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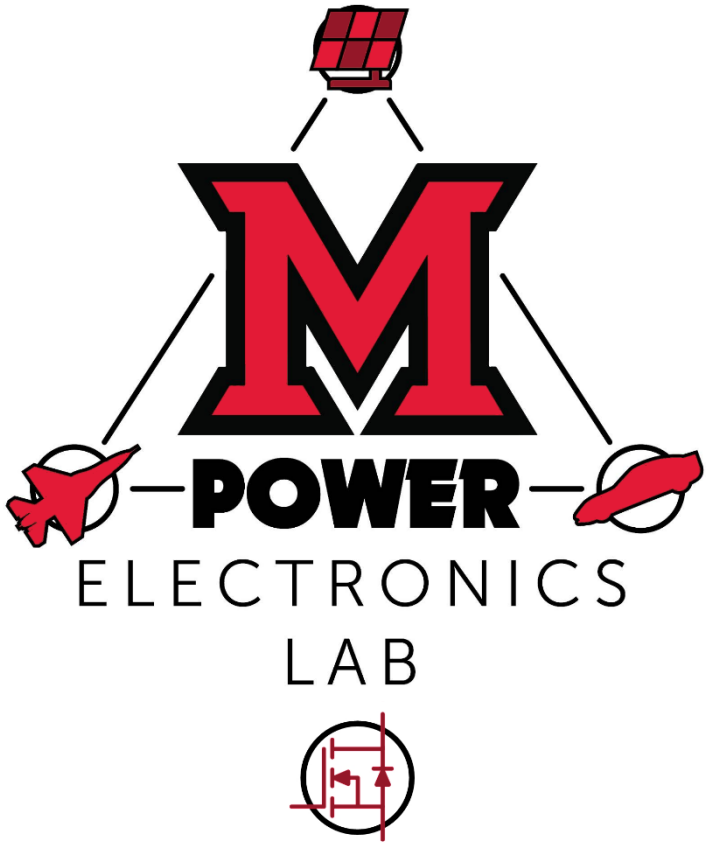
COLLEGE OF ENGINEERING AND COMPUTING
Electrical & Computer Engineering



Conditional Monitor Techniques for Capacitors

Presented By: Dr. Mark Scott

Date: 03/16/2019

Introduction

I. Background and Motivation

II. Failure Mechanisms in DC Link Capacitors

III. Conditional Monitoring Techniques for Capacitors

IV. Electromagnetic Spectral based PHM Approach (E-PHM)
- Theory
- Results

V. Conclusion

Applications of Power Electronics

250 MW PV Plant (Portugal)
http://www.sfgate.com/business/article/PG-E-plans-big-investment-in-solar-power-3199510.php

Tesla Model S
http://www.caranddriver.com/tesla/model-s

Aircraft and High Speed Rail
http://www.bombardier.com/en/about-us/history.html

Google Server Room
https://planetsurprises.wordpress.com/2012/10/18/google-server-room/

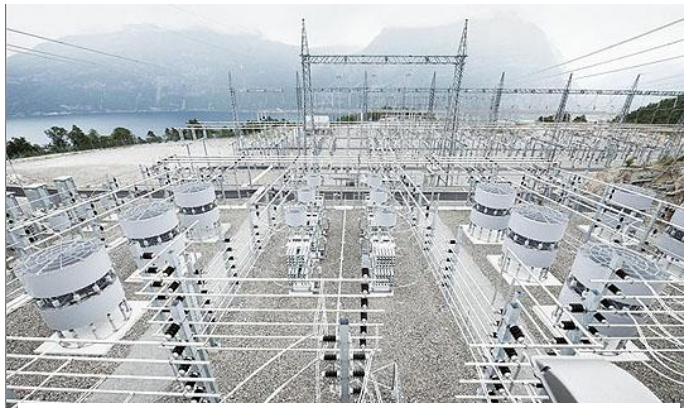
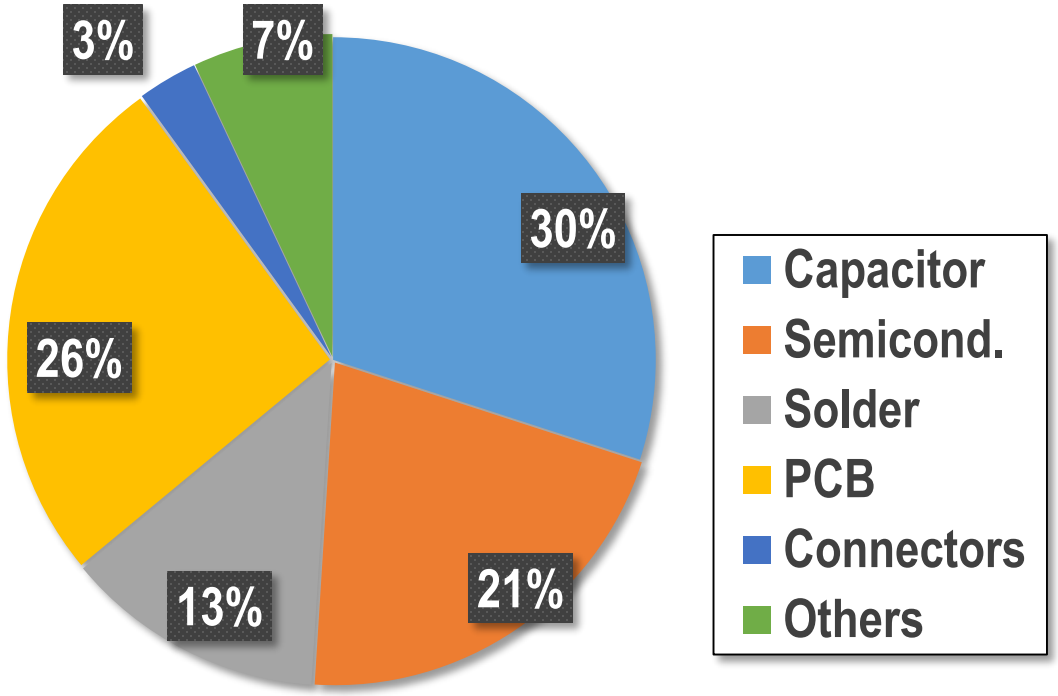


ABB SVC: Norway
http://www.abb.com/cawp/seitp202/c36f4e62da52ab46c1257670003690d3.aspx

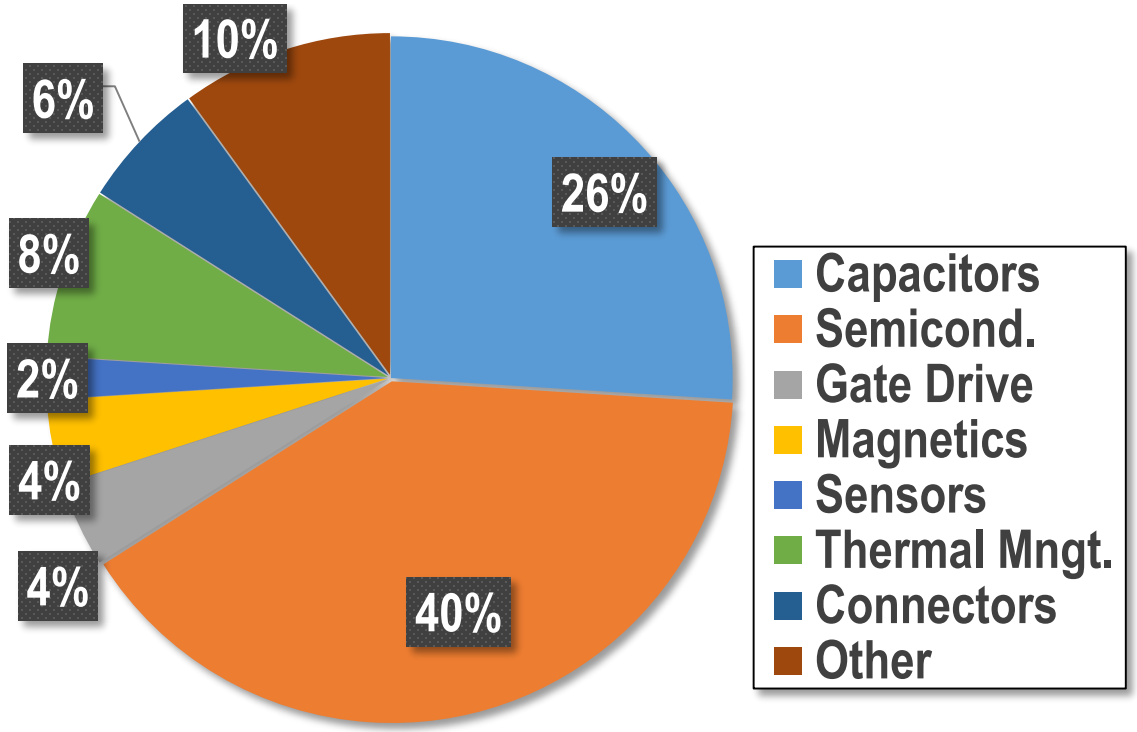
SpaceX Dragon V2
http://www.electronicsweekly.com/uncategorised/space-spacex-dragon-v2-ready-crew-2014-05/

Weak Points in Power Electronics

- **Semiconductor switching devices & capacitors** are the most likely elements to fail in power electronics [1].



Breakdown of Failure in Power Electronics (2007) [2]



Components in need of reliability improvements (2018) [3]

[1]. **Y. Avenas et al.**, *IEEE Ind. Electron. Mag.*, vol. 9, No. 4, pp. 22-36, Dec. 2015.

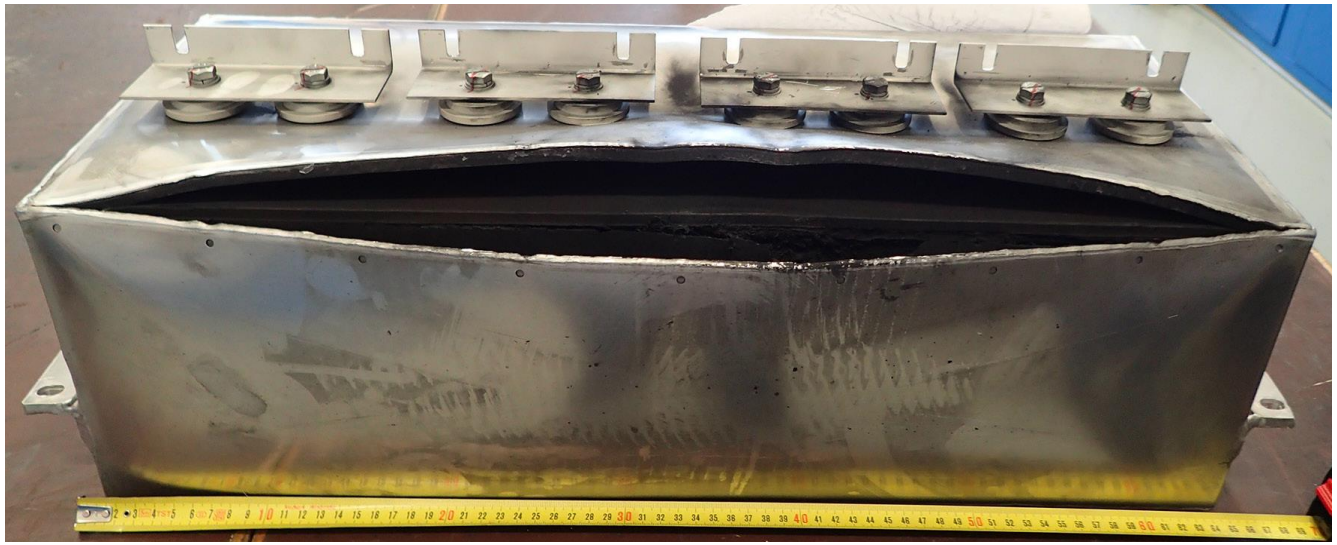
[2]. **S. Yang et al.**, *IEEE Trans. Power Electron.*, vol. 25, no. 11, pp. 2734-2752, Nov. 2010.

[3]. **J. Falck et al.**, *IEEE Ind. Electron. Mag.*, pp. 24-35, 2018.

Film Capacitor Failures in Light Rail

- Melbourne, Australia – December 2014.
- Guildford, London – July 2017.

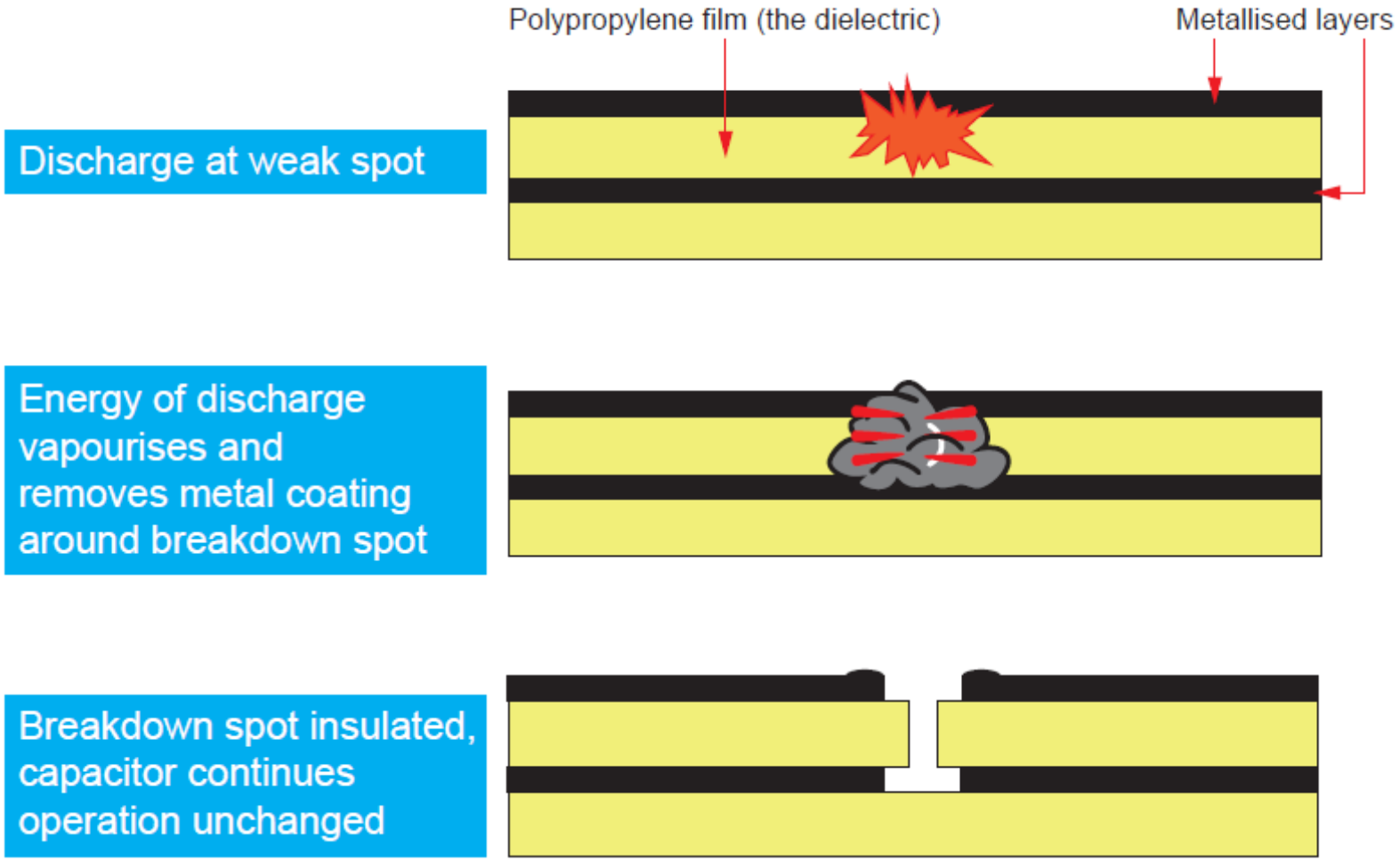
CCTV of Inverter Exploding [1]



11 mF Film Capacitor Bank after Failure [2]

[1]. M. Wong, "Melbourne's Exploding Siemen's Trains", [Online] *Available: https://wongm.com/2015/01/melbourne-exploding-siemens-trains/*
[2]. *Rail Accident Report – Explosion inside an underframe equipment case at Guilford, 7 July 2017,* Rail Accident Investigation Branch, Report 05/2018. [Online] *Available:* https://assets.publishing.service.gov.uk/media/5acb313ded915d5a90e44be4/R052018_180320_Guildford.pdf

Film Capacitors – Self Healing

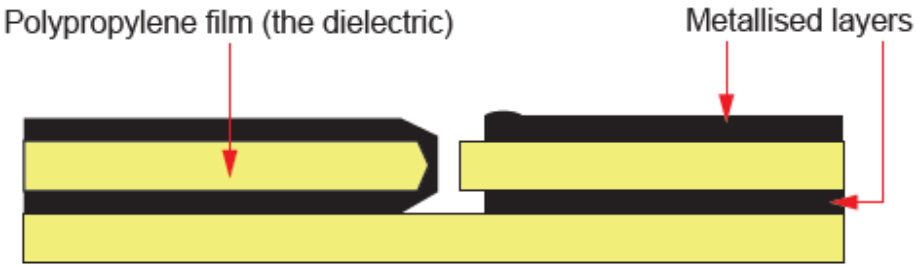


Self Healing Capability [1]

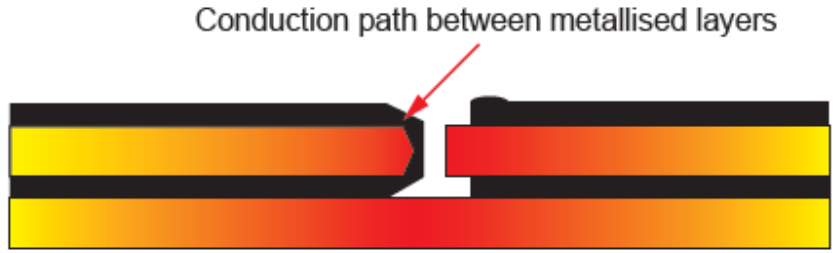
[1]. **Rail Accident Investigation Branch**, Report 05/2018.

Film Capacitors – Explosion [1]

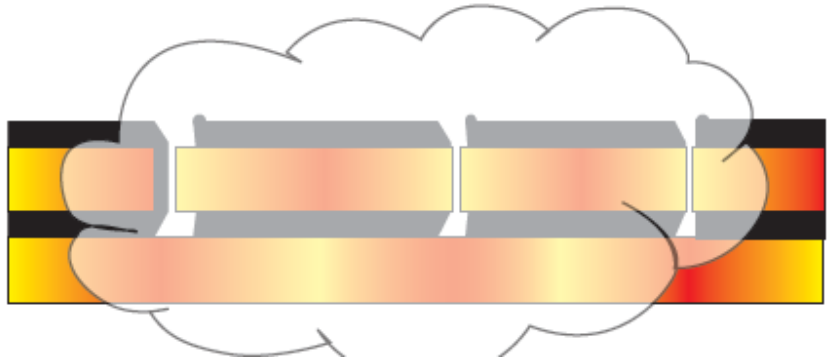
Incomplete insulation, leakage current rising slowly



Step-by-step increase of temperature around the breakdown spot

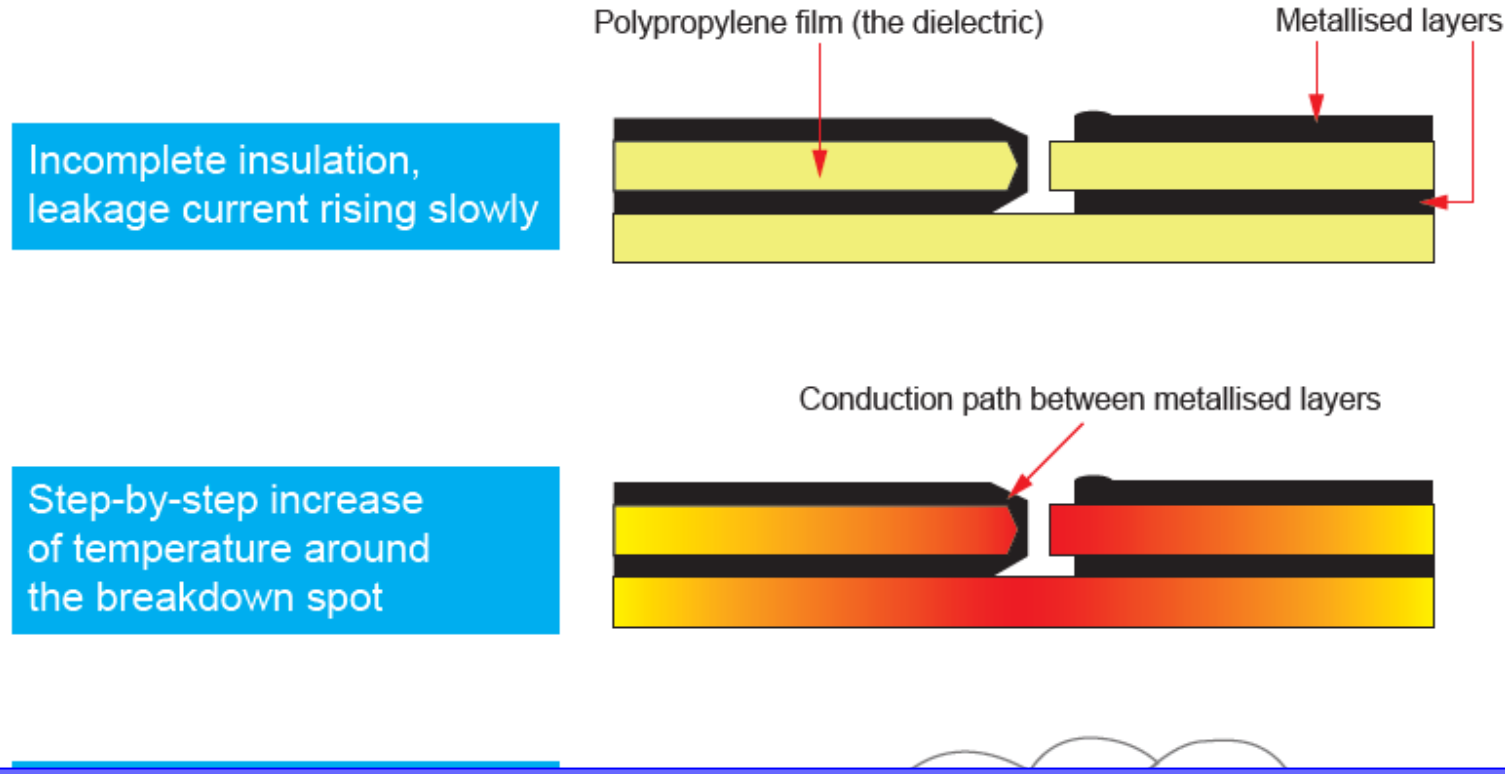


Decomposition of Polypropylene film leads to runaway process of further breakdowns, release of gas and pressure rise inside capacitor case



[1]. **Rail Accident Investigation Branch**, Report 05/2018.

Film Capacitors – Explosion [1]



Solutions:

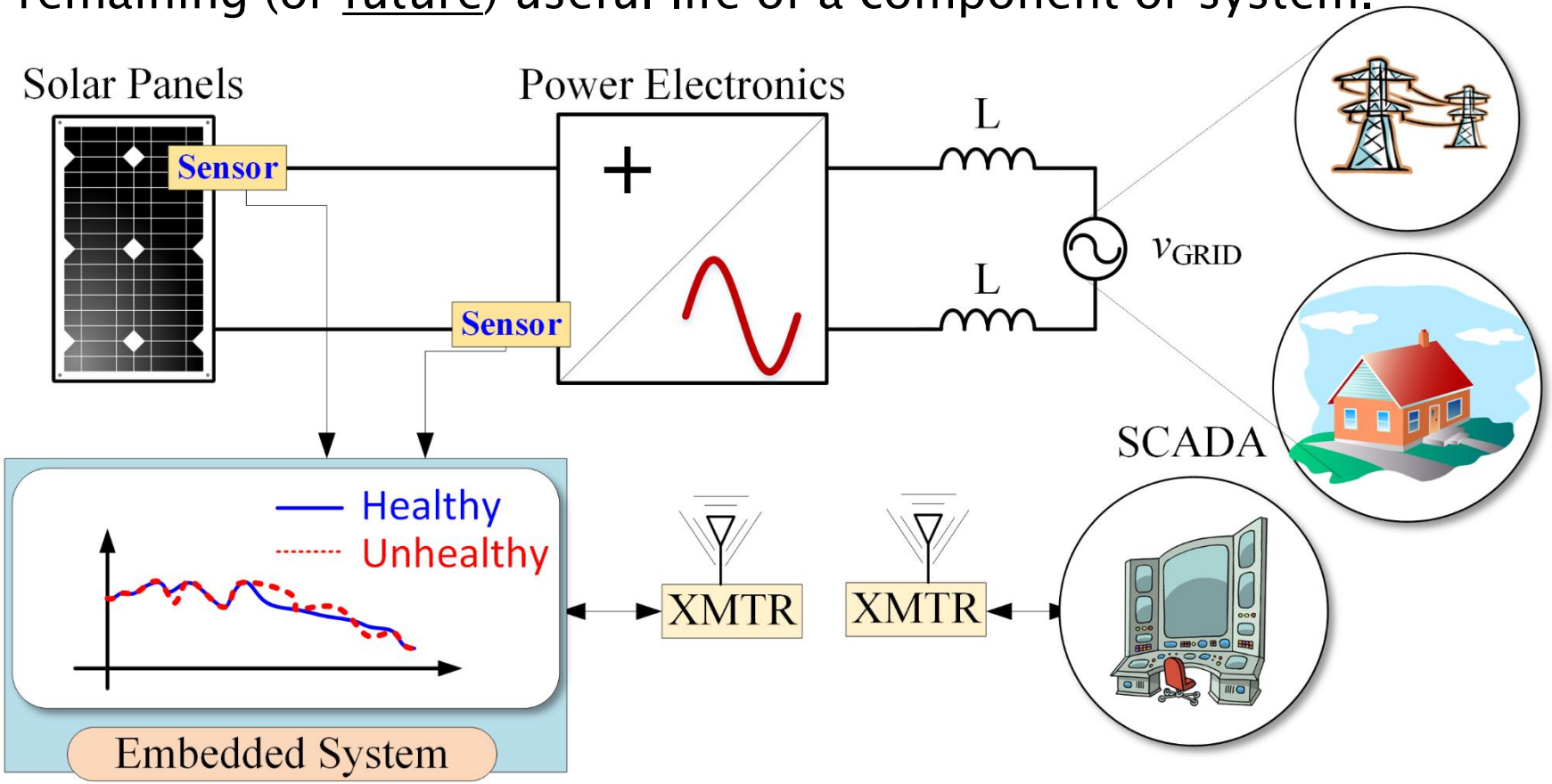
1. Change capacitors often (before the end of their lifetimes)
2. Remove capacitors and evaluate them.
3. Install intelligent systems that provide situational awareness.

Branch, Report 05/2018.

What is PHM?

Prognostic and Health Management (PHM) Systems:

- Monitor the current health of a system's components to ensure safe operation.
- Estimates the remaining (or future) useful life of a component or system.



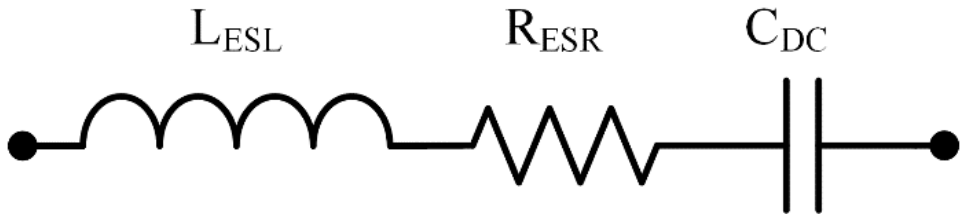
Capacitors Parameters and Aging

DC Link Capacitor Types:

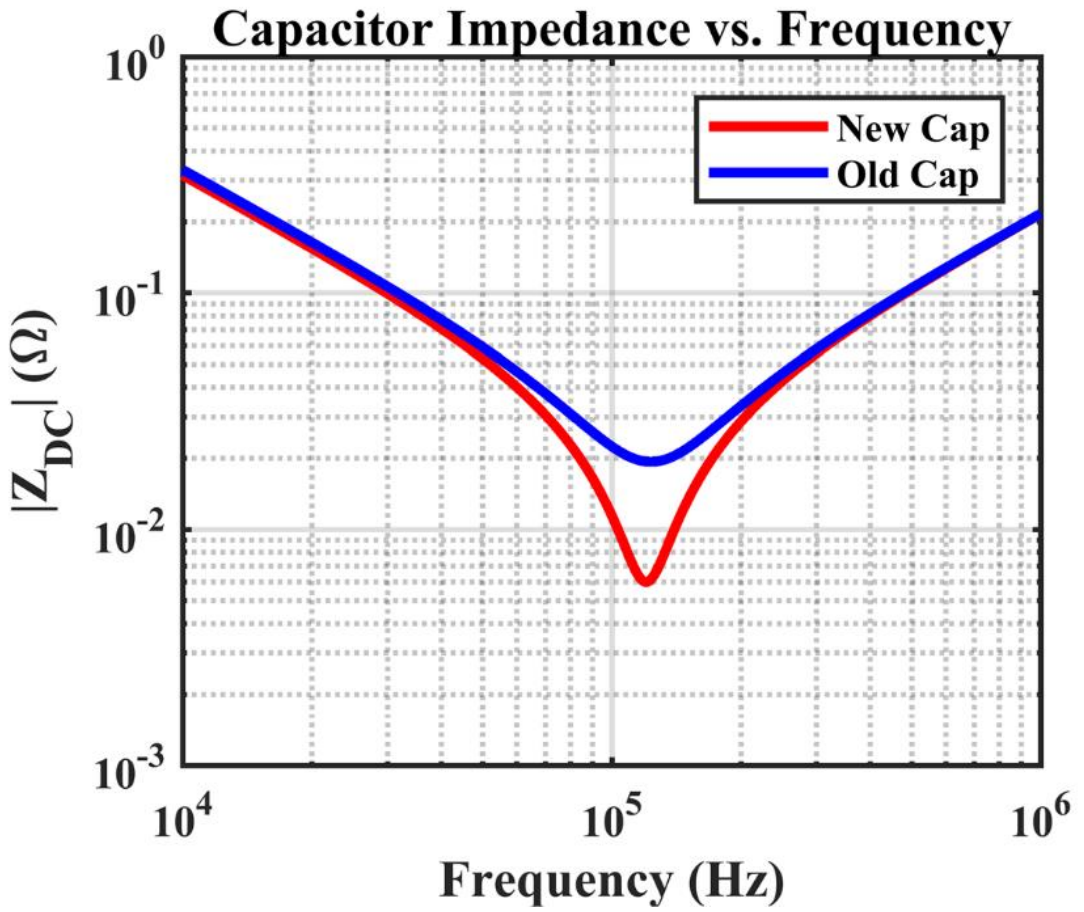
- Aluminum Electrolytic
- Metalized Poly Propylene Film
- Multilayer Ceramic

Capacitors Parameters:

- Capacitance (C_{DC})
- Equivalent series resistance (R_{ESR})
- Equivalent series inductances (L_{ESL})



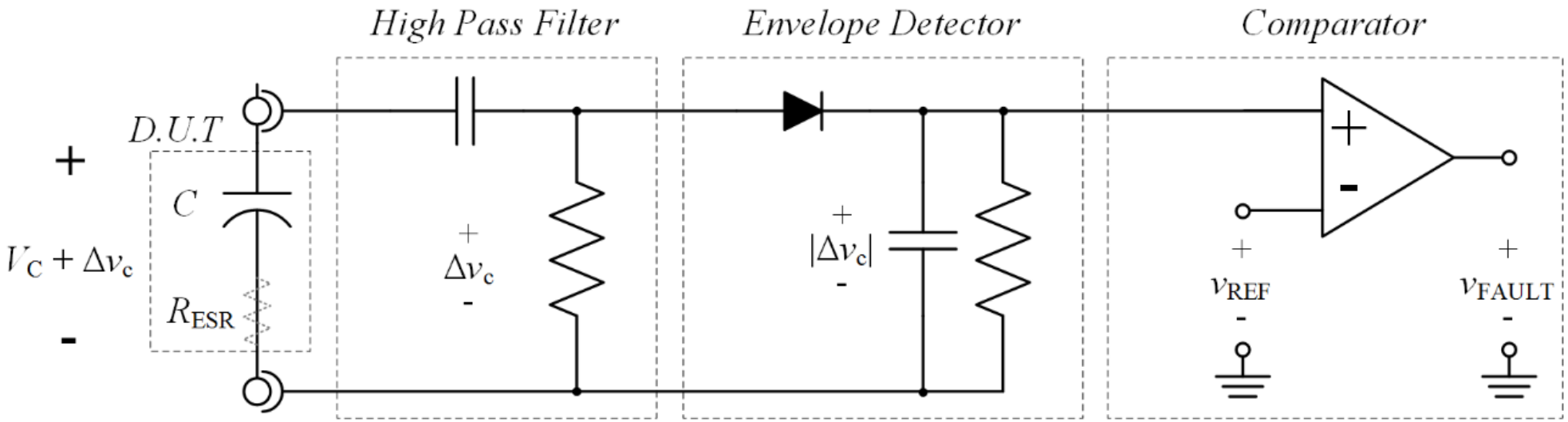
Equivalent circuit of a non-ideal capacitor.



Methods in Literature

Ripple Voltage Measurement:

- Ripple Voltage (Δv_c) is proportional to R_{ESR}.
- **Advantage:** Simple and low cost implementation
- **Disadvantage:** False triggers due to transients and temperatures



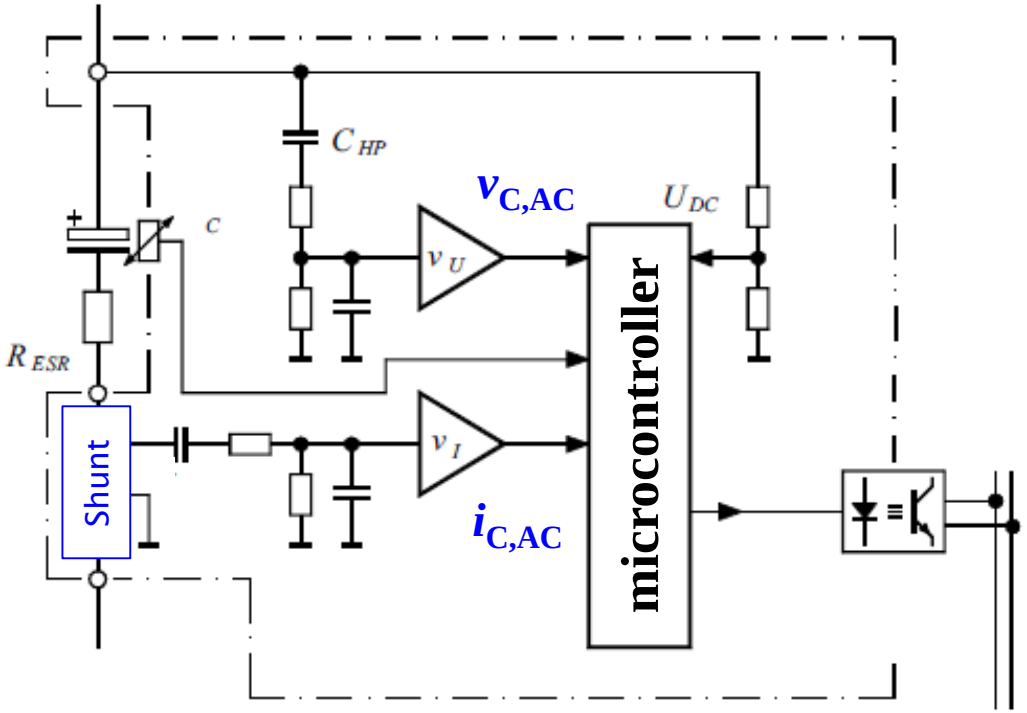
Schematic of Ripple Voltage Measurement Method

K. Harada and A. Katsuki: "Life Detector for Smoothing Capacitor", Japanese Patent Application JP63081277, 1988.

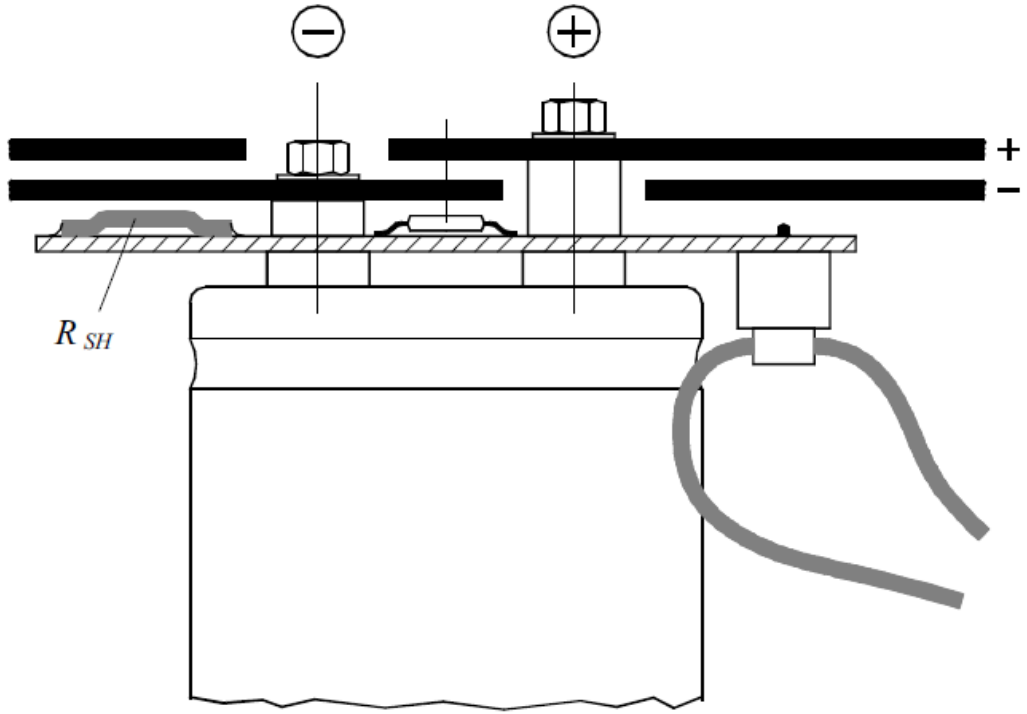
Methods in Literature

Power Loss Measurements:

- Ripple Voltage and capacitor current used to measure capacitor power loss



Block Diagram of Power Loss Measurement



Physical Implementation

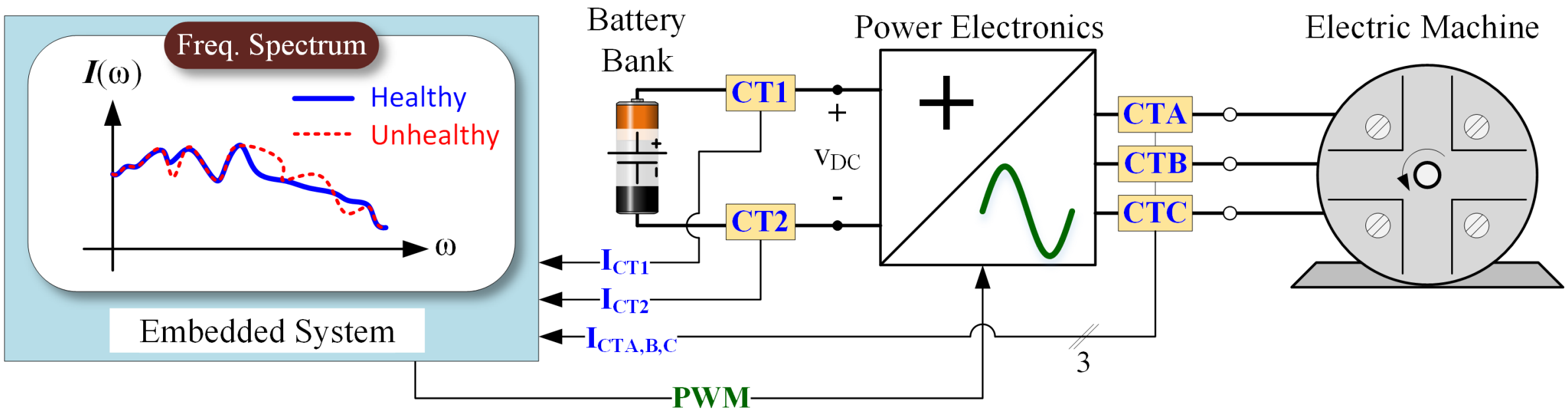
[1]. **M. A. Vogelsberger at al.**, *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 493-503, Feb. 2011.

E-PHM: Overview

Approach: The EM spectrum is analyzed to perform PHM services.

- An embedded system analyzes current transducers (CT) data.

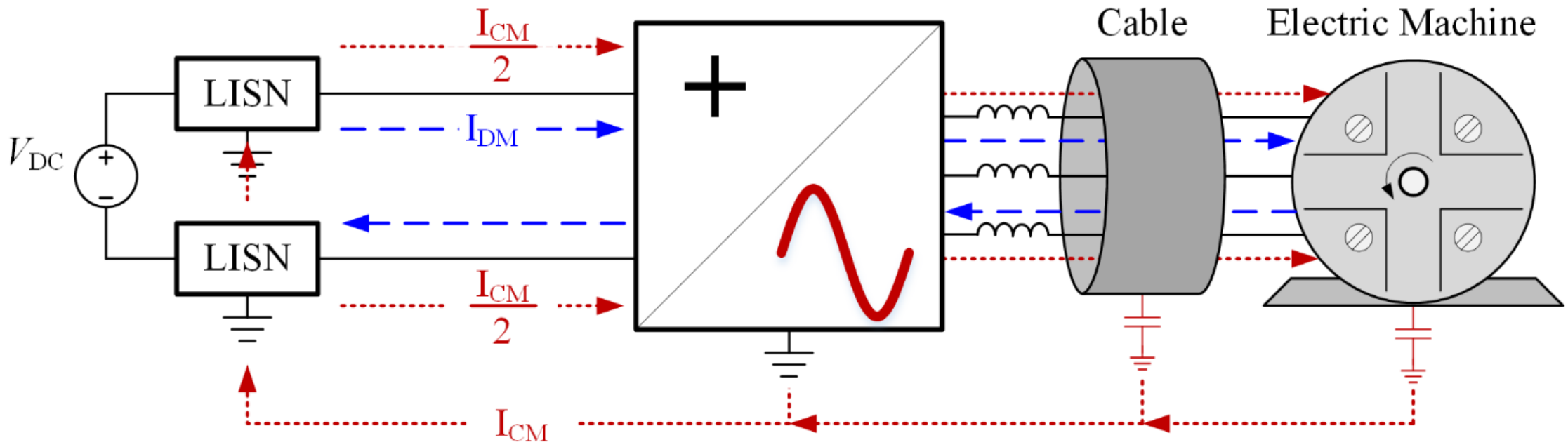
Adv: (1) Enables In-situ measurements.
(2) Integrates into existing control hardware.
(3) Minimal additional components required (Primarily software based).



Conducted EMI in a Motor System

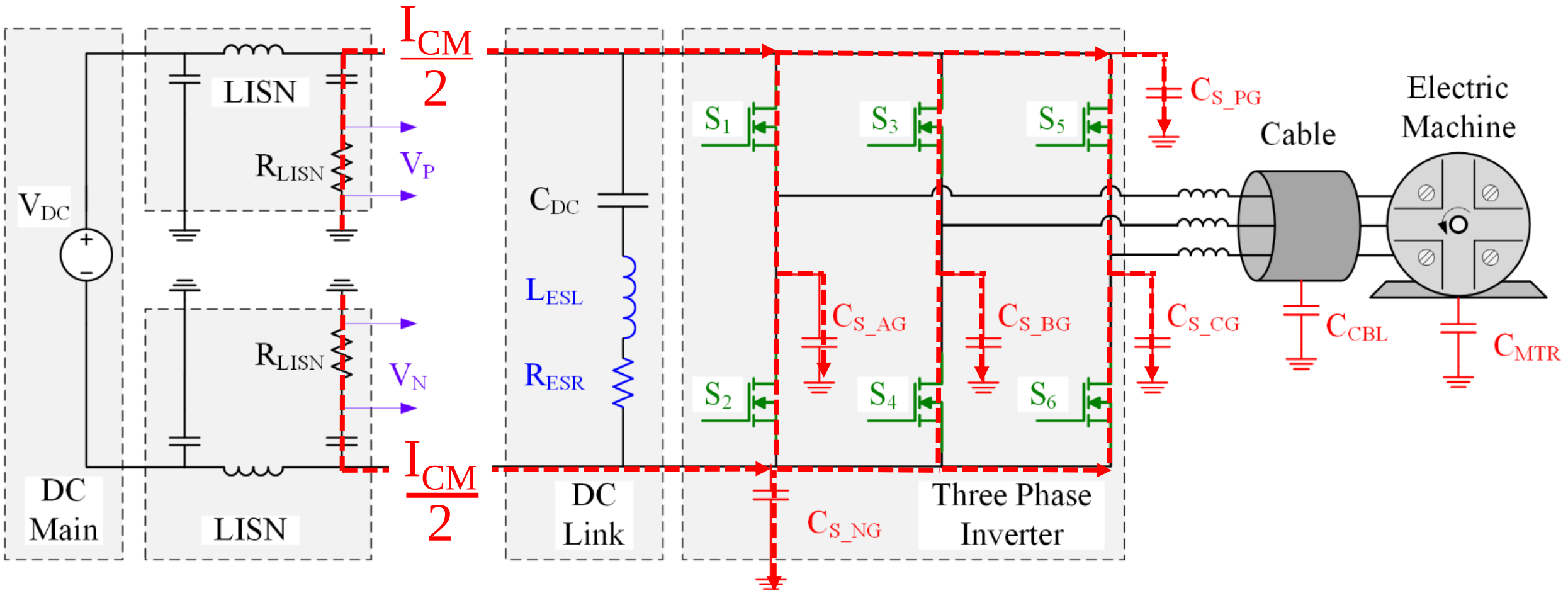
Two types of Noise Paths:

- Differential Mode (DM) Noise: circulates within the system.
- Common Mode (CM) Noise: moves through the grounding.



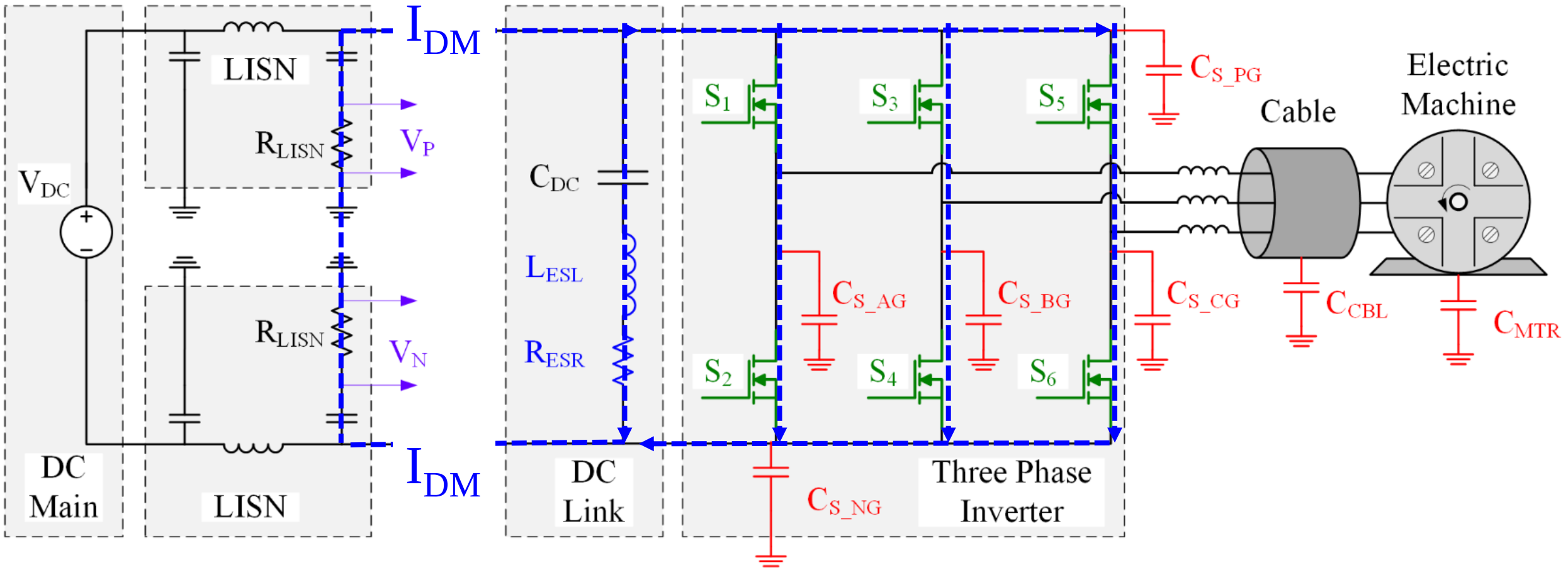
CM Current Flow in the Inverter

Common Mode (CM) Noise: moves through the ground



DM Current Flow in the Inverter

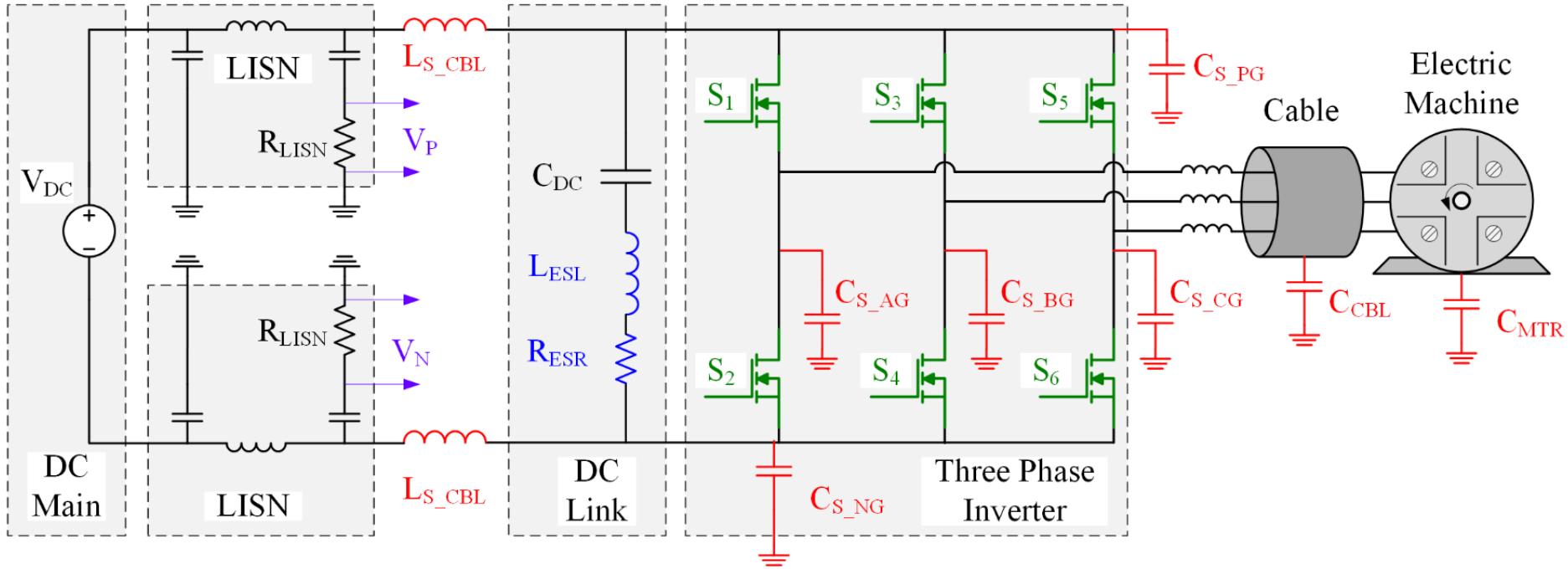
Differential Mode (DM) Noise: circulates within the system.



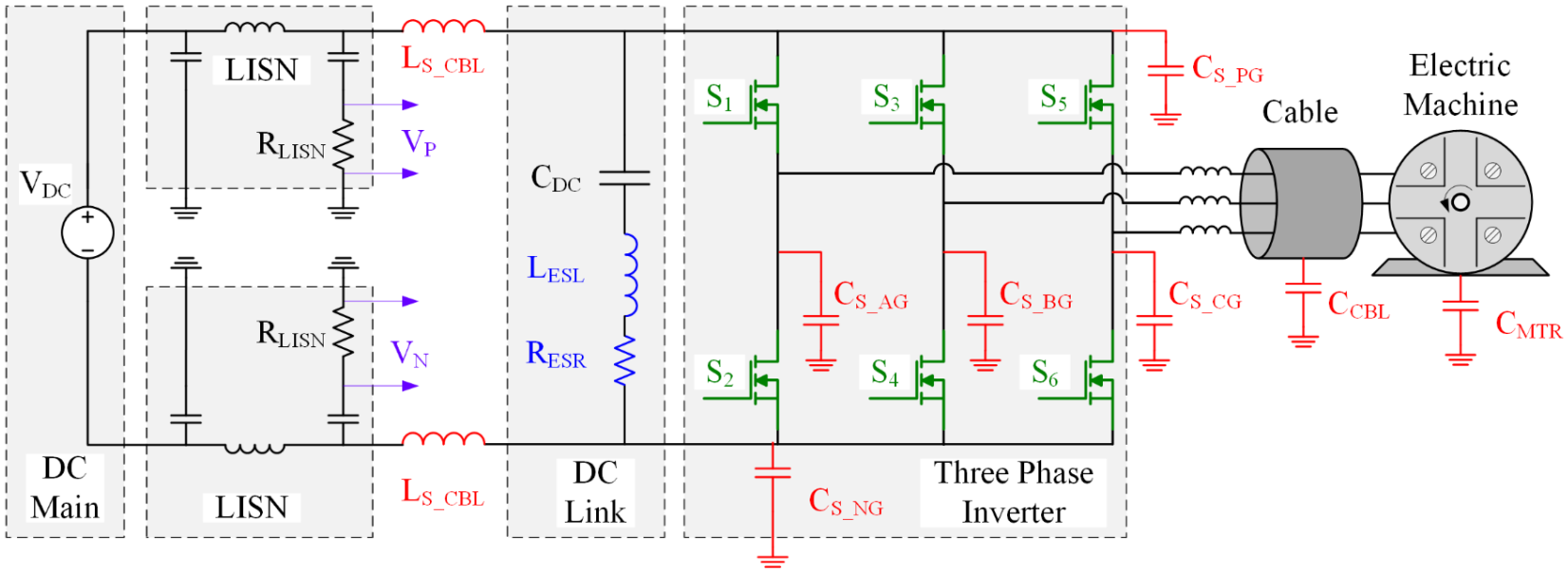
E-PHM: Basic Theory

Overview: Spectral content of power electronics hardware provides a unique signature of the operating conditions and system health.

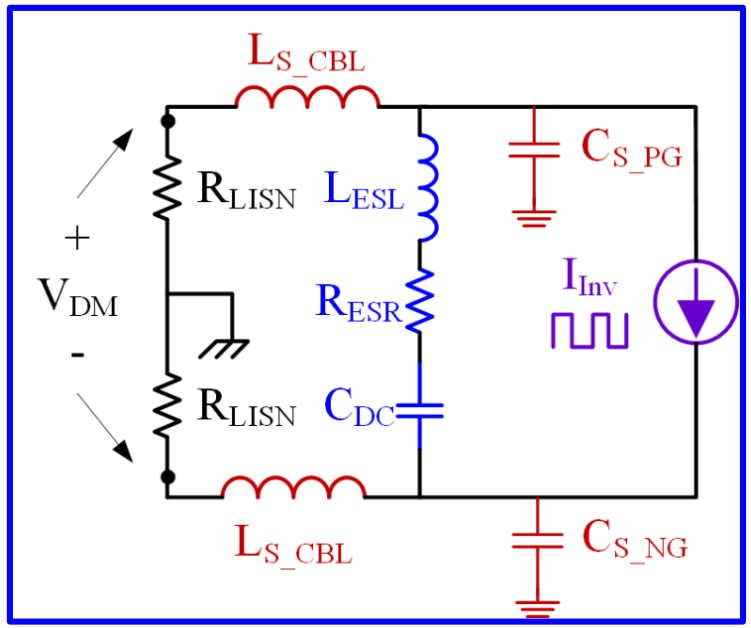
- *Semiconductors*: **dV/dt** changes with temperature & load current. → **Impacts EMI.**
- *Capacitors:* **parasitics** change with health → **Impacts EMI.**



Simplified Model for Capacitor Health



DM Equivalent Circuit



Procedure:

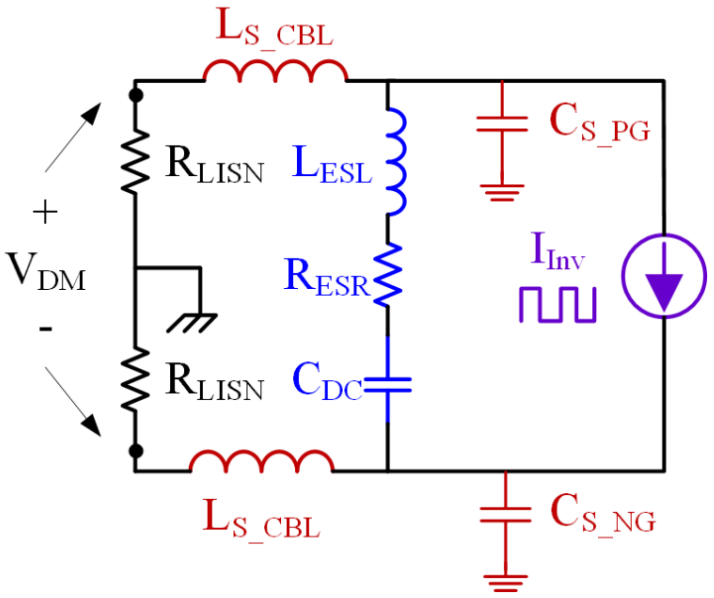
1. Replace load with a current source.
2. Simplify to an equivalent circuit.
3. Approximate switching behavior as a trapezoidal waveform.
4. Apply *s*-domain analysis.

Simplified Model for Capacitor Health

Theoretical Results

- The impedance is 3 times higher.
- Resonant frequency also shifts higher from 120.3 kHz to 123.4 kHz as the components age.

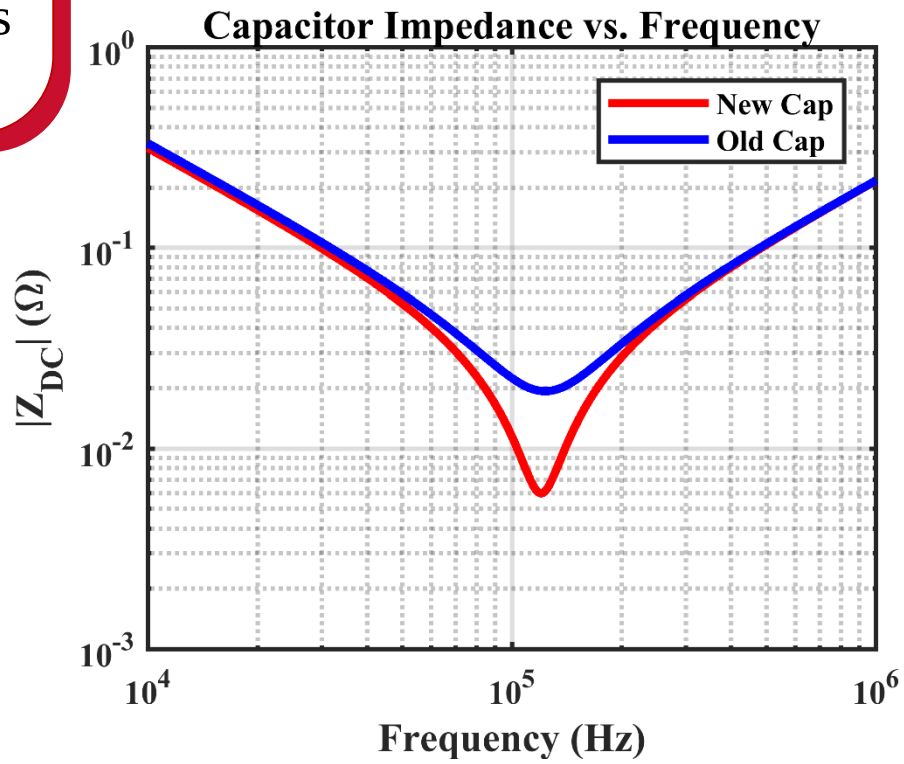
DM Equivalent Circuit



DM Voltage vs. Frequency

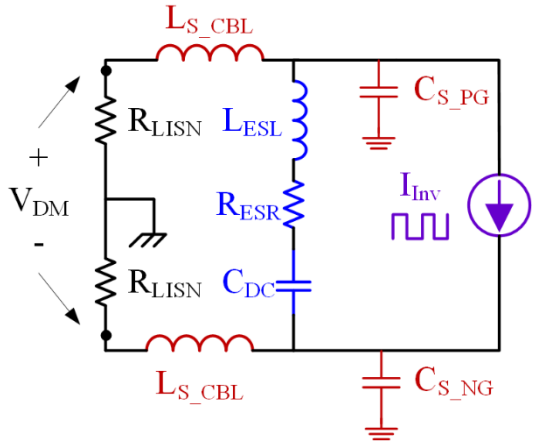
Capacitor Parameters

	New	Aged
C_{DC}	50 µF	47.5 µF
R_{ESR}	6 mΩ	19.4 mΩ
L_{ESL}	35 nH	35 nH

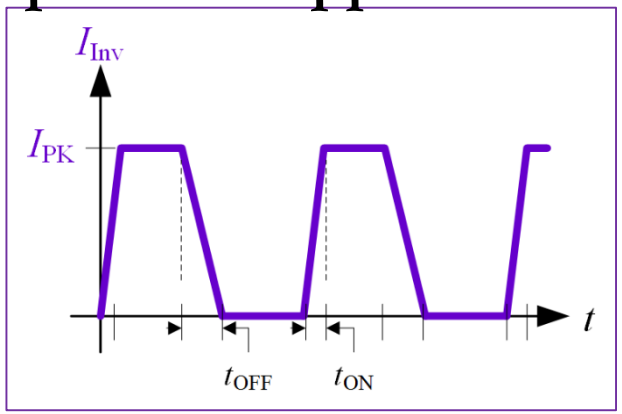


Simplified Modeling Approach Cont'd

DM Equivalent Circuit

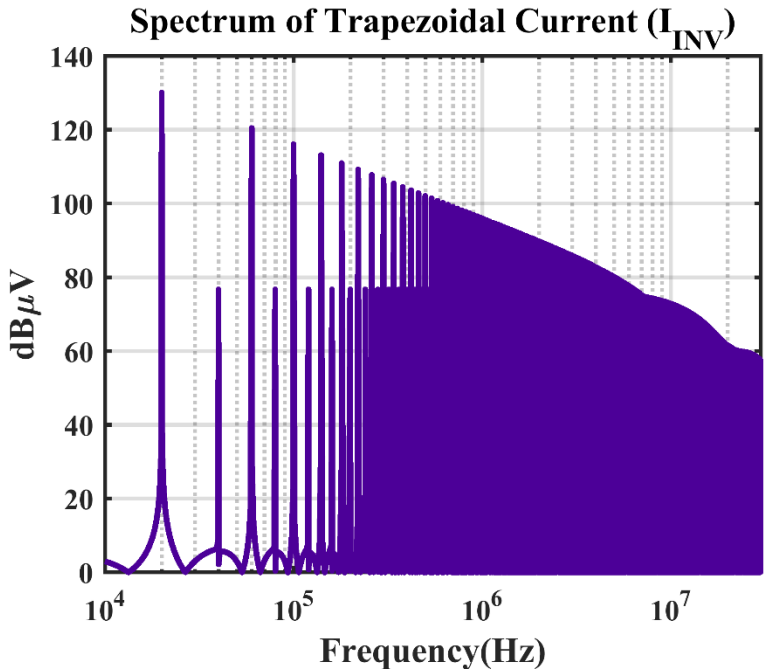


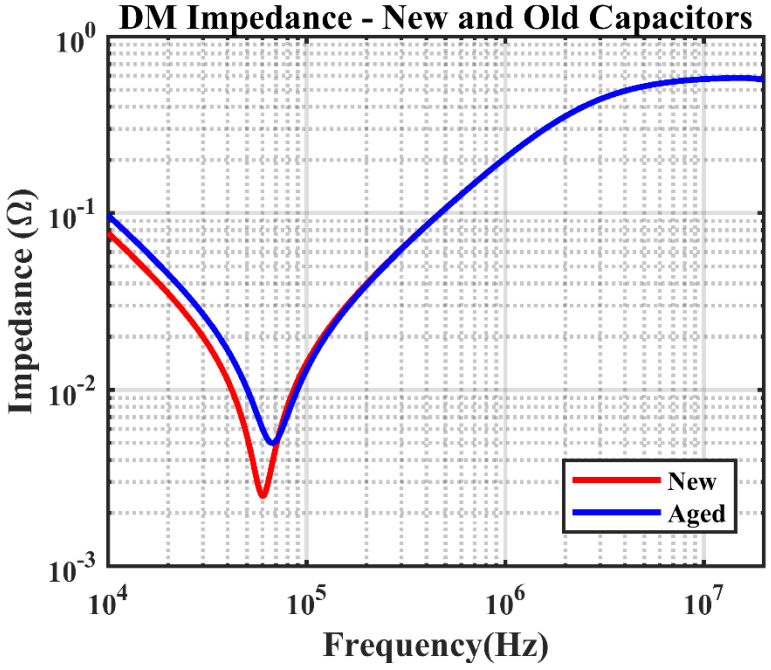
Trapezoidal Approximation

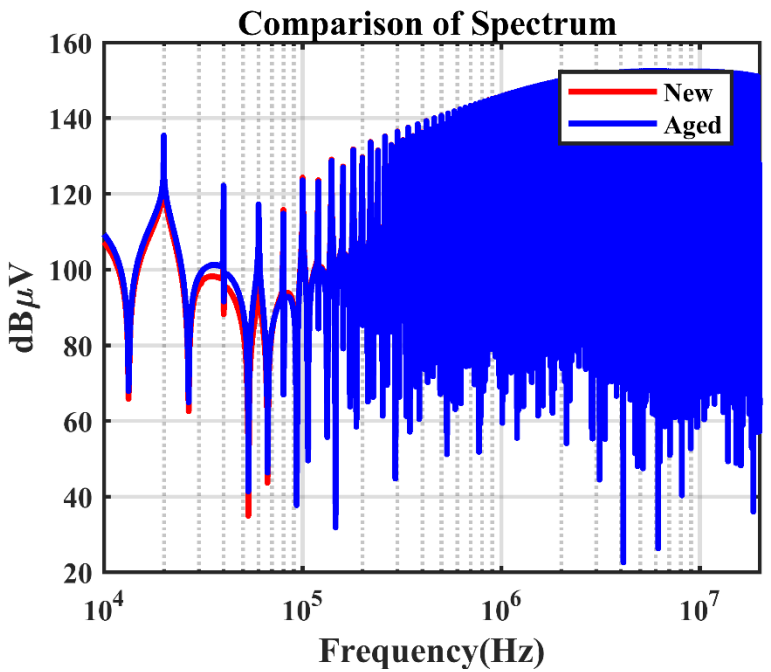


Simulation Criteria

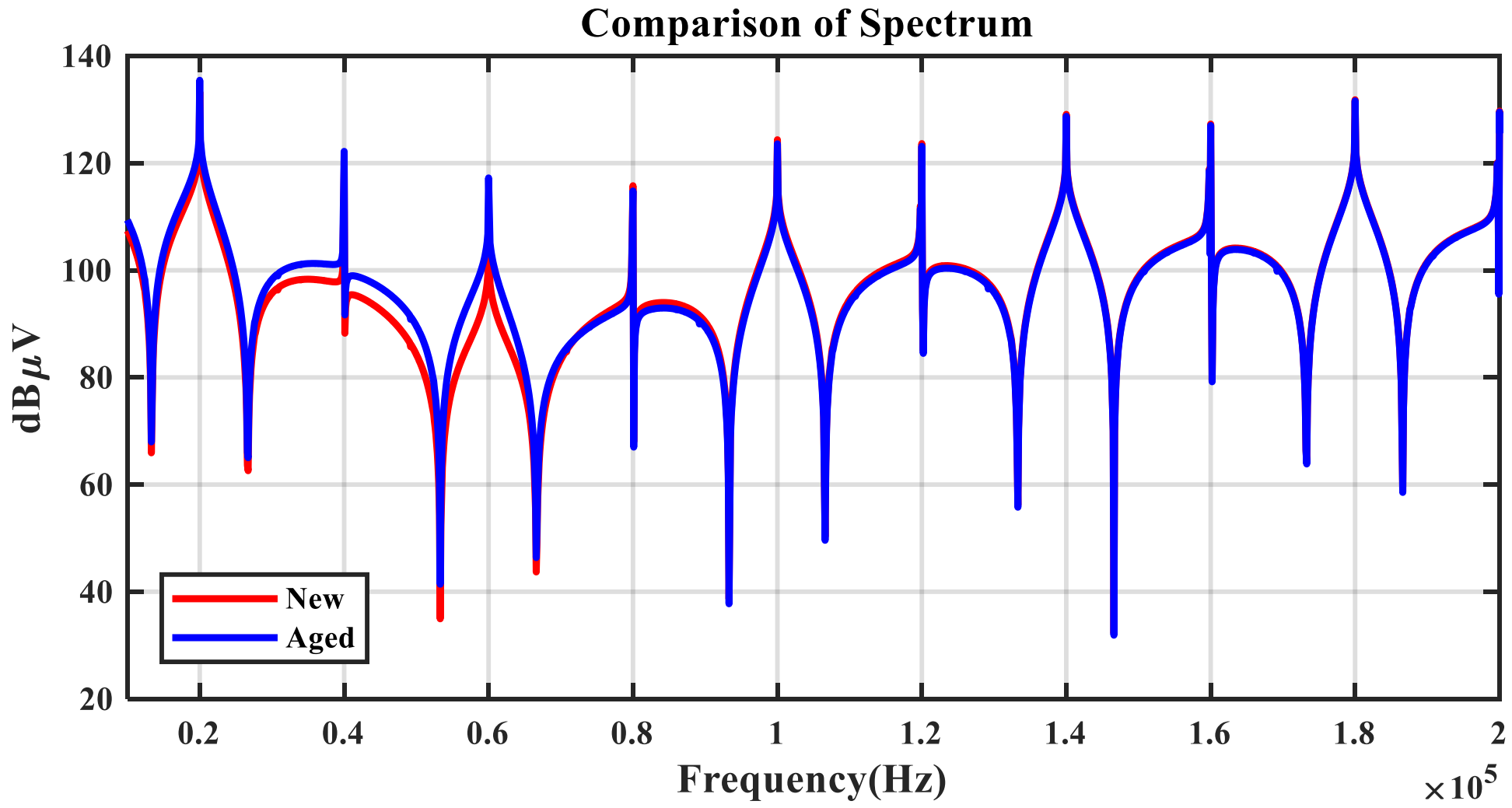
Para.	Value
f_S	20 kHz
t_{ON}	20 ns
t_{OFF}	50 ns







Zoomed View of the Spectrum



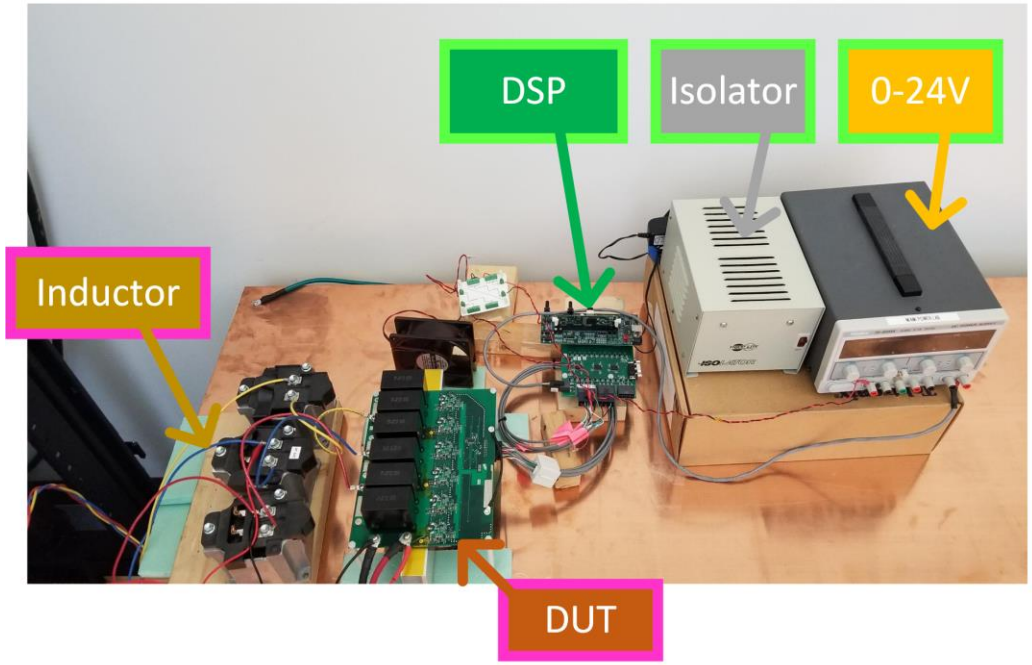
E-PHM: Experimental Validation

Execution:

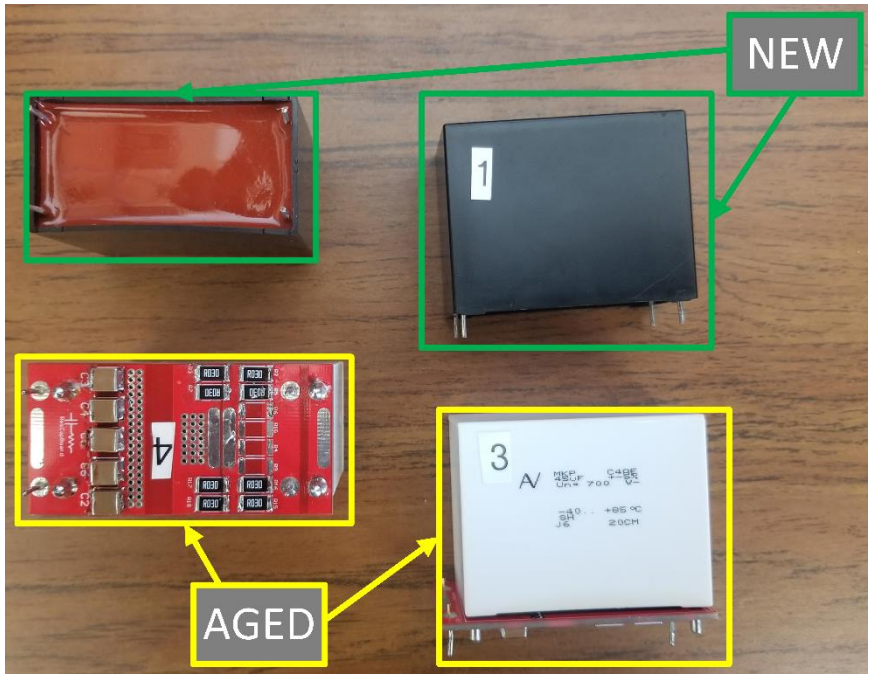
- C_{DC} and R_{ESR} are altered via an interface board.
- Five classes of DC link capacitors are evaluated:
  - N^6A^0, N^5A^1, N^3A^3, N^1A^5, N^0A^6.

Individual Capacitor Parameters

	R_{ESR}	C_{DC}
New	6.0 mΩ	50 µF
Aged	19.4 mΩ	47.5 µF



Modular Three Phase Inverter.



Capacitor Interface Board

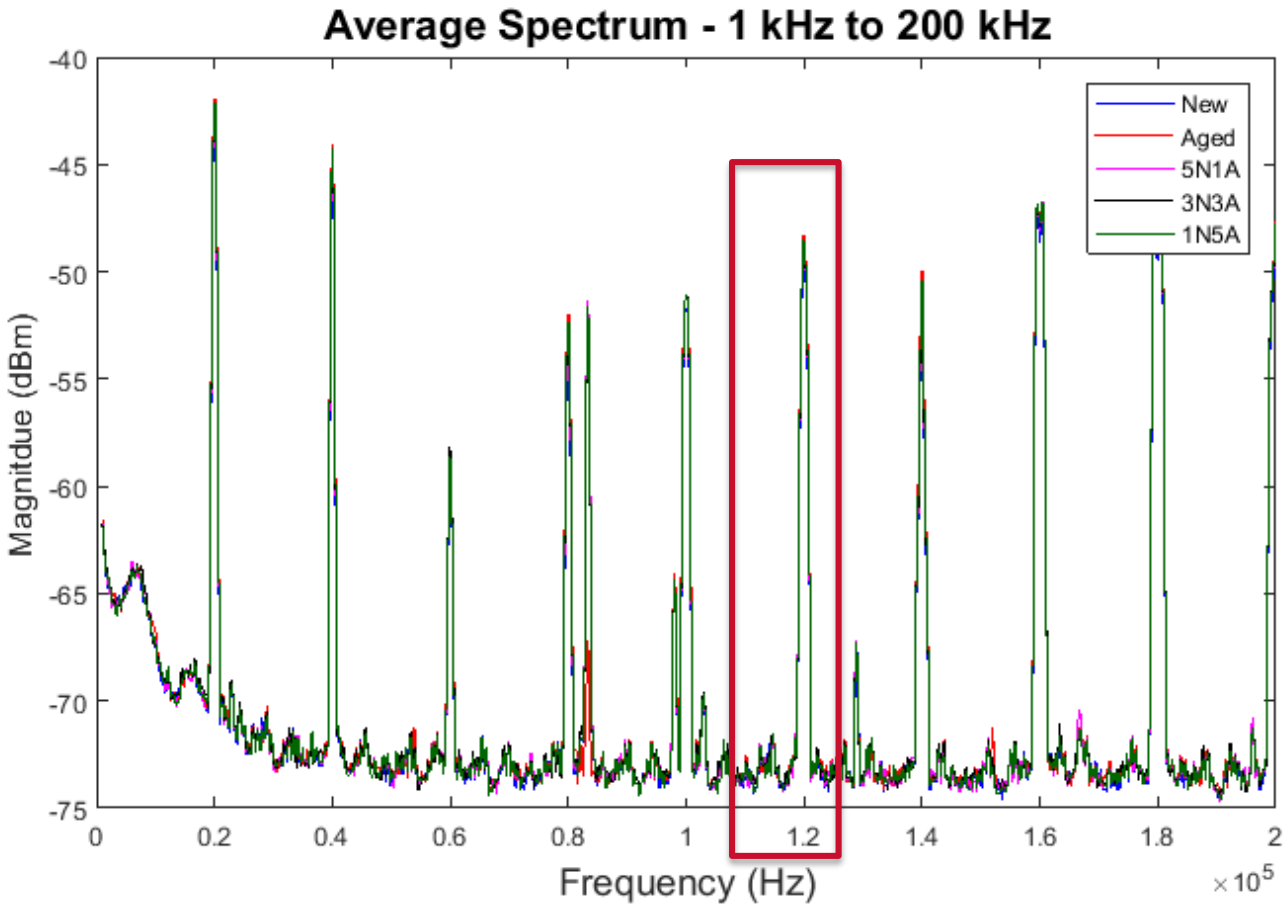
E-PHM Experimental Results

Total Noise Measurements in 10 kHz to 200 kHz Range:

- Difficult to notice differences between the spectrums.

Test Conditions

	New
V_{DC}	540 V
P_{OUT}	5 kW
f_S	20 kHz
f_c	60 Hz



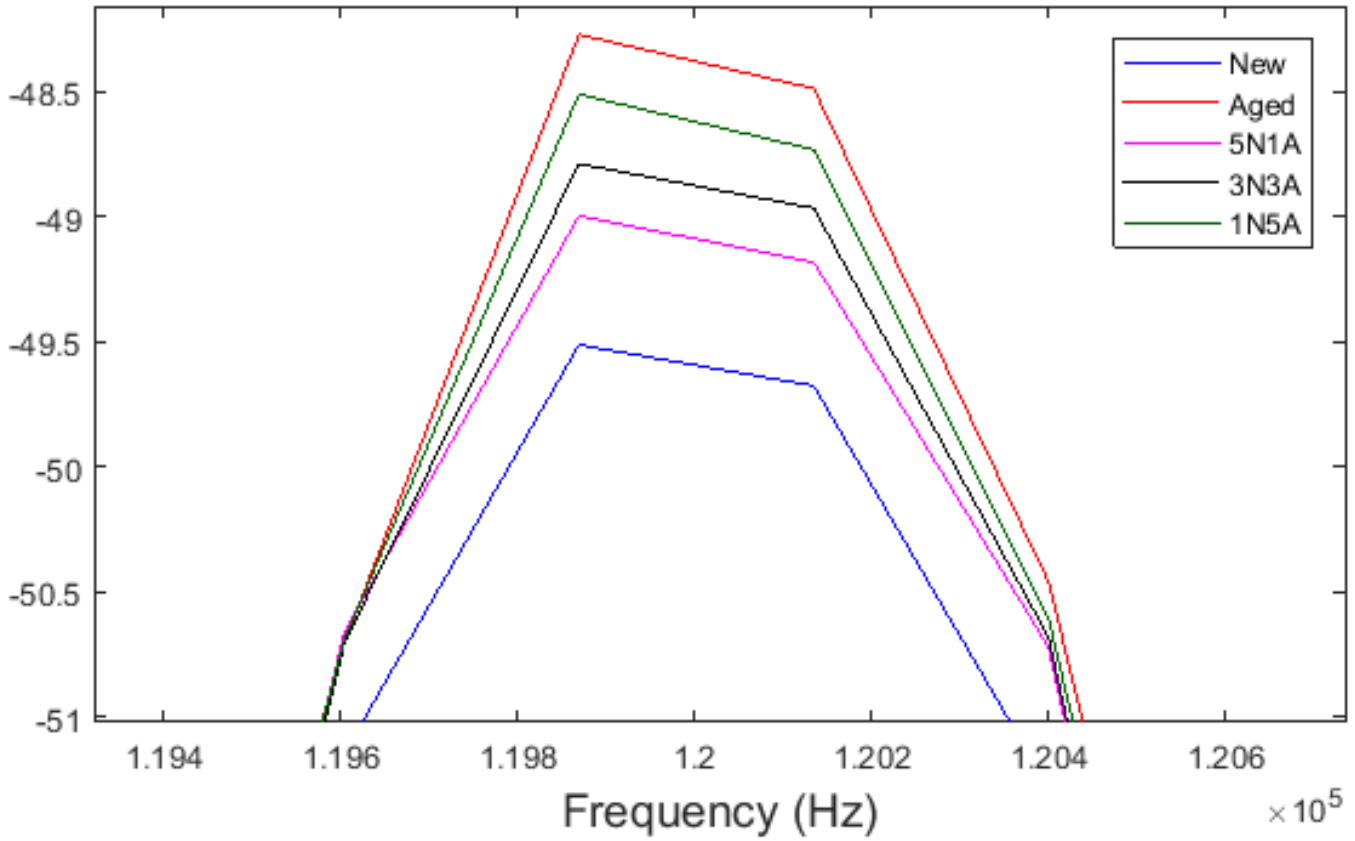
E-PHM Experimental Results

Total Noise Measurements in 10 kHz to 200 kHz Range:

- A close examination at one of the switching frequency's harmonics shows its magnitude increases with capacitor age.

Test Conditions

	New
V_{DC}	540 V
P_{OUT}	5 kW
f_S	20 kHz
f_c	60 Hz

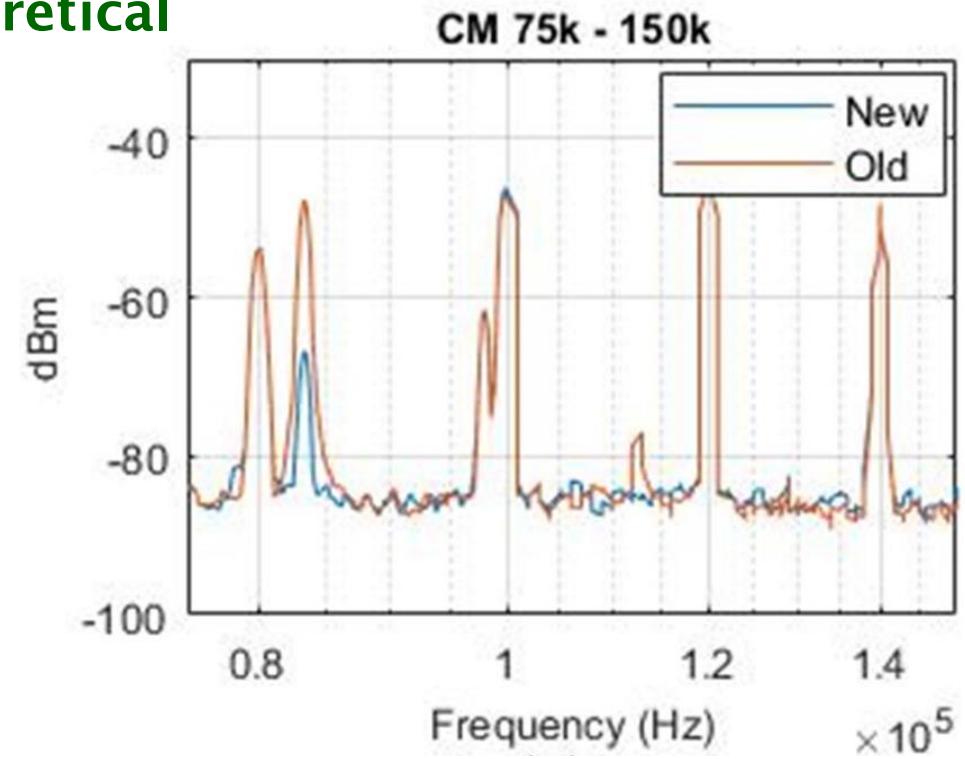


E-PHM: Experimental Results

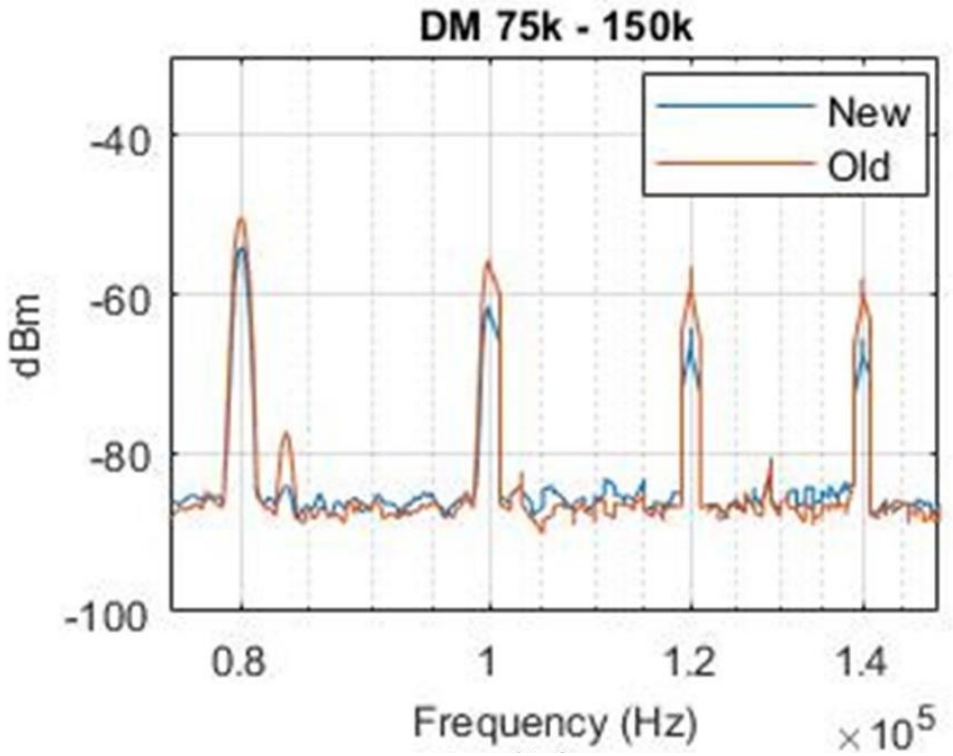
Additional Results:

1. Significant differences in DM noise, but CM noise is basically the same.
2. Magnitude of noise is higher for aged ('old') capacitors.

✓ **Validates theoretical analysis.**



Exp. Results CM Noise



Exp. Results DM Noise

E-PHM: Machine Learning Results

Machine Learning Algorithm Results:

- 250 tests conducted with a total of 5 capacitor classes:
  - 6 New (N^6A^0), 5 New &1 Aged (N^5A^1), 3 New & 3 Aged (N^3A^3), 1 New and 5 Aged (N^1A^5), 6 Aged (N^0A^6).
  - 25 tests / class used to train SVM.
  - 25 tests used to evaluate

- SVM succeeds at identifying the brand new and aged DC link capacitance.

Test Results – 10 kHz to 200 kHz Total Noise

Actual \ SVM Decision	N^6A^0	N^5A^1	N^3A^3	N^1A^5	N^0A^6
N^6A^0	25	0	0	0	0
N^5A^1	0	19	**5**	**1**	0
N^3A^3	0	0	20	**5**	0
N^1A^5	0	0	**5**	20	0
N^0A^6	0	0	0	0	25

On-going Research

- Replacing the current sensors with high-bandwidth current sensor.
- Implementing machine learning algorithms into an embedded system.
- Evaluating robustness against changes in switching frequency and load current.
- Exploring PWM strategies to amplify the phenomenon.
- Applying techniques to semiconductor devices

Conclusions

- ✓ A discussion of failure mechanism for capacitors was provided.
- ✓ A survey of existing conditional monitor techniques was given.
- ✓ A new type of PHM method (E-PHM) was explained.
- ✓ Demonstrated the ability to detect changes in the capacitance.

Thank You for your Attention.

Any Questions?