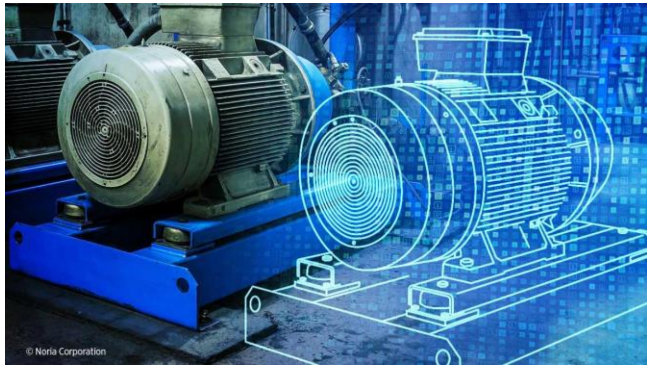
Stony Brook University | Spellman High Voltage Power Electronics Laboratory

Digital Twin based Health Management of Power Electronic converters



Power Symposium, IEEE LI Section

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Outline

- Introduction
- Condition Monitoring: Motivation
- Digital Twin: Basics and Flowchart
- Digital Twin Categorization: Modeling
- Self Evolving Digital Twin : Validation
- Digital Twin Demonstration

Power Electronics Revolutionizing Transportation

Source: NASA

Source: US Navy

Source: Hitachi

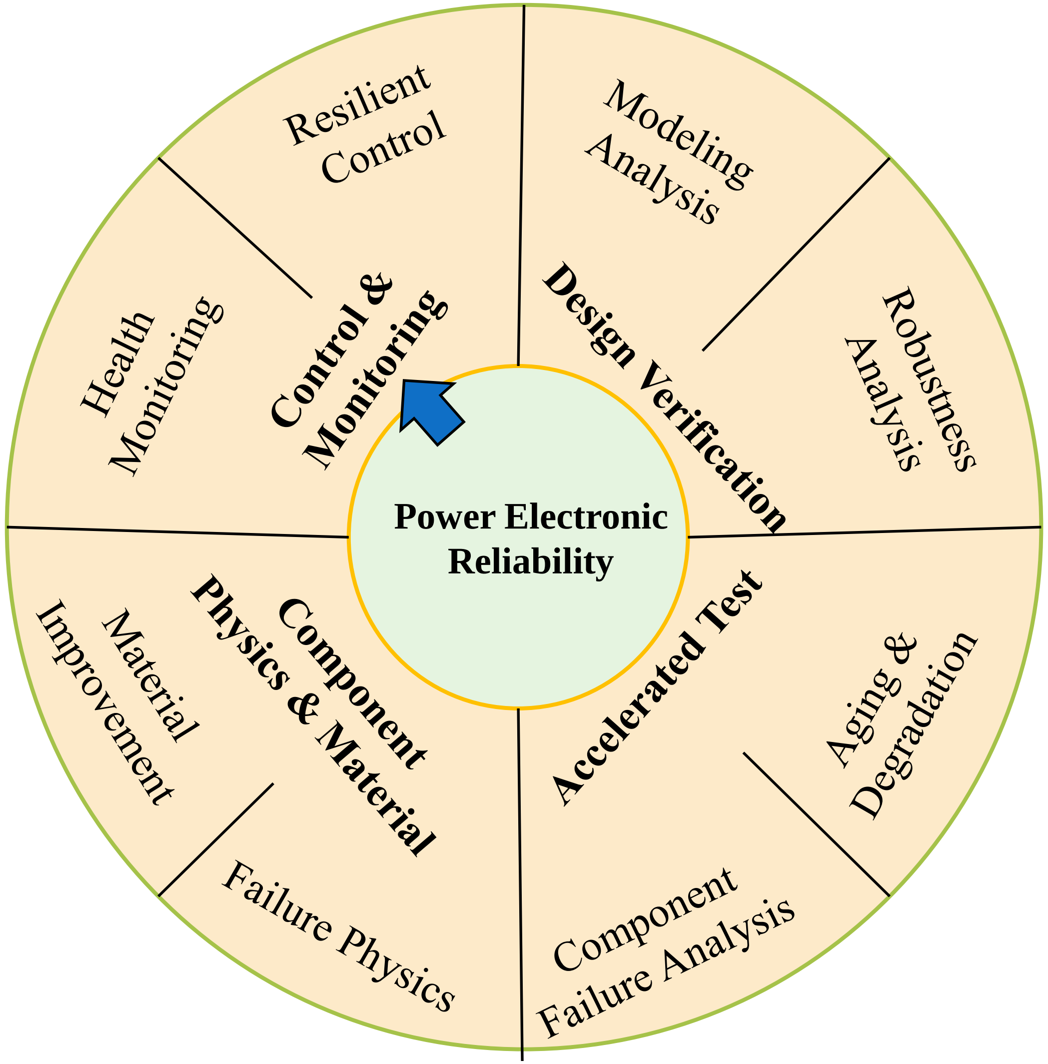
Source: John Deere

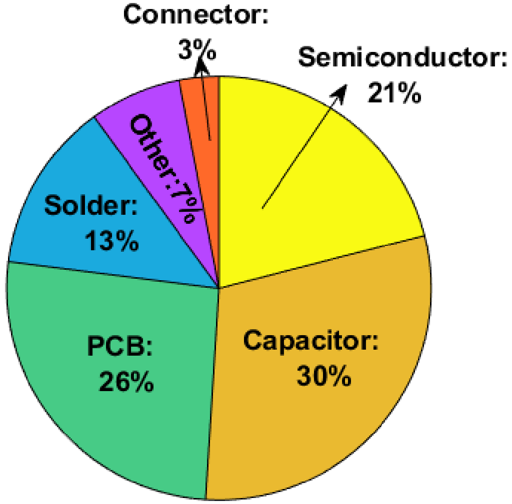
Source: Tesla

- **High power density and efficient power conversion is the key for**
  - Electrification of automotive and aviation Industry
  - Management and grid integration of Distributed Energy Resources (DER), such as photovoltaic and wind
- **Wide bandgap devices (SiC and GaN) are adopted to achieve the goal over Si**
  - Offers faster switching speed, thus, lower switching loss and overall volume reduction
- **Second Order Concerns Due to Faster Switching are Concern to System Reliability**
  - Reflected wave, EMI noise, partial discharge, communication interface, integration interactions, etc
  - Health and Fault Monitoring → Condition Monitoring becomes very important

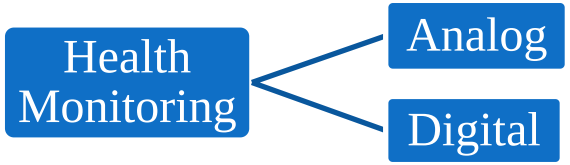
Stony Brook University

Motivation: Why and how of it?





Component Wise Reliability Failure Analysis



Analog:
- ✓ High Density Data
- ✓ Accuracy and speed
- X Complexity

Digital:
- ✓ Flexibility and Scalability
- ✓ Data-Driven Insights & Optimization
- ✓ Robustness
- X Speed
- X Loss of Information

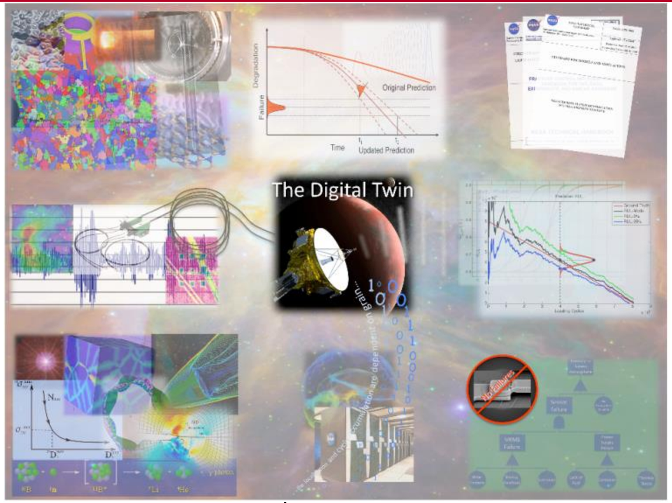
S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran and P. Tavner, "Condition Monitoring for Device Reliability in Power Electronic Converters: A Review," in IEEE Transactions on Power Electronics, vol. 25, no. 11, pp. 2734-2752, Nov. 2010, doi: 10.1109/TPEL.2010.2049377.

Digital Twin- Origins/Timeline

Prof. Michael Grieves
Purdue University **: 2003**

John Vickers and Prof. Micheal Grieves
NASA: **2010**

……………….



- "Digital Twin was coined in terms of product life-time management"
- virtual product representations→ manually collected data

Digital Twin as a virtual representation of a physical product containing information about said product

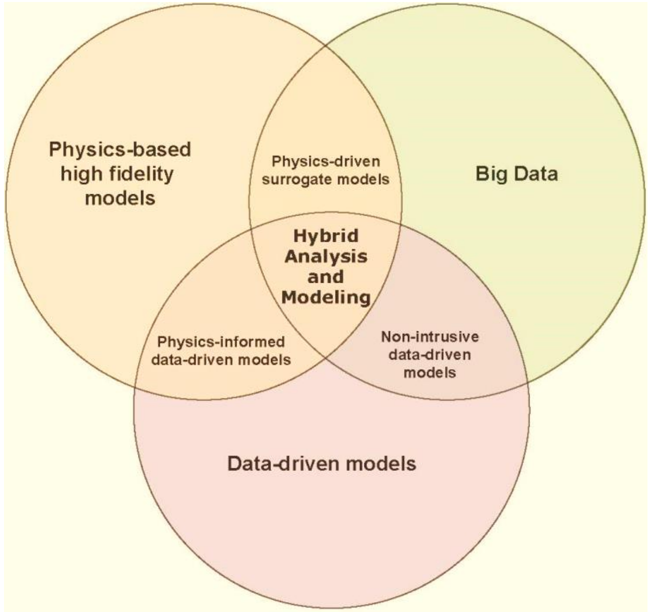
- More mature definition covering communication layer as well

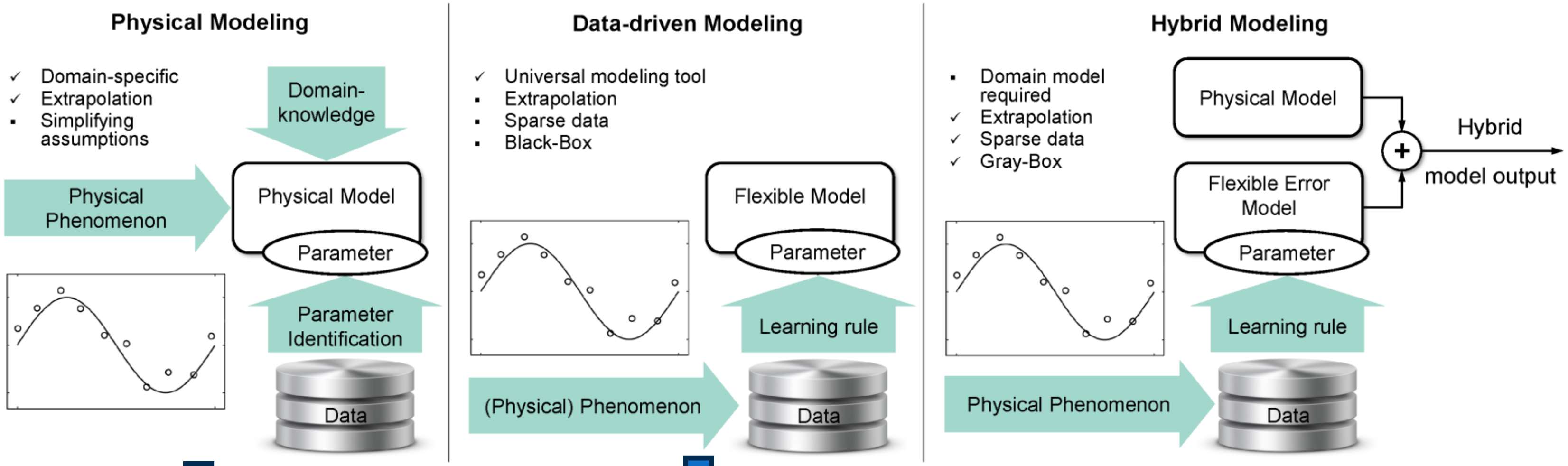
Digital Twin as consisting of three components,
A physical product, a virtual representation of that product, and the bi-directional data connections that feed data from the physical to the virtual representation, and information and processes from the virtual representation to the physical.

First white paper → NASA: **2012**

- It was for product lifetime management for aircraft systems.

Digital Twin: Models Categorization

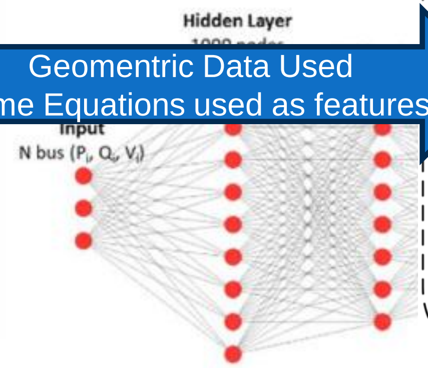




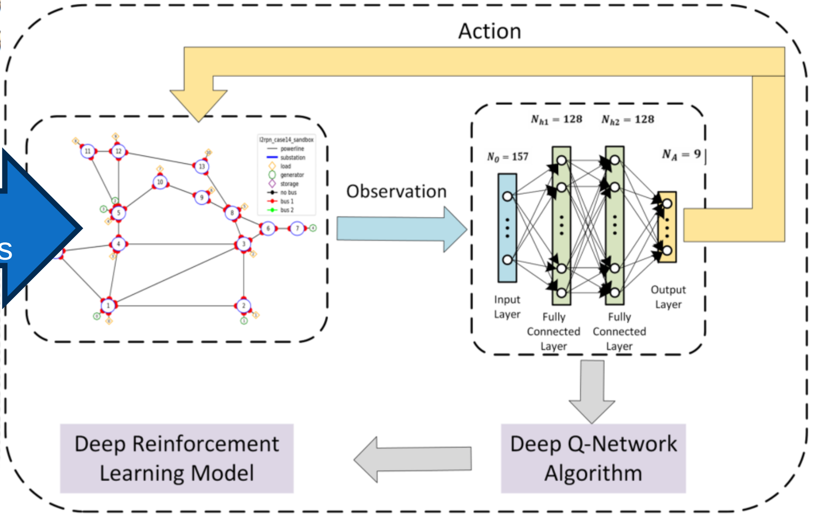
Big Data Solution

$P_i - \sum_{k=1}^{N} |V_i|\,|V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta$

$Q_i - \sum_{k=1}^{N} |V_i|\,|V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta$

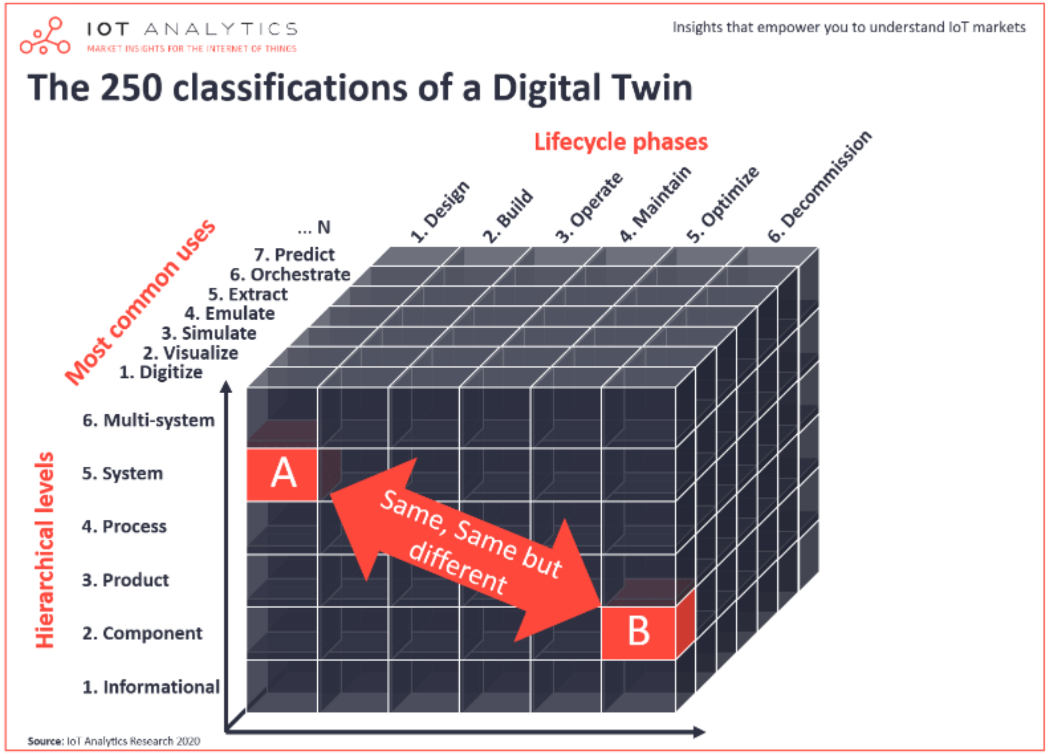


Geomentric Data Used
Some Equations used as features



Big Data Problem

Health Management Categorization: Digital Twin



DT Used Cases

1.**Digitize**: Any digitized information
2.**Visualize**: Basic digital representation of a physical object
3.**Simulate**: Simulation model of a physical system in its environment
4.**Emulate**: Emulation model of the physical system with real software
5.**Extract**: Extraction model of real-time data streams, physical to virtual system
6.**Orchestrate**: Orchestration model for virtual control/updating of physical devices
7.**Predict**: Prediction model to predict future behavior of the physical system

DT based Life Cycle Phases

1.**Design:** Designing a product based on DT.
2.**Build**: Build more cost intensive physical counterparts for testing using Dt based geometric modeling.
3.**Operate**: DT helps in maintaining operating levels. i.e Controls
4.**Maintain**: Reliability and cyber threat detection during operation.
5.**Optimize**: DT helps optimize operating condition or power flow amongst multiple systems. i.e Distributed networks
6.**Decommission**: The decommissioning physical system based on DT based lifetime prediction.

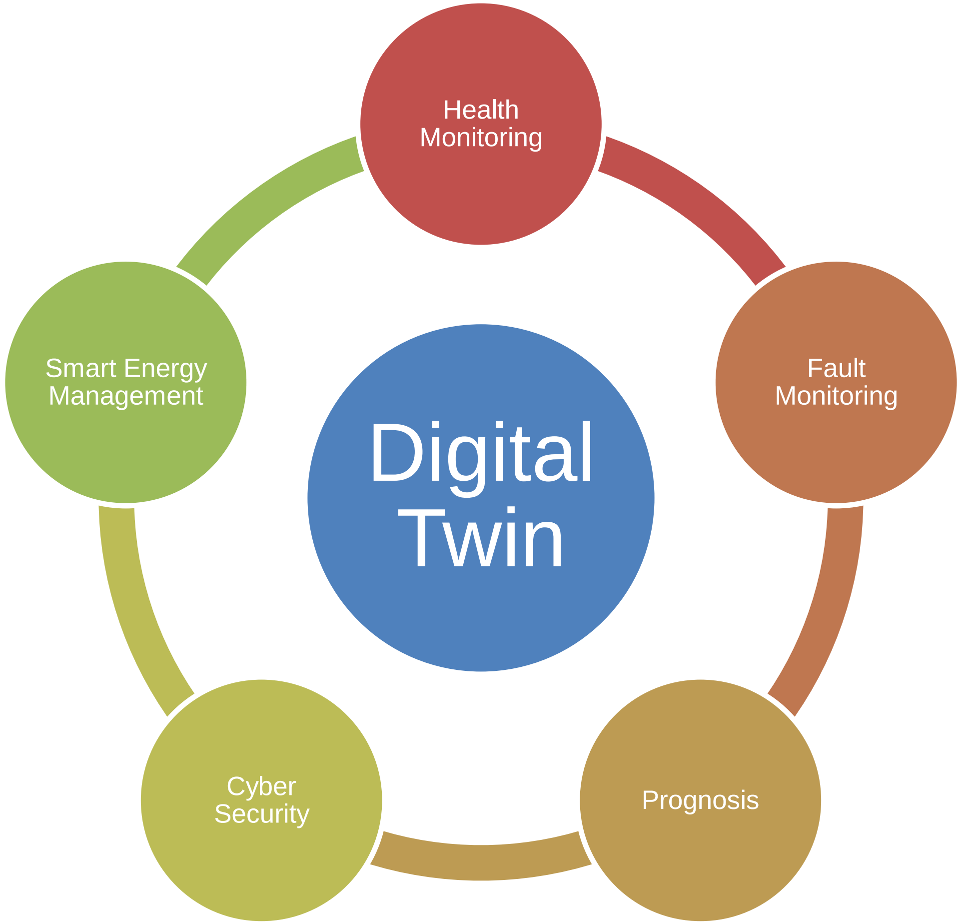
Hierarchical Levels

1. **Informational**: Digital manuals and documents.
2. **Component:** Virtual representations of individual parts.
3. **Product:** Interoperable component representations.
4. **Process**: Virtual representation of production processes.
5. **System**: Digital twins for multiple processes.
6. **Multi-system**: Integrated digital twins for diverse systems.

Basics and Components of Digital Twin

Digital Twin Definition

- **Digital twin is a virtual representation of a physical system.**
  - It shares same characteristics with its physical counterpart.
- **Applications: for installed physical systems in real time**
  - Used to better understand: Noise and Operation
  - Optimize: Control and Power Sharing
  - Predict: Aging , Degradation and abnormalities
  - Monitor the performance
- **Basically, digital twin is a looped system implementation consisting of**
  - Physical system
  - Sensors
  - Information processing unit and actuators
  - Communication



Proposed Health Monitoring

System Level [1-5]

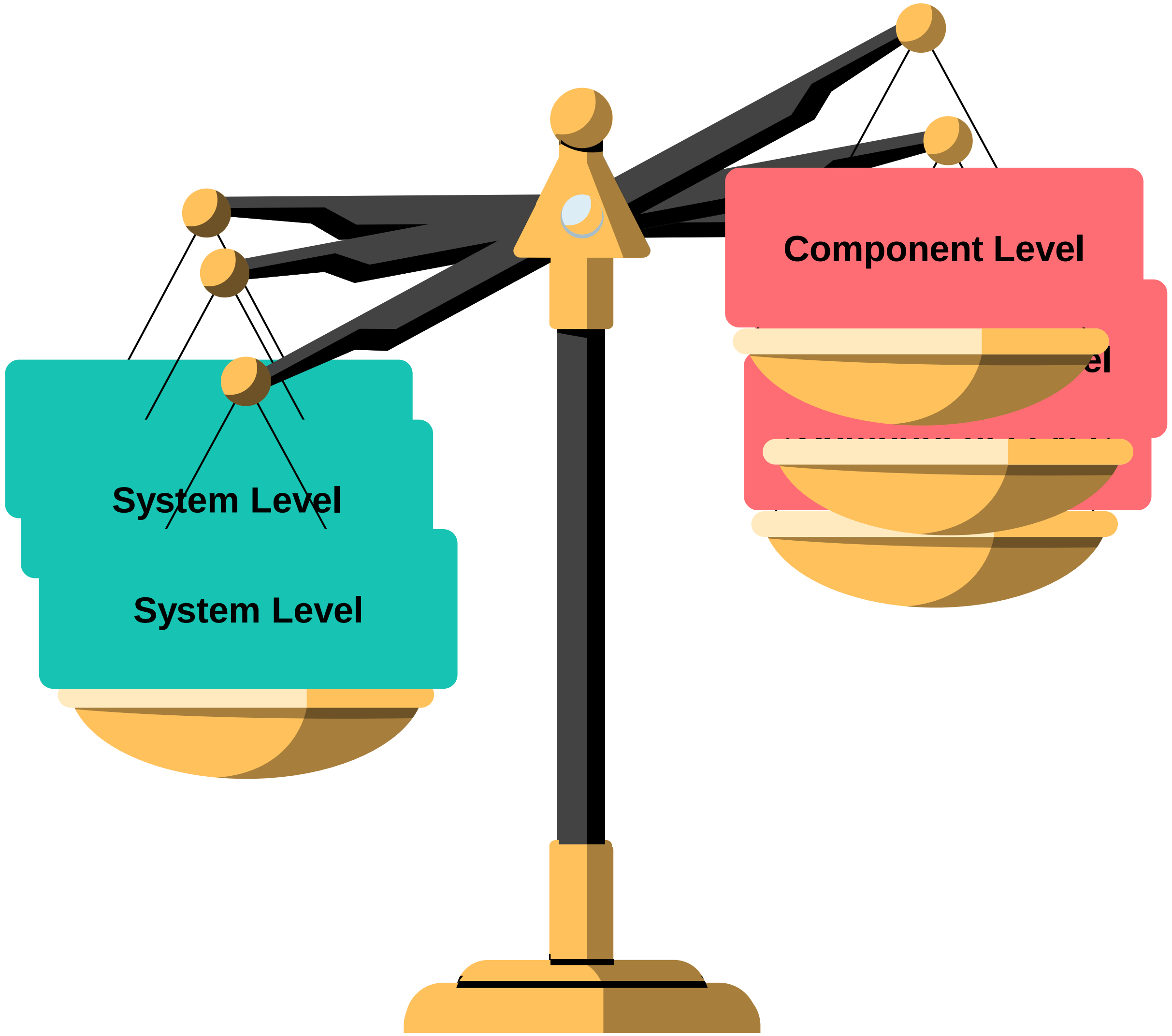
- ✓ Less Invasive
- ✓ Easy Implementation
- ✓ Less Sensor
- × Less Accurate

Monitoring Approach

- ➢ Online
- ➢ Offline

Model

- ➢ Physics Based
- ➢ Data Driven
- ➢ A.I. Based
- ➢ Noise Injection Based



Component Level [6-14]

- × More Invasive
- × Complex Hardware Implementation
- × More Sensor/circuitry
- ✓ More Accurate

K. Choksi, A. B. Mirza, A. Zhou, D. Singh, M. Hijikata and F. Luo, "Self-Evolving Digital Twin-Based Online Health Monitoring of Multiphase Boost Converters," in IEEE Transactions on Power Electronics, vol. 38, no. 12, pp. 16100-16117, Dec. 2023, doi: 10.1109/TPEL.2023.3311710.

Basic Mathematical Formulation

$$\textbf{minimize}: (f_{obj}) \quad (L, C, RDSON, Rc, RL)$$

$$f_{obj} = \alpha f_{obj2} + ß f_{obj2}$$

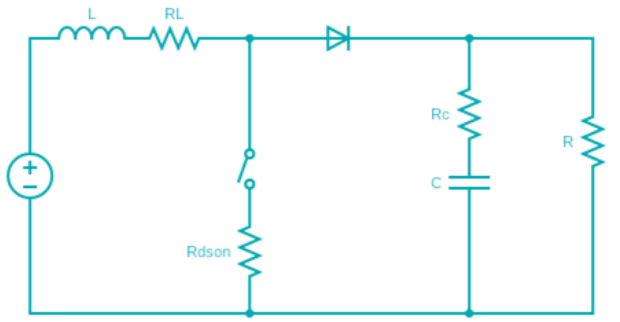
$$f_{obj1} = \sum_{k=1}^{n} (i_{L,M}{}^{k} - i_{L,A}{}^{k})^2 \qquad f_{obj2} = \sum_{k=1}^{n} (V_{C,M}{}^{k} - V_{C,A}{}^{k})^2$$

$$\textbf{variables}: \quad V_{C,M} = f(L, C, RDSON, Rc, RL)$$

$$i_{L,M} = f(L, C, RDSON, Rc, RL)$$

- $V_{C,M}$: Computed
- $i_{L,M}$: Sensor Data
- $V_{C,A}$: Computed
- $i_{L,A}$: Sensor Data

Boost Converter Hardware



subject to:

$$L_{min} < L \le Lmax$$

$$C_{min} < C \le Cmax$$

$$R_{DSON,min} < R_{DSON} \le R_{DSON,max}$$

$$R_{L,min} < R_L \le R_{L,max}$$

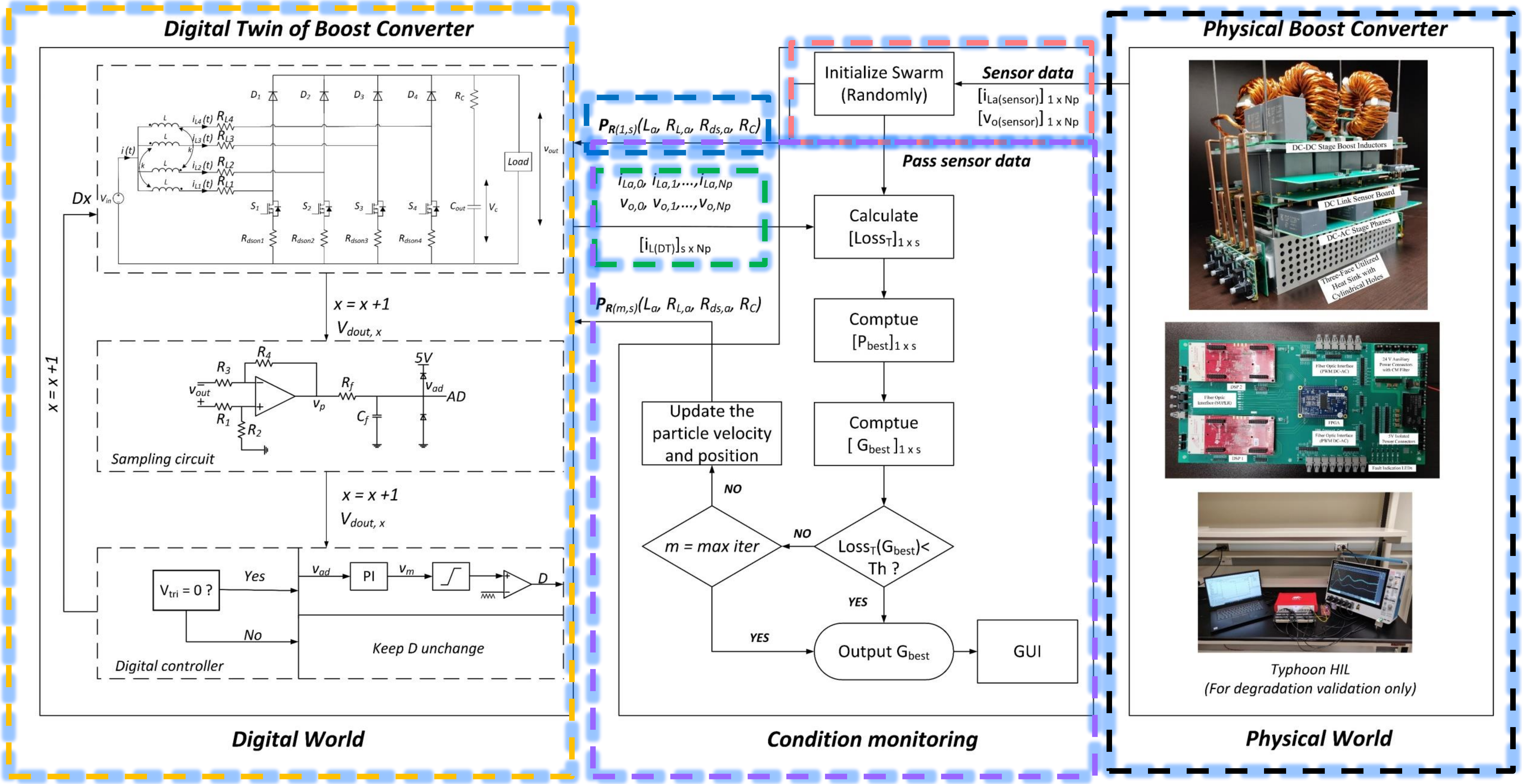
$$R_{c,min} < R_c \le R_{c,max}$$

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_L}{L} + \frac{DR_d}{L}\right) - \frac{(1-D)}{L} \frac{RR_c}{(R+Rc)L} & \frac{-(1-D)}{L} + \frac{-(1-D)}{L} \frac{V_c R_c}{(R+Rc)L} \\ \frac{(1-D)}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [V_{in}]$$

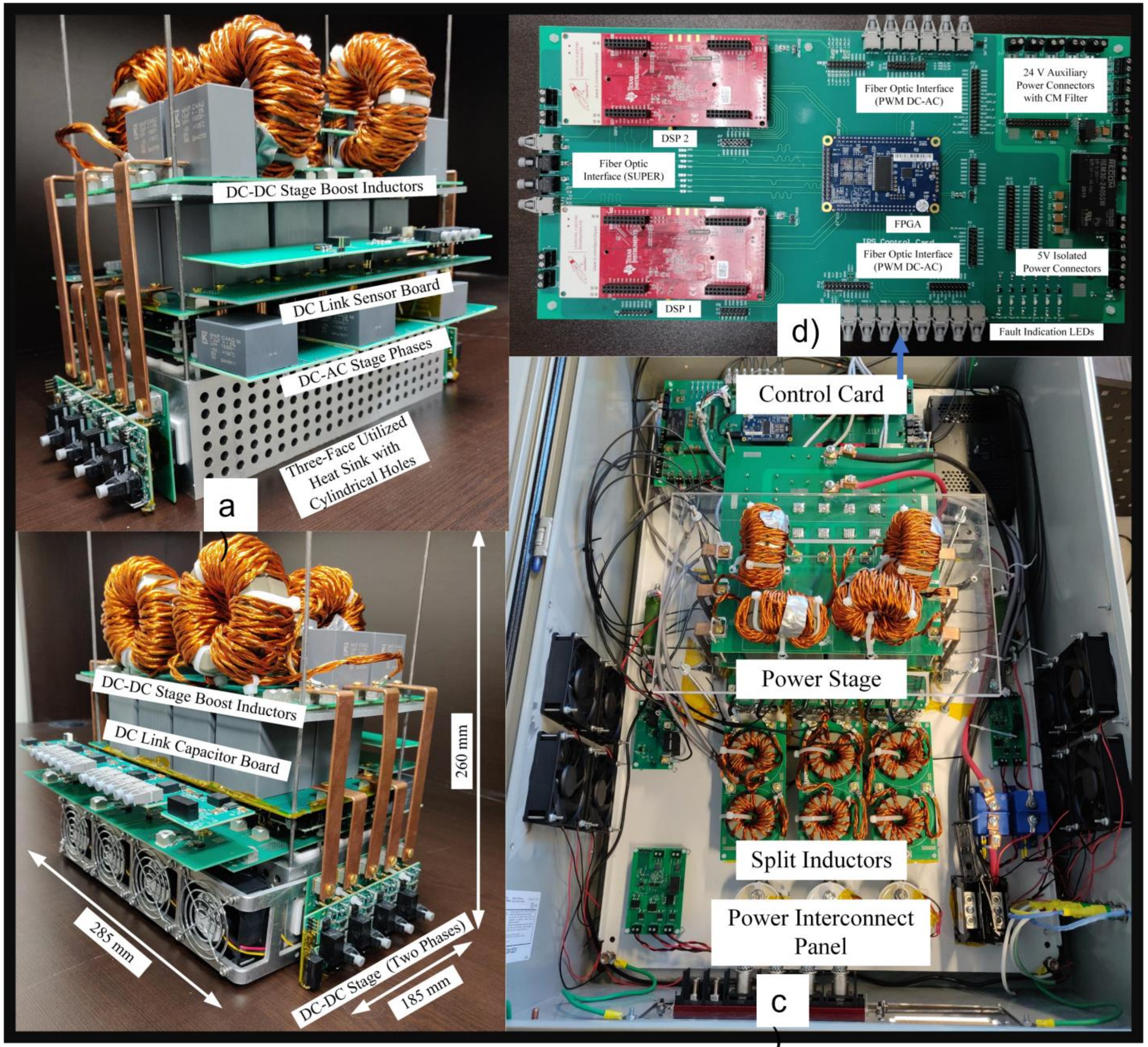
State Equations: Piece Wise Linear Differential Equation

- This can be solved using RK 4th order ODE
- Compared with Physical System to get $fobj$
- PSO can be used to estimate health of original system

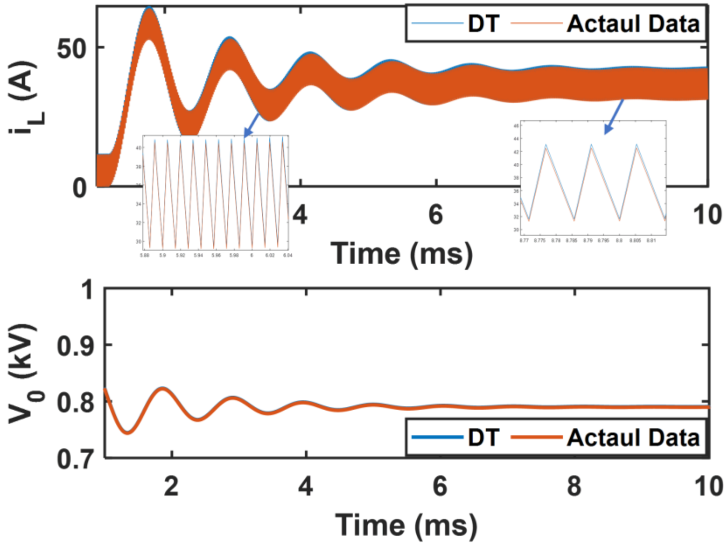
Digital Twin based Condition Monitoring: Flowchart



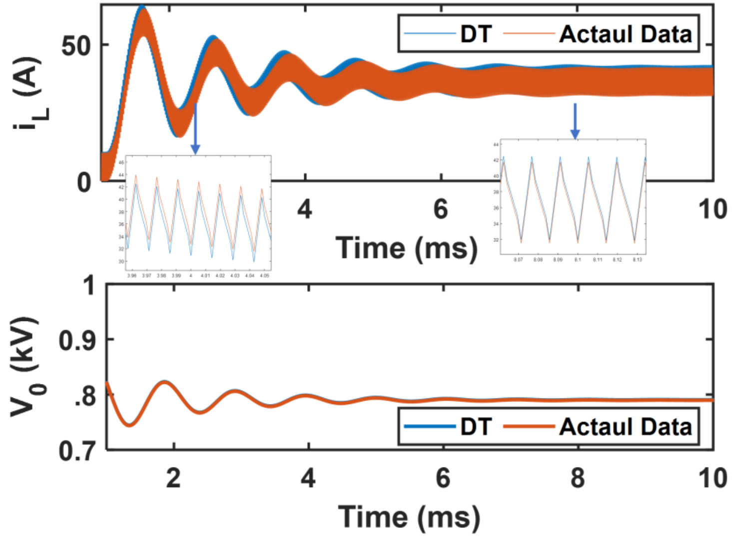
DT Performance



Experimental Setup



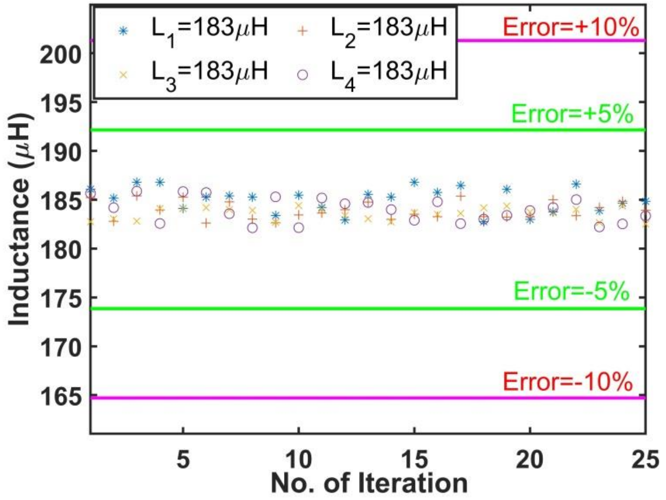
Uncoupled 4 Phase DT Modeling

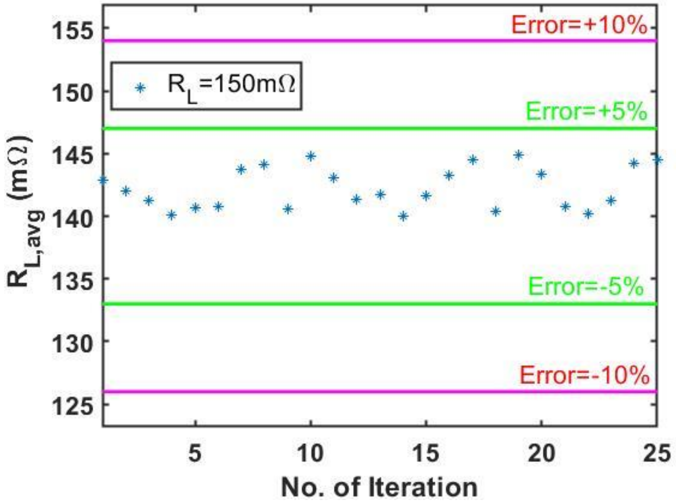


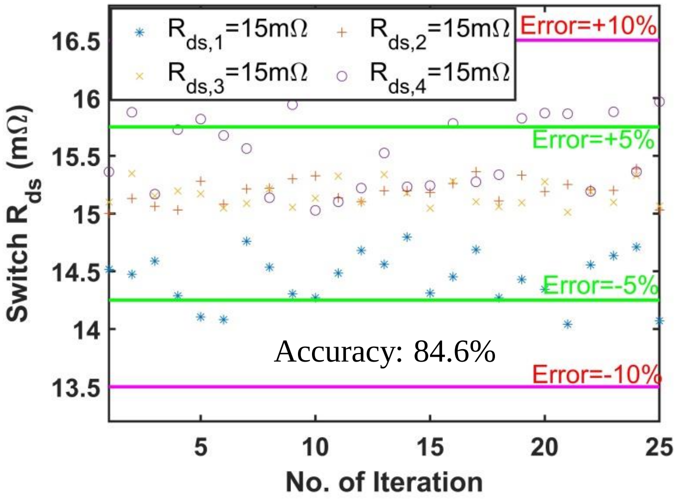
Coupled 4 Phase DT Modeling

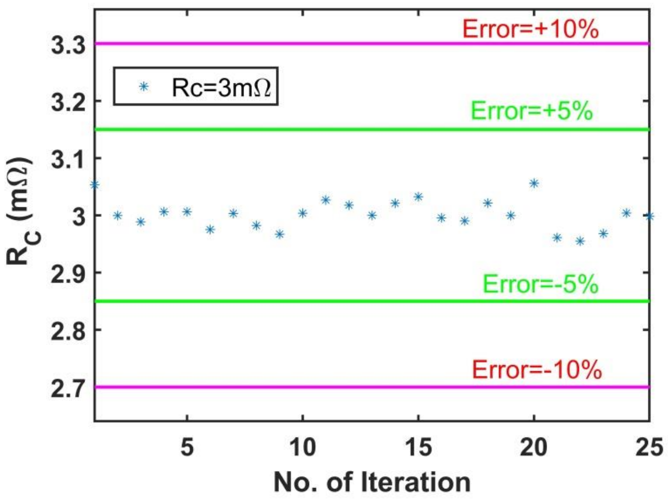
Parameter Identification

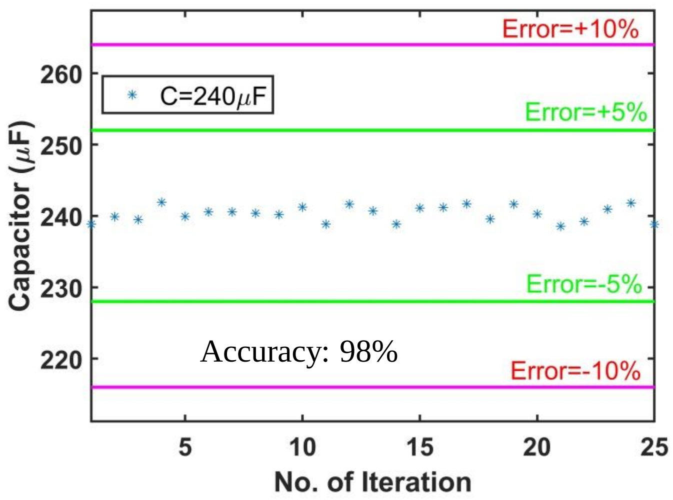
Phase Leg	Actual Values of Parameter				
	$L(\mu H)$	$R_L(m\Omega)$	$R_{ds,on}(m\Omega)$	$R_C(m\Omega)$	$C\mu F$
1	183	147	15		
2	182	148	15	3.5	240
3	184	150	15		
4	183	151	15		



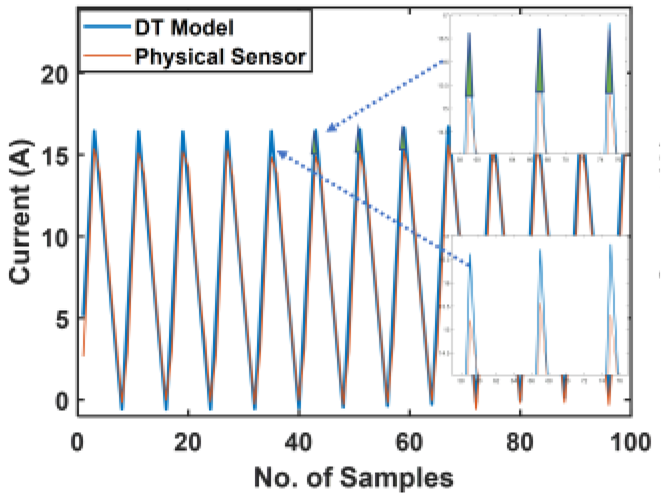




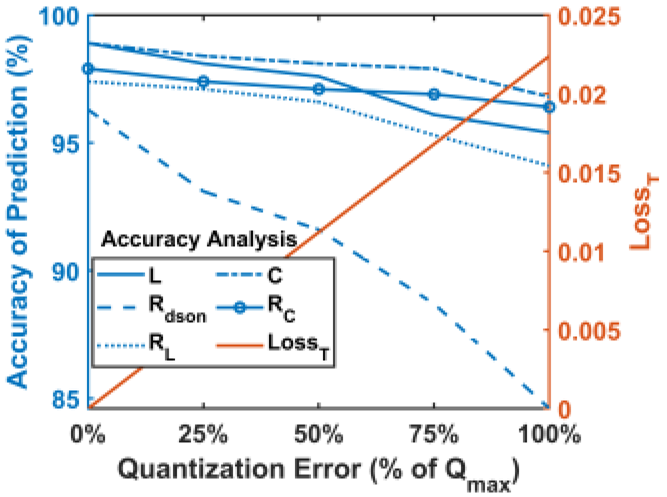




Impact of Error: DT Accuracy



(a) Quantization Error



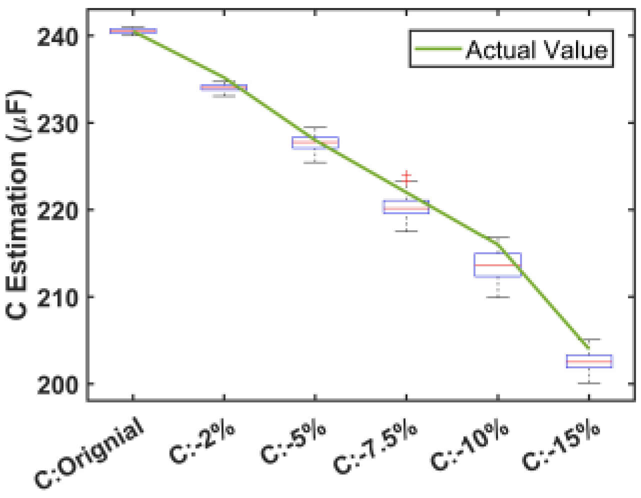
(d) Impact of Quantization Error

- Error due Analog to Digital
  - ADC Resolution
  - Sensor Resolution
  - Low Sampling Frequency
  - It is worth noting that Nyquist
  - As Triangular Wave are infinit

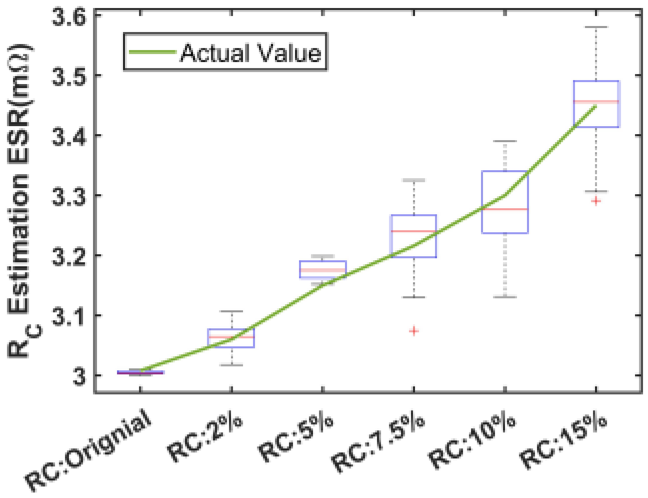
- DC offset Error
  - Sensor Metastability
  - External EMI Noise
  - ADC Metastability

- Synchronization Error
  - Non linear sampling delay
  - Non linear sensing delay
  - Communication delay

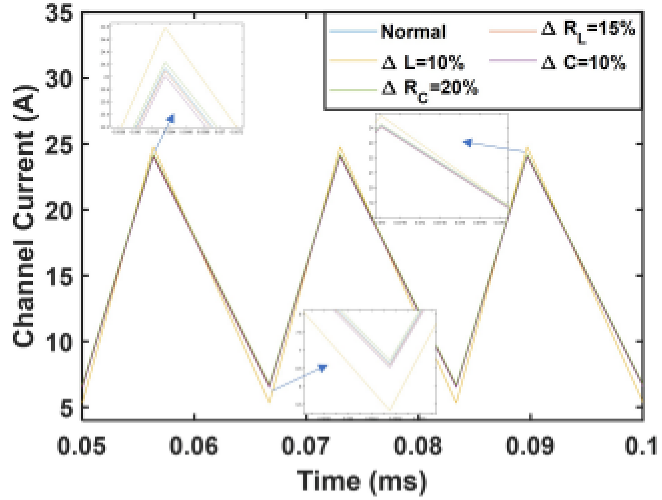
Impact of Degredation



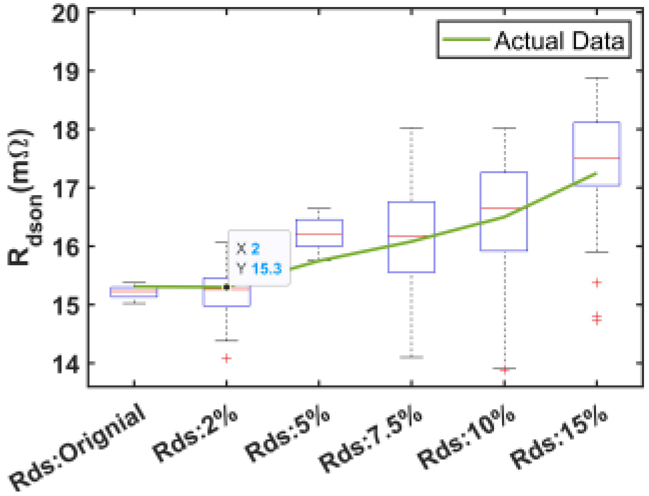
(a) C Degradation: Boxplot Analysis



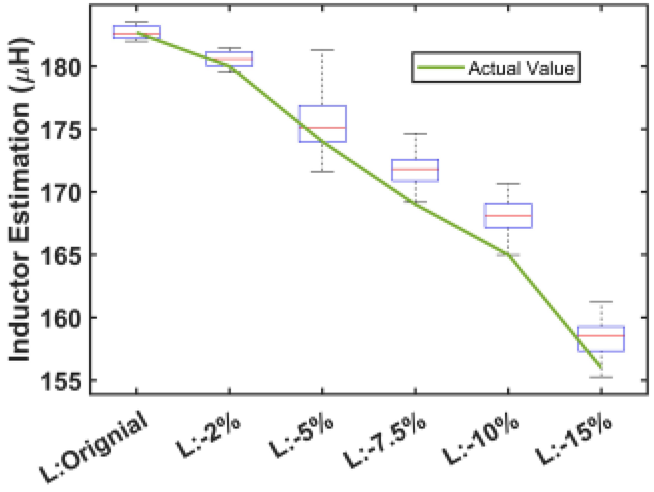
(b) R_C Degradation: Boxplot Analysis



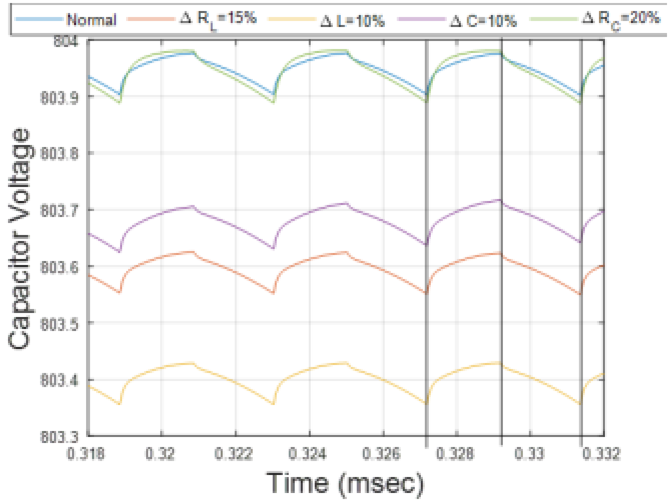
(c) Impact of degradation on state variable i_L



(d) $R_{ds,on}$ Degradation: Boxplot Analysis



(e) L Degradation: Boxplot Analysis



(f) Impact of degradation on state variable v_c

Summary

- **Development of system level meta heuristic condition monitoring approach for boost converter health monitoring.**
  - Parameter identification: 84~96%
  - It is an online, robust, calibration free and non invasive approach
  - It is extendable to various interleaved boost converters

Future Scope/work

- **Digital twins will be an important part of power electronics**
  - Condition Monitoring
  - Maintenance scheduling
  - Controls
  - Lifetime scheduling
- **Hierarchical DT based approaches**
- **Fault monitoring compared to analog protection methods**

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