Influence of PWM Inverters on Bearing Currents

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Scope

- Introduction
    - PWM Inverter Topology
    - Common Mode Voltage and Shaft Voltage
- Factors Affecting Shaft Voltage and Bearing Current
- Study of Bearing Insulation Characteristics When Subjected to Externally Injected Signal
- Techniques to Reduce Bearing Current Issues Caused by PWM Inverters

1. 2-Level PWM Inverter Topology

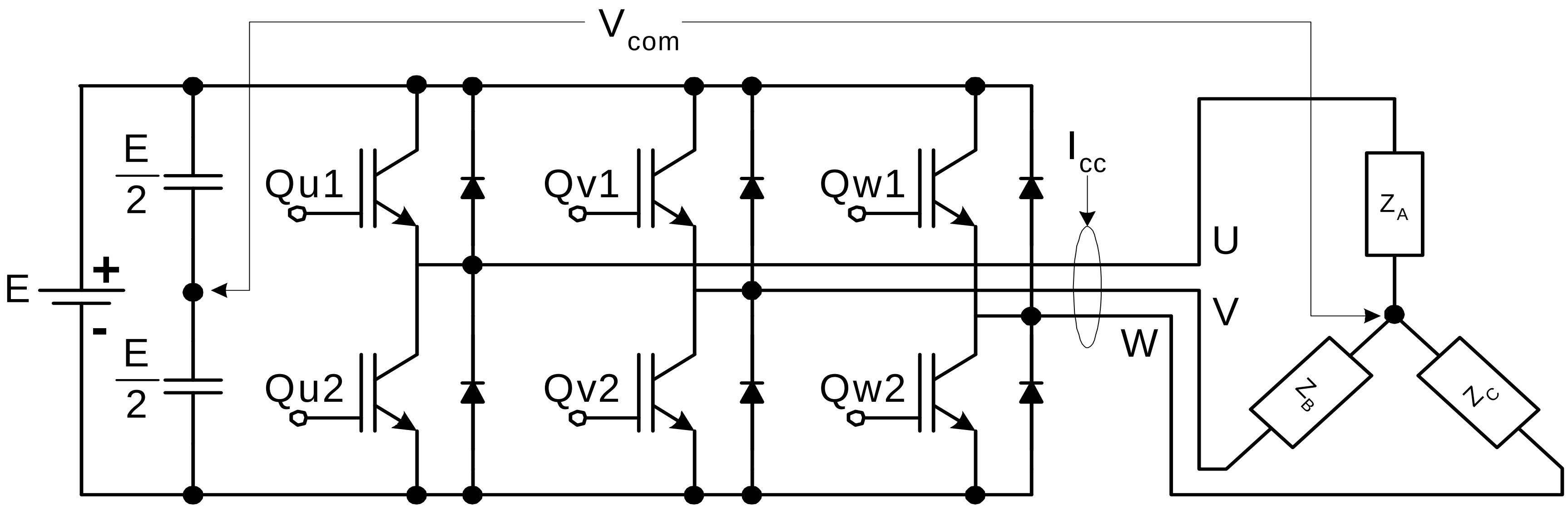


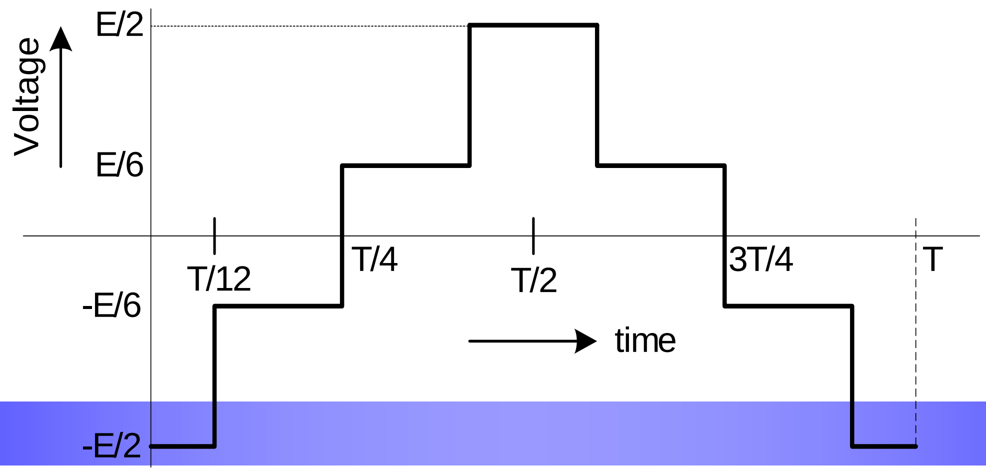
Table 1. Relation between switching states and output voltage

	Q_{u1}	Q_{u2}	V_u
Switching State	ON	OFF	+E/2
	OFF	ON	-E/2

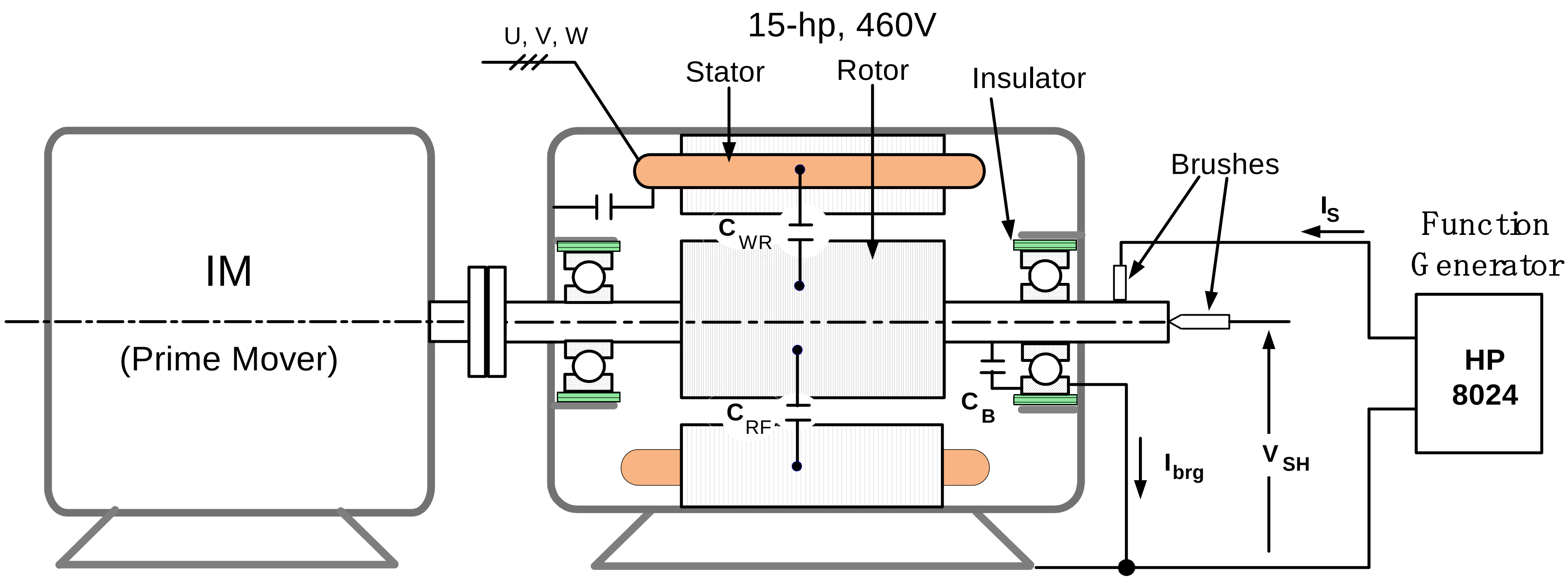
1. Common Mode Voltage in 2-Level Inverters

Table 1. Relation between switching states and output voltage

	Q_{u1}	Q_{u2}	Q_{v1}	Q_{v2}	Q_{w1}	Q_{w2}	V_{com}
Switching State	OFF	ON	OFF	ON	OFF	ON	-E/2
	ON	OFF	OFF	ON	OFF	ON	-E/6
	ON	OFF	ON	OFF	OFF	ON	+E/6
	ON	OFF	ON	OFF	ON	OFF	+E/2
	OFF	ON	ON	OFF	ON	OFF	+E/6
	OFF	ON	OFF	ON	ON	OFF	-E/6
	OFF	ON	OFF	ON	OFF	ON	-E/2

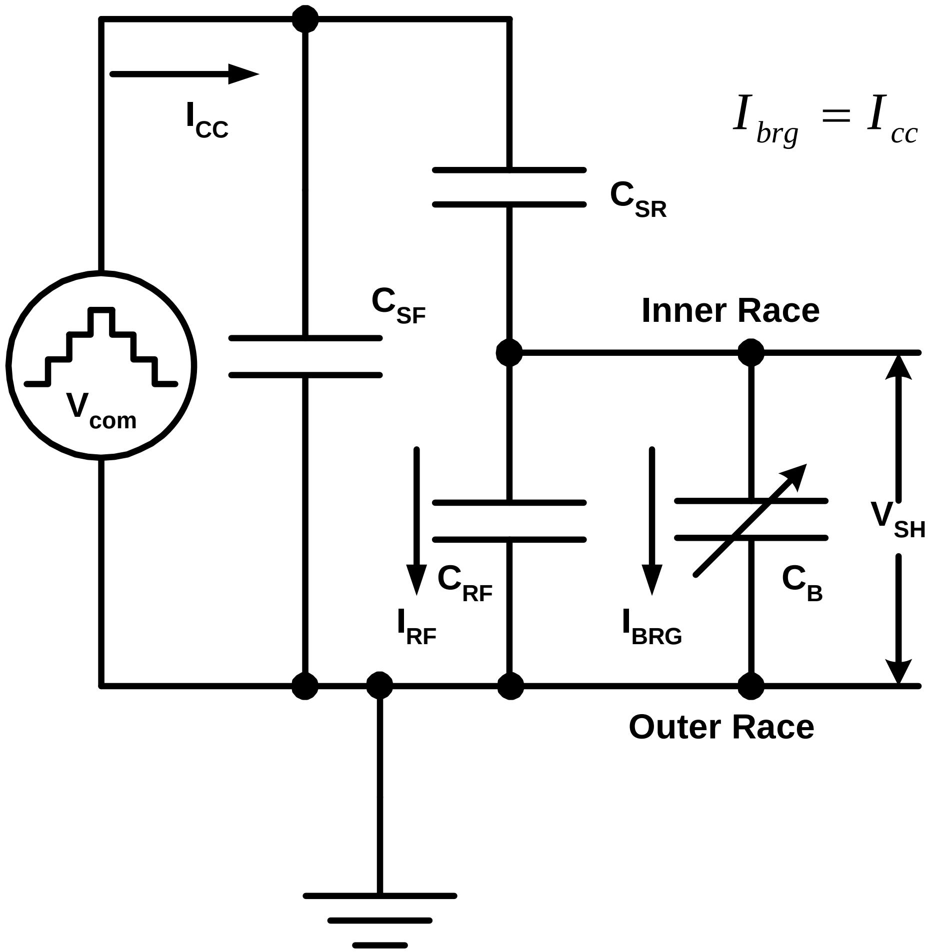


2. Test Setup



- Test motor – driven by another motor
- Waveforms applied from Function Generator to study bearing breakdown phenomenon

3. Parasitic Model for Bearing Test

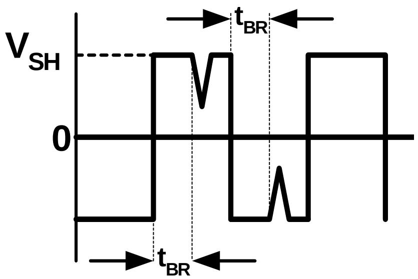


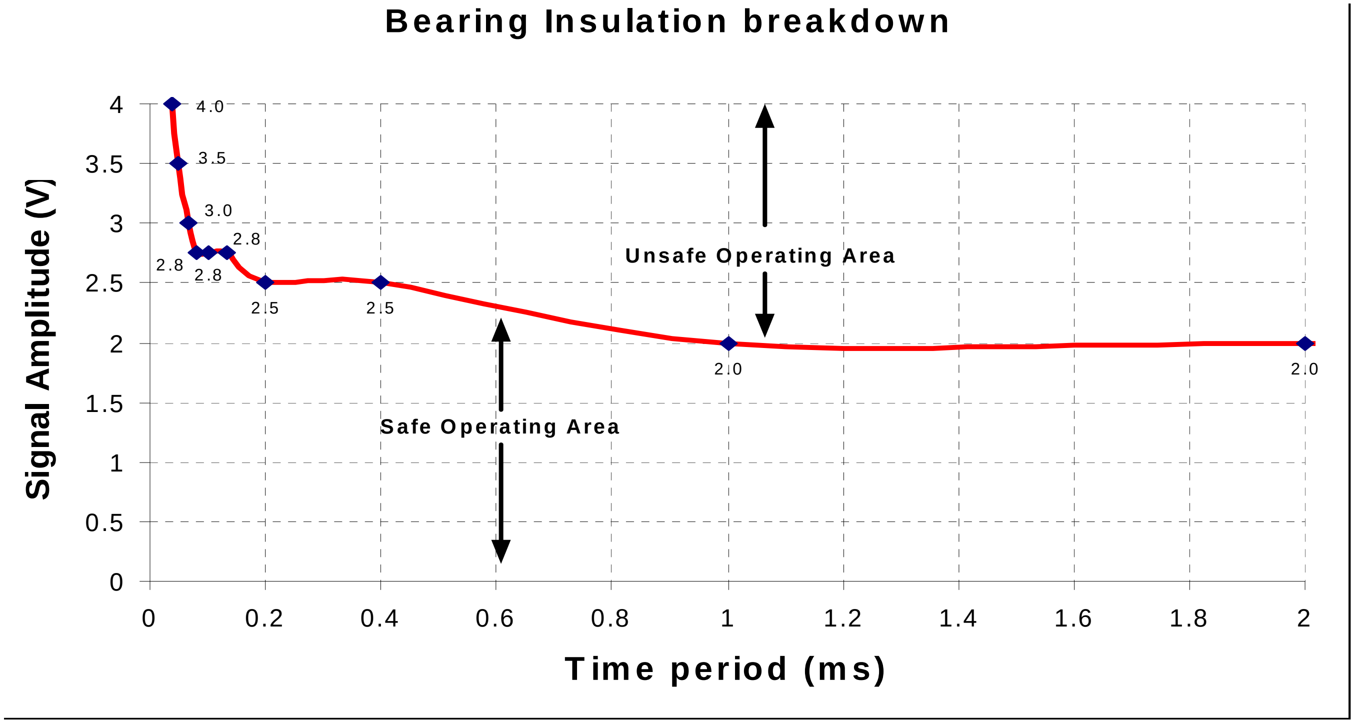
$$I_{brg} = I_{cc} \cdot \frac{1/C_{SF}}{(1/C_{SF}) + (1/C_{SR}) + (1/(C_{RF} + C_{B1} + C_{B2}))}$$

Electrical representation of parasitic capacitances in a motor

Test 1. Time-Period (Frequency) vs. Shaft voltage (V_{SH})

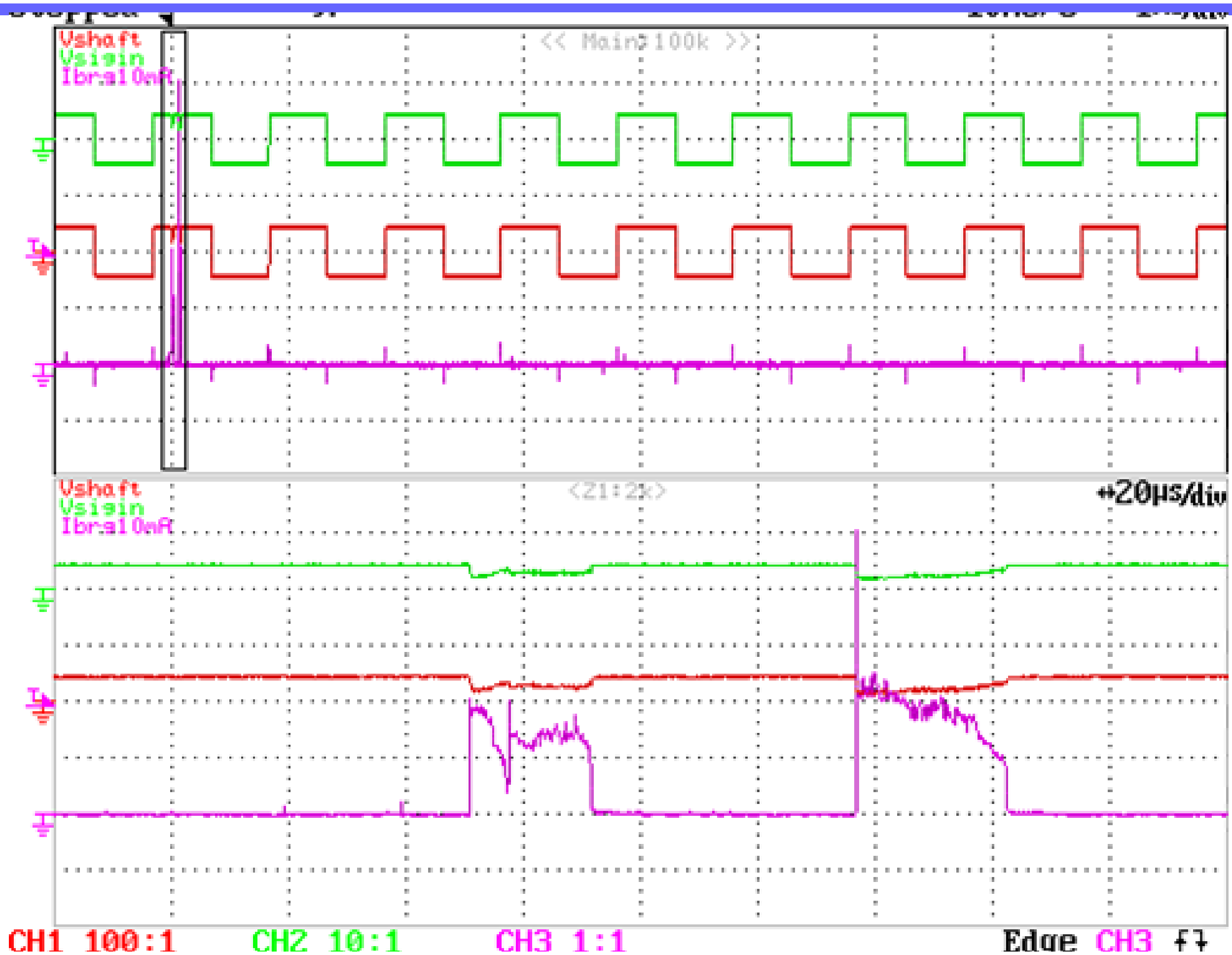
(Symmetric Rectangular Waveforms of Different Frequencies)





- At higher frequency, breakdown occurs in shorter time for a given shaft voltage. Breakdown voltage is also higher at higher frequency
- At low frequency (180Hz), bearing insulation breaks down at lower shaft voltage – though it takes longer time to breakdown

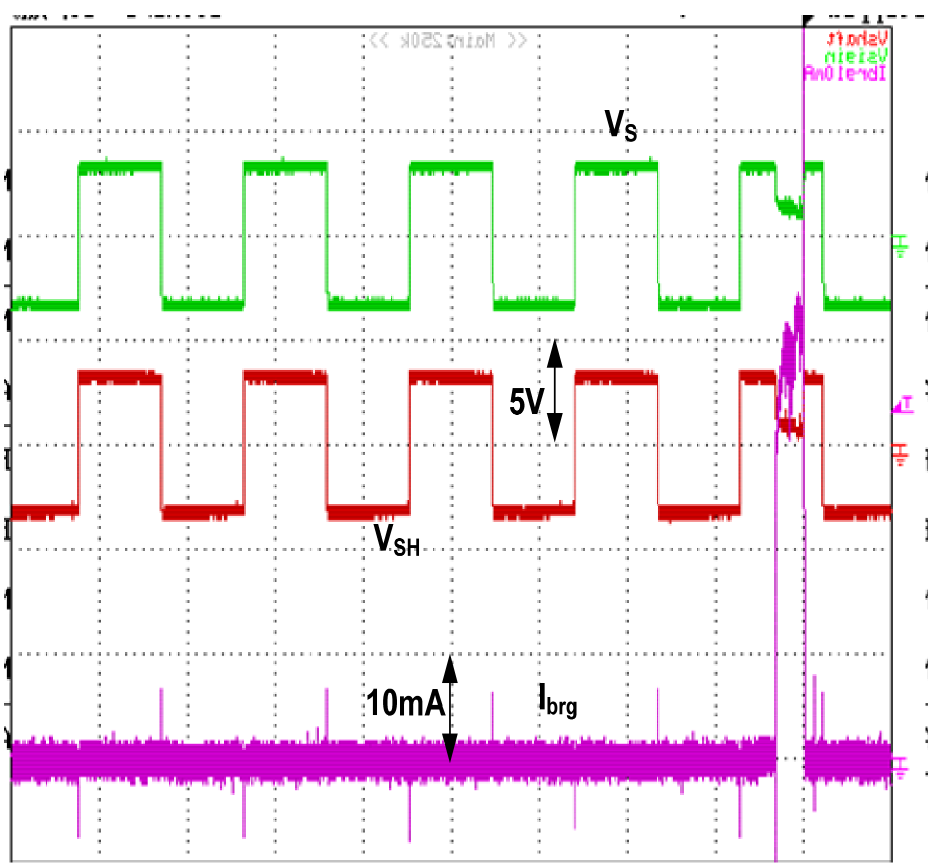
Sample Waveforms for Test 1



Time period= 1.0ms

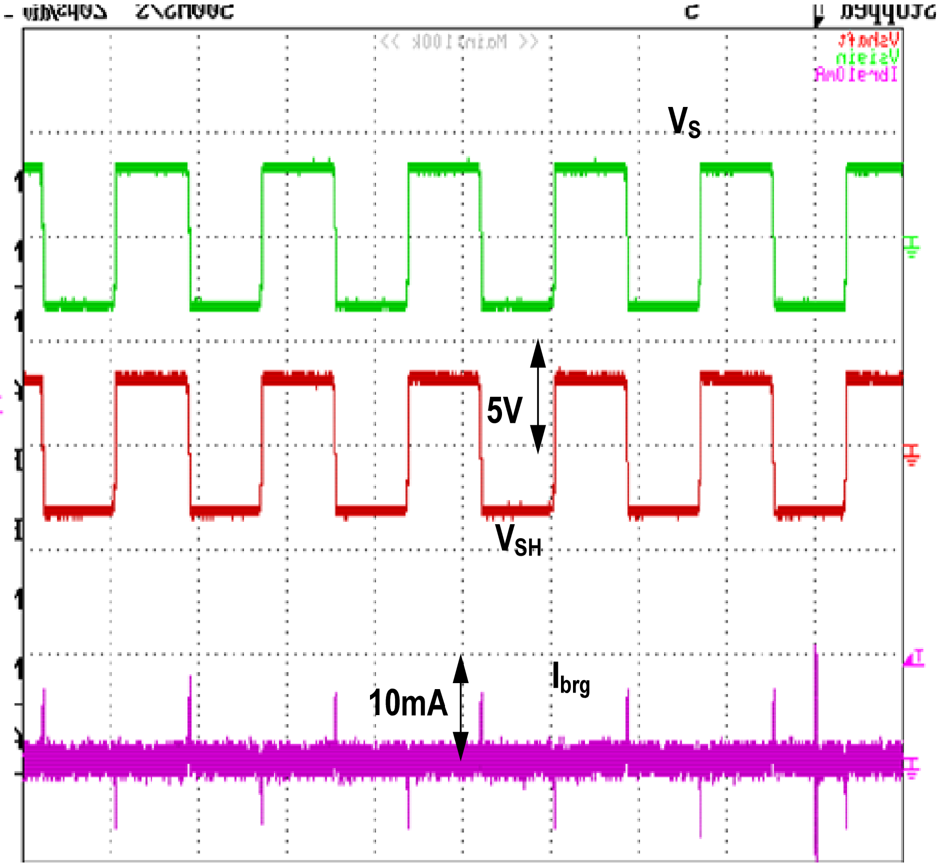
Breakdown occurs at 2.0 Vp-p

Sample Waveforms for Test 1 – Contd.



Time period= 0.1ms

Breakdown occurs at 3.5 Vp-p

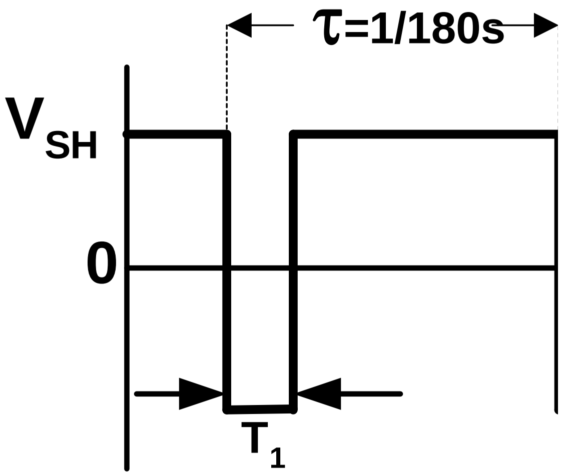


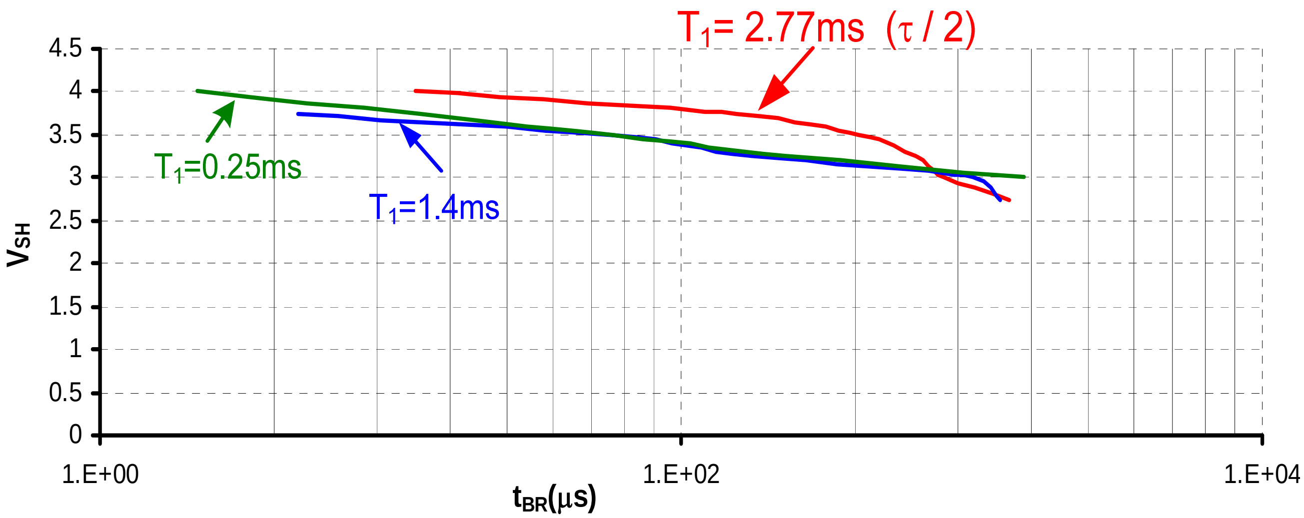
Time period= 0.033ms

No Breakdown occurs at 3.5 Vp-p

Test 2. Time-to-breakdown (t_{BR}) vs. Shaft voltage (V_{SH})

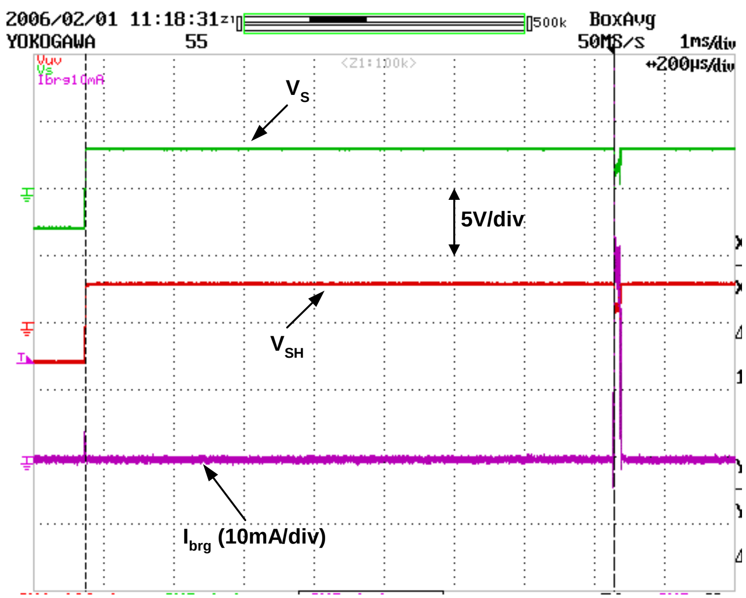
(180Hz, Asymmetric Rectangular Waveform)

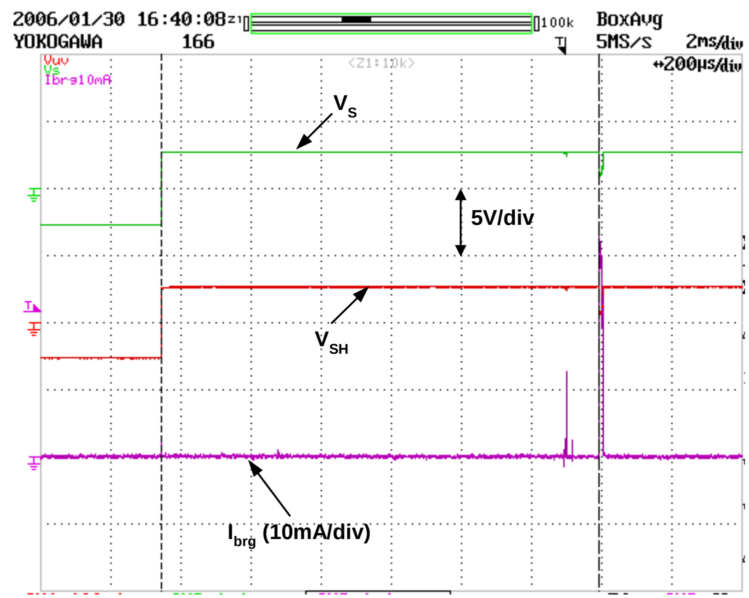




- At low frequency, duration of T_1 does not significantly influence the shaft breakdown voltage.
- However, influence of Asymmetry is not pronounced.

Sample Waveforms for Test 2





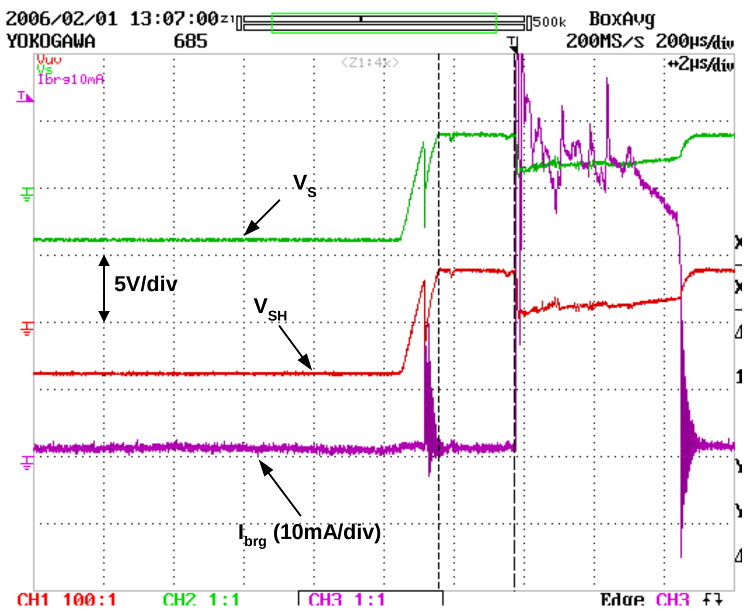
180Hz, T_1=0.25mS

t_{BR} = 1.51ms at V_{SH}=+/-3V

180Hz, T_1=1.4mS

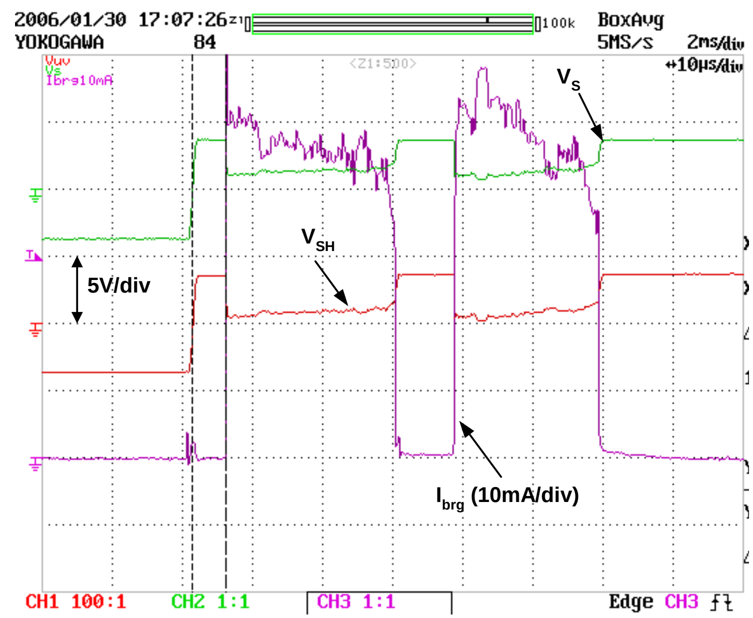
t_{BR} = 1.24ms at V_{SH}=+/-2.75V

Sample Waveforms for Test 2 – Contd.



180Hz, T_1=0.25mS

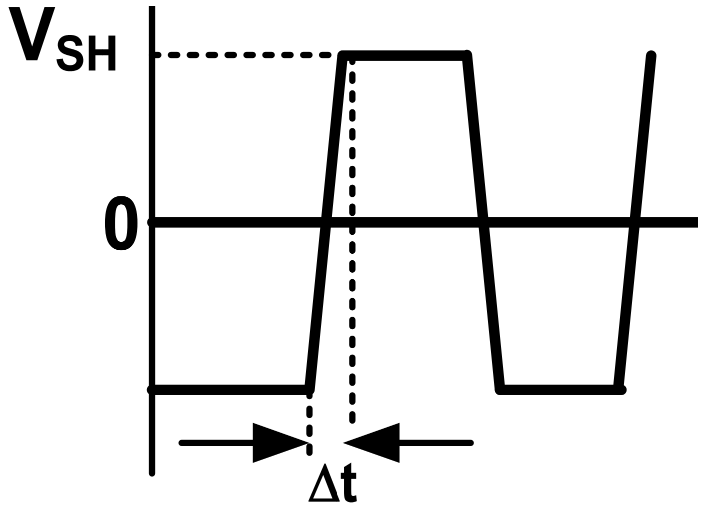
t_{BR} = 2.15µs at V_{SH}=+/- 4V



180Hz, T_1=1.4mS

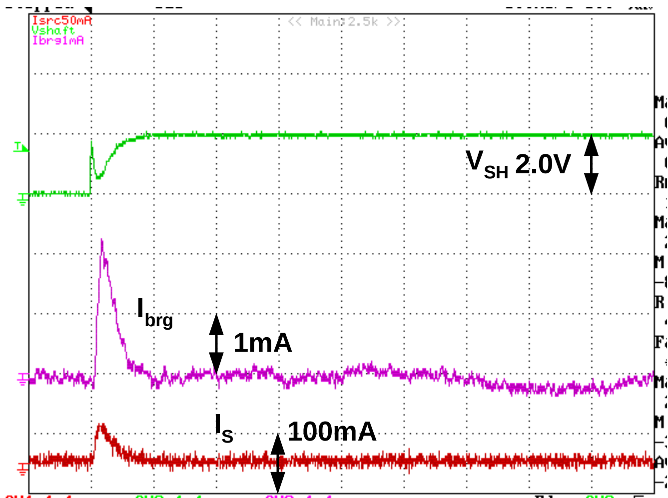
t_{BR} = 4.8µs at V_{SH}=+/-3.75V

Test 3. Bearing insulation break down versus dv/dt of shaft voltage

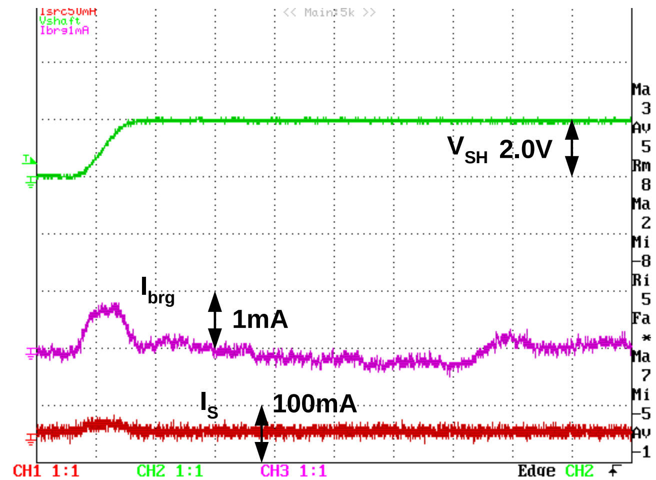


- Bearing film insulation breakdown phenomenon is observed to be independent of the dv/dt of the applied voltage.
- Low shaft voltage, even with high dv/dt, does not cause the bearing film insulation to breakdown.
- High shaft voltage, even with low dv/dt, causes the bearing film insulation to breakdown easily.
- When the dv/dt of the externally injected square voltage is changed from 4ns to 400ns or greater, the charging current into the bearing does not reduce by the same factor, as does the dv/dt. This shows that the charging bearing current is also a function of the dc component of the applied voltage.

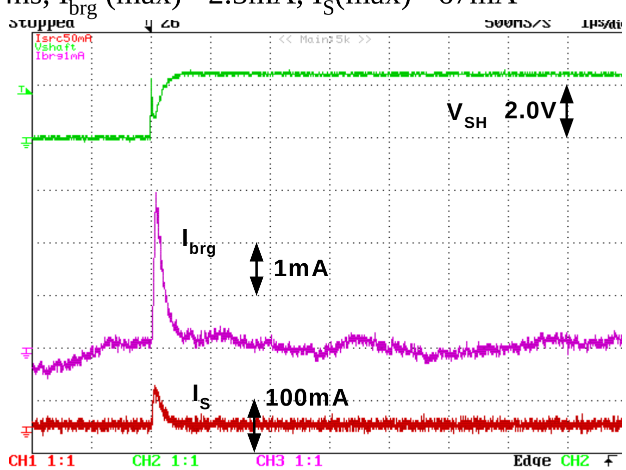
Tests: Bearing insulation break down versus dv/dt of shaft voltage



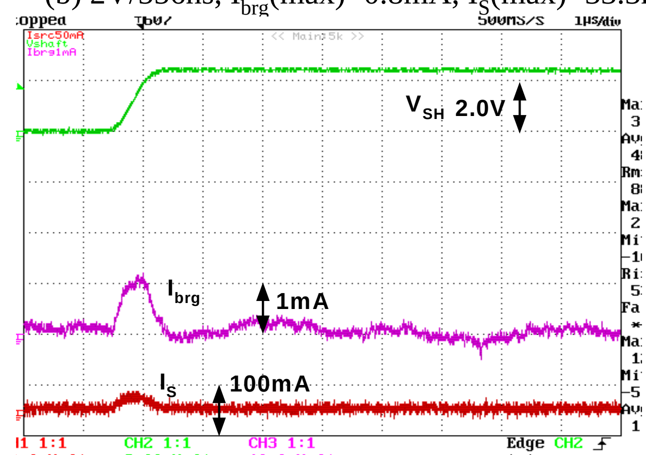
(a) 2V/4ns, I_{brg} (max)= 2.5mA, I_S(max)= 67mA



(b) 2V/556ns, I_{brg}(max)=0.8mA, I_S(max)=33.3mA

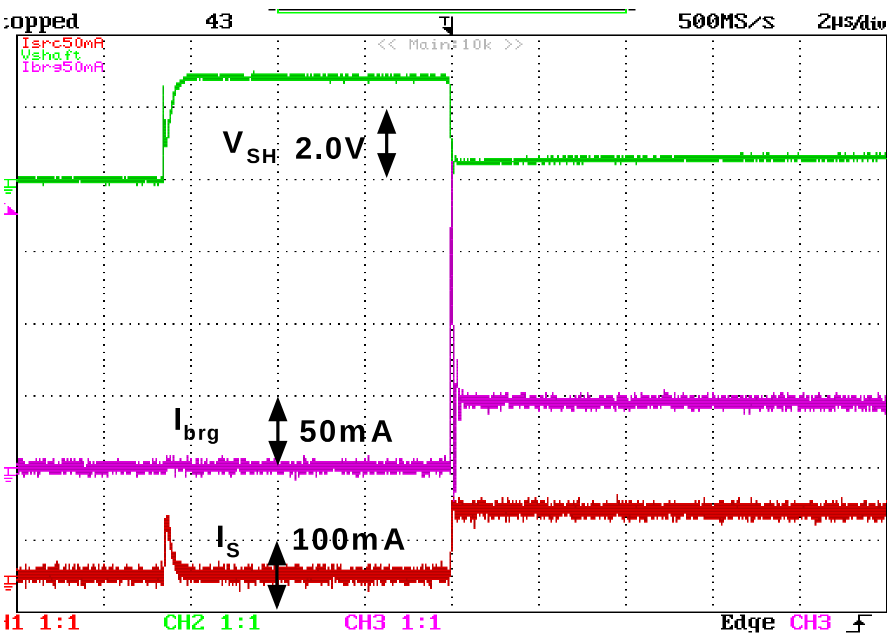


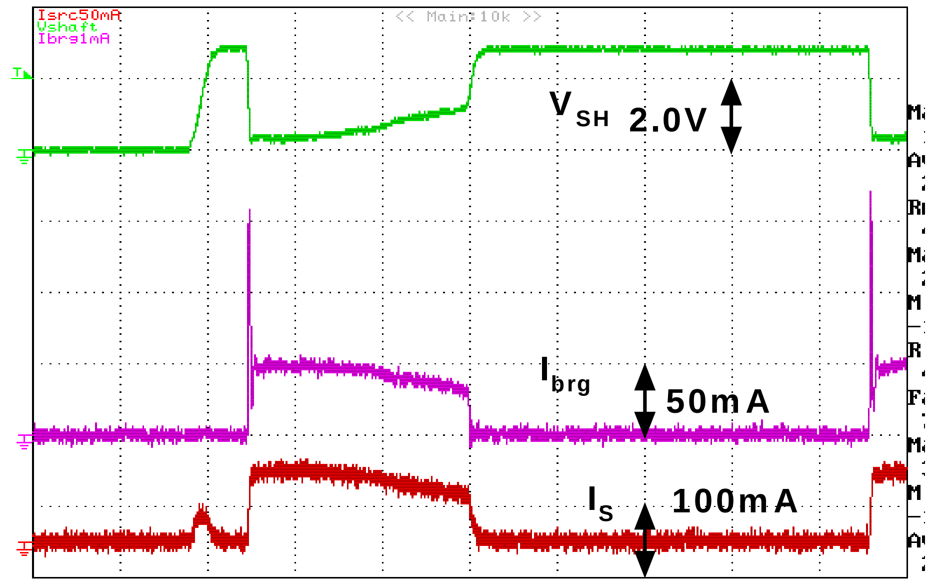
(c) 2.5V/4ns, I_{brg}(max)= 2.95mA, I_S(max)= 79mA



(d) 2.5V/534ns, I_{brg}(max)= 1.2mA, I_S(max)= 37mA

Tests: Bearing insulation break down versus dv/dt of shaft voltage



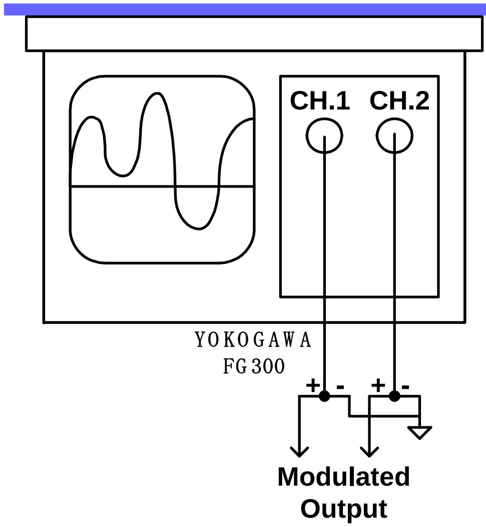


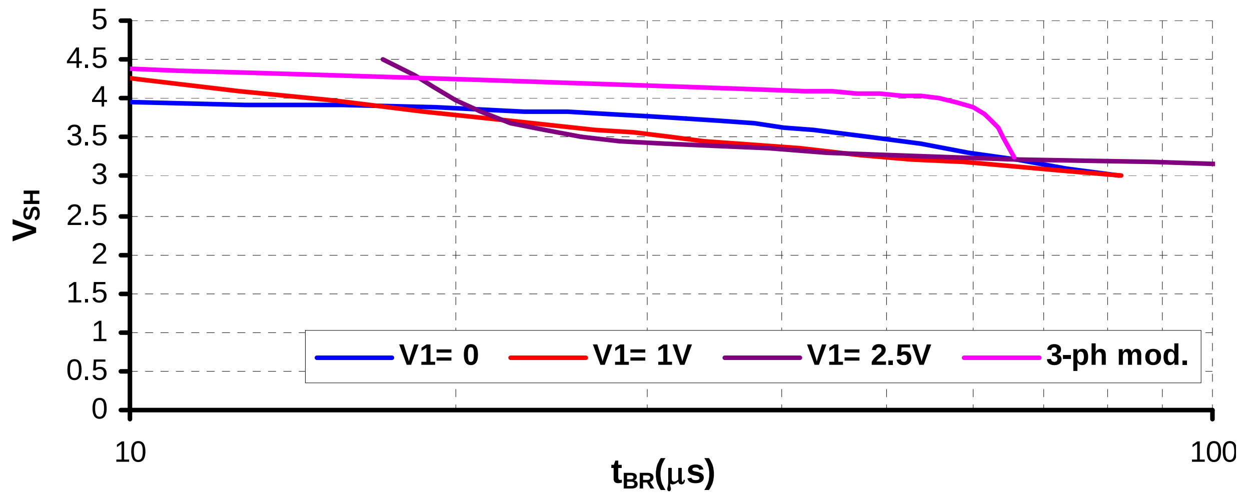
(e) Breakdown at 3V/4ns, Ibrg(max)= 212.5mA, IS(max)= 56.25mA

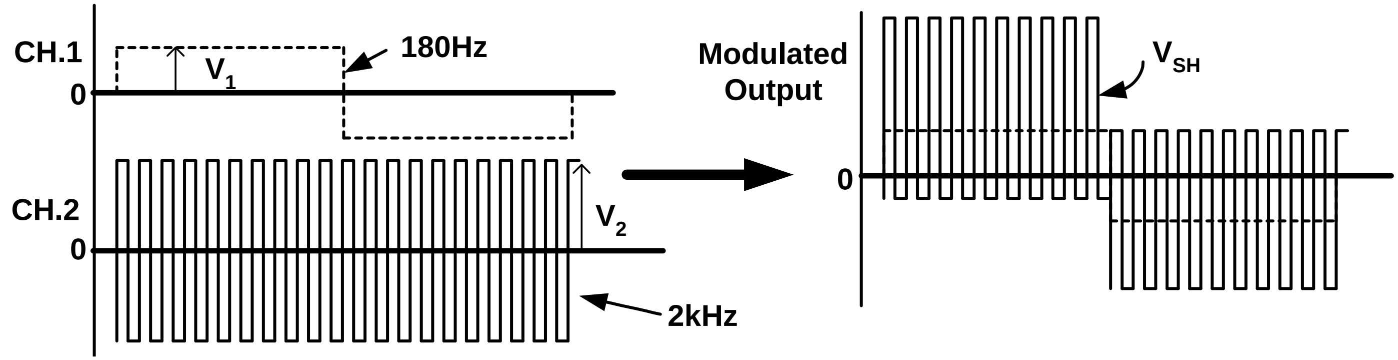
(f) Breakdown at 3V/404ns, Ibrg(max)= 170mA, ISmax)= 58mA

Test 4. Time-to-breakdown (t_{BR}) vs. Shaft voltage (V_{SH})

(2kHz Rectangular Waveform Modulated with 180Hz Signal)

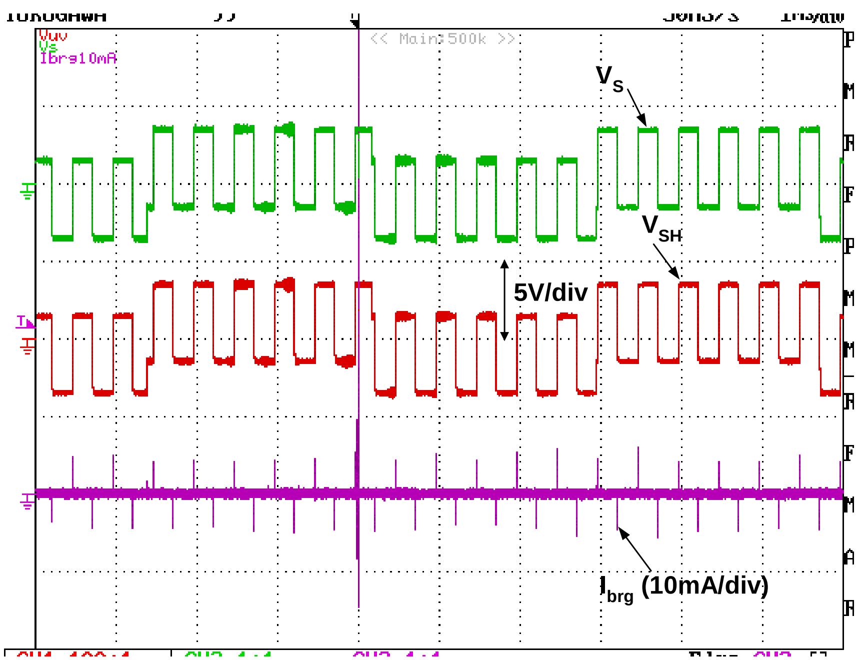






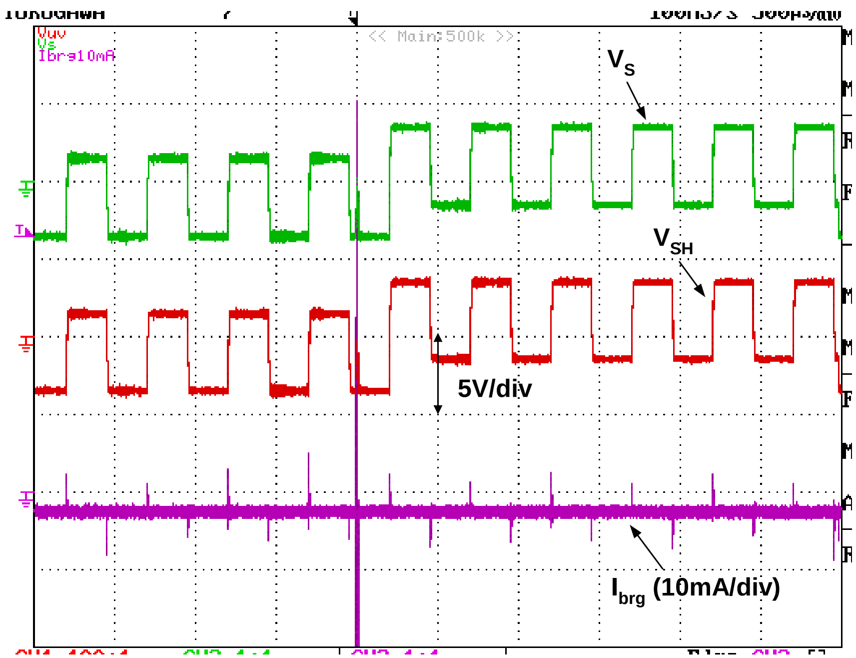
- The modulated waveform emulates shaft voltage associated with 2-Phase modulation.
- No orderly effect of modulation to breakdown time was observed.

Sample Waveforms for Test 4



V_1= 1V

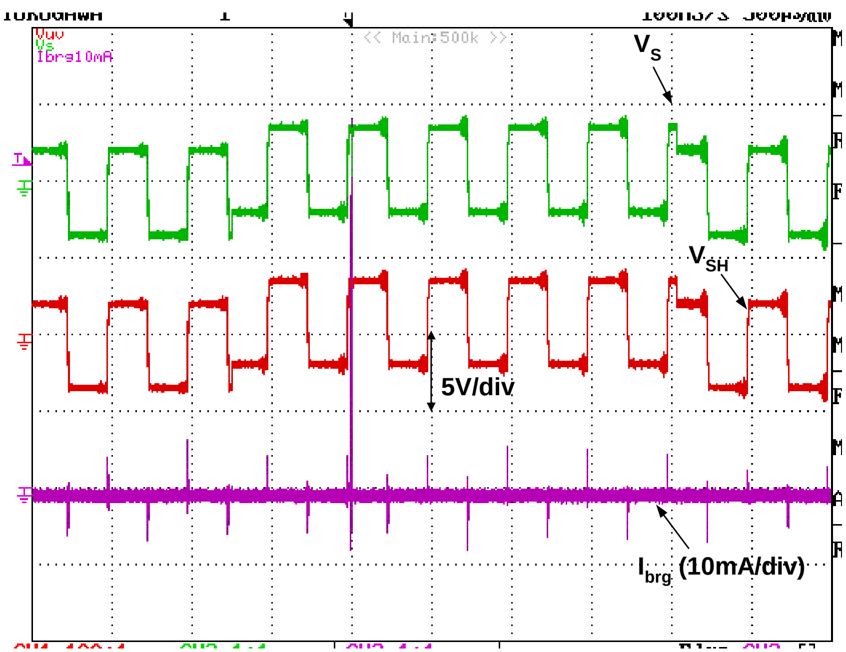
t_{BR} = 31.5μs at 7.0 $V_{p\text{-}p}$



V_1= 1.5V

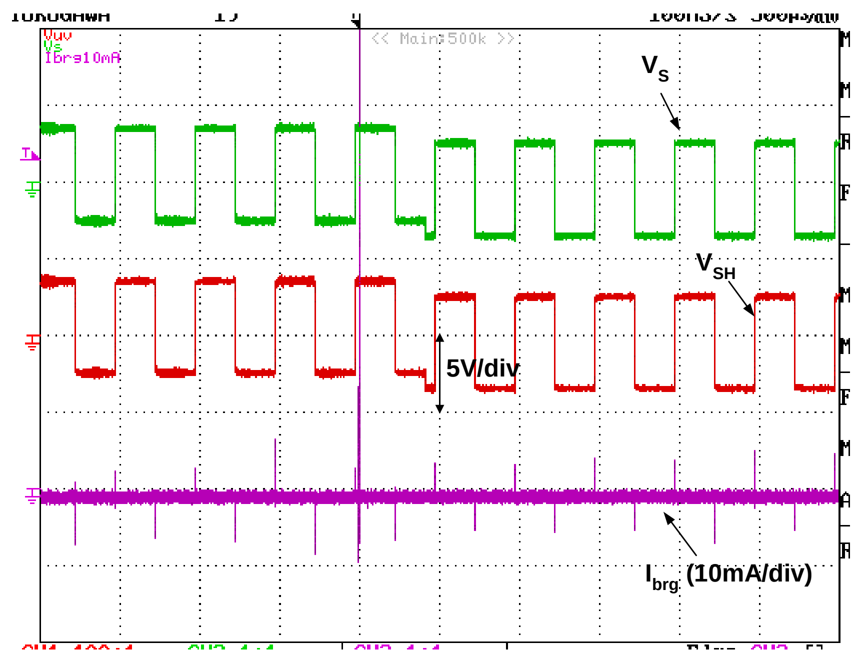
t_{BR} = 40.4μs at 7.0 $V_{p\text{-}p}$

Sample Waveforms for Test 4



V_1= 2V

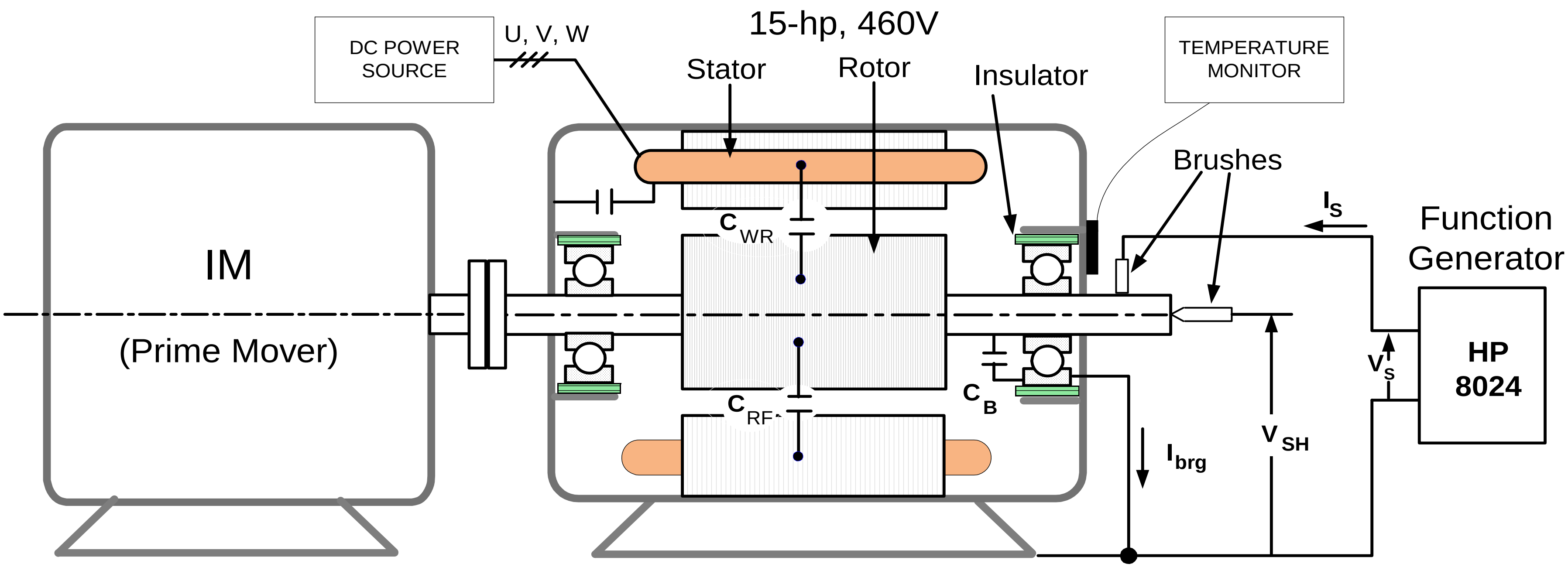
t_{BR} = 21.8μs at 7.0 $V_{p\text{-}p}$



V_1= 2.5V

t_{BR} = 26.1μs at 7.0 $V_{p\text{-}p}$

Effect of Temperature



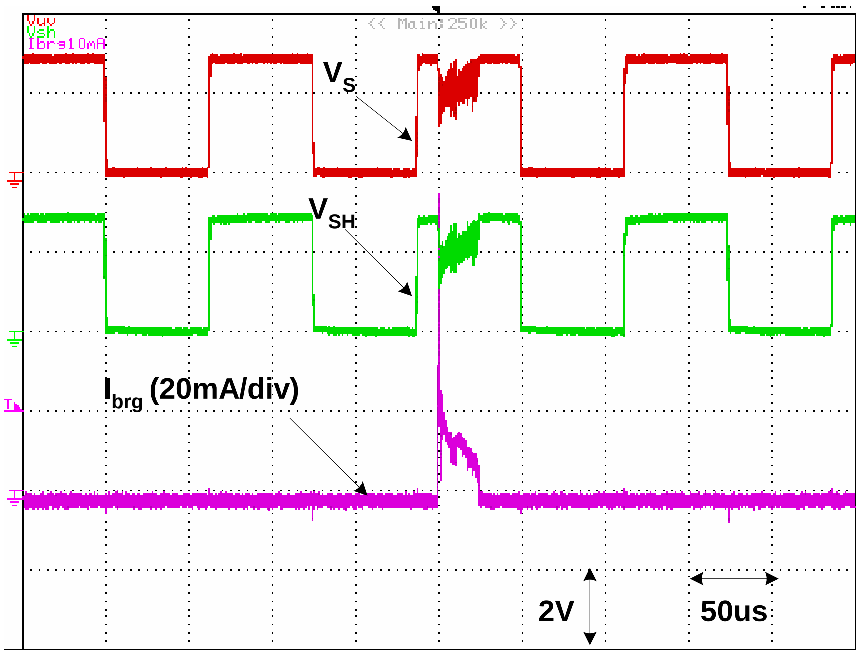
J-Type Thermocouple used

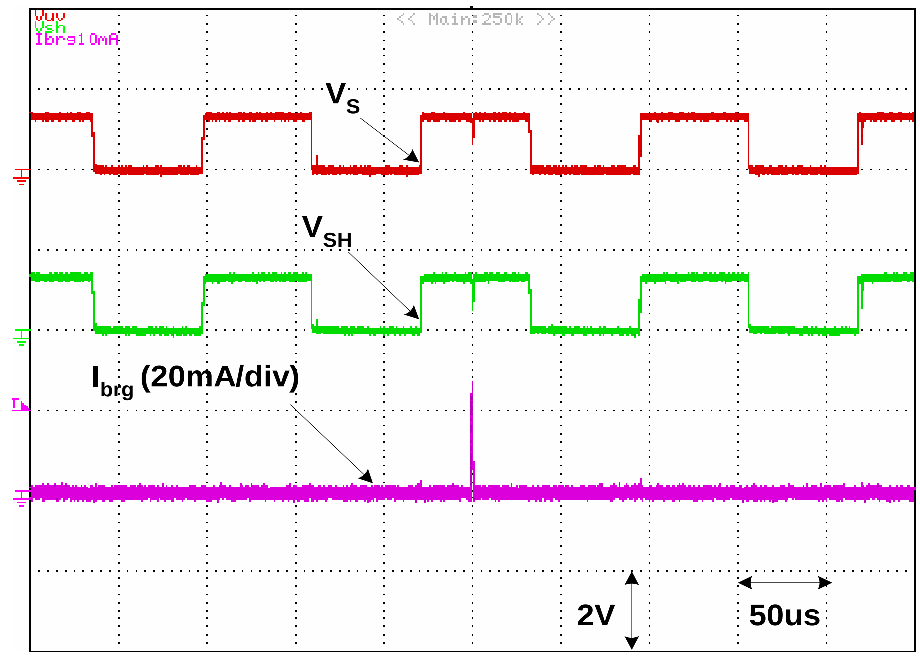
External signal was injected at shaft

Motor was heated using DC injection

Breakdown voltage as a function of Temperature was studied

Sample Waveforms for Temperature Test





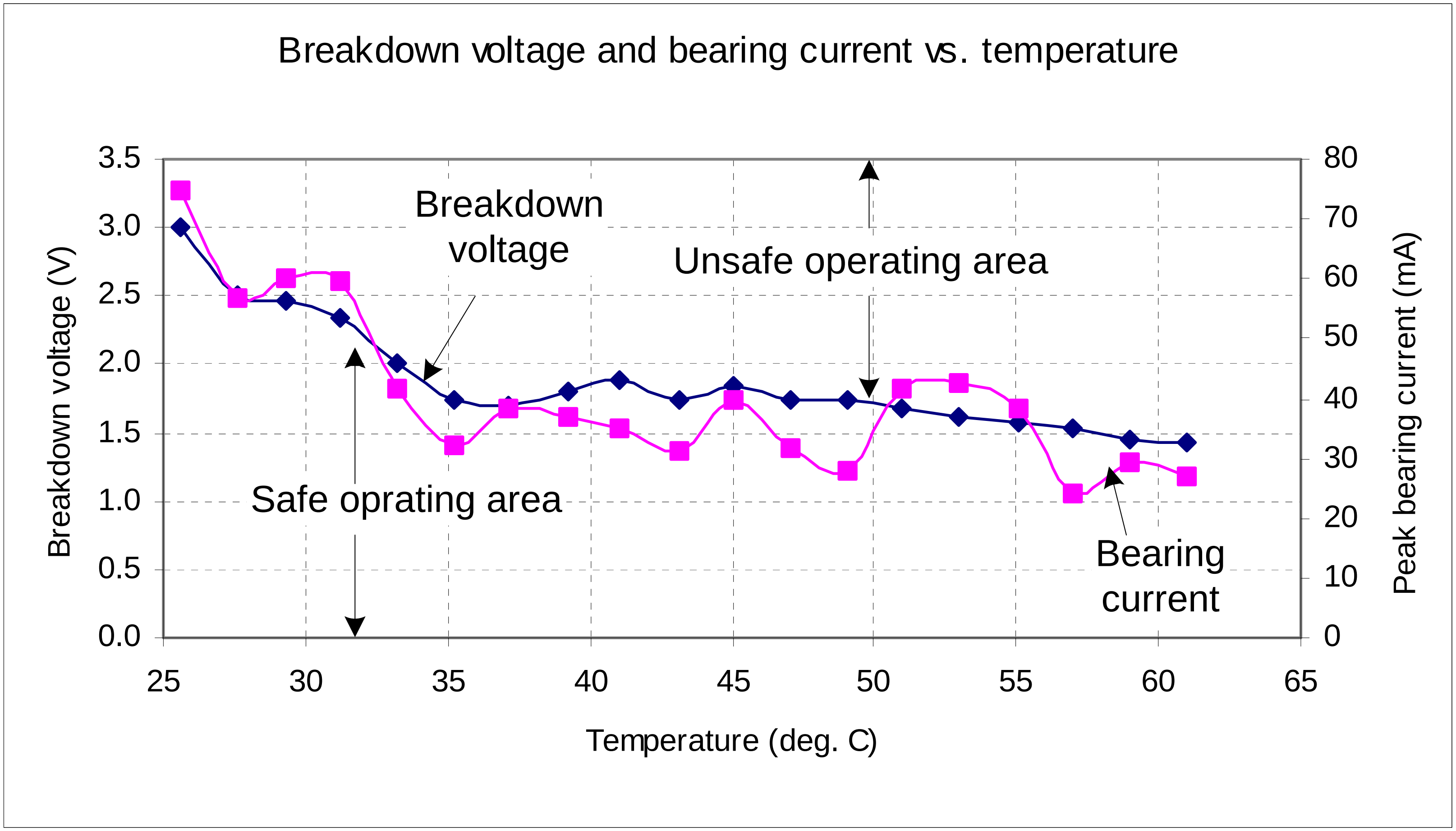
Temperature = 25.6 deg. C

Breakdown Voltage= 3V

Temperature = 61 deg. C

Breakdown Voltage= 1.42V

Breakdown Voltage Versus Temperature



4. Key Observations

- At higher frequency, breakdown occurs in shorter time; At low frequency (180Hz) break down occurs at lower shaft voltage.

- Asymmetric Waveform with shorter negative period shows lower breakdown voltage.

  However, influence of asymmetry is not pronounced.

- dv/dt of waveform does NOT directly influence the breakdown of bearing phenomenon – it may be responsible to increase the temperature of the bearing and hence accelerate the breakdown

- Modulated waveform showed no definite correlation with breakdown time.

- Higher temperature reduces shaft breakdown voltage significantly.

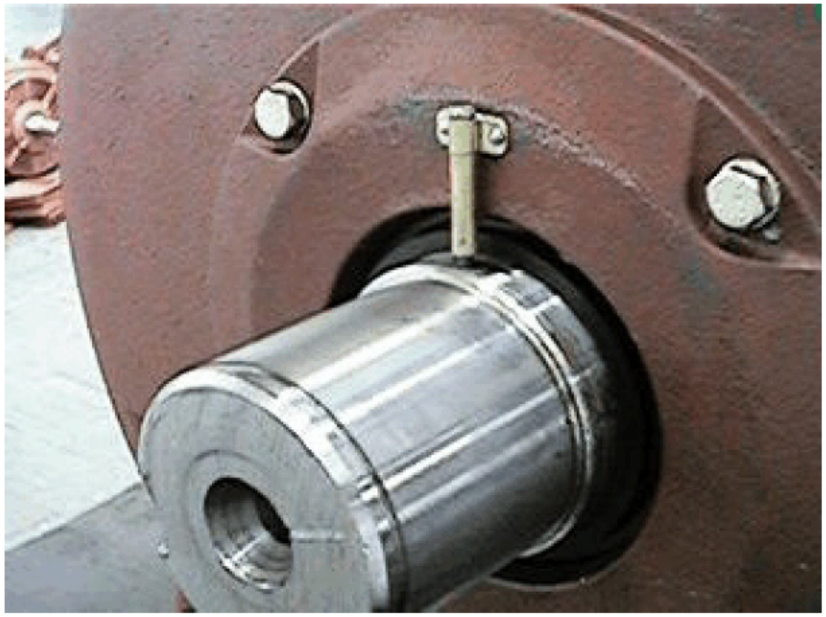
5. Mitigation Techniques

- Shaft Brush.
- Faraday Shield.
- Common Mode Filters
- 3-Level Inverters.

6. Shaft Brush

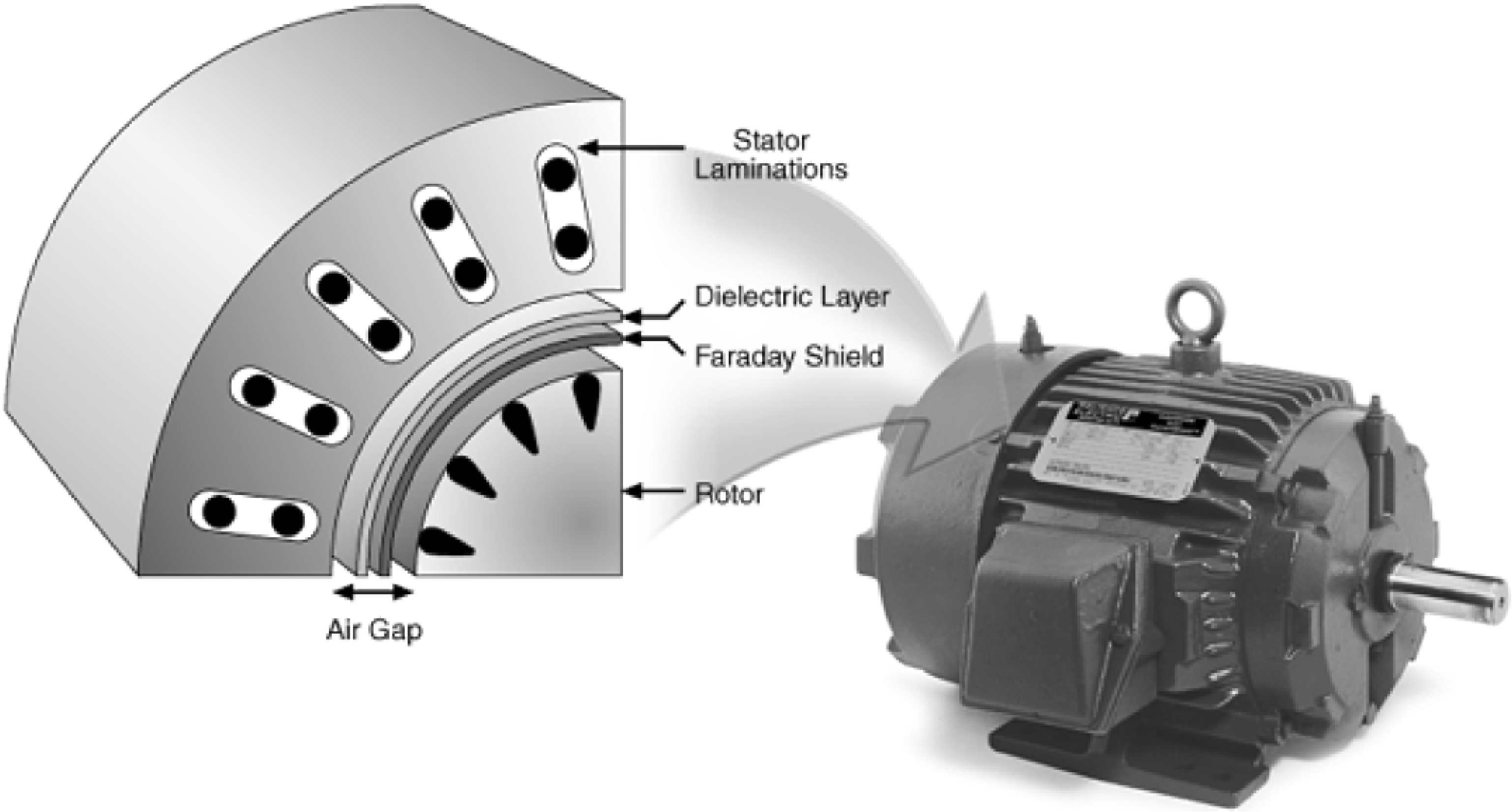
BRUSH-HOLDER KIT FOR GROUNDING OF ELECTRIC MOTORS BEARINGS

(APPLIED WITH FREQUENCY INVERTER)



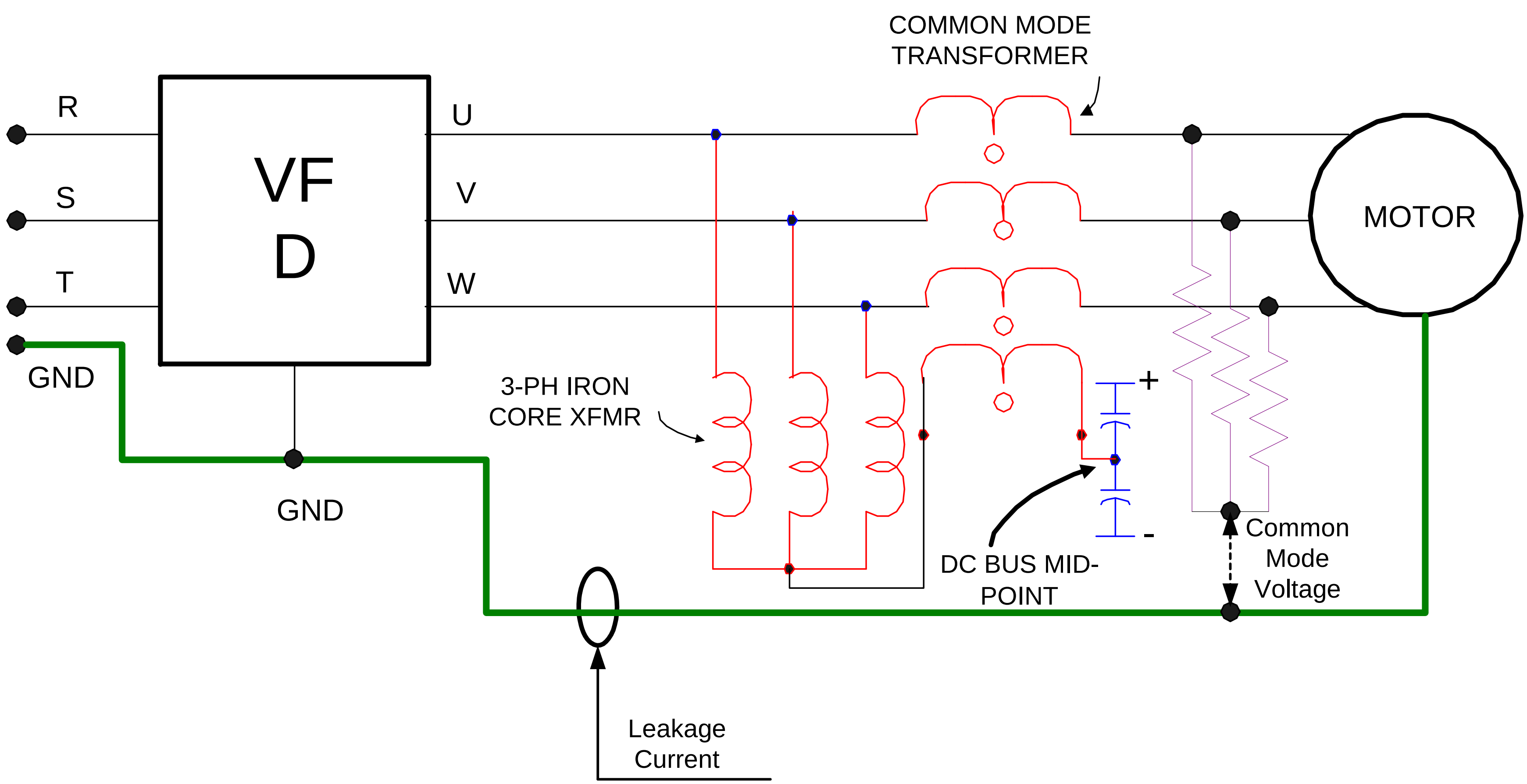
- Simple and effective
- Needs maintenance, typically after 20,000hrs of operation
- Metallic dust in air is not suitable for clean room applications

7. Faraday Shield

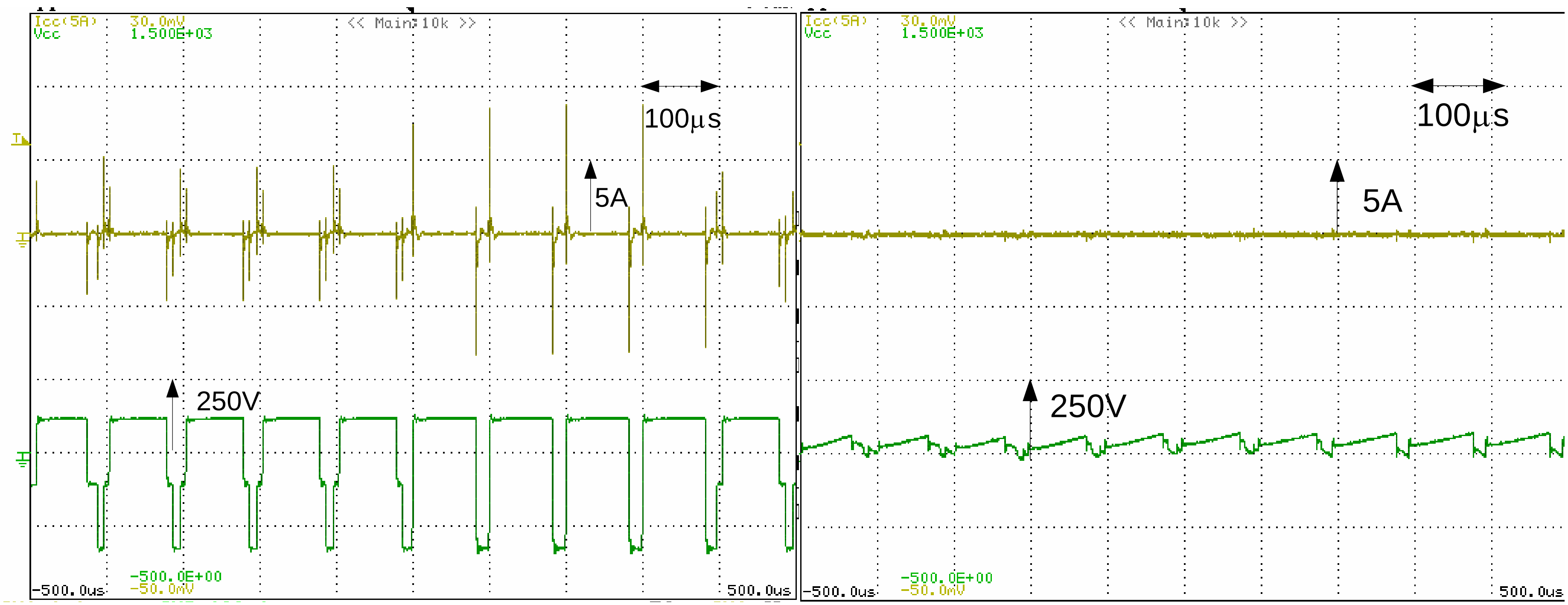


- Quite effective
- Needs to be inserted during manufacturing of motor
- Expensive and causes low frequency power loss

8. Common Mode Voltage Cancellation Circuit



8a. Test Results



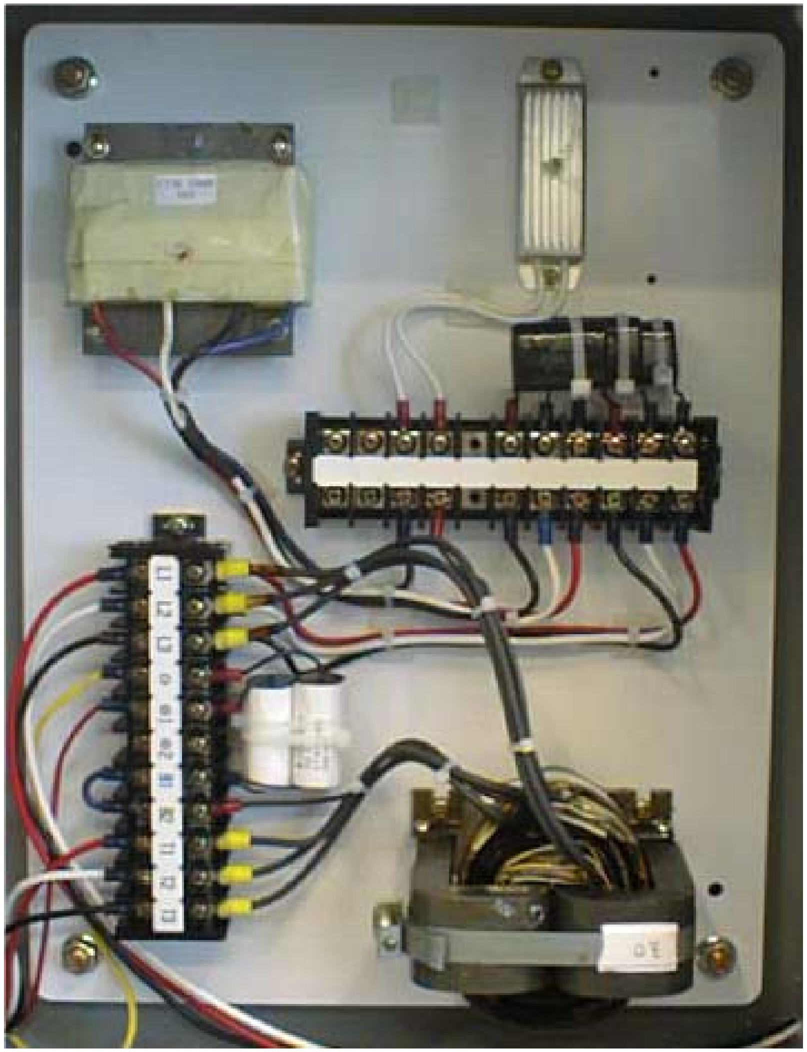
I(pk) Common mode current: 8A

V(max) Common mode Voltage (wrt dc bus mid-point): 345V

I(pk) Common mode current: 0.7A

V(max) Common mode Voltage (wrt dc bus mid-point): 75V

8b. Photo of Common Mode Filter

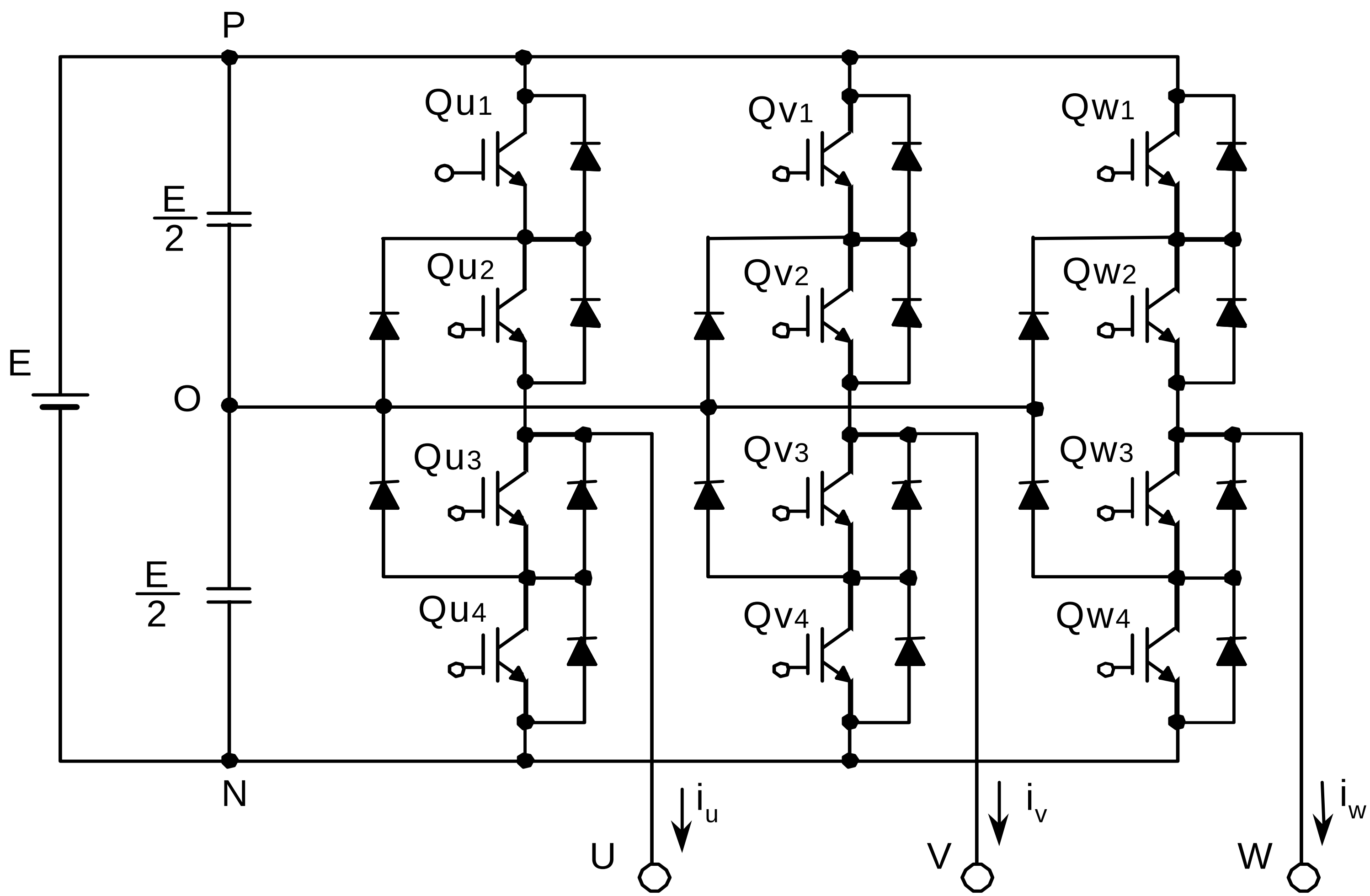


9. NPC Three-Level Inverter

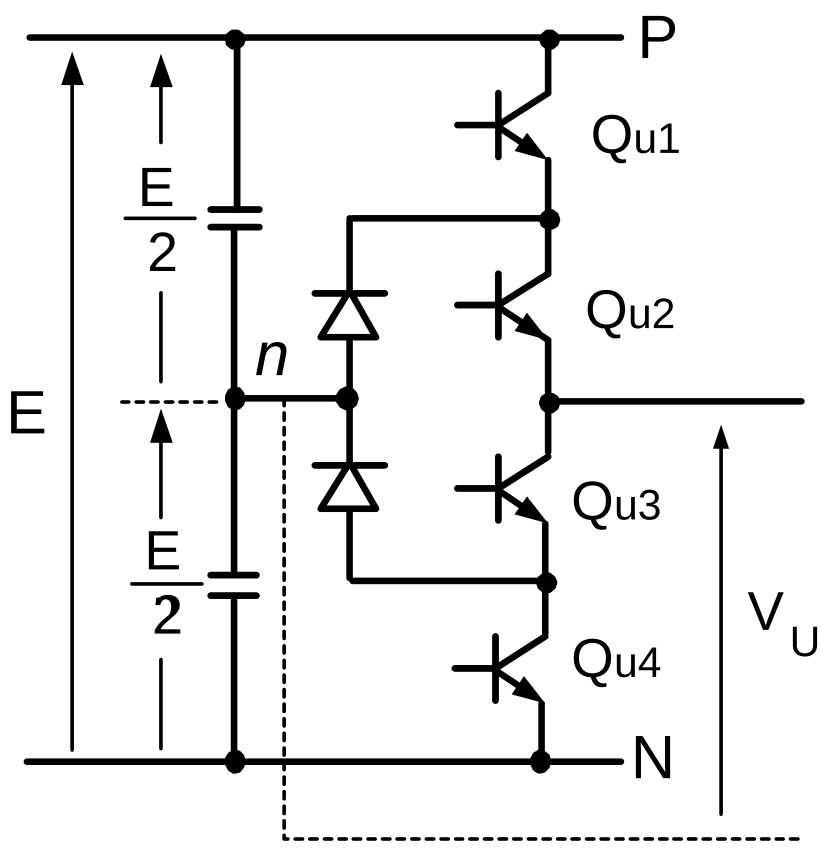
- Common Issues of Voltage Source PWM Inverters:
  - **Surge voltages at motor terminals.**
  - **Leakage current**
  - **Shaft voltage and bearing current (possible bearing failures)**

Three-level topology addresses the above issues in a cost effective manner.

9a. 3-Level Topology



9b. Switching States and Output Voltage



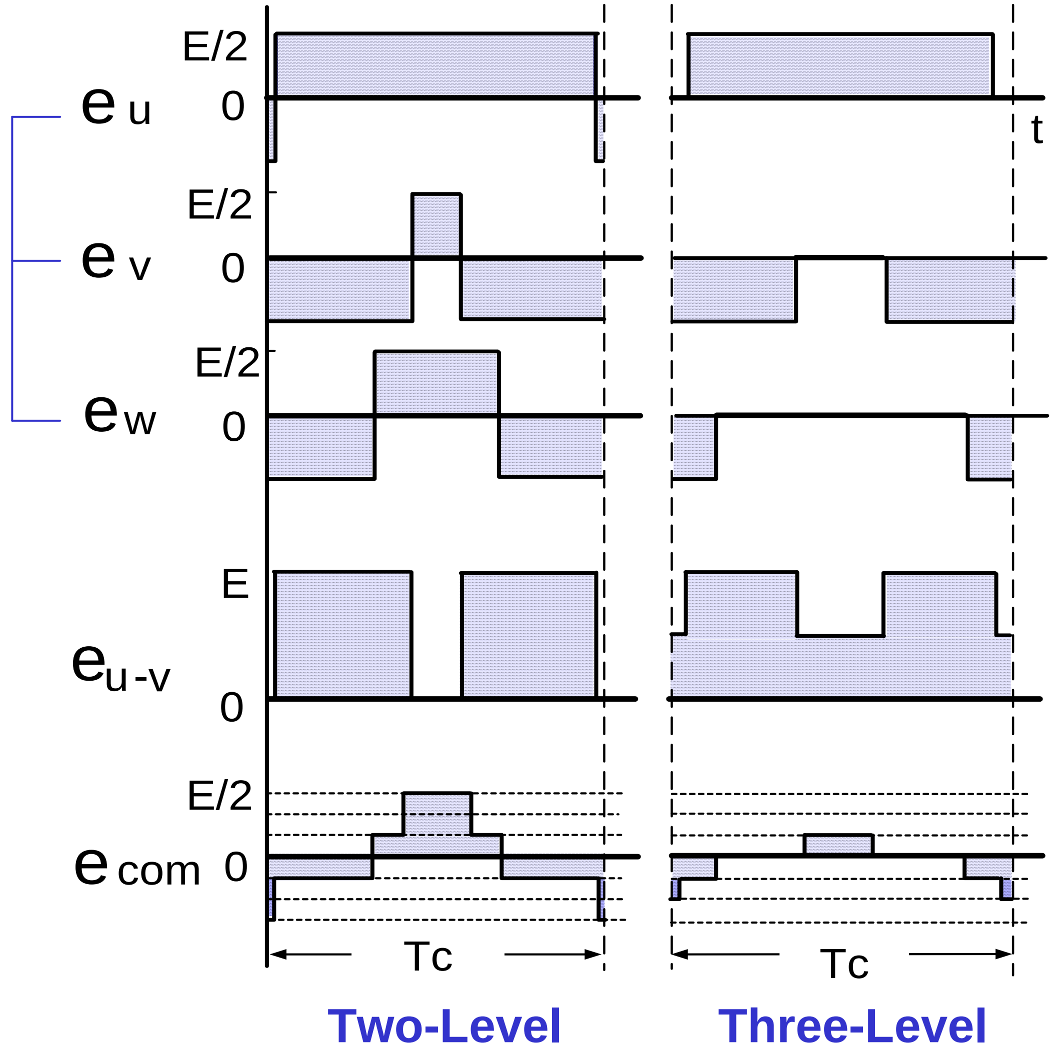
Qu1	Qu2	Qu3	Qu4	Vu
ON	ON	OFF	OFF	+E/2
OFF	OFF	ON	ON	-E/2
OFF	ON	ON	OFF	0

9c. Output Voltage Waveforms

Phase voltages

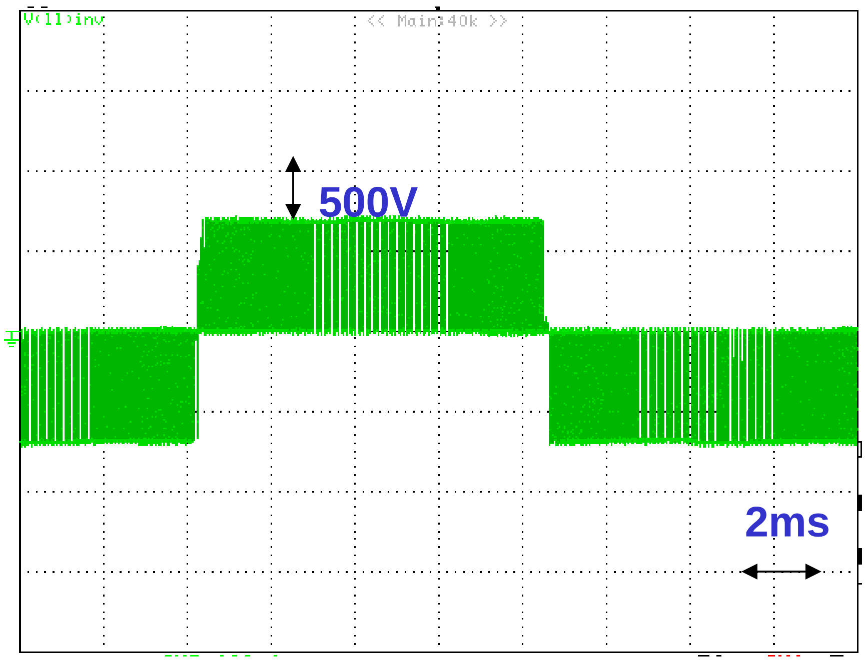
Line-to-line voltage

Common-mode voltage

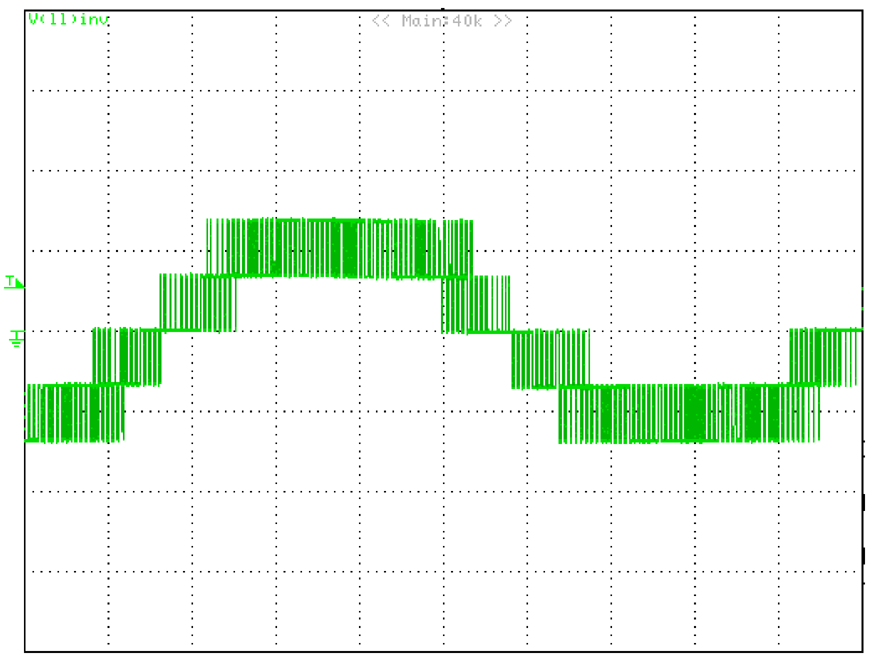


10. Test Results

(460V, 7.5 kW motor drive system)

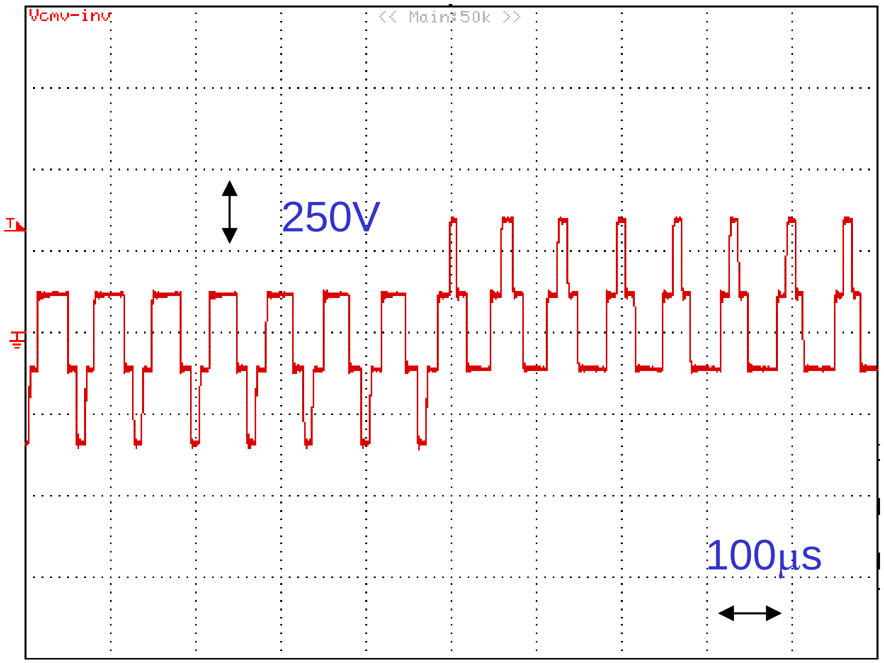


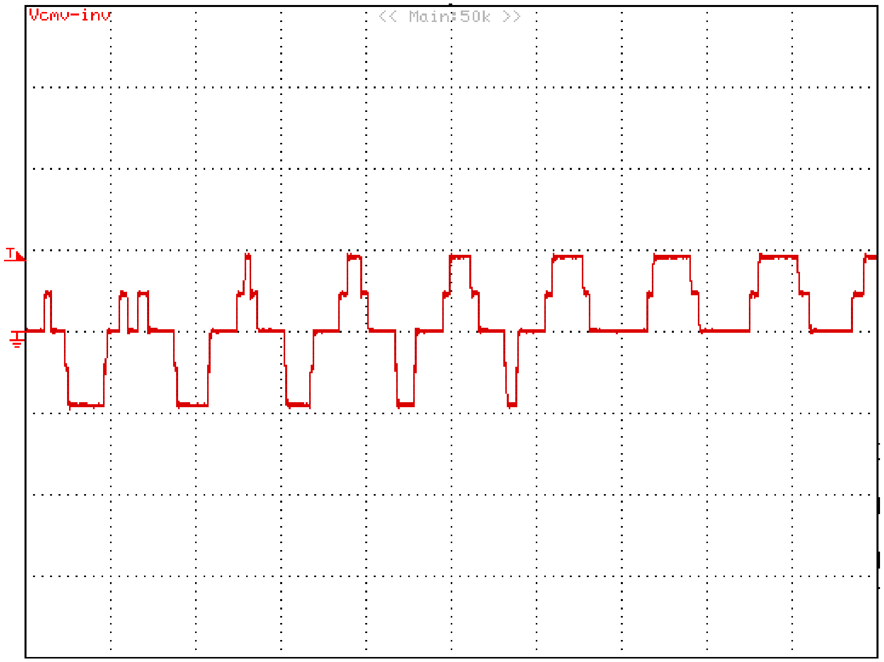
Two-Level Inverter



Three-Level Inverter

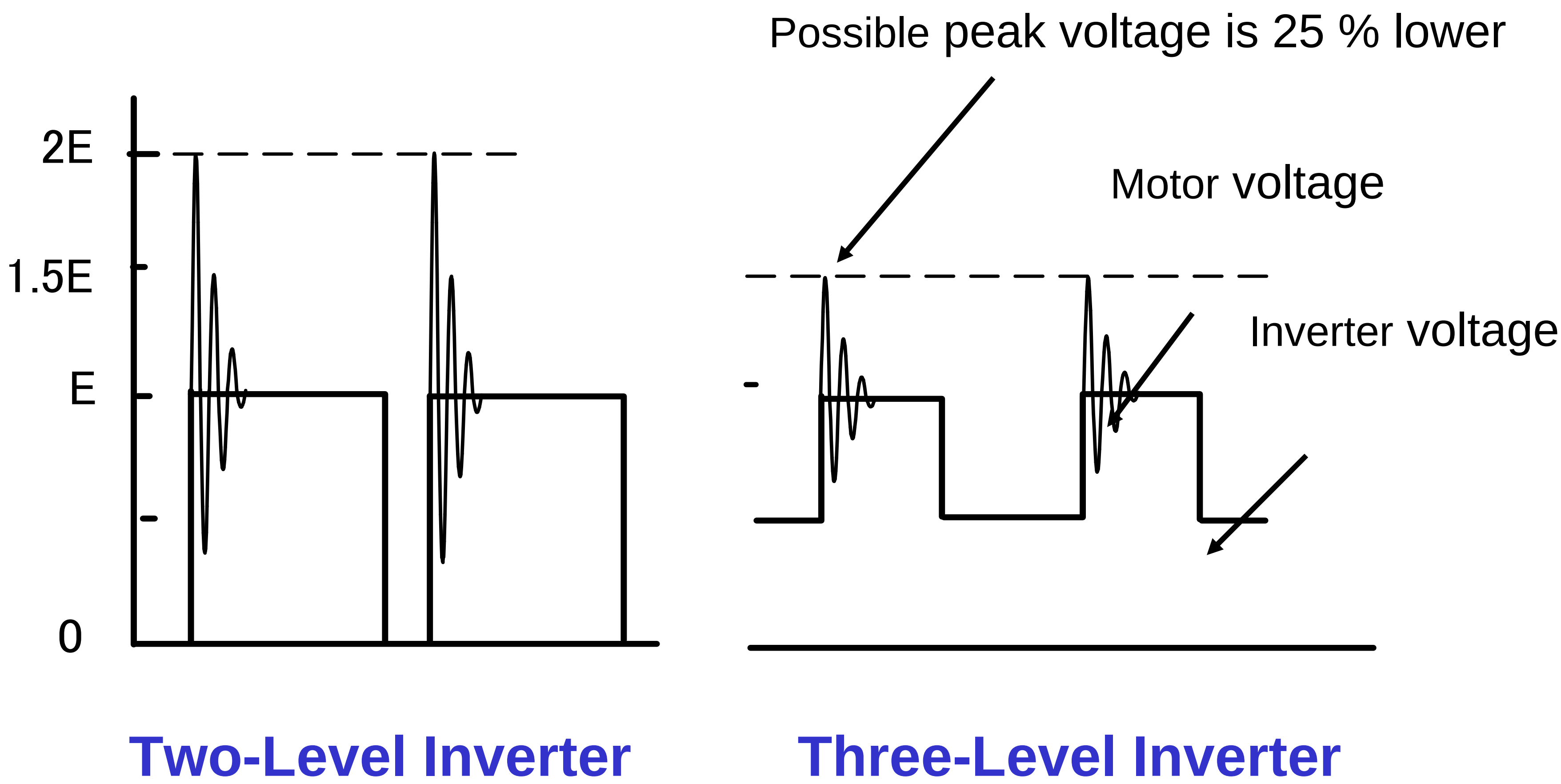
10a. Measured Common-Mode Voltages





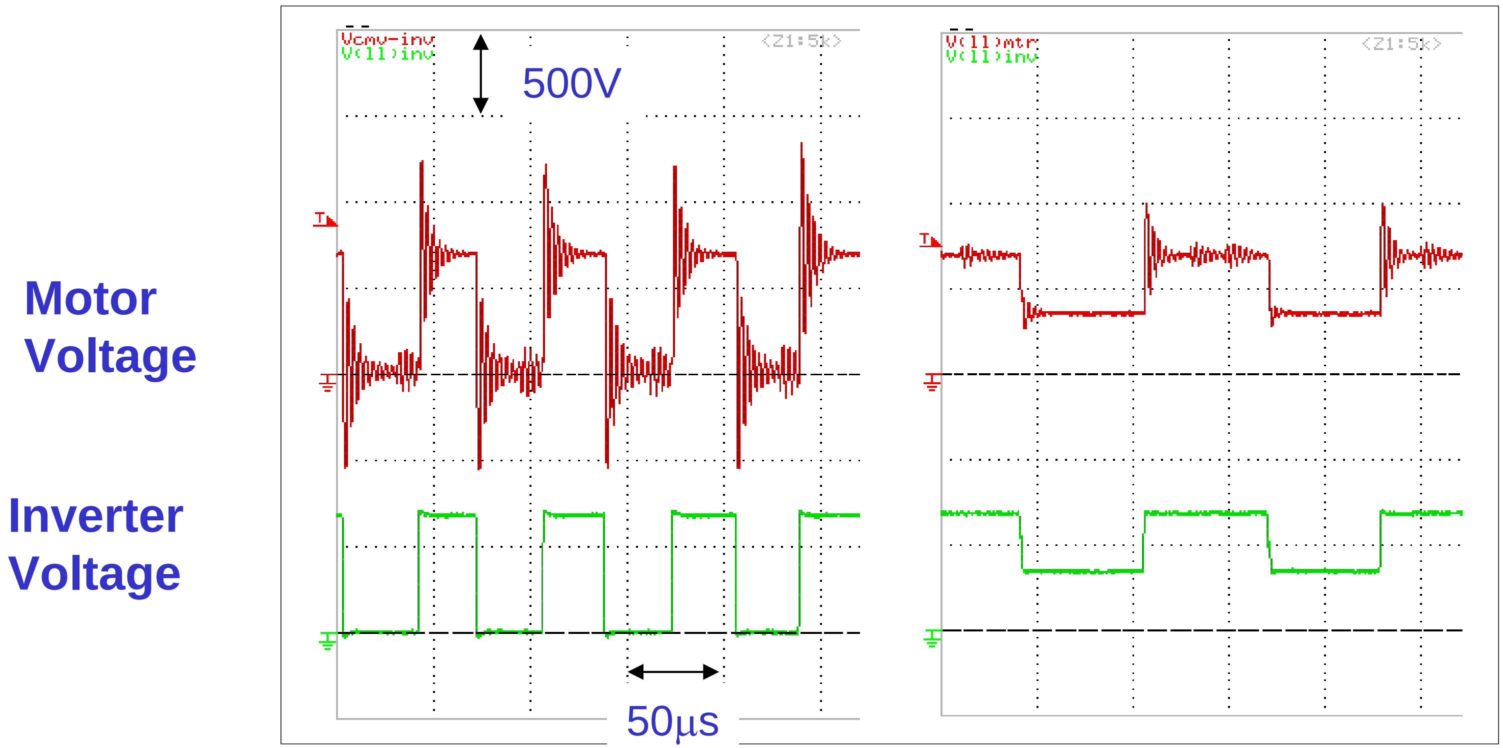
Two-Level Inverter **Three-Level Inverter**

10c. Voltage Overshoot at Motor Terminals



10d. Measured Surge Voltage at Motor Terminals

(460V, 7.5 kW with 100m cable)

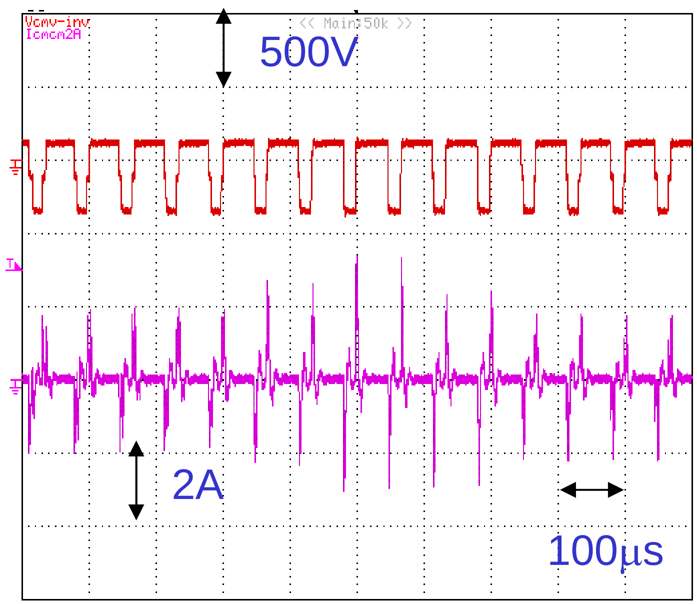


Two-Level Inverter **Three-Level Inverter**

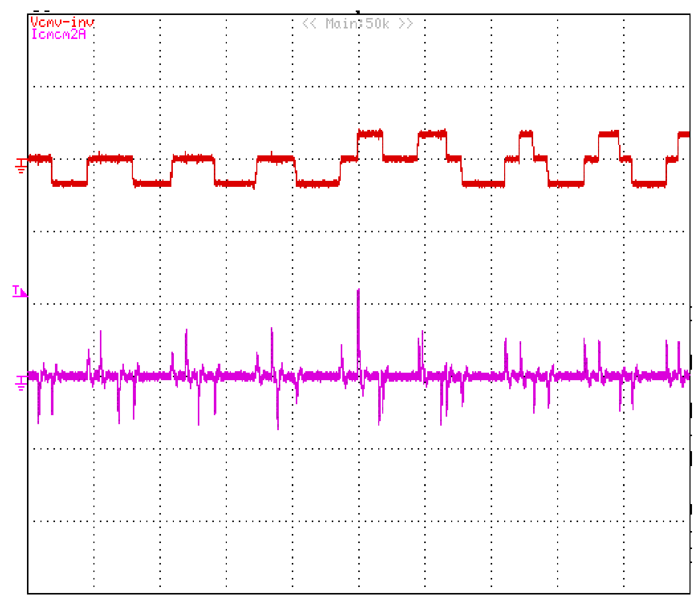
10e. Leakage Current (460V, 7.5 kW with 100m cable)

Common-mode voltage

Leakage current

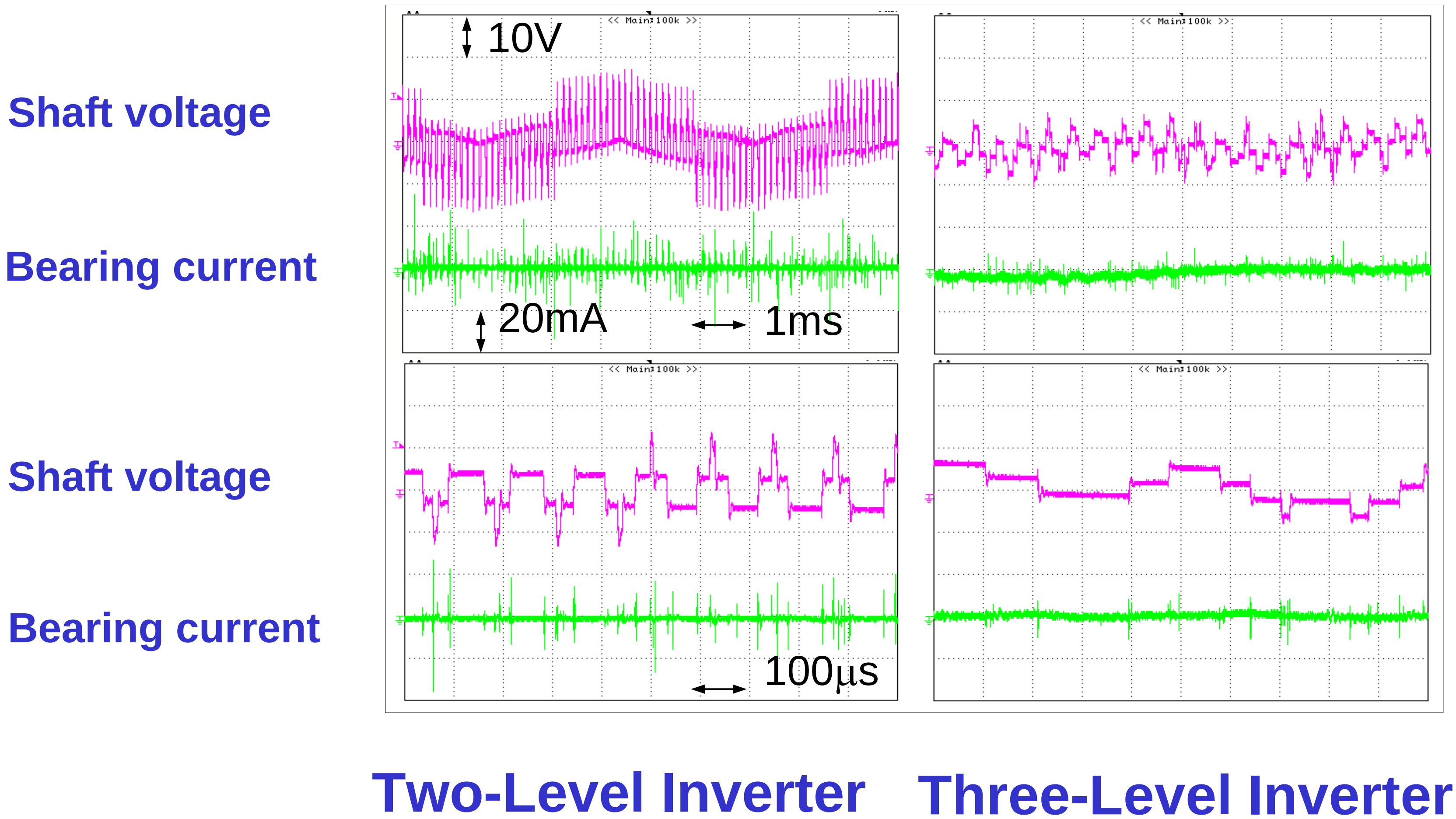


Two-Level Inverter

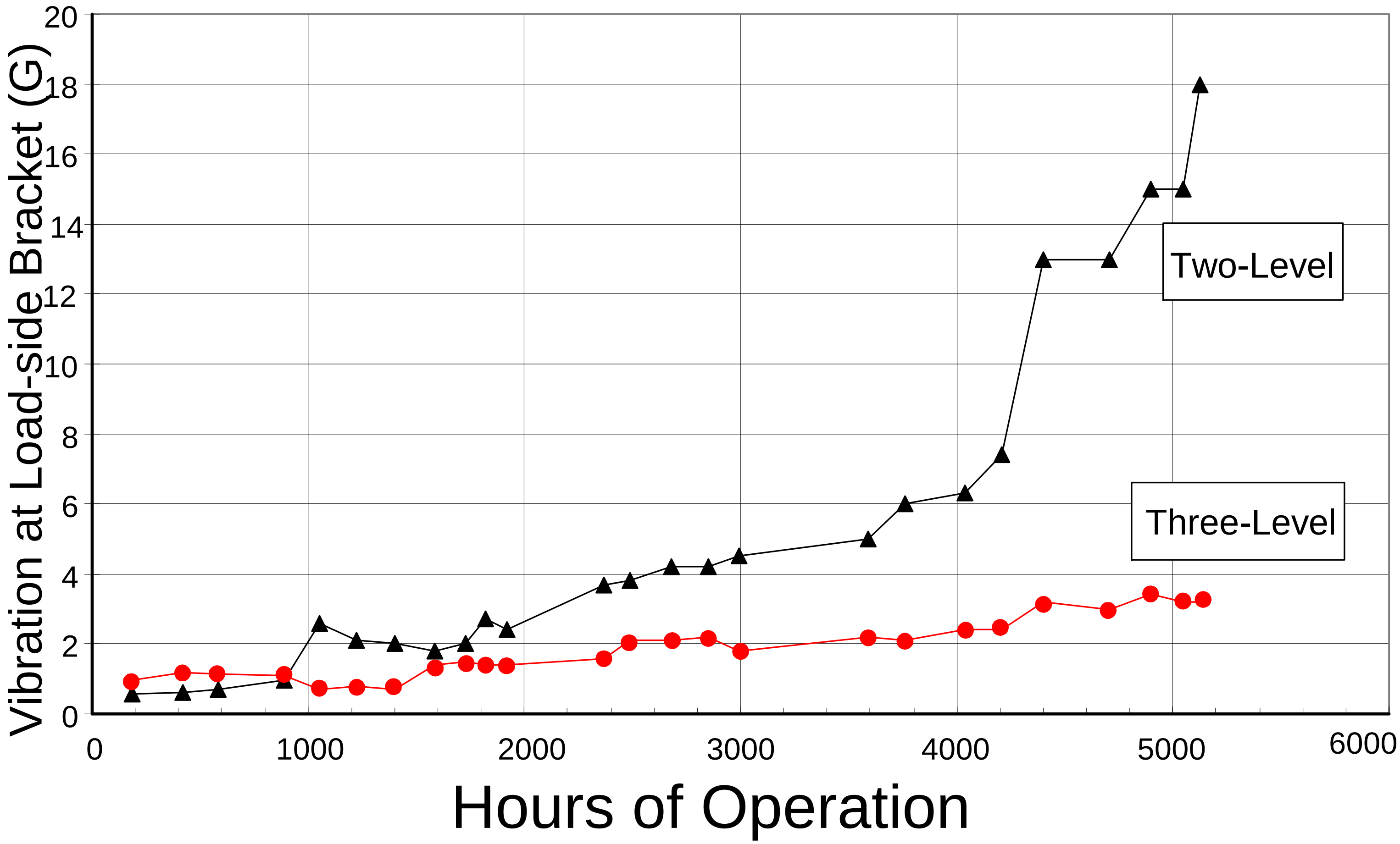


Three-Level Inverter

10f. Shaft Voltage and Bearing Current



11. Bearing Life Test



Bearing life expectancy improves significantly

12. Conclusions

- Bearing insulation characteristics was studied – Level of shaft voltage influences bearing current significantly; Temperature is also very crucial

- Common Mode Filter is helpful when used with 2-level drives to reduce shaft voltage and bearing currents

- 3-Level NPC Inverter is an important tool in mitigating bearing failure – Results in space savings and makes it adaptable to clean room applications; Reduces Surge Voltage as well.