The Impact of fast switching converter on machine insulation and reliability

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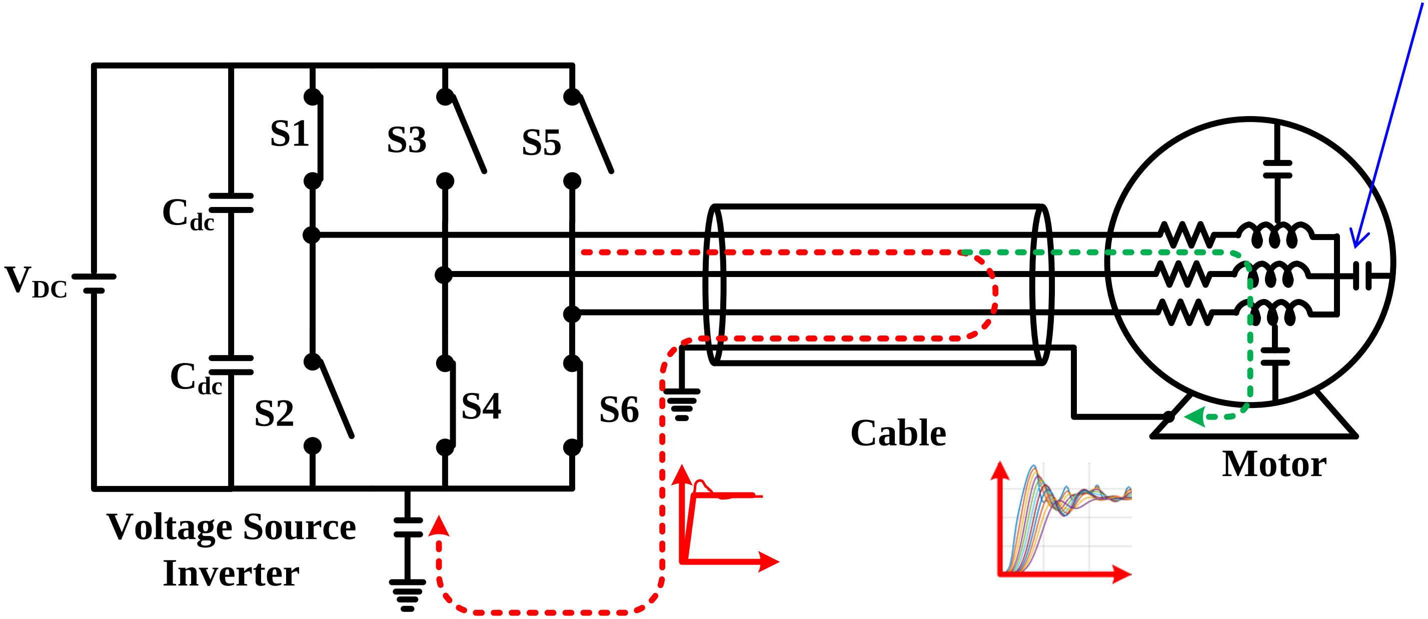
Outline

- Problems with inverter-fed drive and its detrimental effects
- Modelling high frequency behaviour of cable-machine system
- Main oscillation modes of cable-machine system and resultant peak voltages
- Experimental validation
- Effects of wave propagation and reflection in cable and machine
- Impact on insulation life and reliability
- Summary

Problems with converter-fed drive

High dv/dt and high switching frequency lead to

- ❑ Voltage ringing at inverter outputs
- ❑ More significant transmission line effect
  - Voltage surge at motor terminal
  - Uneven voltage distribution in turns and coils
  - Common mode voltage oscillation at star-neutral



Detrimental effects

- Excessively high voltage stress on insulation
    - Significant increase in partial discharge
    - Premature insulation failure
- High frequency(HF) common mode voltage and current
    - EMI problems
    - Shaft voltage
    - Bearing current → premature bearing failure

To avoid premature insulation failure, it is essential to know peak voltage stress and distribution in machine windings fed by inverter.

For this purpose, we’ve developed representative HF models of cable and machine

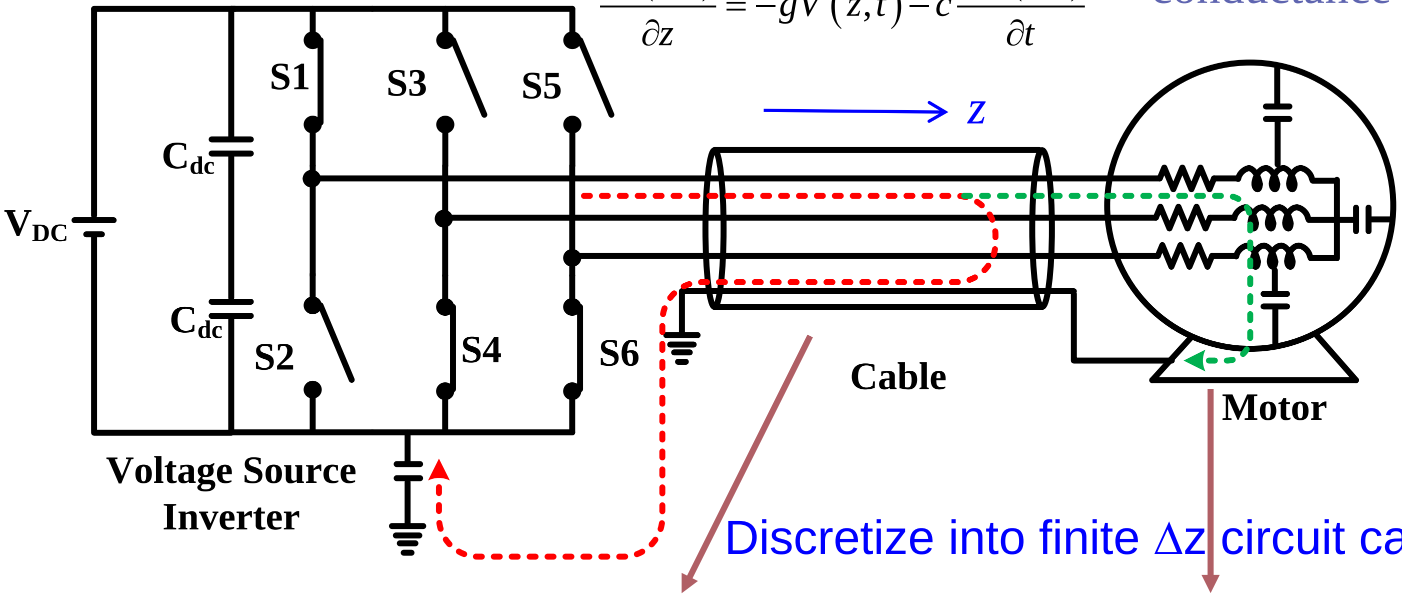
HF Model of AC Machine

Governing equations

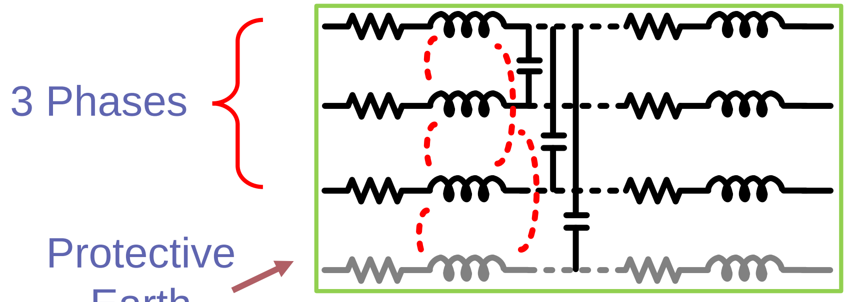
$$\frac{\partial V(z,t)}{\partial z} = -rI(z,t) - l\frac{\partial I(z,t)}{\partial t}$$

$$\frac{\partial I(z,t)}{\partial z} = -gV(z,t) - c\frac{\partial V(z,t)}{\partial t}$$

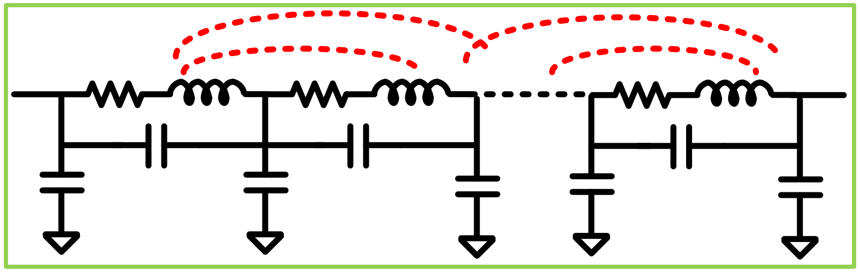
r, l, g, c : per unit length resistance, inductance, conductance and capacitance



Discretize into finite Δz circuit cascaded cells

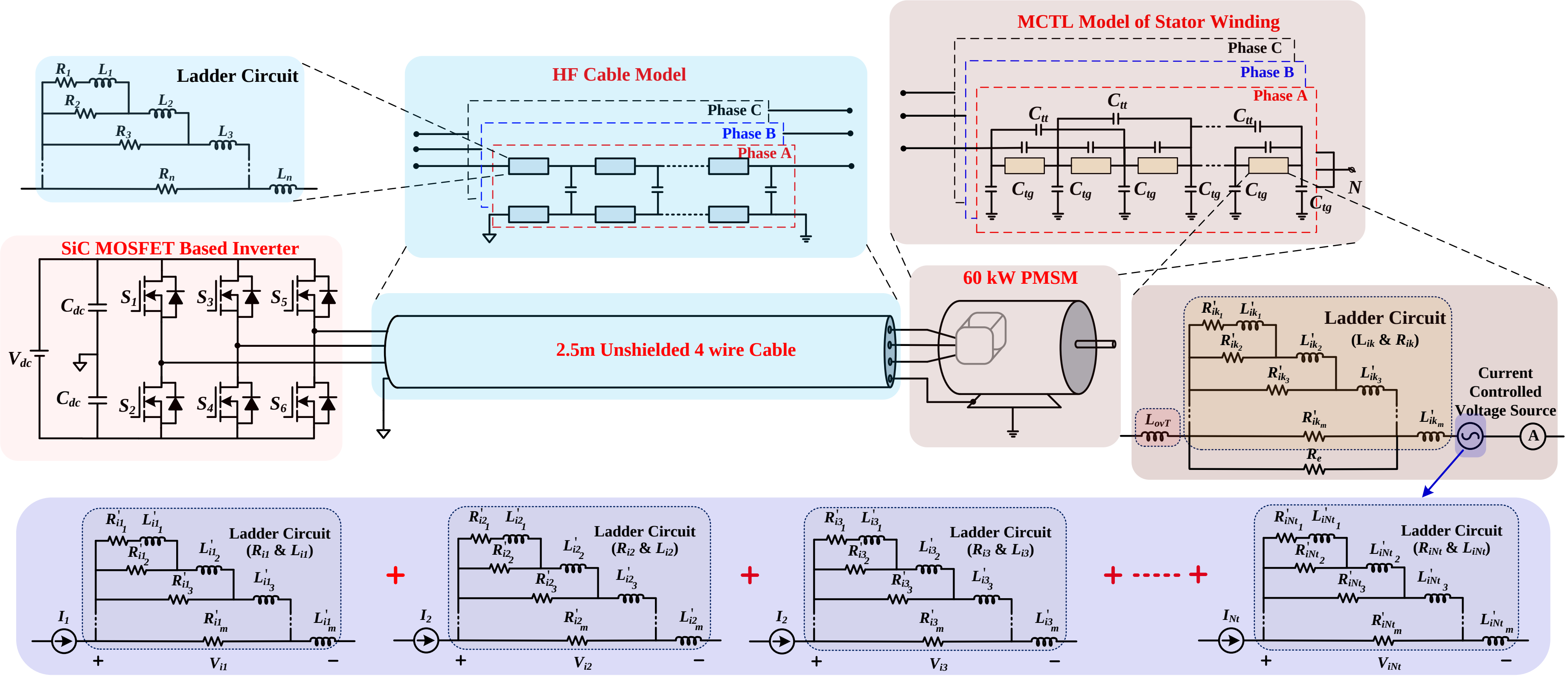


(Cascaded Γ sections)



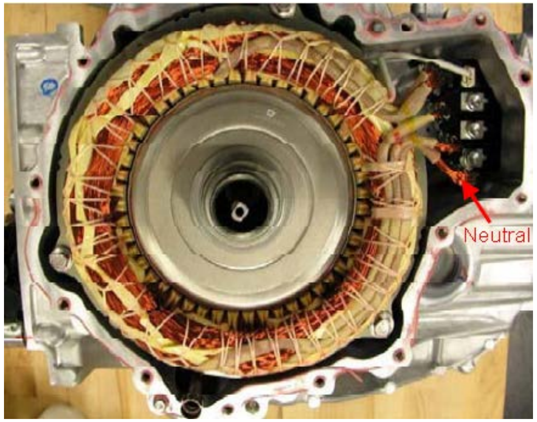
Multi-Conductor Transmission Line Model

Multi-Conductor Transmission Line (MCTL) Model

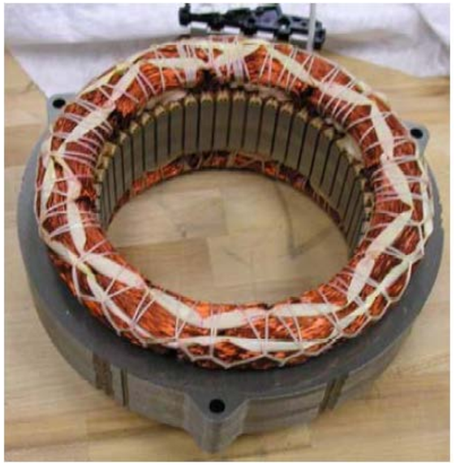


Electrical Machine Studied

- 2010 Toyota Prius 60 kW PM Machine
- Key specifications
    - Stator slots = 48
    - Coils per phase = 8
    - Turns per coil = 11
    - Each turn = 12 strands of AWG20
- Simulation Condition:
    - Rise time = 20 ns
    - DC link voltage = 560 V
    - Step time = 1 ns

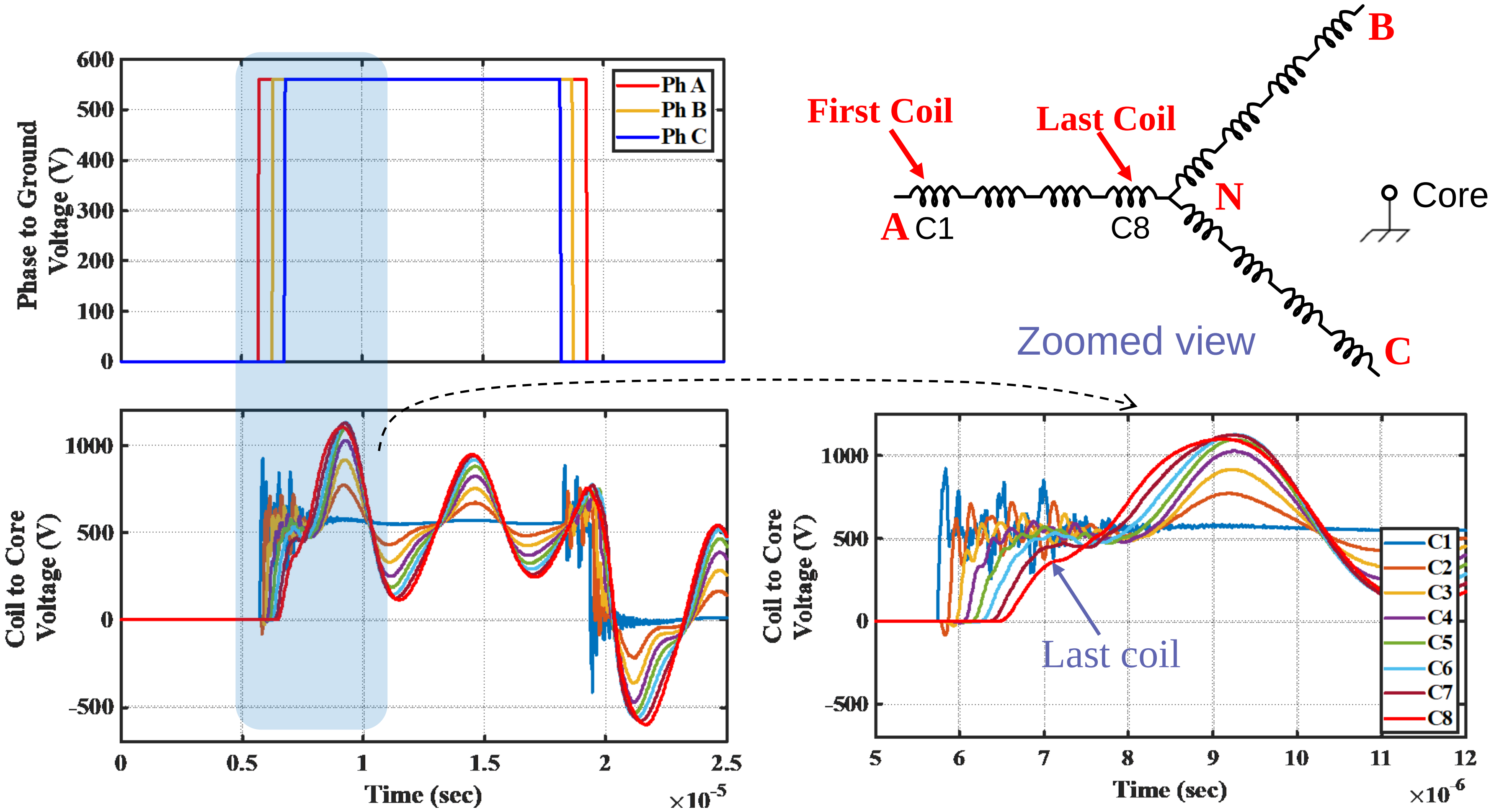


2010 Toyota Prius Motor



Stator

Coil-to-core Voltages

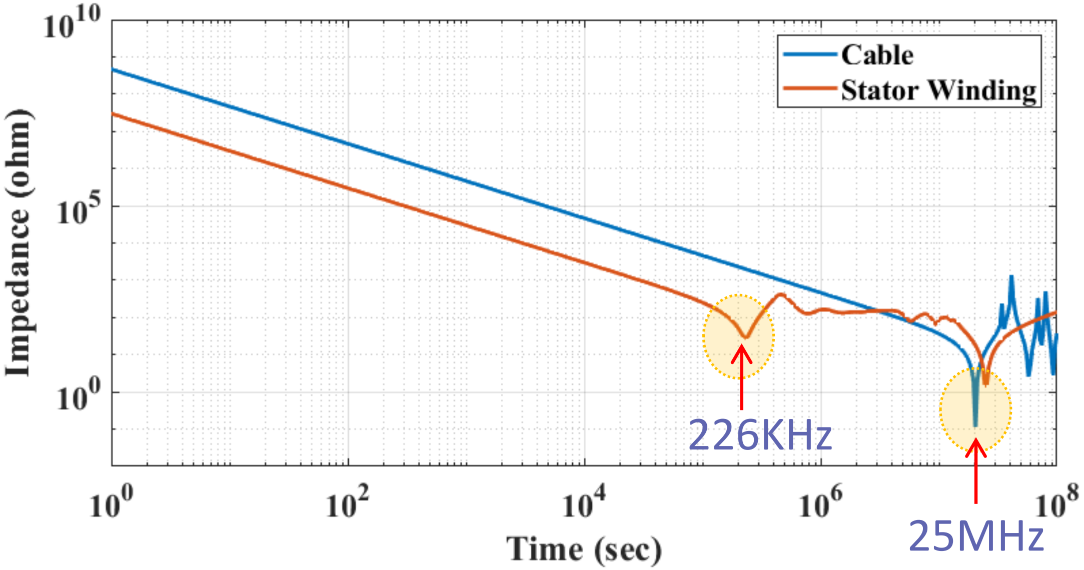


- **Last coil (near neutral point) of the phase experiences maximum voltage !! Similar behaviour seen on falling edge**

HF behaviour of cable & machine

- HF behaviour of cable and machine can be characterised by their 1st anti-resonant frequency, respectively.

Measured CM impedances of cable and machine



1st anti-resonance of machine at 226kHz

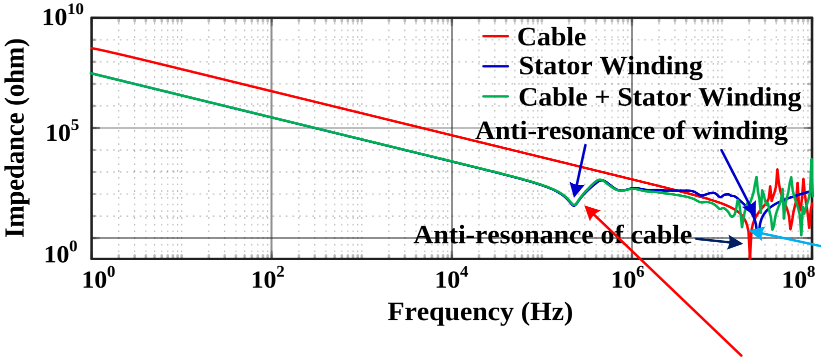
1st anti-resonance of cable (2.5m) at 25MHz

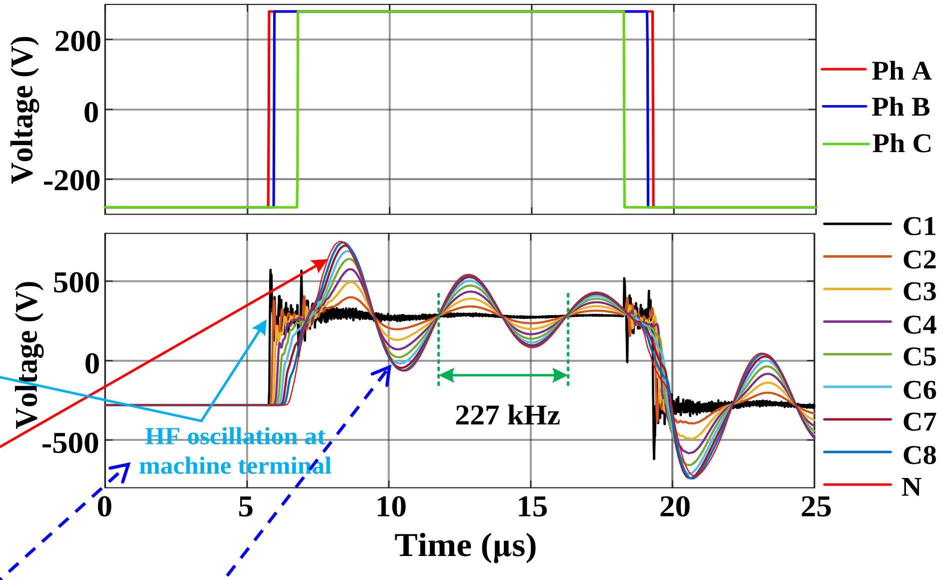
- The HF behaviour of cable-machine system is dictated by the combined effects of the two.

HF behaviour of cable-machine

- Peak voltage stress in machine are dictated by two oscillation modes

With a short cable,1st Anti-resonant frequency of the system = that of machine



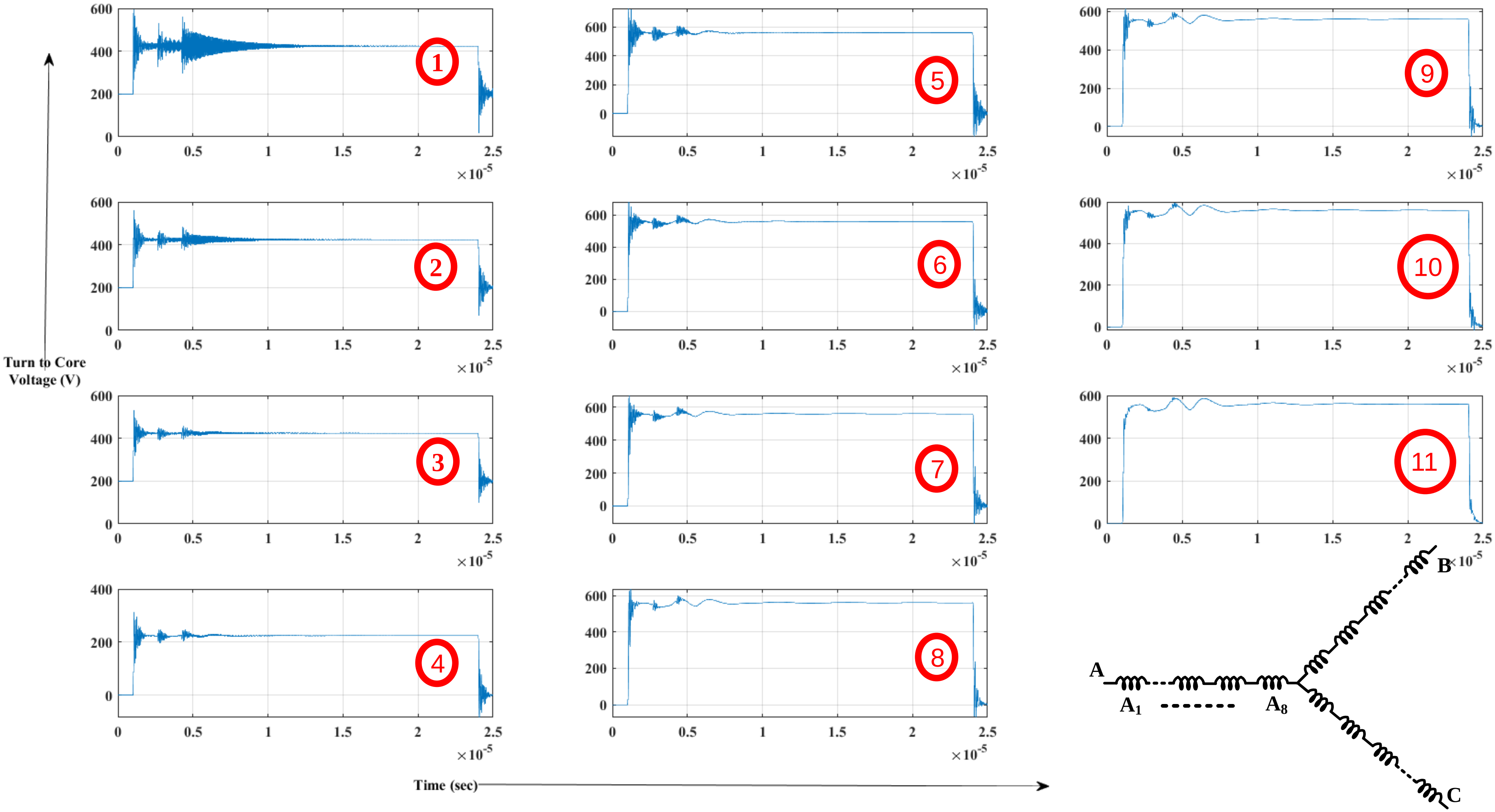


Voltage oscillation at 2nd cable-machine anti-resonant frequency, ~6MHz, denoted as HF

Voltage oscillation at machine anti-resonant frequency,~227kHz, denoted as LF

HF oscillation only appears in the first few turns of 1st coil, and affects turn-to-turn voltage, phase-to-ground voltage and phase-to-phase voltage

Turn-to-Core Voltage of 1st Coil



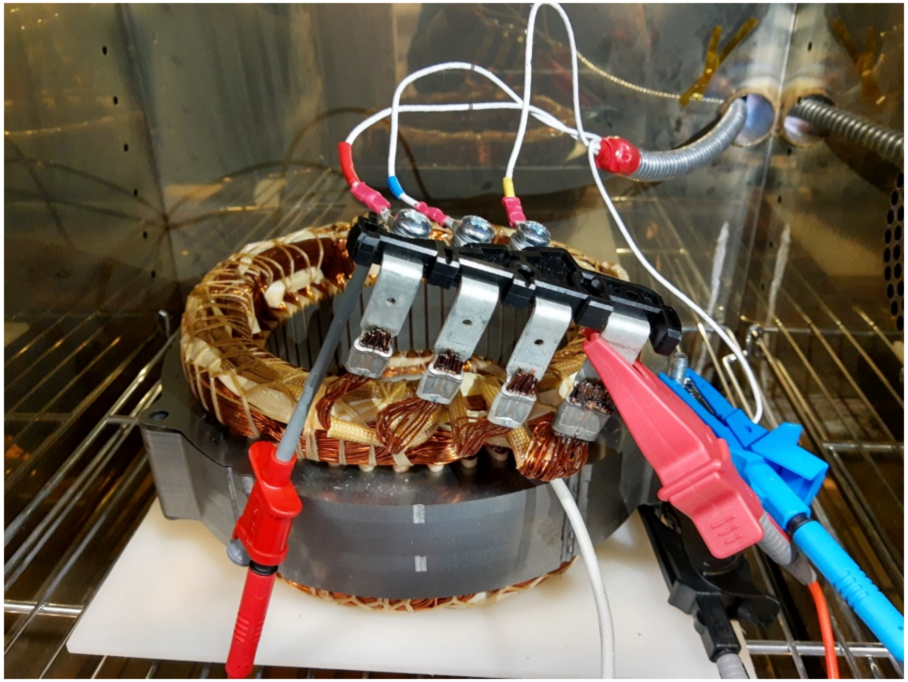
- Voltage oscillation at HF due to cable is significant only in the first a few turns

HF behaviour

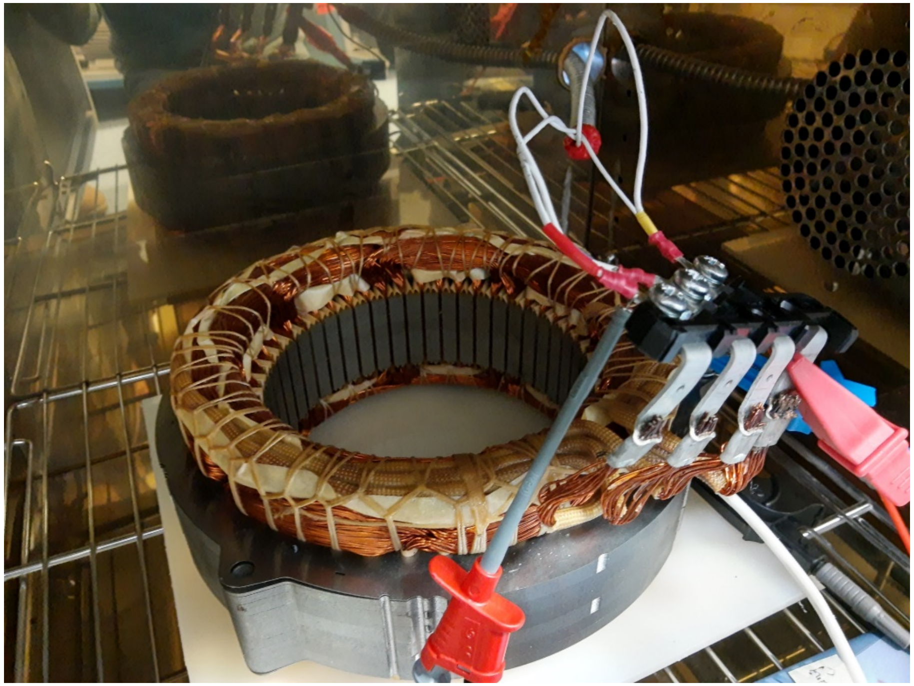
- The LF oscillations can **penetrate deep** into machine winding, and may give rise to excessive voltage stress across winding conductors and ground →mainwall insulation .
- The voltages associated with this oscillation are **of CM nature** and hence they only affect turn-to-ground voltage, coil-to-ground voltage and phase-to-ground voltage
- The presence of the LF oscillation and its potential interaction with the HF oscillation may lead to a number of problems which **are not known in literature**

Experimental Setup

Toyota 2010 Prius motor modelled and tested



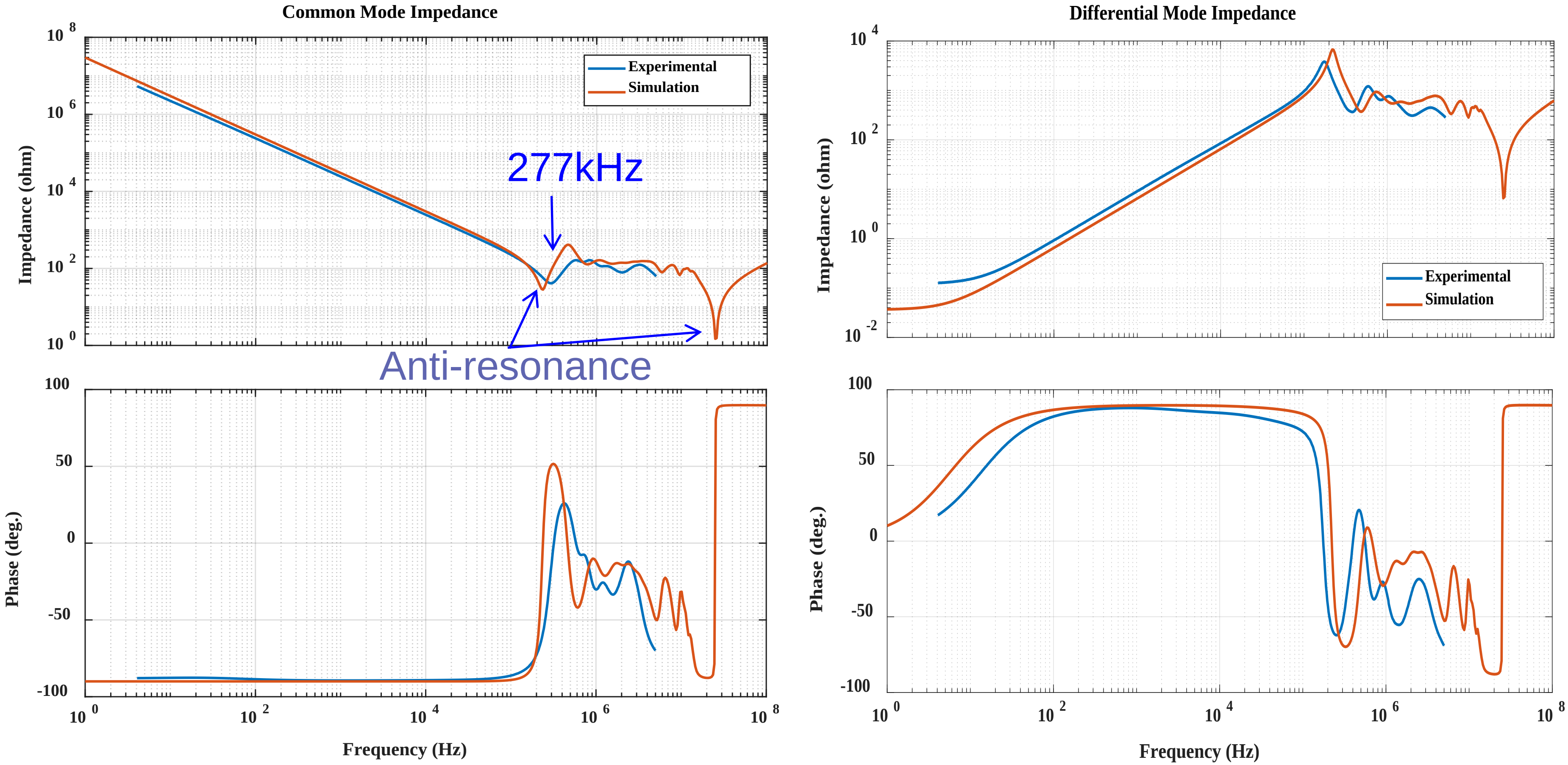
Side View



Top View

Common mode and differential mode impedances of stator winding measured by impedance analyser

Comparison of measured & predicted Impedance



277kHz

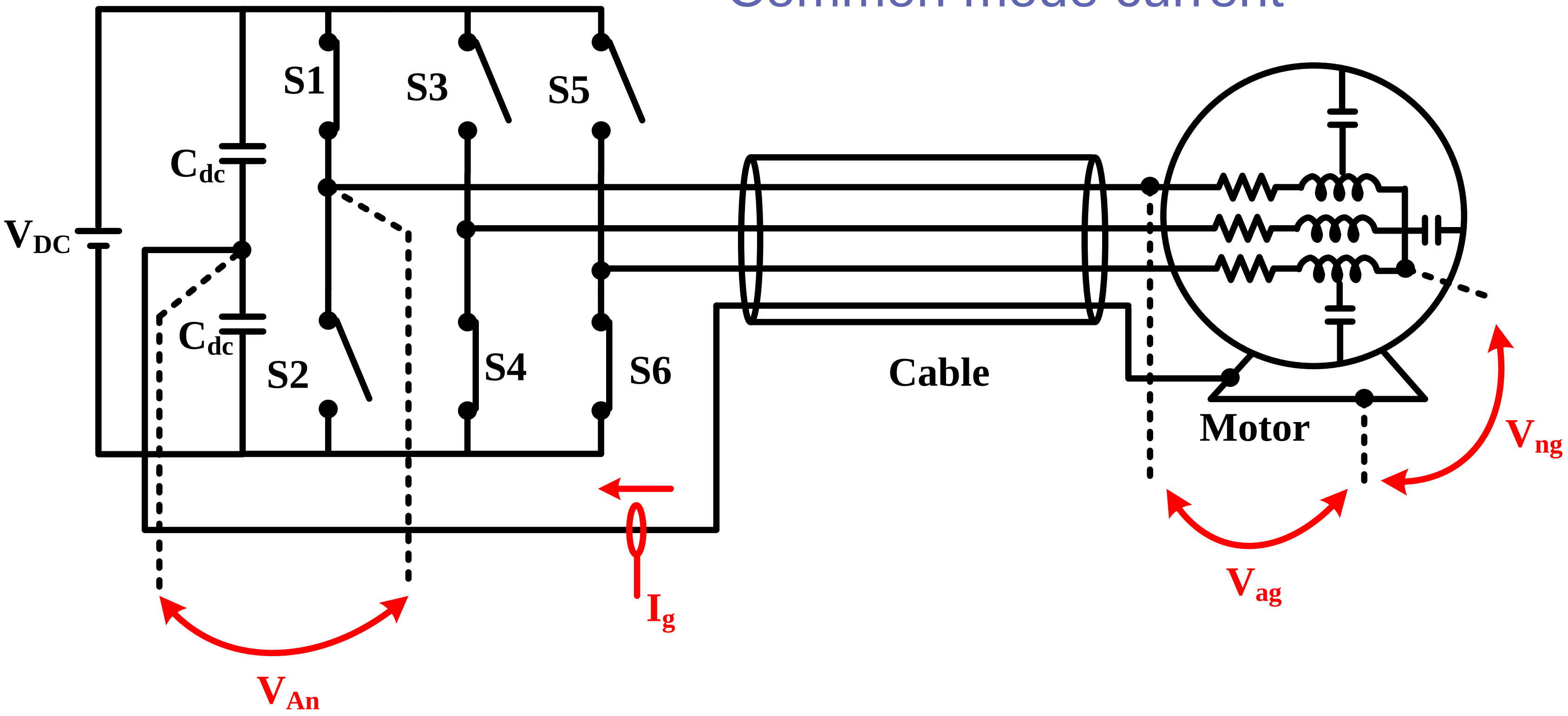
Anti-resonance

The CM and DM impedance of the MCTLM of stator winding are within **reasonable accuracy**.

Tests under inverter excitation

Measured:

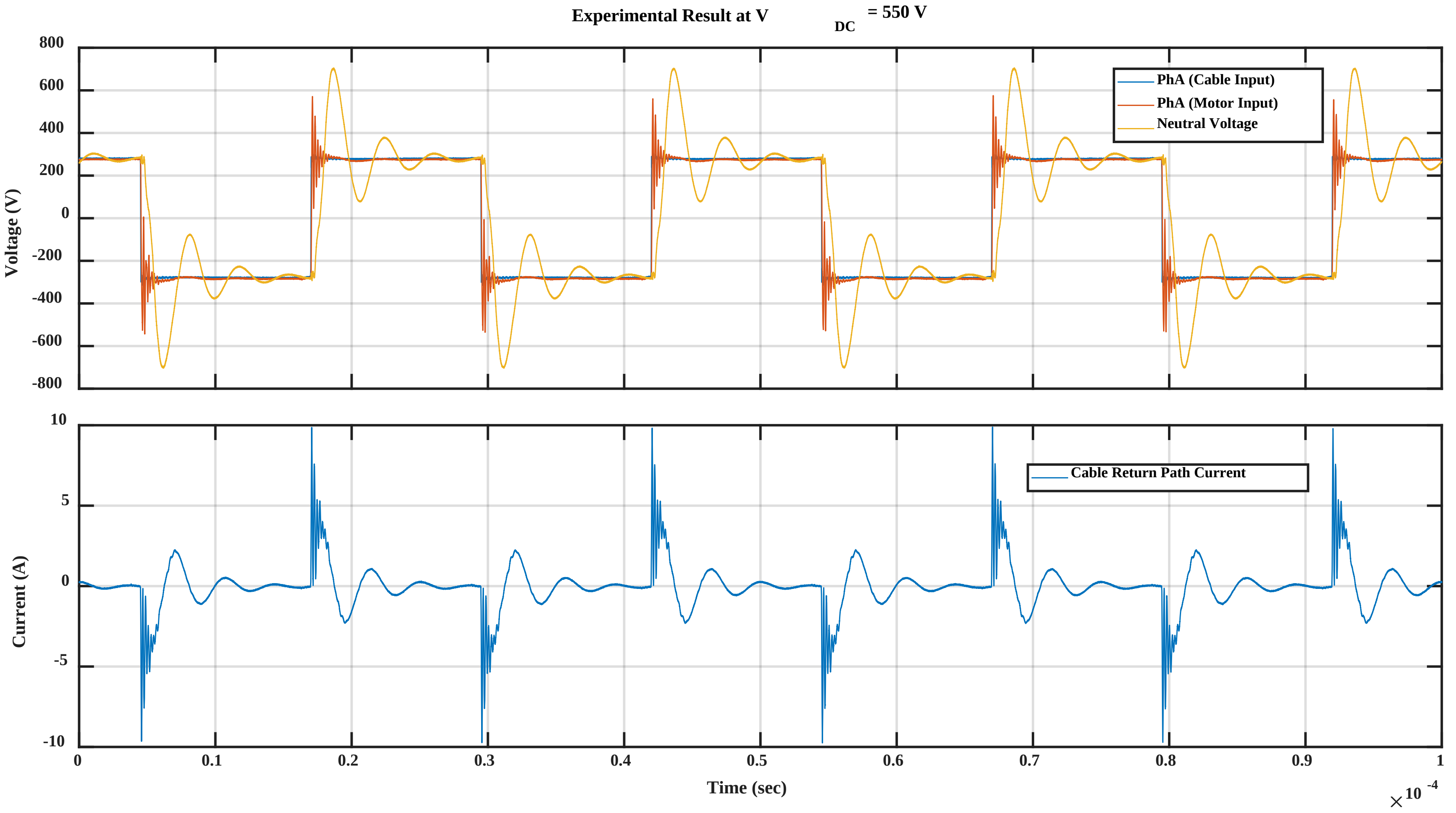
- Inverter output-to-DC reference voltage
- Machine terminal-to-core voltage
- Machine neutral point-to-core voltage
- Common mode current



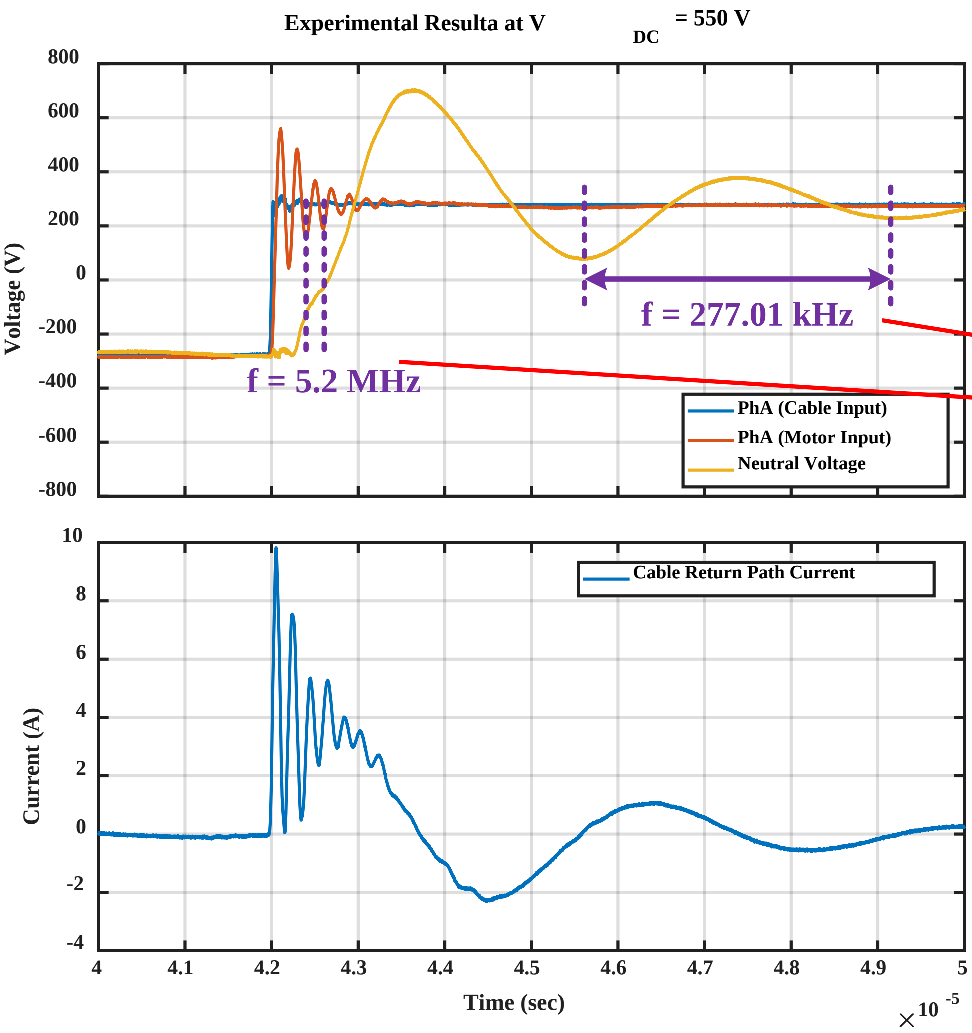
Test Conditions

- DC link voltage = 550V
- Switching frequency = 40kHz
- Inverter rise time = ~20ns
- Cable length = 2.5m

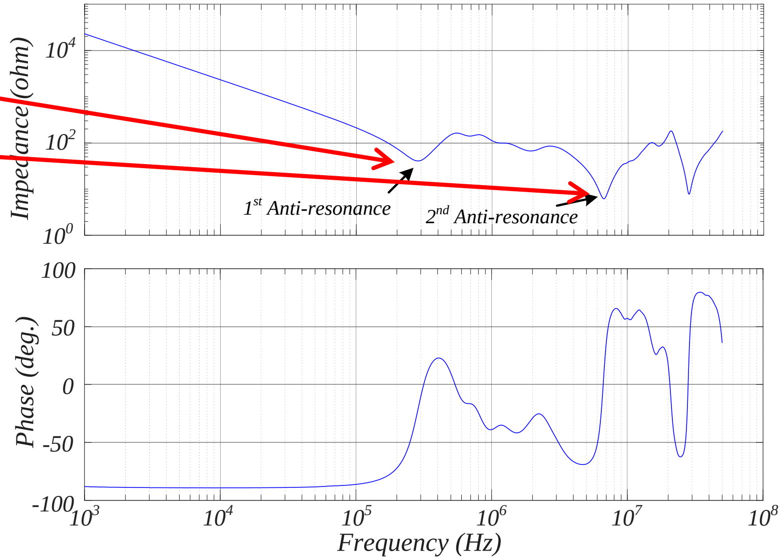
Experimental Results (Phase A)



Experimental Results (Phase A)



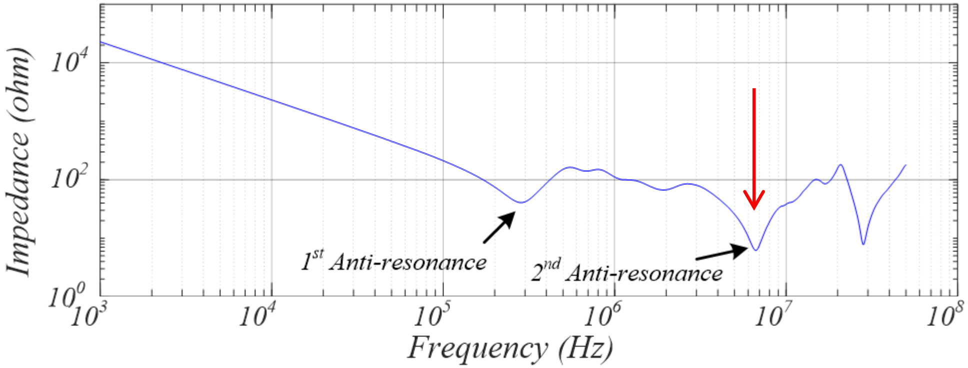
Measured CM impedance of cable-machine



Effects

Due to wave propagation and reflection in cables

- Excessive voltage at machine terminals, phase-to-phase, and phase-to-ground → at 2nd anti-resonant frequency of cable-machine CM impedance
- Excessive turn-to-turn voltage in the first few turns
- Excessive voltage across the 1st coil, **worst case → the coil voltage across turn-to-turn insulation in mash windings**.
- With a short cable length, the 2nd anti-resonant frequency is quite high in MHz and tens of MHz range



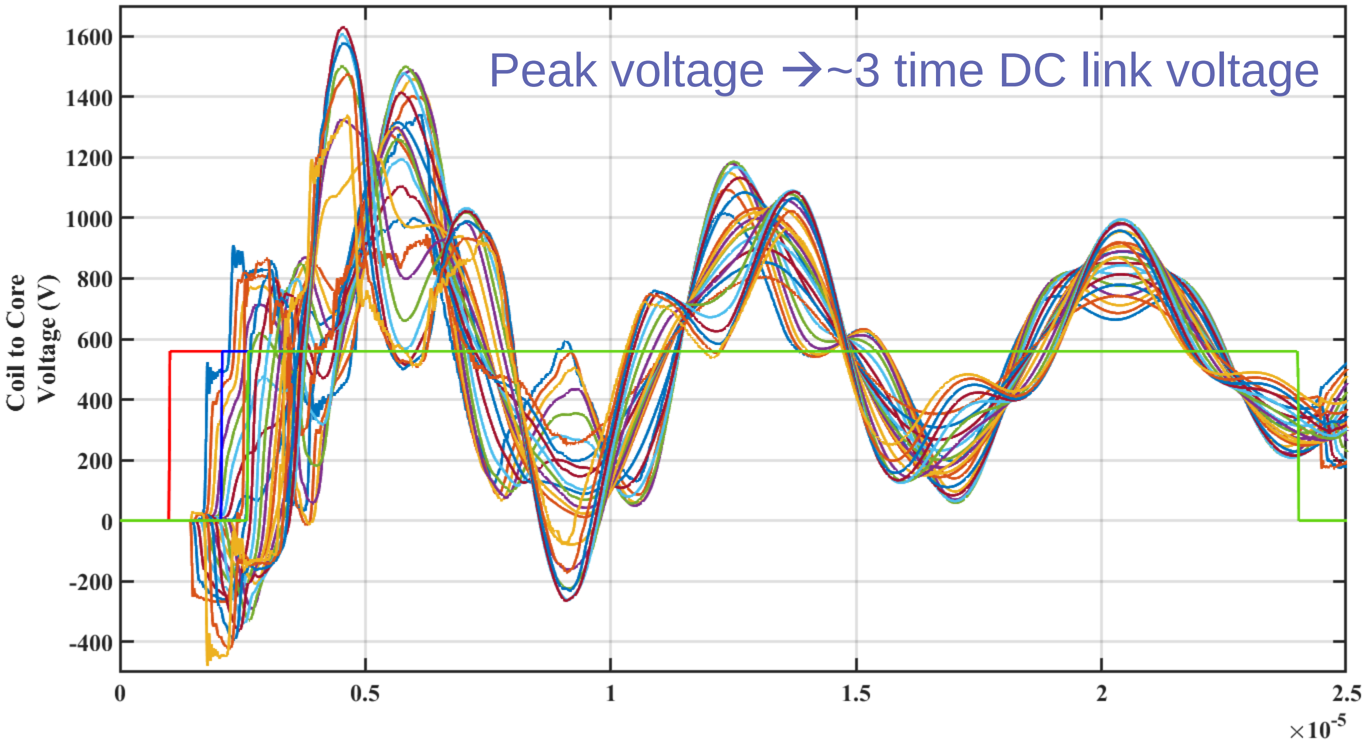
Effects

Due to wave propagation and reflection in machine windings

- High frequency components of oscillation will largely be damped when they propagate into windings
- However, common mode voltage at the inverter output interacts with CM winding impedance to excite excessive voltage oscillations at the **machine anti-resonant frequency, being** relatively low, in a few hundred kHz range
- This oscillation **exists even without cable** and is more significant in the coils **close to star neutral** or in the **middle of a Δ-connected phase winding.**
- The effects are on the turn-, coil-, phase-to-ground voltages and their insulations

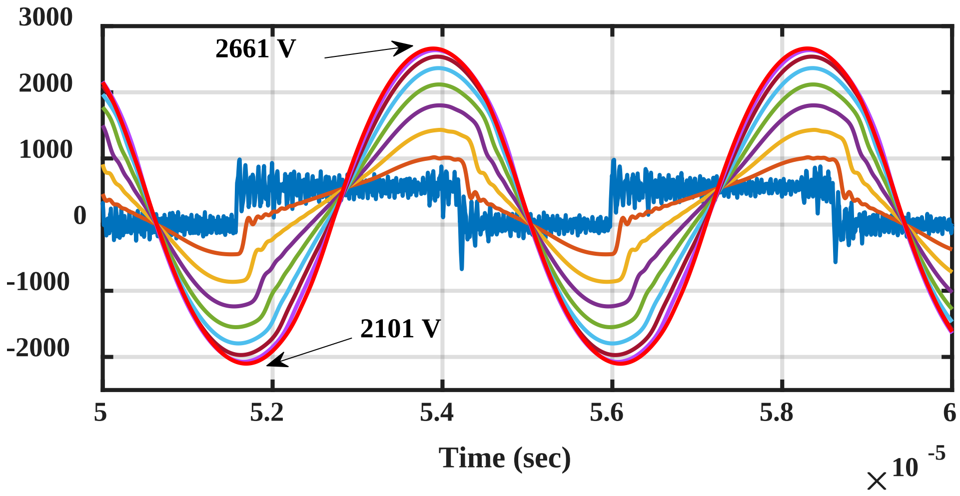
Effects

- If the anti-resonant frequencies of cable and machine windings are close to each other, which may occur with **long cable**, the two oscillations may superimpose, leading to a massive voltage stress, peak-to-peak voltage > 6 times DC link voltage



Effects

- If PWM switching frequency is close to or coincides with the 1st anti-resonant frequency of the winding, sustained resonant oscillation occurs, resulting into an high amplitude (**>8 times V_{DC}**)



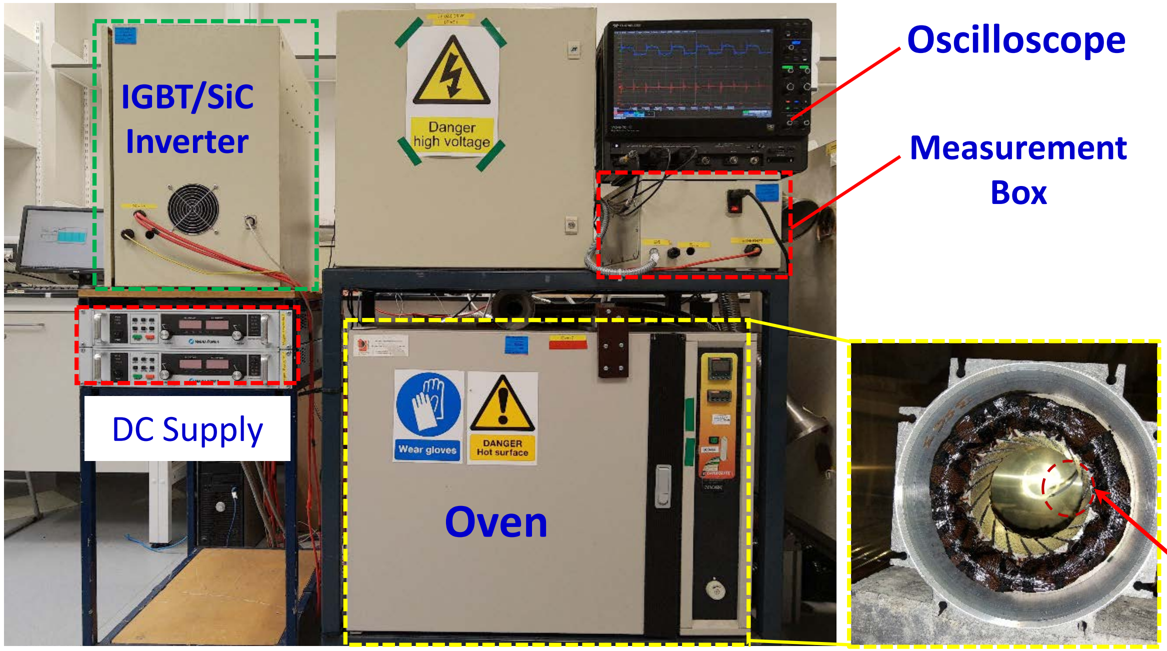
$V_{pk\text{-}pk}$ > 8 times V_{DC} !!

Impact on insulation and reliability

- If peak voltage on insulation is greater than its partial discharge inception voltage (PDIV), partial discharge (PD) will take place.
- Organic based insulation materials used in low voltage machines can fail very quickly when sustained PDs occur.
- Impact on lifetime investigated via accelerated aging tests of **2.8kW PM servo motor**

Insulation materials:

- Essex ultra shield plus **magnet wire** of 200^{o}C thermal class
- Nomex 410 **slot liner**
- Polyster resin **impregnation**



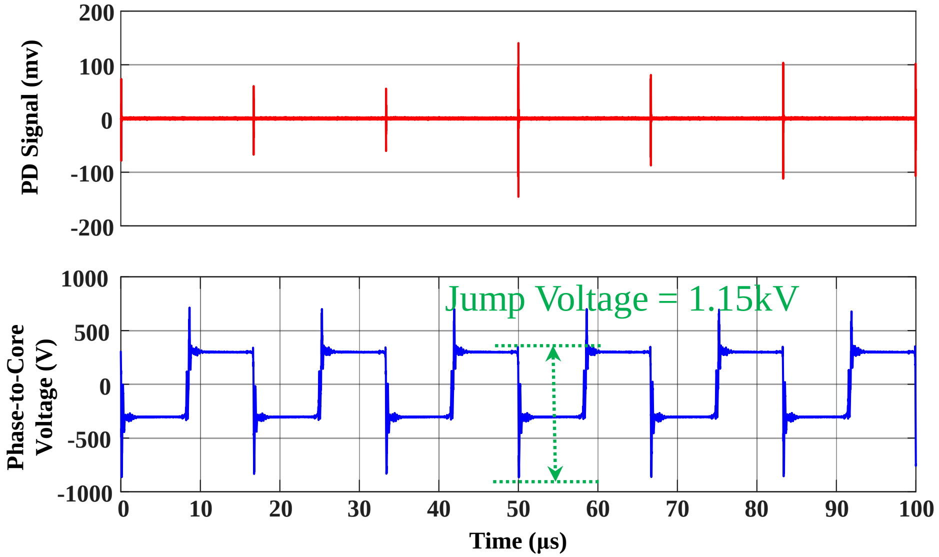
- Insulation state and PD are monitored

Impact on insulation and reliability

Accelerated aging at 230 ^{o}C

	Inverter	V_{DC}	F_{sw}	t_r	Lifetime (days)
1	IGBT	600V	6kHz	500ns	35 (average of 4 sample, no PD)
2	SiC	600V	40kHz	40ns	35 (no PD detected)
3	SiC	600V	60kHz	20ns	17 (sustained PD after 8 days)
4	SiC	800V	20kHz	40ns	17.2 (sustained PD after 9 days)
5	SiC	800V	40kHz	20ns	13 (sustained PD from start)

PD and voltage waveform of sample 3 on day 13



- In the test condition, PDIV of main-wall insulation ≈1.1kV < the peak jump voltage 1.15kV
- PD occurs on every falling edge

Summary I

- The HF model of machine windings can be characterised by its 1st **anti-resonance frequency,** in a few hundred kHz range
- Significant voltage oscillation at the anti-resonance frequency occurs at modulation index when CM voltage from inverter is high.
- This oscillation occurs even without (or very short) cable. The **peak voltage stress occurs** in the **coils near the neutral point**.
- HF behaviour of a drive system can be characterised by the 1st and 2nd anti-resonant frequencies of cable-machine CM impedance

Summary II

- With a short cable, the 1st anti-resonant frequency is dictated by that of machine while the 2nd anti-resonance frequency is greater than a few MHz.
- The voltage oscillation seen at machine terminals or in 1st a few turns due to impedance mismatch is at the 2nd anti-resonant (high) frequency.
- The **HF** voltage oscillation at the 2nd **anti-resonance frequency** is filtered by the **turn-to-core capacitance**, hence cannot penetrate deep inside the coils.
- The **coil-to-core voltage** of the winding close to the neutral point **oscillates** at the 1st **anti-resonance frequency** of the machine (or cable-machine).

Summary III

- The worst case occurs when the cable anti-resonance frequency is close to that of machine winding. The peak coil voltage can reach ~3 times DC link voltage.
- If switching frequency is closed to the 1st anti-resonant frequency, the peak coil voltage can be 4 times DC link voltage
- Through prediction or measurement of machine CM winding impedance, its high frequency behaviour under inverter operation can be characterised.
- Accelerated aging testing demonstrated significant lifetime reduction under sustained PD

Acknowledgement

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