renewable energy systems.

# A Quasi-Resonant Soft-Switched DC-DC Converter




- Power: 1 kW
- Switching frequency: 200 kHz
- Input Voltage: 50-100 V
- Output voltage : 600 V
- GaN Switches: GS66508T (650 V, 30 A, $R_{DS(on)}$ of 50 mΩ)




This topology has the capability of modularity; so, it can be extended for high voltage and high power applications.

- The setup is implemented using Gallium Nitride (GaN) enhancement high electron mobility transistors (E-HEMTs).
- Using a resonant branch**, the zero-voltage-switching at turn-on instant is realized, which improves the efficiency.**
- The cascaded configuration, along with active clamp topology, is used to decrease the voltage stress across the semiconductor devices.
- It is suitable for electric vehicle and renewable energy systems.

-To reduce the voltage stress of switches, the output stage of the converter are cascaded.
-To reduce the current ripple, the modules are connected in interleaved configuration. So, the current will be divided equally between modules. Also, interleaved connection allows to employ the switches with lower rated-current.

# Power Electronic Building Blocks

- The **Power Electronic Building Block (PEBB)** is a generic power electronic converter circuit that can be configured in different ways to synthesize popular power electronic architectures (DC-DC, DC-AC, AC-DC, and AC-AC converters).
- This can reduce the number of spare parts needed onboard a ship, plane, … etc., also the PEBB can reduce the manufacturing cost of the power electronic systems since the mass production of one generic power electronic architecture is more economical than producing application-specific power electronic architectures.

**All PEBBs in literature are either built with Si or SiC MOSFETs/IGBTs.**

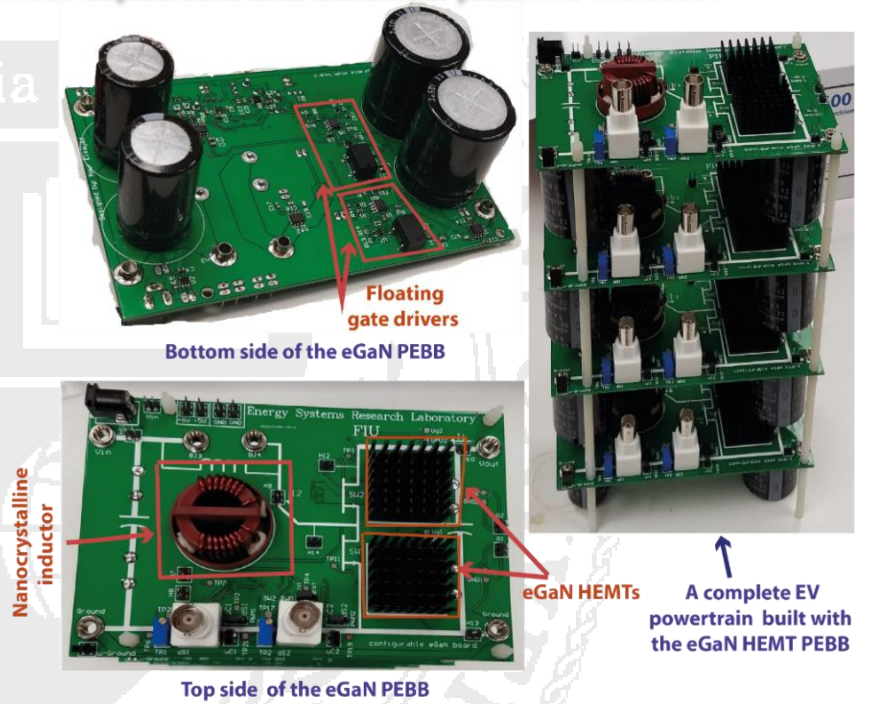
**Building PEBBs using GaN HEMTs could reduce the conduction and switching losses of the PEBB and enables high power density and high specific power.**

The main restraint in using GaN HEMTs is the limited breakdown voltage compared to their Si/SiC FETs counterparts.

# Power Electronic Building Blocks using GaN E-HEMT

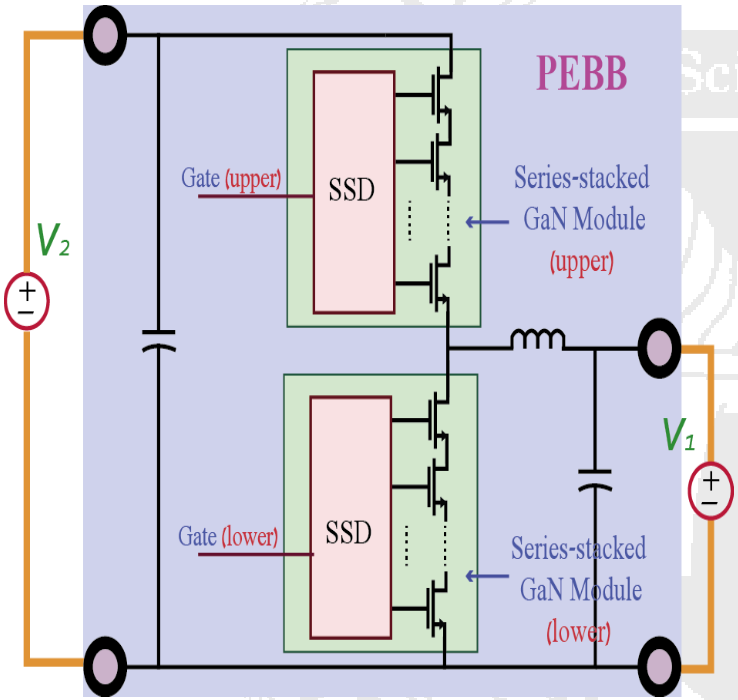
- **Aim to develop a generic and compact Power Electronic Building Blocks (PEBB) using GaN E-HEMT and soft magnetic materials**
- **Can be non-isolated or isolated**
- **GaN-based PEBBs can have 2-3 times the power density and specific power of the Si/SiC-based PEBBs**
- **Integrated active energy buffer can have a significant impact on the PEBB size and weight**

**An integrated non-isolated E-GaN PEBB with input/output filter capacitors and a Nanocrystalline inductor**

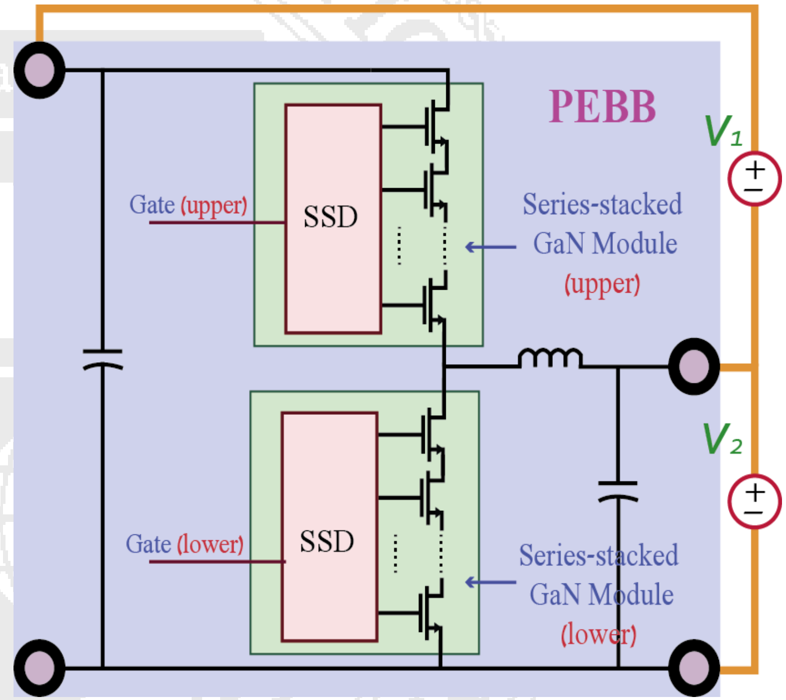



- **E-GaN PEBB has supply-independent gate drivers making them suitable for unconventional PWM techniques such as bus clamping PWM**
- **This E-GaN PEBB can be used to synthesize a wide variety of power electronic converter topologies (DC-DC and DC-AC) including single-phase and three-phase DC-AC inverters**

# Example: DC-DC Architectures synthesized with the 1.3kV GaN PEBB




**Bidirectional Buck-Boost DC/DC Converter synthesized by series-stacked GaN modules**

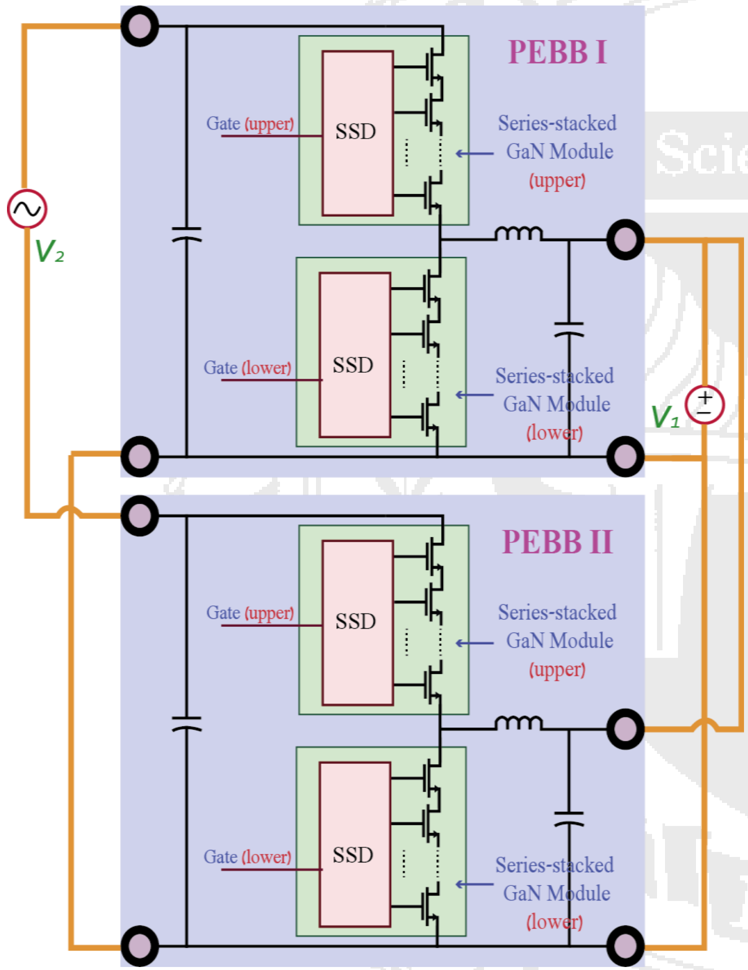



**Bidirectional Non-inverting Buck-Boost DC/DC Converter synthesized by series-stacked GaN modules**

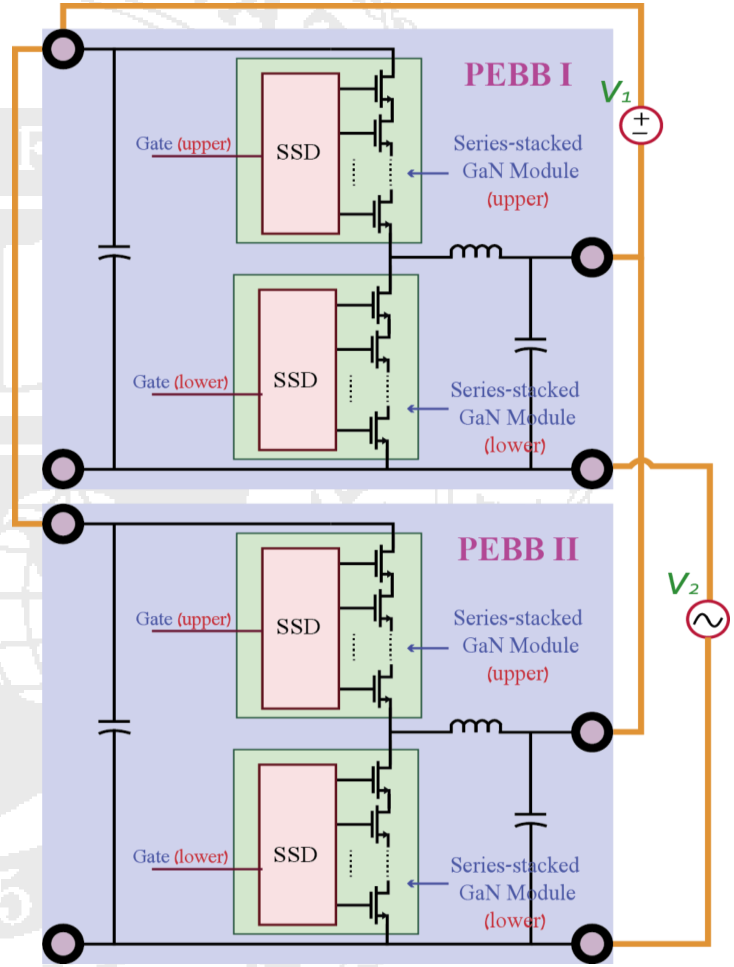
One PEBB can be used to synthesize a dc-dc converter (buck, boost or buck-boost)

# Example: Single-phase Inverters synthesized by the 1.3kV GaN PEBB:

Two PEBBs can be used to synthesize a single-phase inverter

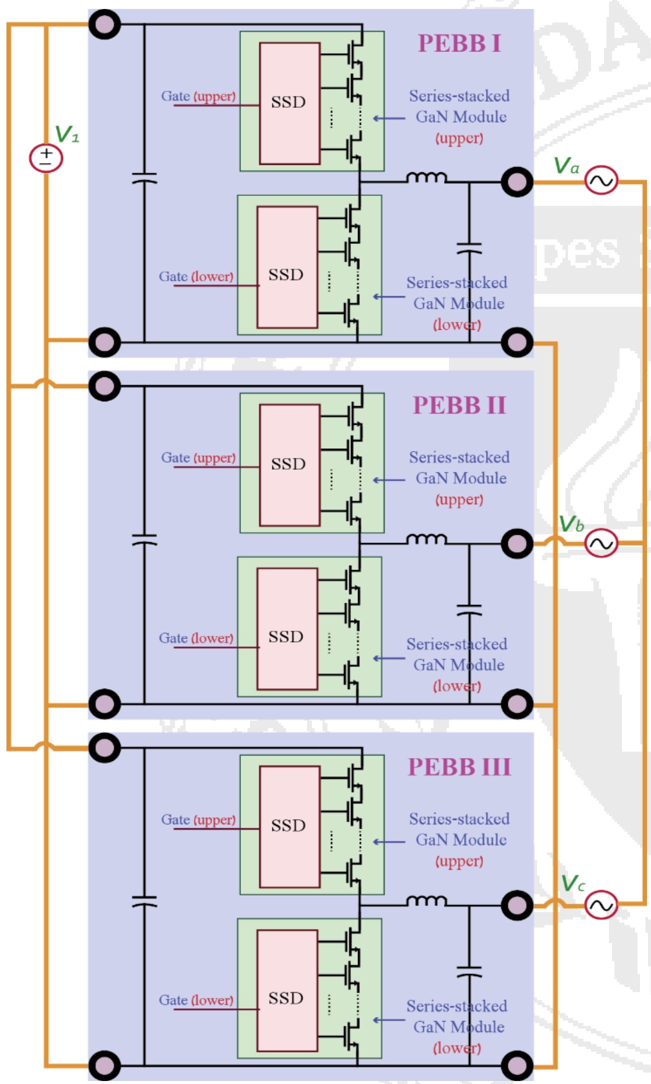



A Single-phase boost Inverter synthesized by series-stacked GaN modules

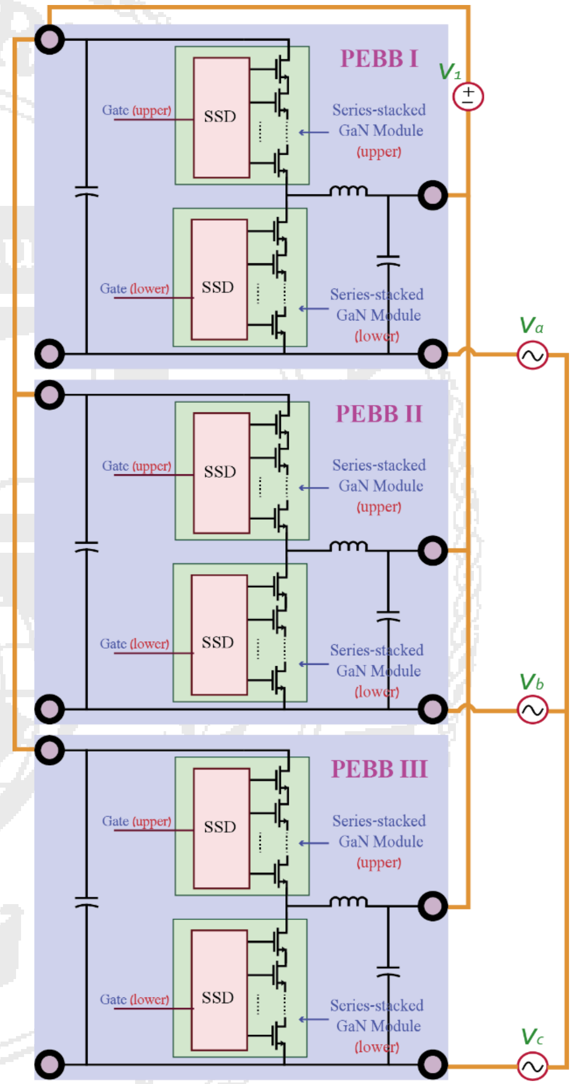



Single-phase Buck-Boost Inverter synthesized by series-stacked GaN modules

# Example: Three-phase Inverters synthesized by the 1.3kV GaN PEBB:




Three PEBBs can be used to synthesize a single-phase inverter.



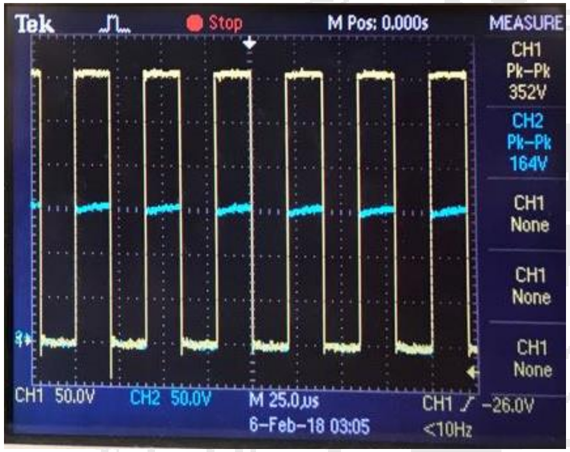

**Three-phase Buck Inverter synthesized by series-stacked GaN modules**

**Three-phase Buck-Boost Inverter synthesized by series-stacked GaN modules**

# Experimental Evaluation:

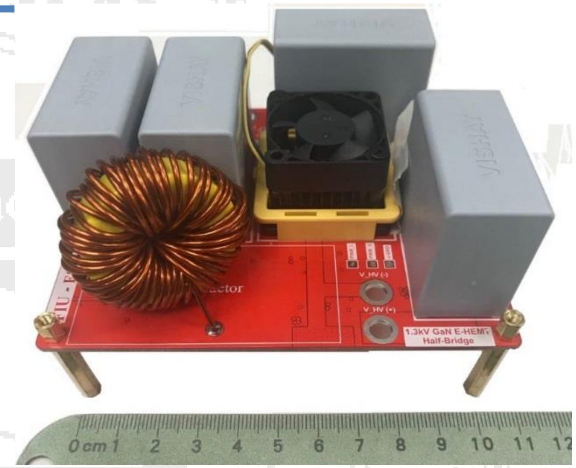
The voltage stress on the whole 1.3kV GaN module

1



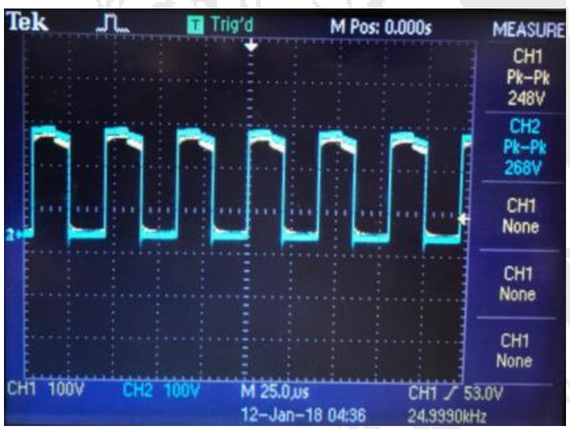

**Voltage Stress of switches in module versus the voltage across one switch**

4



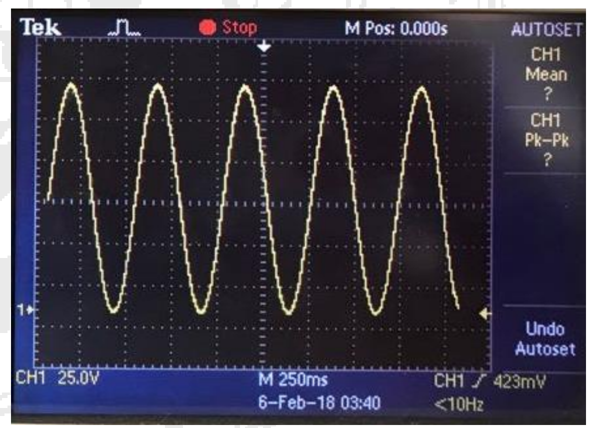

**1.3 KV PEBB prototype using GaN Switches**

2




**Voltage Stress of switches connected in series**

3




**Differential mode inverter using PEBB**

The voltage across 1 HEMT equals half the total voltage on the whole module

# High-Power Integrated Modules

- ❖ **Data Center**
- ❖ **On-board chargers**
- ❖ **Solar inverters**
- ❖ **HEV Power train**

Integrated modules are used to minimize the size and weight of the power converter by integrating the inductors and capacitors within the structure of the PCB

| Architecture | Feature | Advantage | Disadvantage |
|---|---|---|---|
| •Multi-phase converters: | •Paralleling a number of dc-dc converters,<br><br>•Phase shifts between the carrier signals of these converters | •Low input current<br><br>•Current sharing between the paralleled phases. | •Higher number of magnetic components<br><br>•Voltage stress on semiconductor devices |
| •Multilevel architectures | •Neutral point clamped network or<br><br>•Flying capacitor network | •Low input current ripple<br>•Low voltage stress on the semiconductor devices<br>•Does not require any extra magnetic components | •No current sharing |

# Challenges in EV Applications

**Requirements**

- ❖ High power density
- ❖ High Efficiency
- ❖ Small size

**Solution**

- ❖ Increasing the Frequency
- ❖ Soft-Switching operation
- ❖ Using Wide band-gap semiconductors
- ❖ Improvement in structure of converters

**Challenges**

- ➢ Increasing the switching losses
- ➢ Limitations in High-frequency high-power magnetic components
- ➢ Issues related to utilizing WBG devices
- ➢ Embedding of Actives and Passive Components

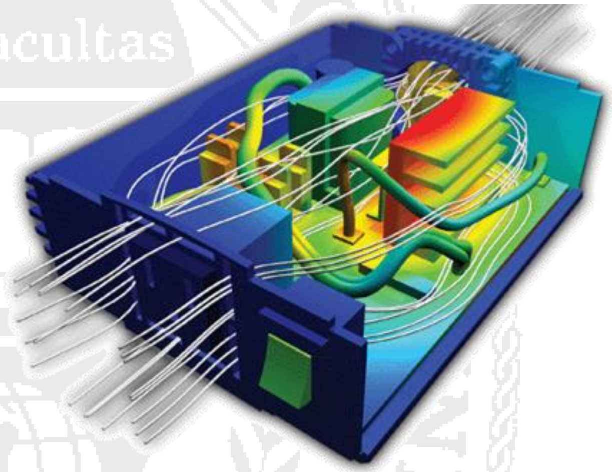
# EMI in PCB Designs and Circuit Optimization for Transportation Electrification Systems

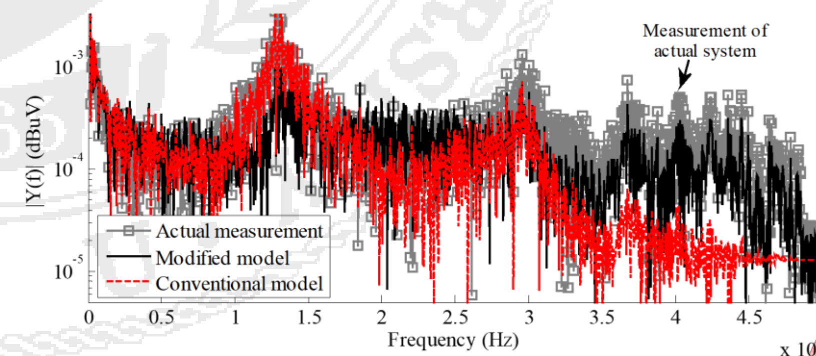
# EMI in PCB Designs

Reducing size of power electronic converters

Increased switching frequency

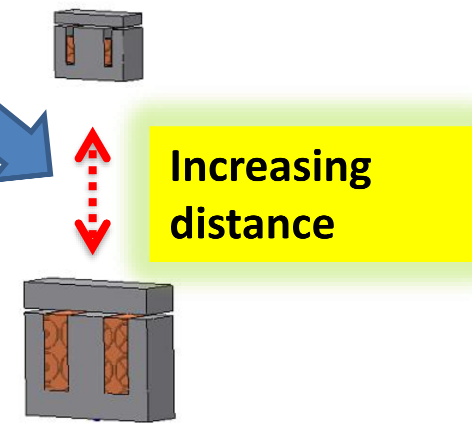
Size minimization increase EMI issues on susceptible devices (transducers)





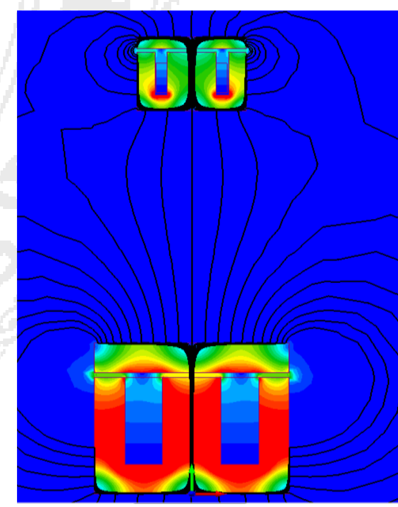
Two reasons cause the EMI problem:

- ❑ The distance between EM sensitive devices and EM sources is reduce.
- ❑ The increase in switching frequency




more harmonics » more EM emissions

- ➢ PCB design in DC-DC converters must comply with
  - ➢ conducted emissions
  - ➢ radiated emissions
- ➢ Standards CISPR22, FCC part 15 and EN 55022, MIL-STD-464

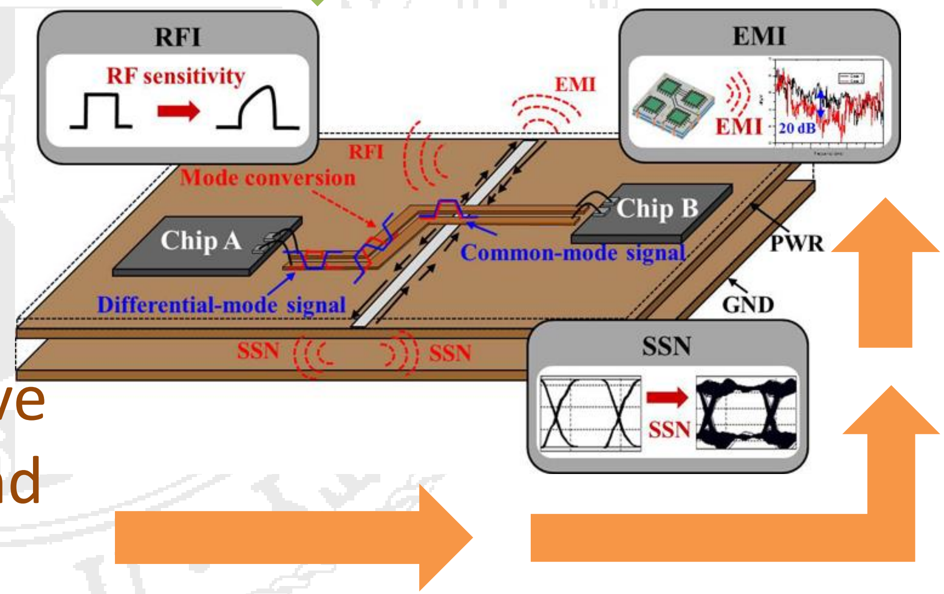


## ➢ CONDUCTED EMI:

- ➢ Is a complex problem that can be analyzed by building a HF FE model to extract the parasitic and mutual coupling elements of the tracks and the components on the PCB.
- ➢ Equivalent model of the circuit can be analyzed by any circuit-solver (Spice, MATLAB, etc.)

## ➢ RADIATED EMI:

- ➢ Even more complicated
- ➢ Has many different sources
- ➢ The radiation analysis should consider different effects (physical location of the passive elements, their dimensions and conducted EMI).



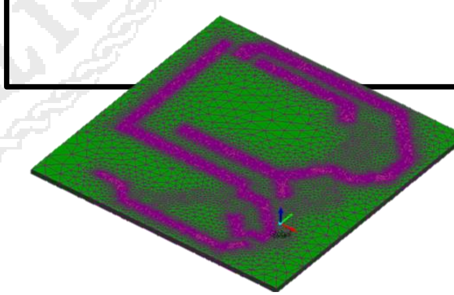
# EMI Reduction Measures

Measures to reduce the EMI effects in high frequency power electronics converters

EMI Filter: Leads to an increase in the circuit volume. Also the design and the tuning should be completed following the implementation stage

Improving the modulation techniques: to suppress EMI with emphasis on the conduction form. Even when this technique does not affect the dimensions of the PCB, it need complex algorithm.

Predicting EMI using numerical analysis: solving the problem in the pre-design stage studying the location of components in a PCB.



# Predicting EMI using numerical analysis

The placement and orientation of passive components on a PCB in the pre-design stage.

**Optimization Problem**

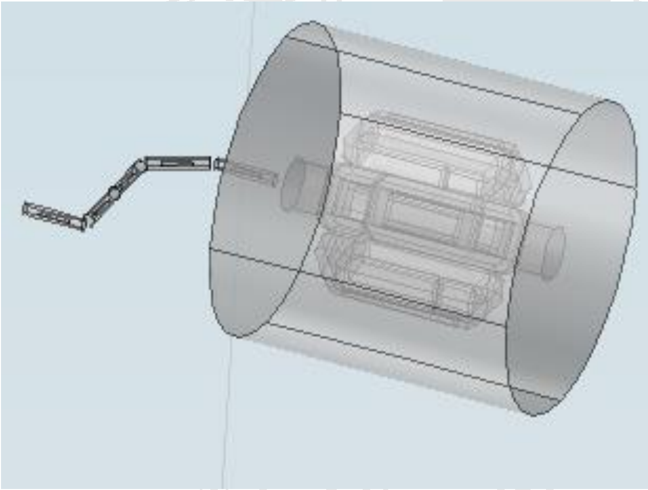
For positioning components in PCB designs, the susceptible ones (transducers and microprocessors) should be as far as possible from inductors and capacitors operating at high frequency.

Varying the distance and angle of the adjacent passive components between them using numerical models (3DFE)

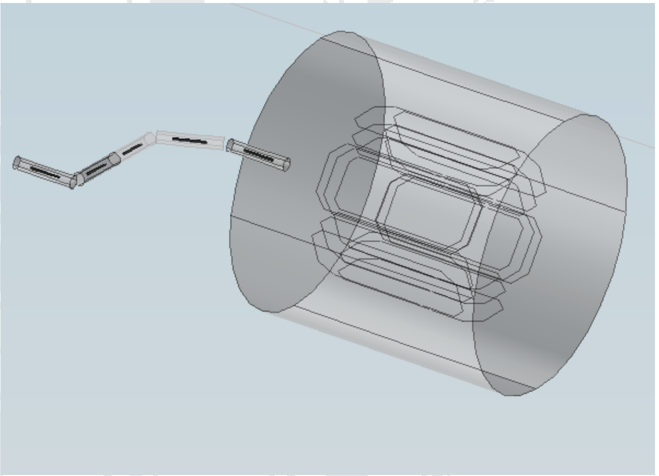
Search for the cancelation of their coupling effects at the sensitive devices

# Coupling of the cable with a synchronous machine

**The equivalent source model is analyzed in connection of cable with a synchronous generator.**



the detailed model



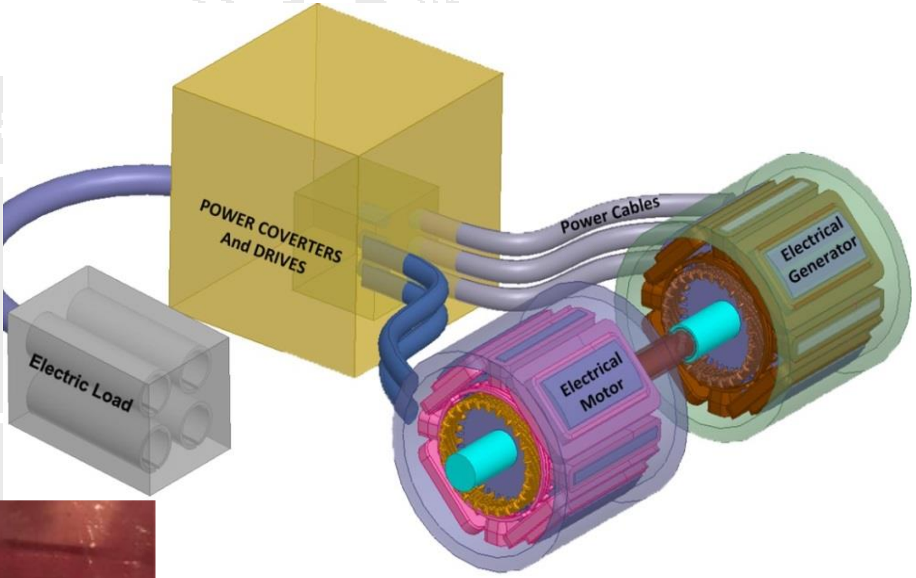
the equivalent source model

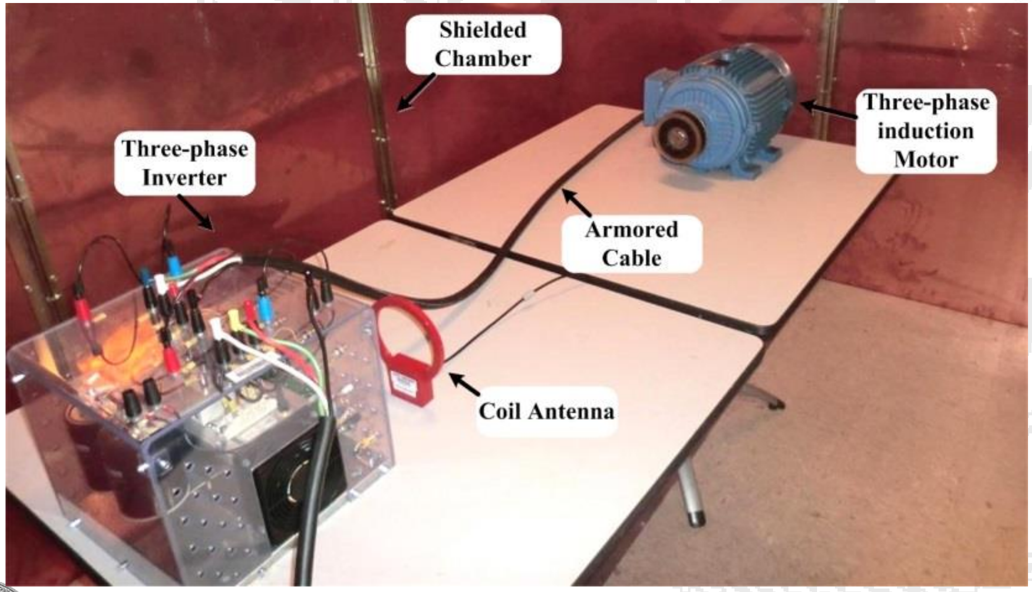
**Wire modeling was used here which similar to the modeling of the cable**

# Evaluating Signatures

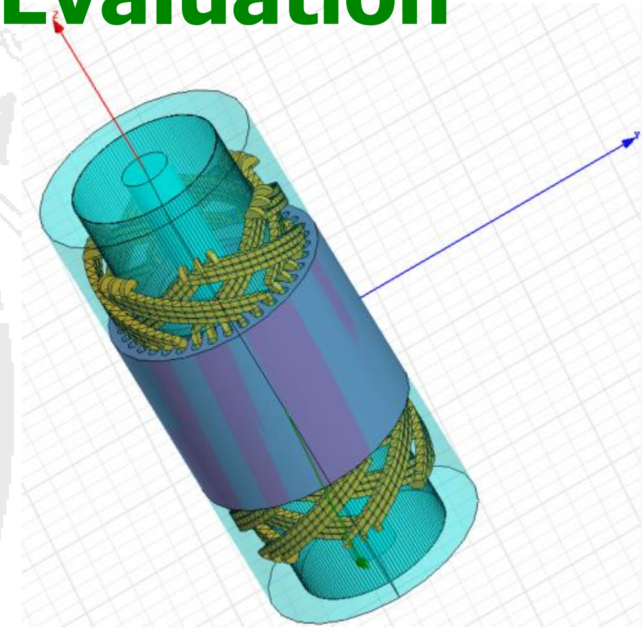
The electromagnetic signature method is noninvasive/ nondestructive method

It's flexible for detecting faults various types of components such as machines, converters, pulse loads, and …

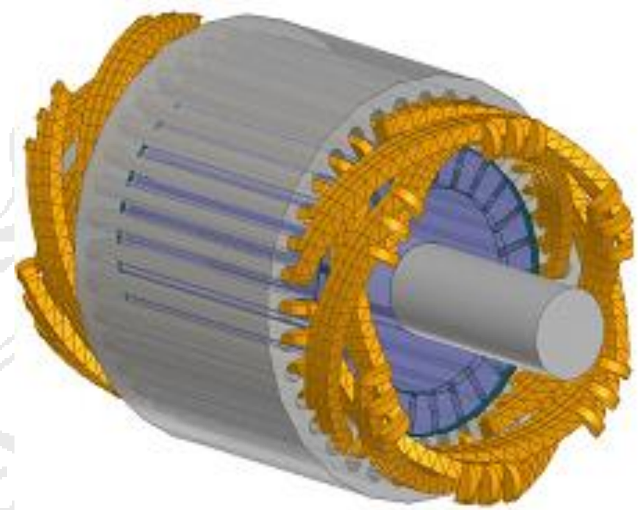


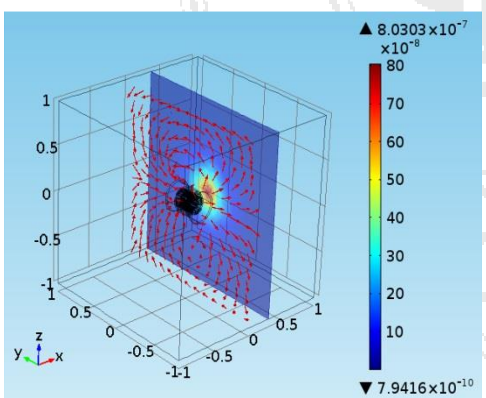



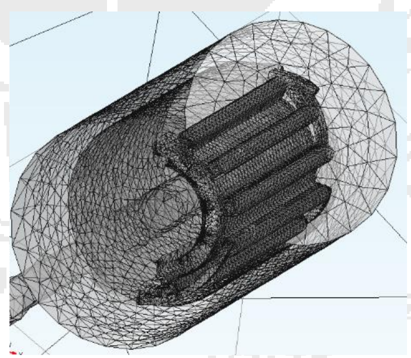
# Electromagnetic Signature Evaluation



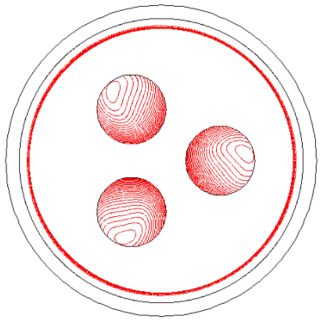
- To study the electric and magnetic behavior of power components, **an accurate physics-based model** of each component should be considered:
  - All windings
  - Type of connections
  - Geometrical features slot shapes
  - Rotor and stators structure
  - Material properties

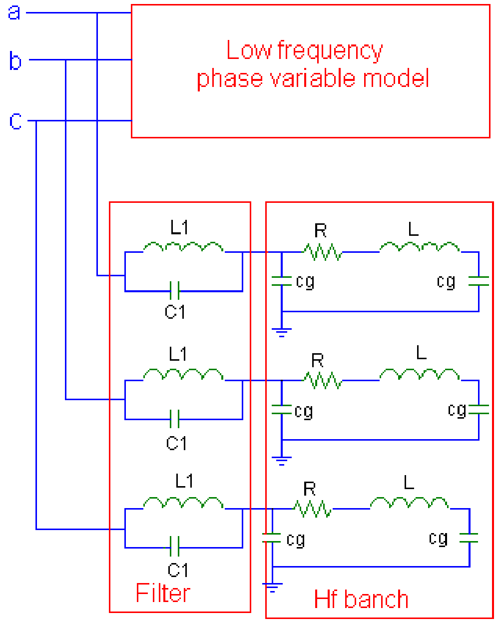




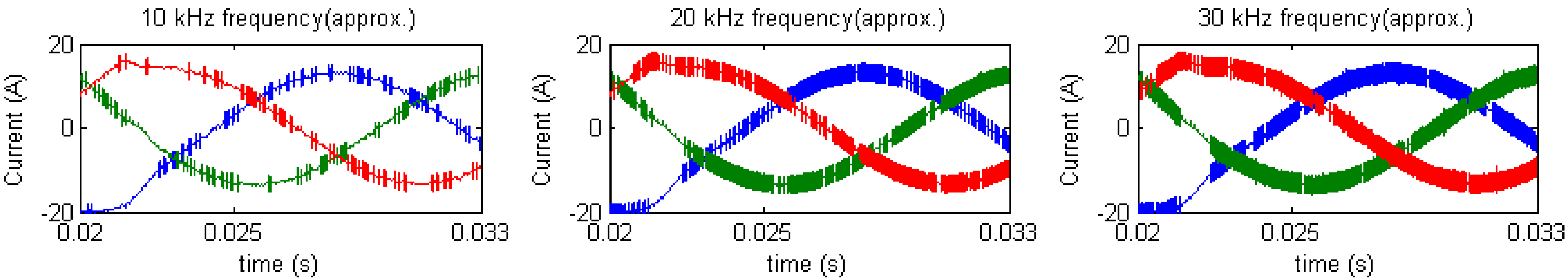



# High Frequency and Connecting Cable Models



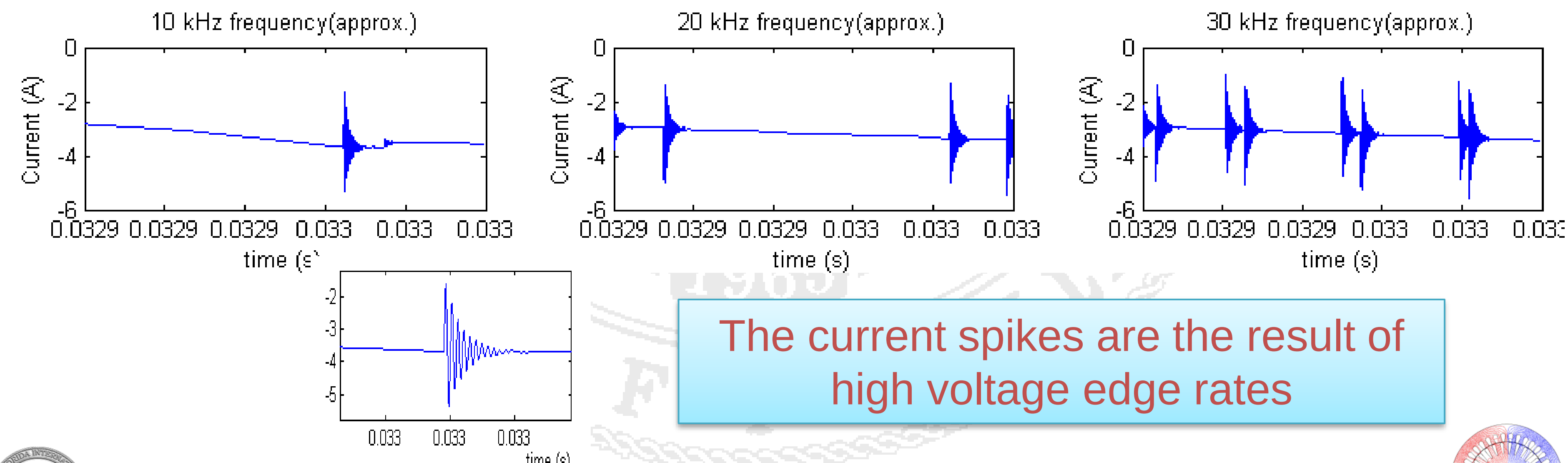


# Inverter-motor interaction in integrated system




**Steady state three phase current profile**

The increase in the switching frequency increases the magnitude of the current spikes. This is because phase to ground capacitance provides low resistance path to increased switching frequency harmonic components.



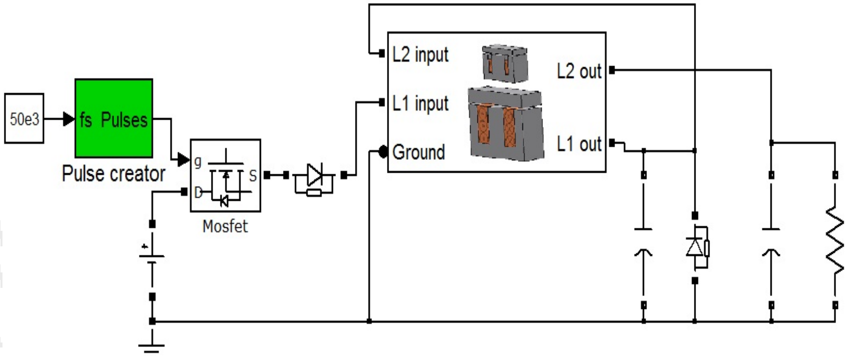

The current spikes are the result of high voltage edge rates

# Optimization for EMI Mitigation in Power Converters for EMC Compliance Example

Problem:

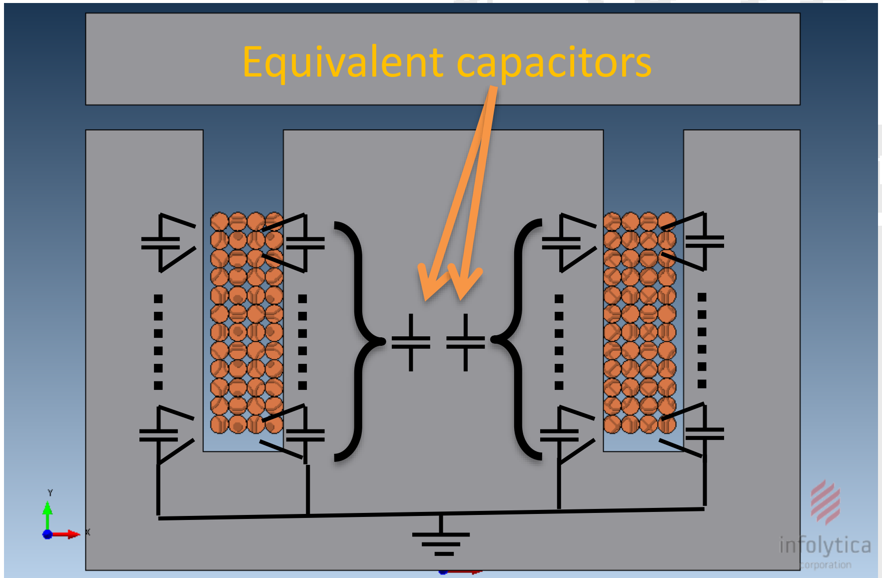
Positioning of Ferrite Inductors in the Field Domain for minimum EMI Using population-based optimization methods

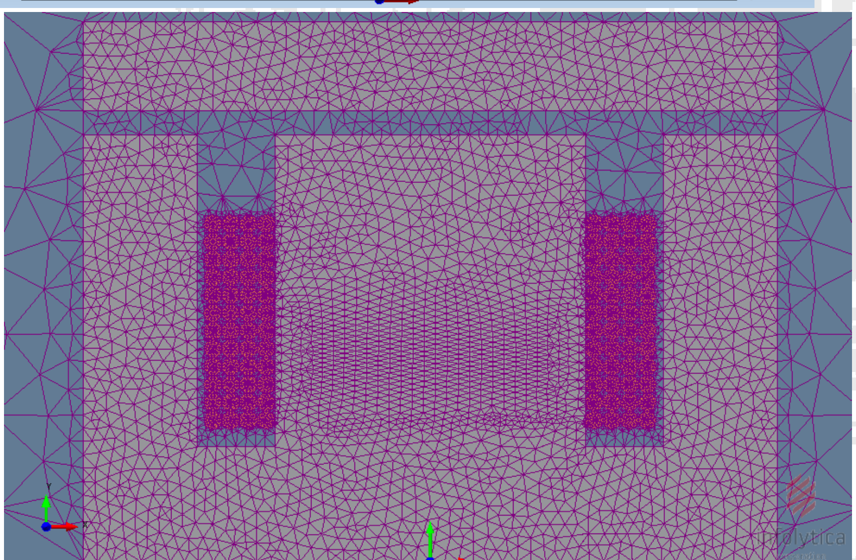
Objective Function = Occupied area by conductors + Energy of common mode current




- **The coupling between the FE model and the external circuit provides an effective tool to study the effects of converter operating conditions.**
- **The FE equations and the external circuit equations are solved simultaneously to simulate the converter behavior.**
- **The frequency response of the converter is obtained by coupling the converter magnetic component's FE domain model and external electric circuits.**

# FE modeling of Inductors:



Step1: Detailed modeling of Inductors in FE domain Using Solid Conductors

Step 2: Positioning of inductors for minimum EMC and EMI Using population-based optimization methods

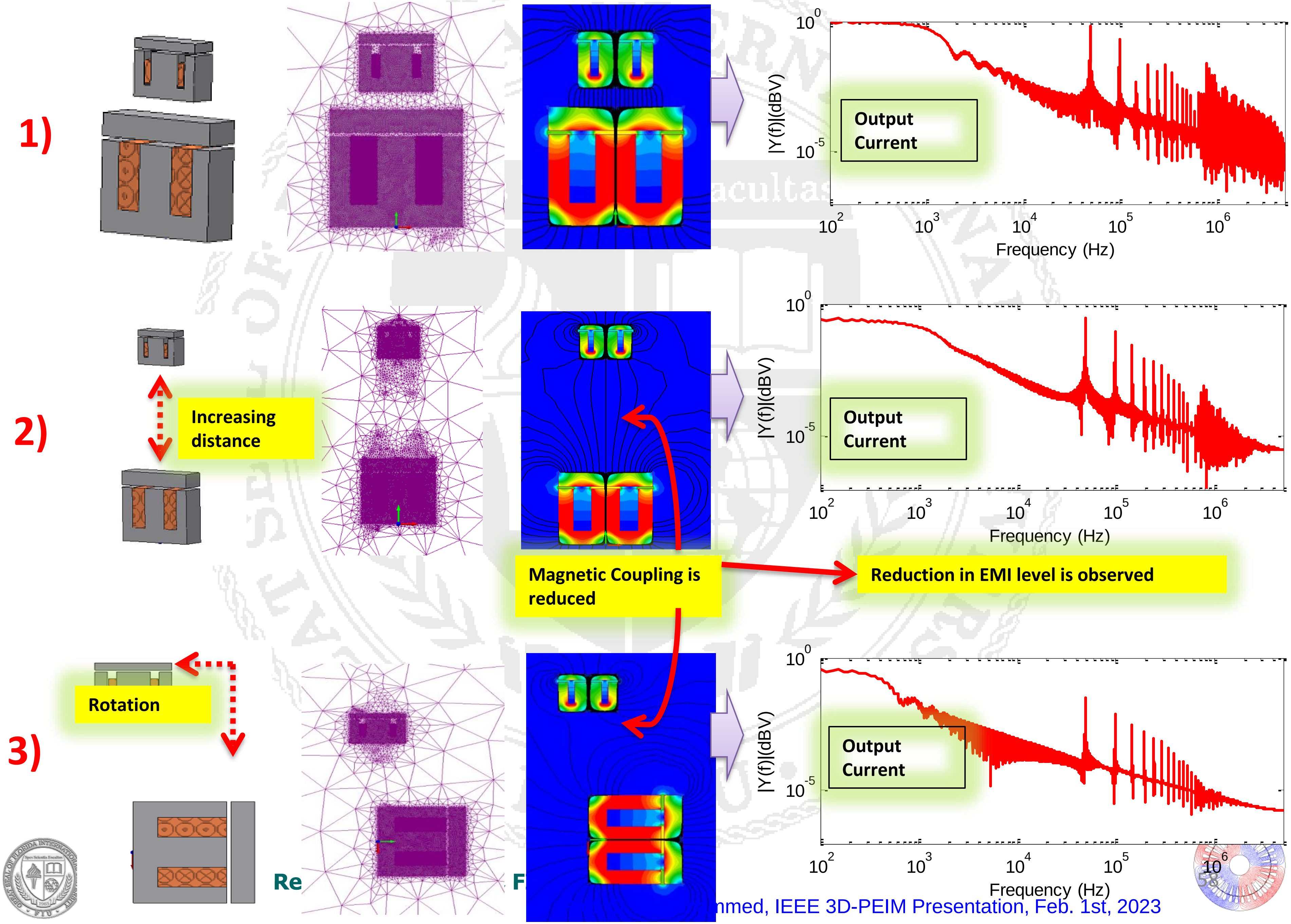
Physical Description

FEM simulation

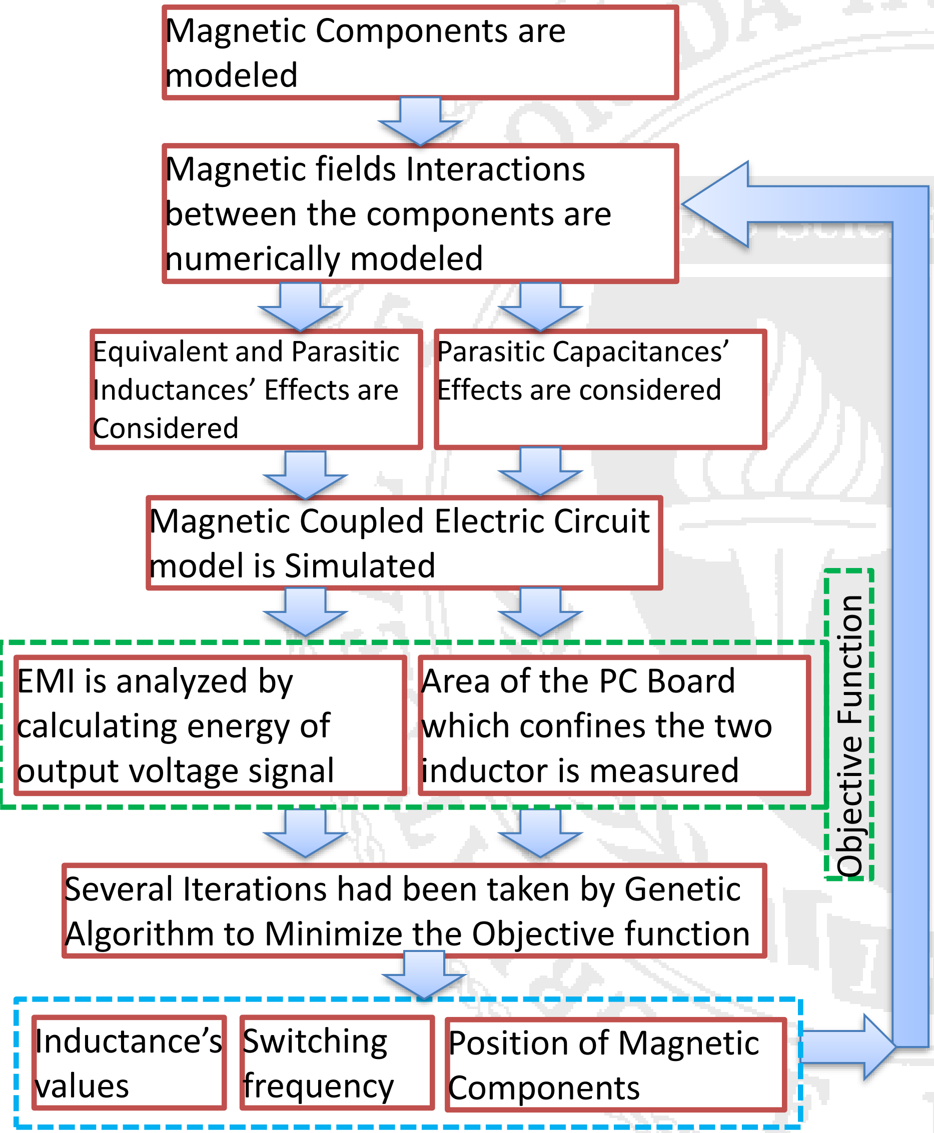
Parameters calculation

Model generation

# Effects of different geometries on EMI level of the system



# Optimization Process For Inductor positioning & EMI Mitigation



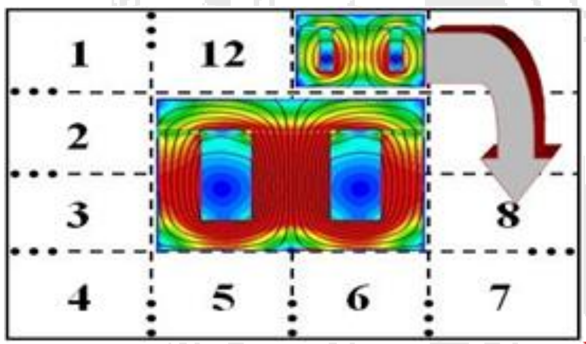

- The main Objective of this study is to reduce the size of the PCB while keep the EMI at low level.
- Frequency response of the converter is obtained by coupling the converter magnetic component’s FE model and its coupled electric circuits.
- 2D electromagnetic FE analysis is used as a tool to have an accurate physics-based simulation.
- By physics-based modeling of the converter components high-frequency oscillations are observed which in the ideal cases were not observed.

# Design and Optimization Procedure: Genetic Algorithm Procedure

- In the optimization process the objective function is: $O(t) = \alpha_1.|Area|^2 + \alpha_2.|E_f|^2$
- The objective variables are :

- ***Inductance values***, *20μH< $L_r$< 200μH*
- ***Switching frequency***, *50kHz< $F_s$ < 200KHz*

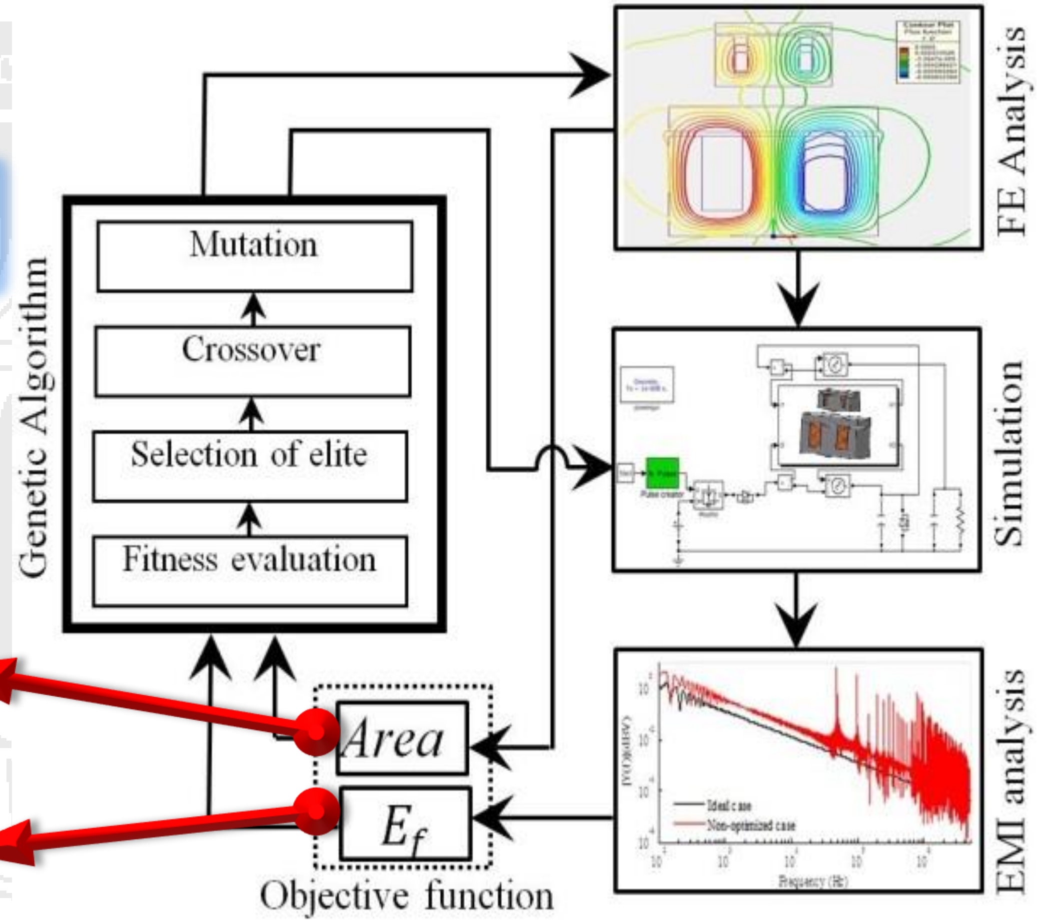
**Position of the two Inductors are changing with respect to each others**




Calculation of energy of a signal:

$$E_x = < x(t), x(t) > = \int_{-\infty}^{\infty} |x(t)|^2 dt$$

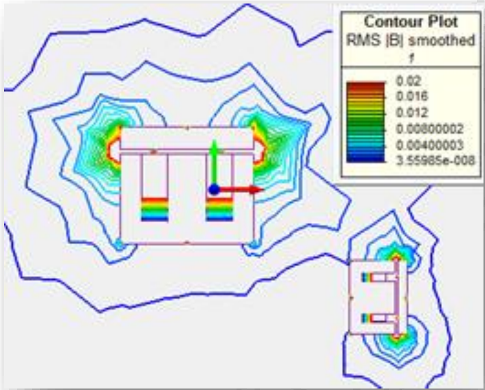
$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega$$



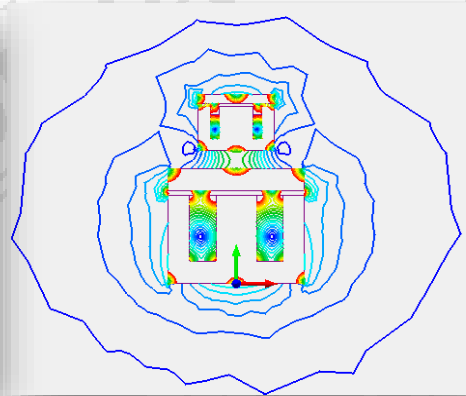

The optimization process diagram.

# Optimization Results:

**Note that the magnetic coupling in the Optimized case is less than its corresponding Non-optimized case**



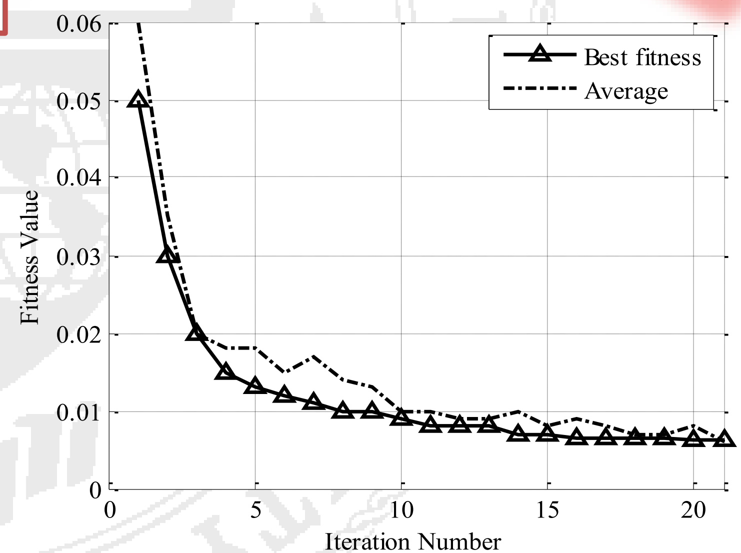

After Optimization



Before Optimization

## Optimization results

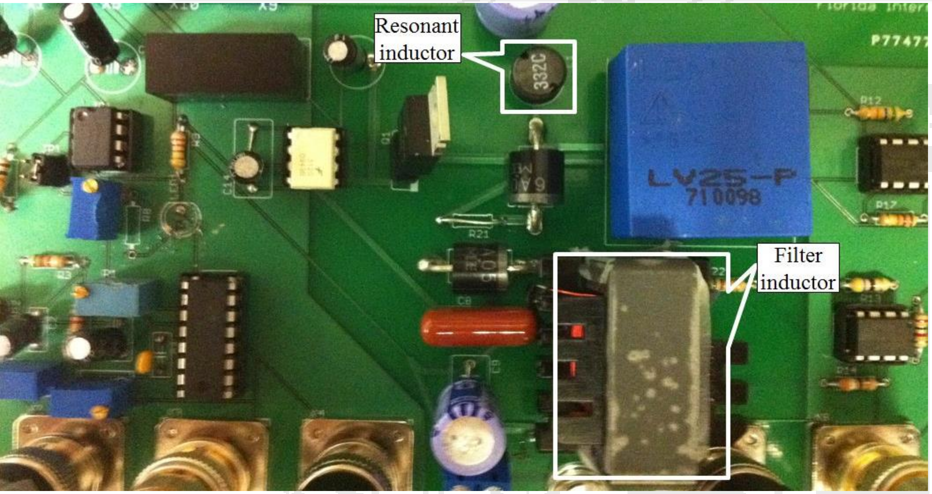
| Parameters | $L_r$ (µH) | f (kHz) | Area ($mm^2$) |
|---|---|---|---|
| **Before optimization** | 120 | 50 | 3360 |
| **After optimization** | 45 | 90 | 11000 |



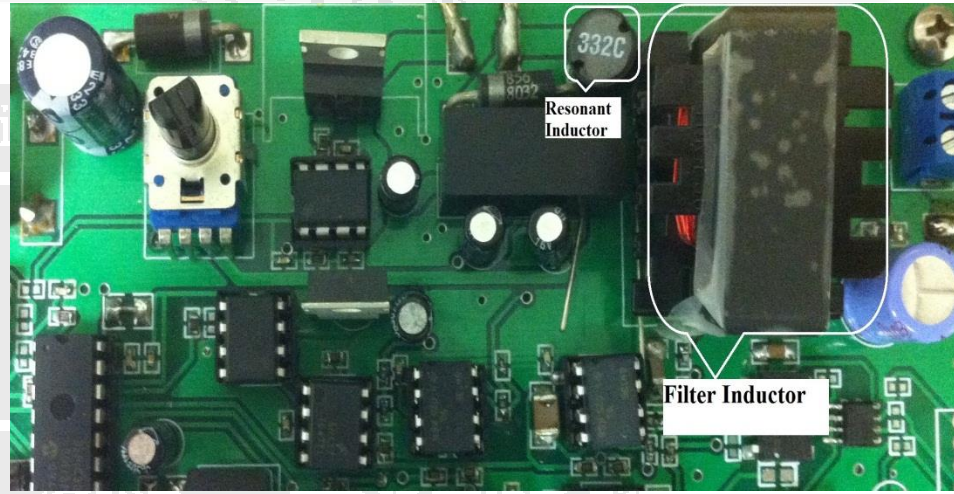

Iteration accomplished by GA to minimize the objective function.

# Experimental Results on The inductance placement problem:

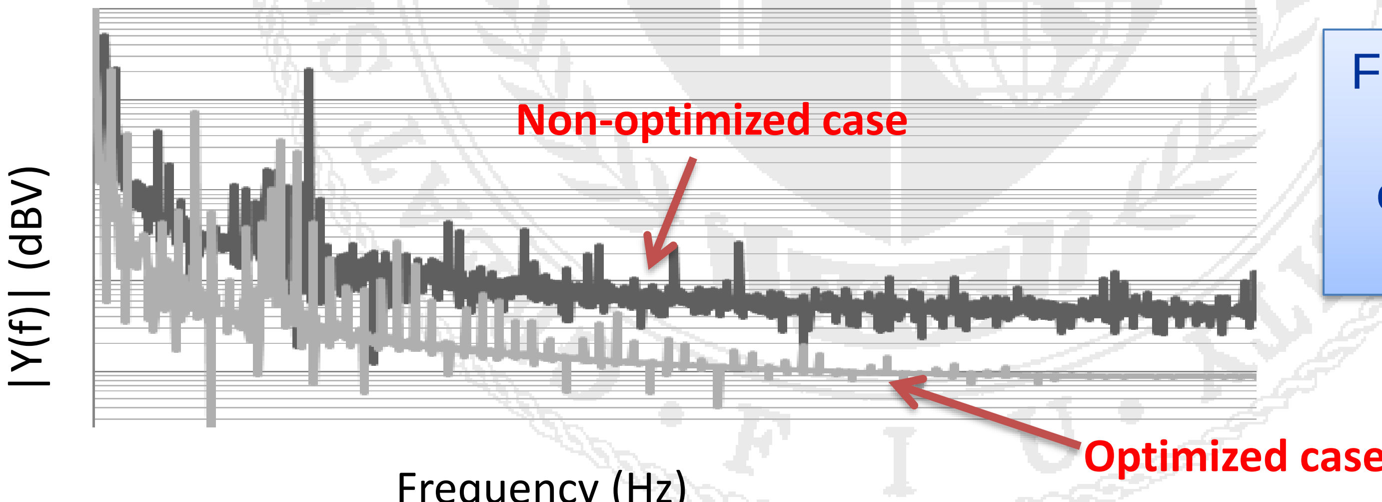
ZCS quasi-resonant buck converter's circuit in the optimized layout.




**Optimized case**

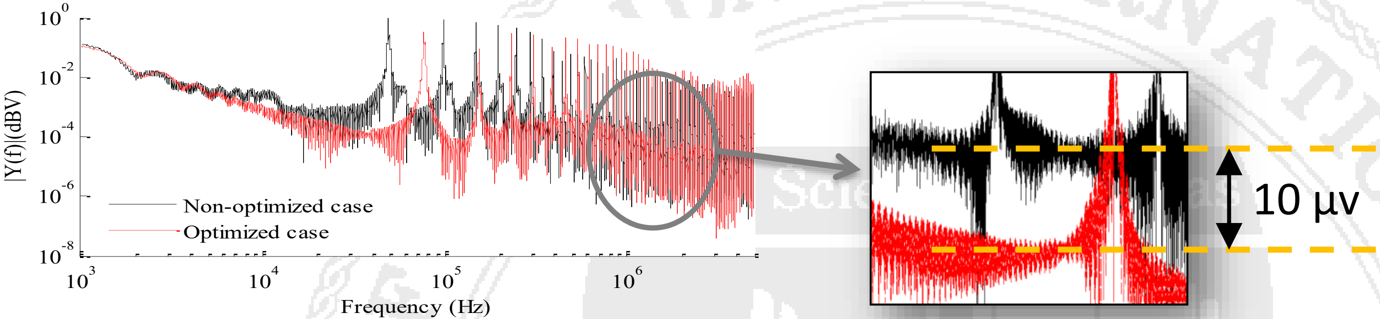



**Non-optimized case**

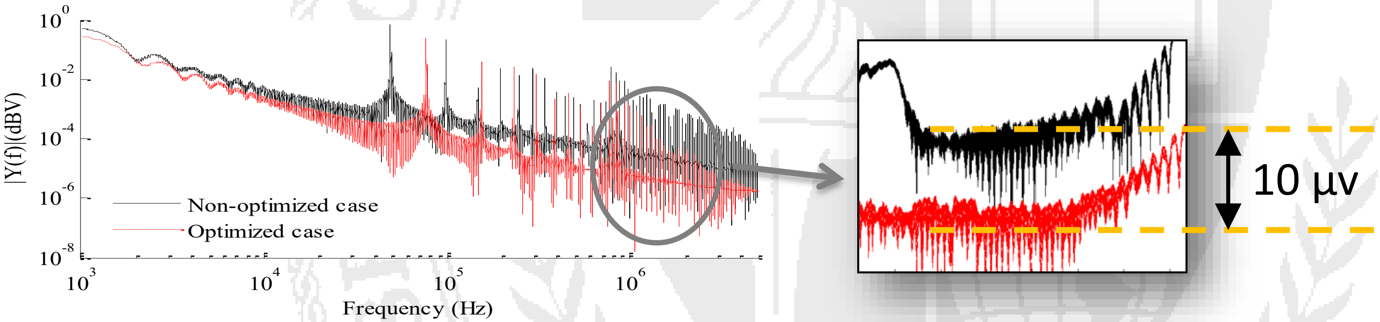



FFT spectrum of the ZCS-QRC Buck converter's output voltage

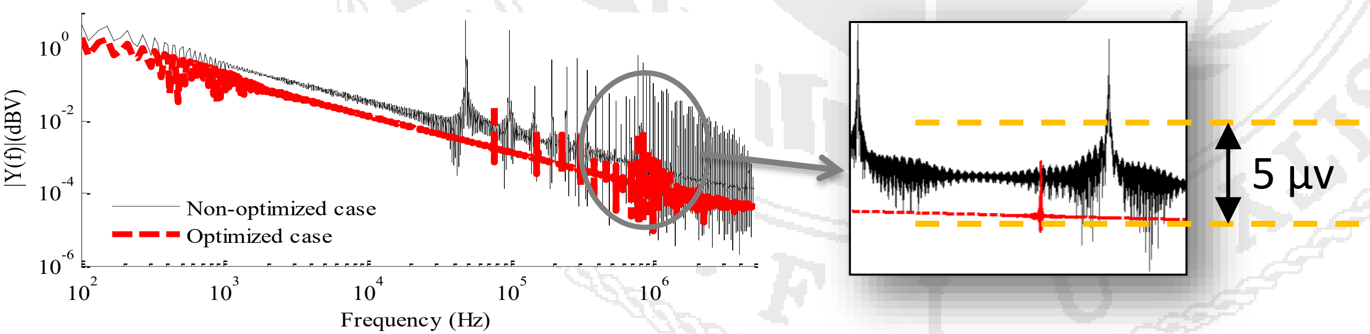
# Experimental Results and Discussion of Inductor placement optimization problem:




Resonant inductor's current




Filter inductor's current




Output voltage

- It's observed that using the optimization techniques on the operation parameters and geometry of the PCB, EMI is reduced.
- The Picture shows about 10 (dBuV) reduction in the signal oscillations.


Thank You