New Protection Scheme for Type 4 Wind Turbines

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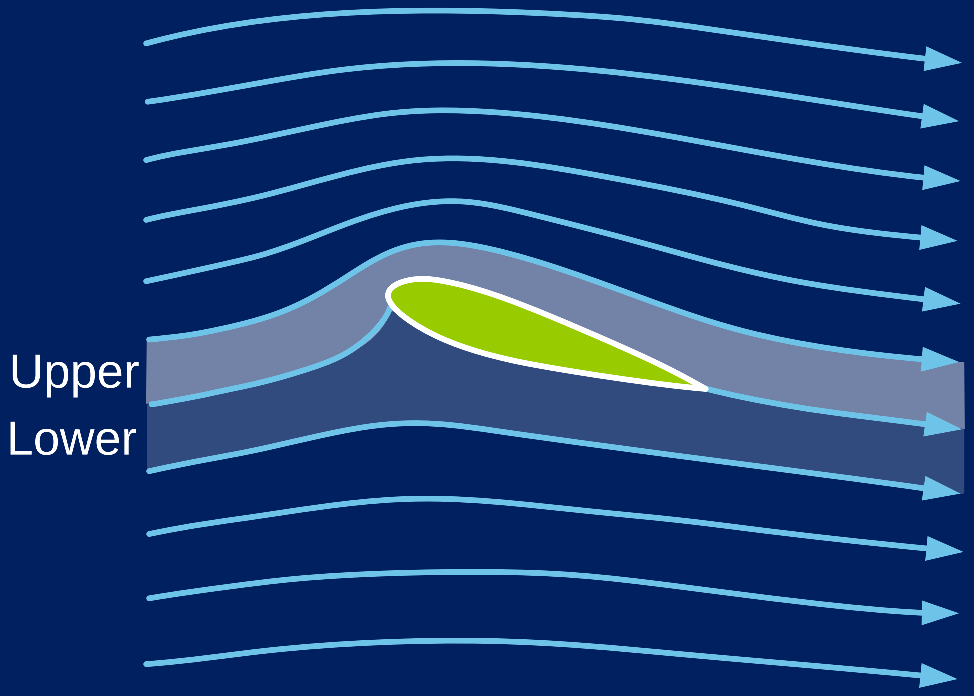
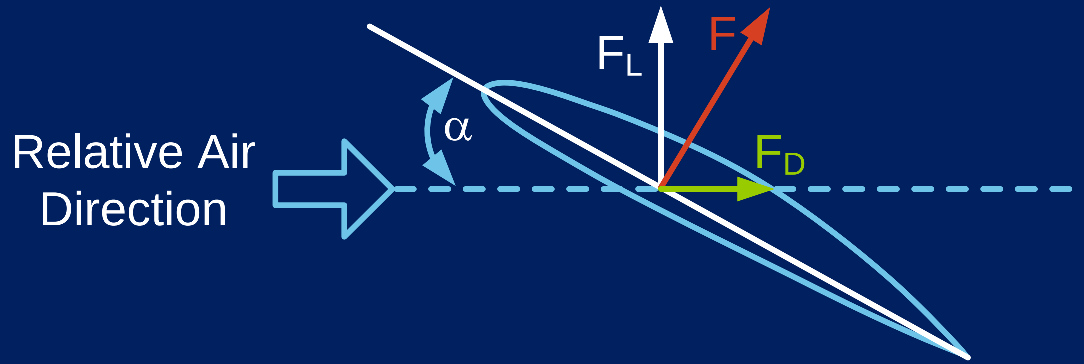
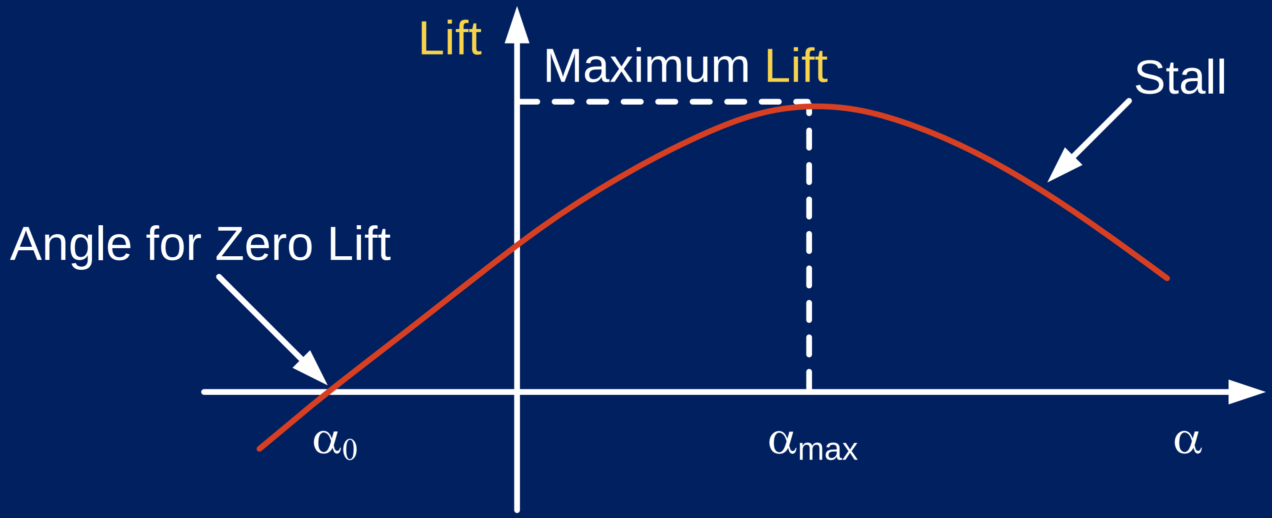
Wind Turbine Generators

$$P = \frac{1}{2}\rho\pi R^2 V^3 C_P$$

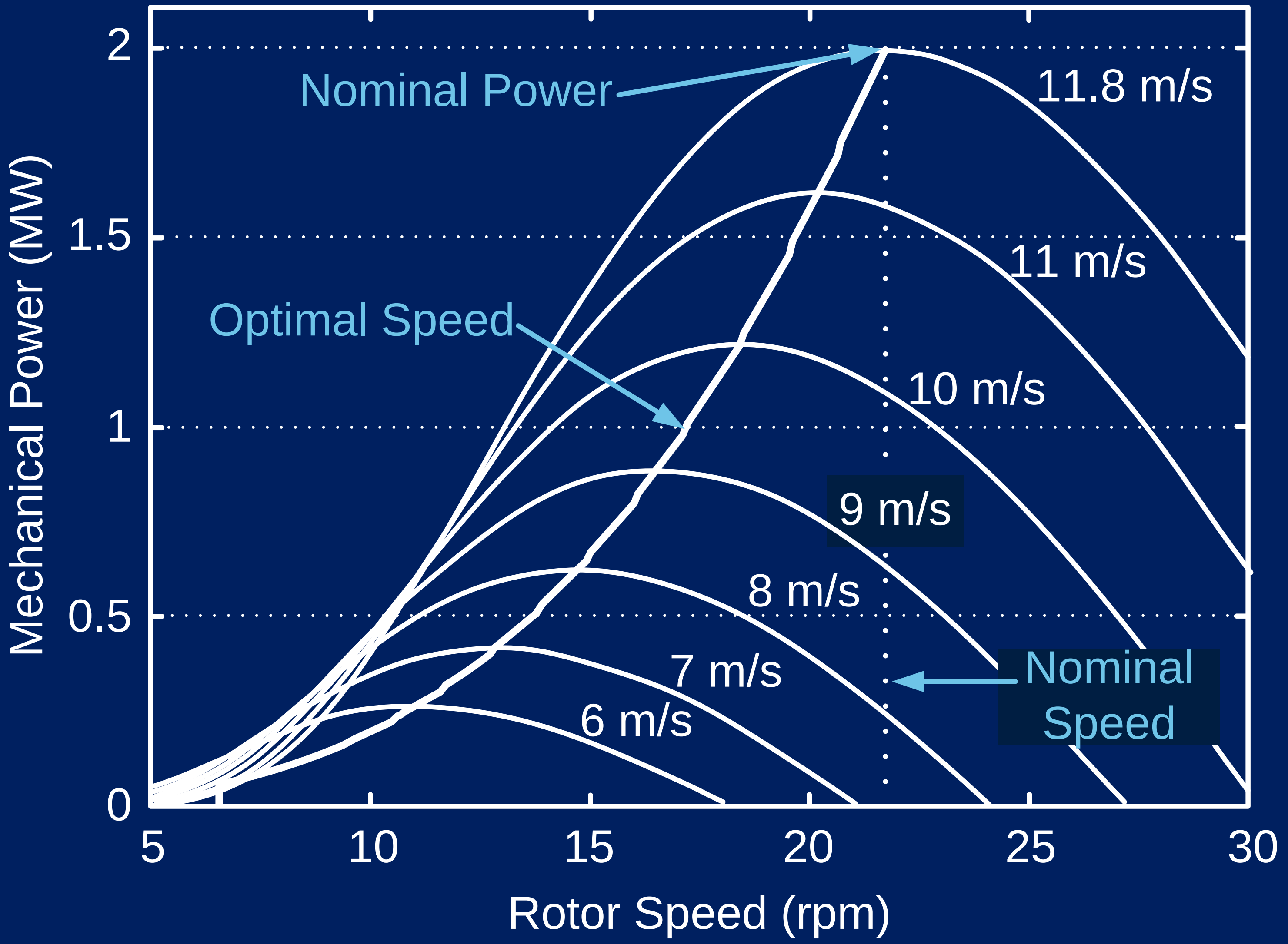
Wind Turbine – Dynamics







Efficiency Curve

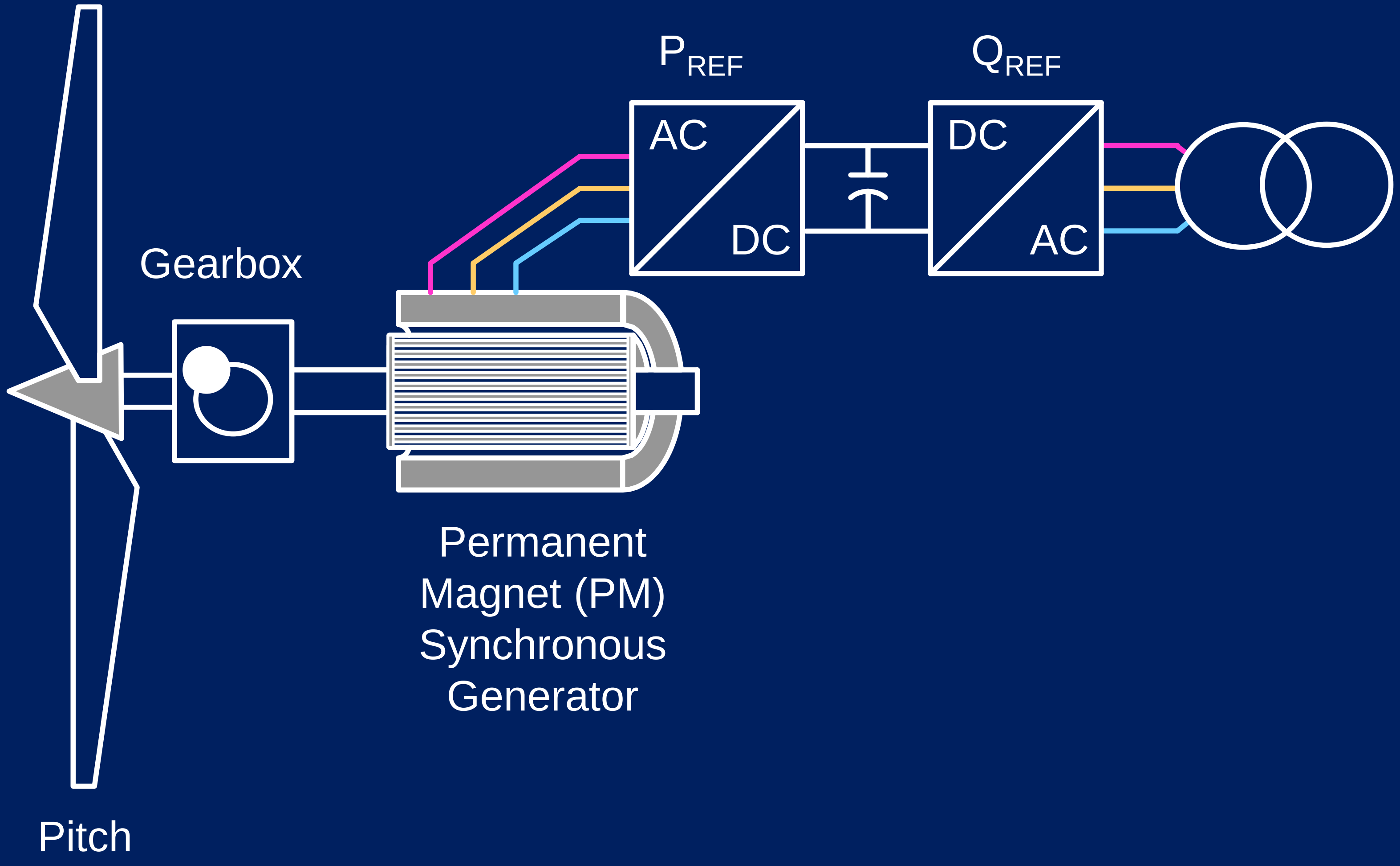


Tip Speed Ratio

$$\lambda = \frac{Tip\ Speed\ of\ Blade}{Wind\ Velocity}$$

$$= \text{constant}$$

Type 4 – Synchronous Generator With Full-Power Back-to-Back Converter

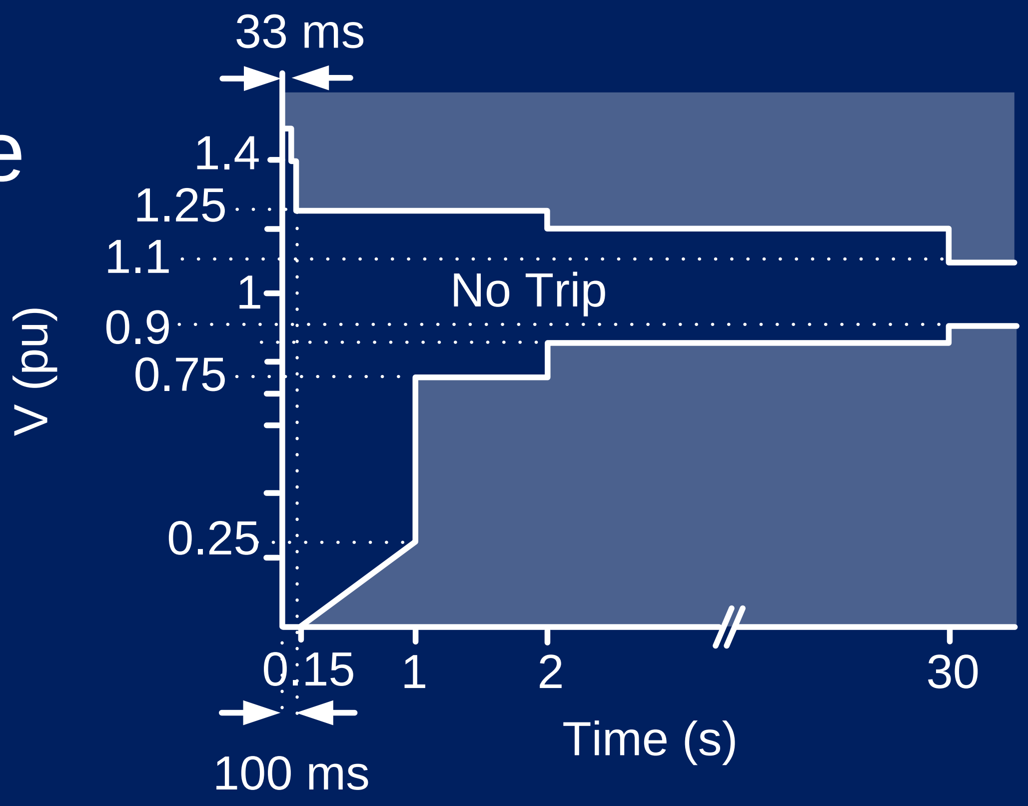


Type 4 WTG

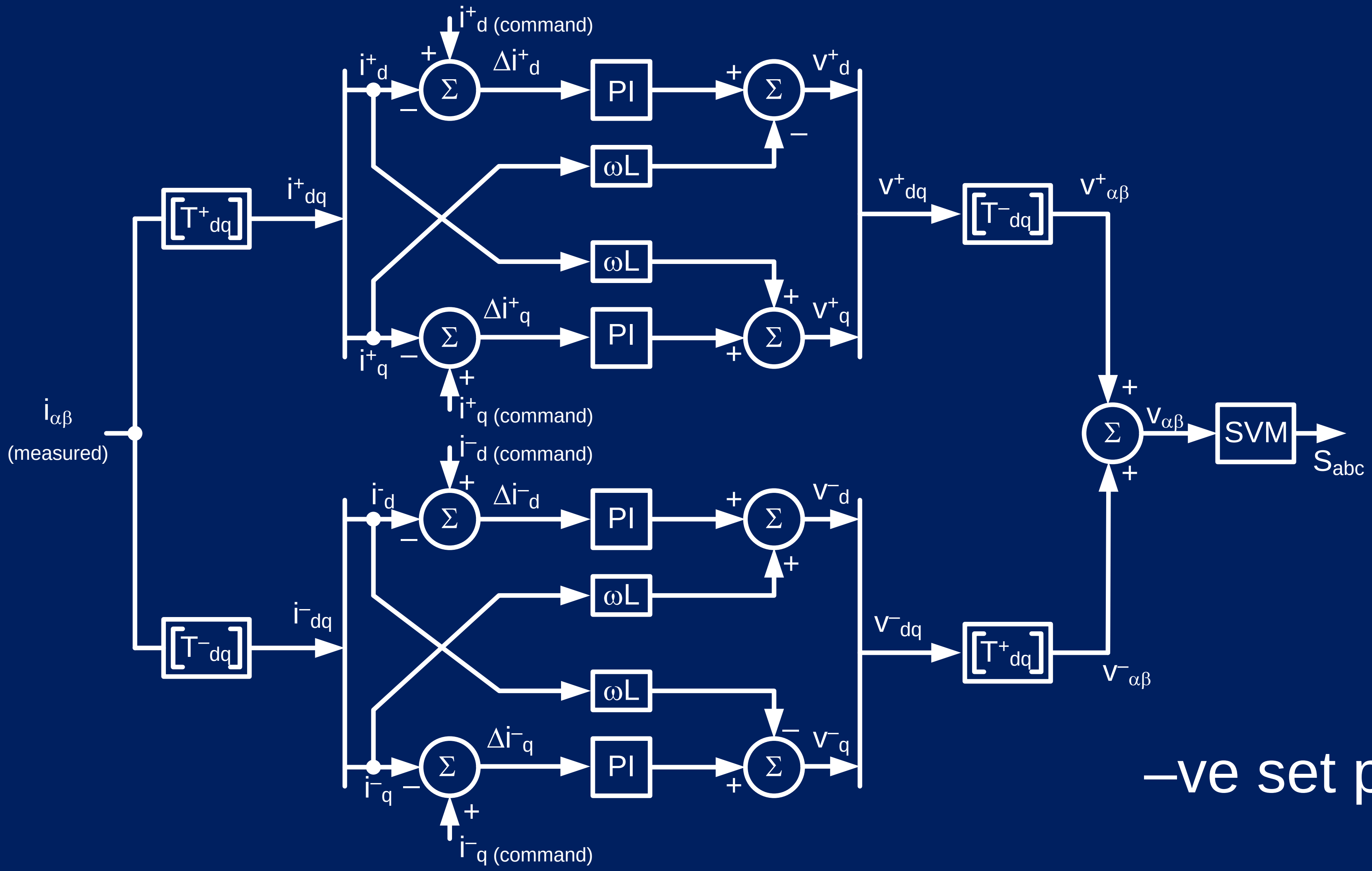
- PM synchronous machine
  - Excitation – permanent magnets (neodymium)
  - Simple bridge rectifier ⇒ dc
- Squirrel cage induction machine (IM)
  - Active machine-side converter (supplies VARs to IM)
  - Prime mover ⇒ torque production
  - Maximum theoretical power extracted from wind = 59.3% (Betz’s law)

Grid Codes

- Continuous voltage operating range
- Frequency operating range
- Power control
- High-voltage operation
- LVRT
  - Remain connected for specific amount of time for voltage drop
  - Time ⇒ drop in voltage
  - Reactive power support



Decoupled Double-Synchronized Reference Frame



–ve set point = 0

Determining Power Requirement

$$P = \frac{3}{2}(V_d i_d + V_q i_q)$$

$$Q = \frac{3}{2}(V_d i_q - V_q i_d)$$

$$\Rightarrow$$

$$P = \frac{3}{2}V_d i_d$$

$$Q = \frac{3}{2}V_d i_q$$

Synchronizing reference so that $V_q = 0$

Outer Loop Control

- I_d and I_q reference values are extracted from real and reactive power values
- Real power keeps changing as wind speed changes – I_d reference (regulate dc link voltage)
- Reactive power – no one pays, so $I_q = 0$

Inner Current Control Loop

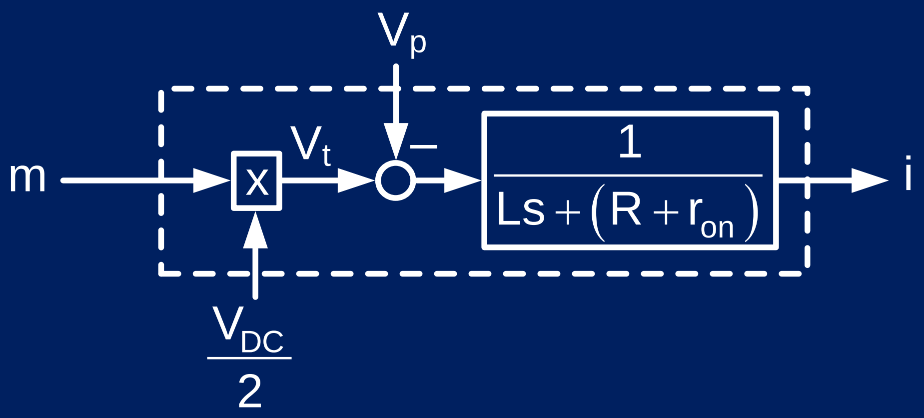
- Modulating signal of voltages (m_a, m_b, m_c)
  - Usually sinusoidal waveforms-three phase set
- Obtained by comparing the reference and measured values of currents
- PI controller
  - To ensure that measured values closely track reference values
  - Zero steady-state error

Controller Design

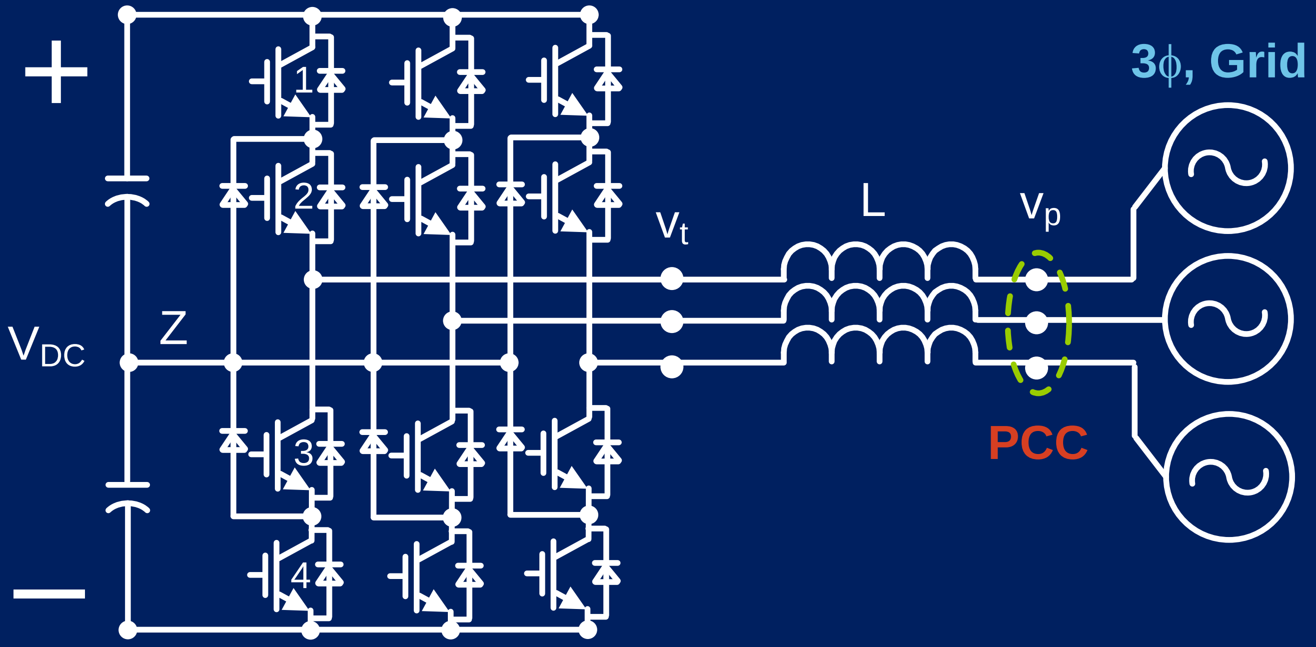
$$V_t - V_p = L\frac{di}{dt} + Ri$$

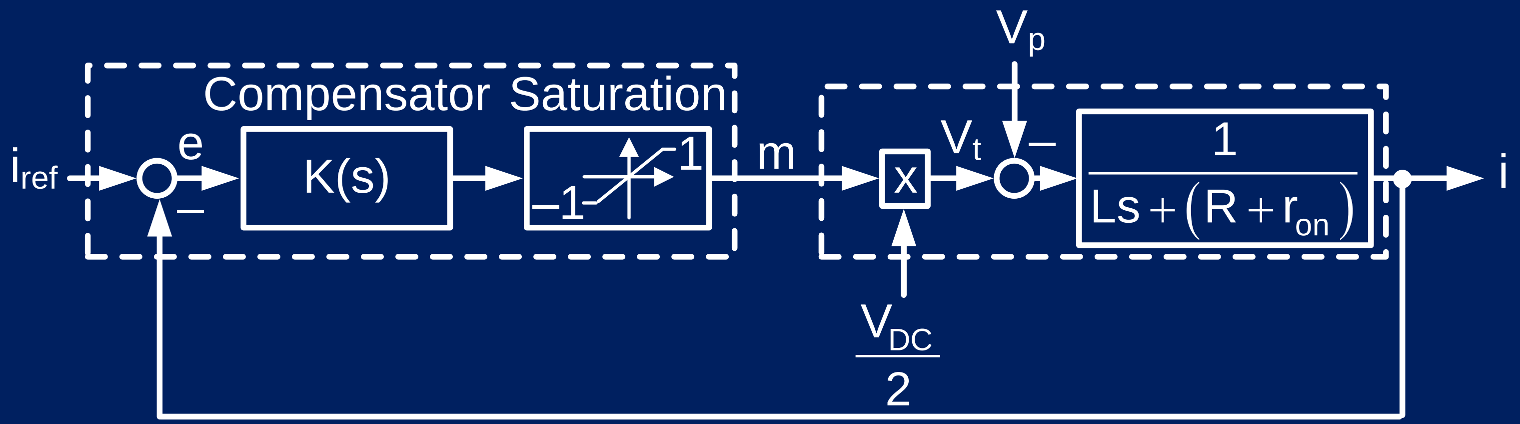
$$V_t = m \bullet \frac{V_{dc}}{2}$$

Control model would be:



Grid-Side Inverter





Controller Design

Total loop gain would be: $LG(s) = \left(K_p + \frac{K_i}{s}\right) \bullet \frac{1}{Ls + R}$

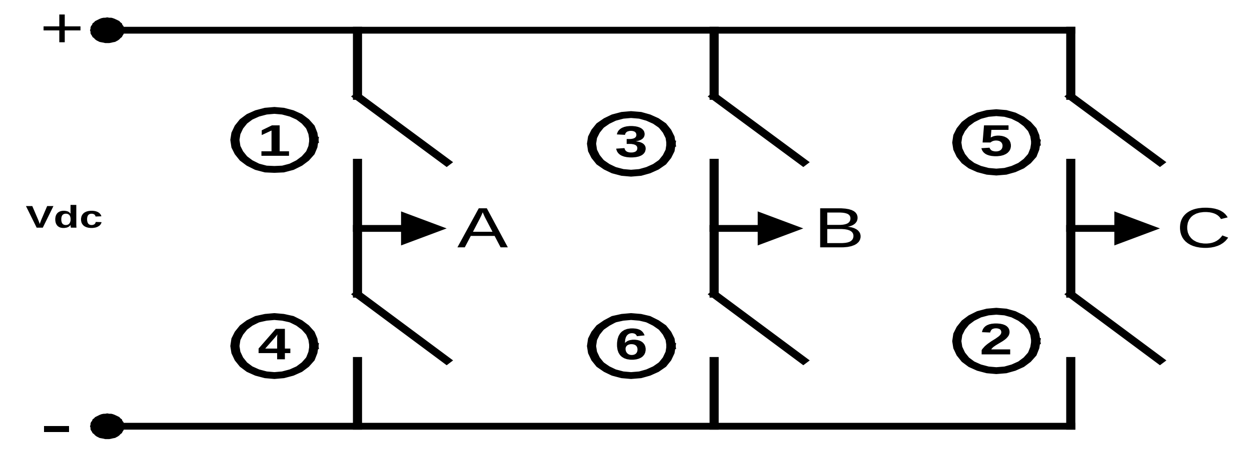
Rearrange the equation: $LG(s) = \frac{K_p}{sL} \bullet \frac{\left(s + \frac{K_i}{K_p}\right)}{\left(s + \frac{R}{L}\right)}$

If pole and zero cancel each other ⇒ improved frequency response: $LG(s) = \frac{K_p}{sL} \bullet \frac{\cancel{(s + \frac{K_i}{K_p})}}{\cancel{(s + \frac{R}{L})}}$

Time constant is generally chosen as 5 ms

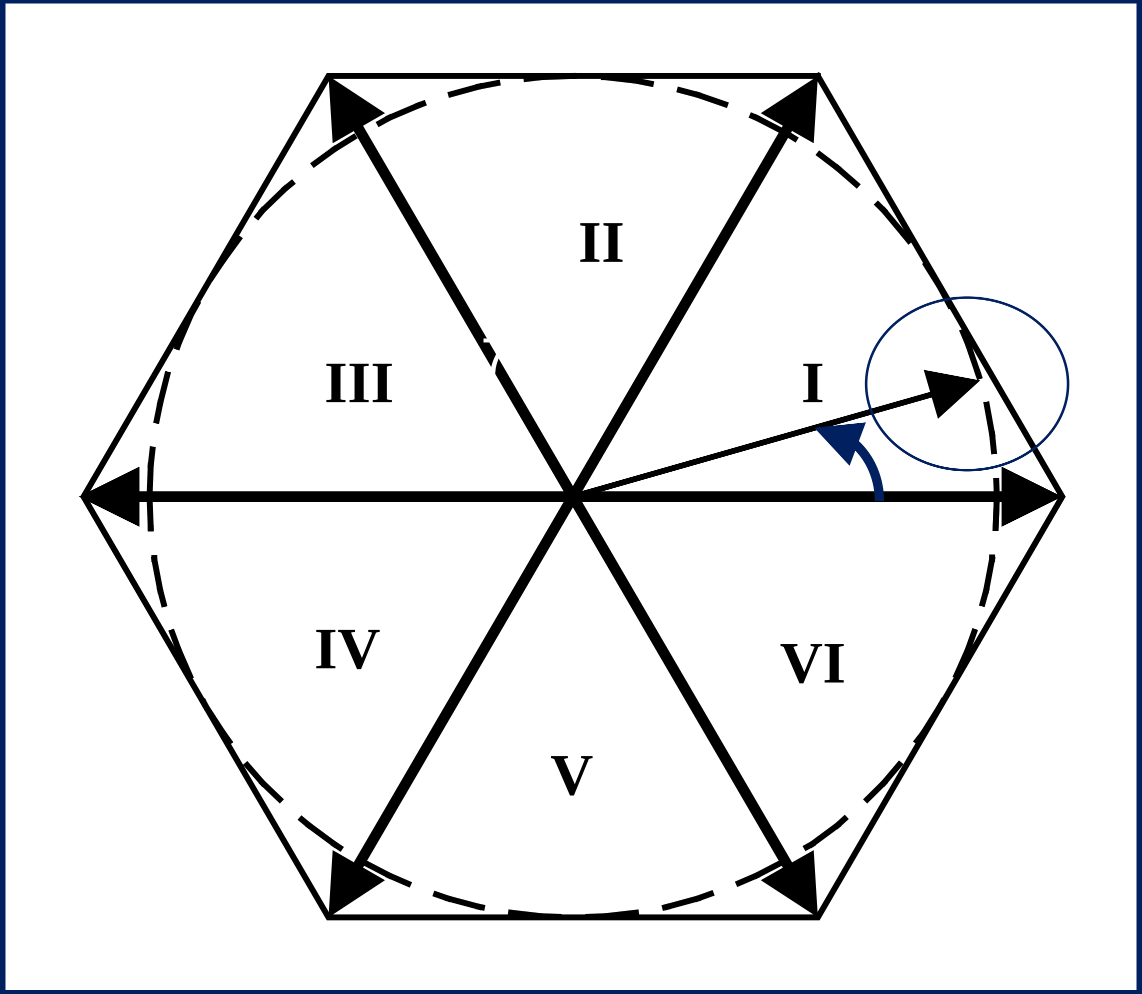
This gives us the equations: $\tau = \frac{L}{K_p}$ $\quad \frac{K_i}{K_p} = \frac{R}{L}$

Switching Control: Basic Two Level VSC



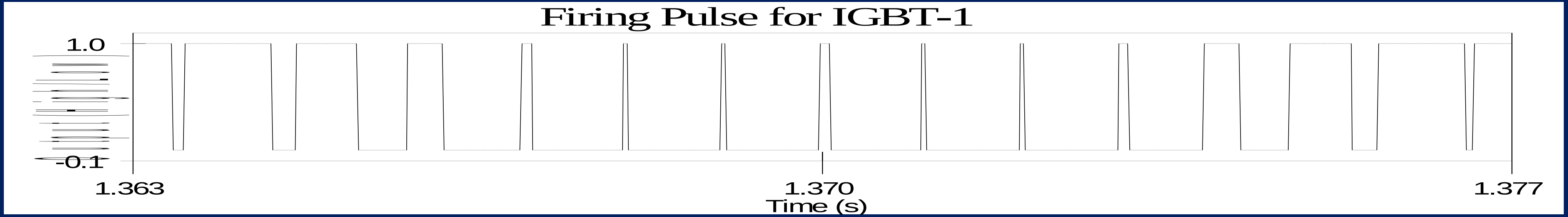
- 6 switching devices
- 8 switching combinations
  - 6 active states
  - 2 zero states ($V_{ab} = V_{bc} = V_{ca} = 0$)

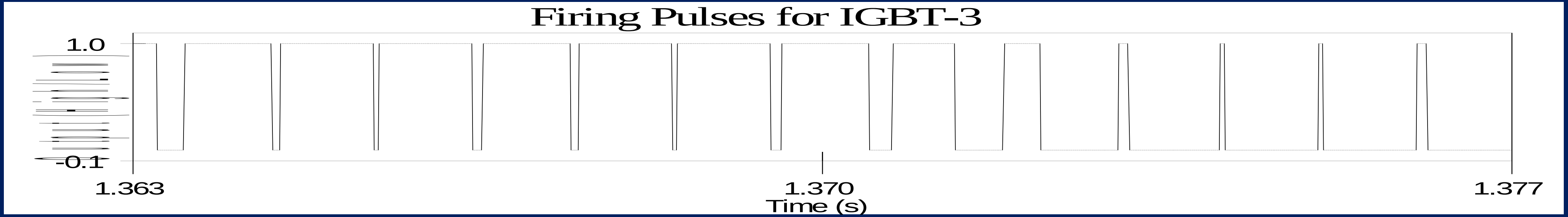
Space Vector PWM Pulse Generator Model

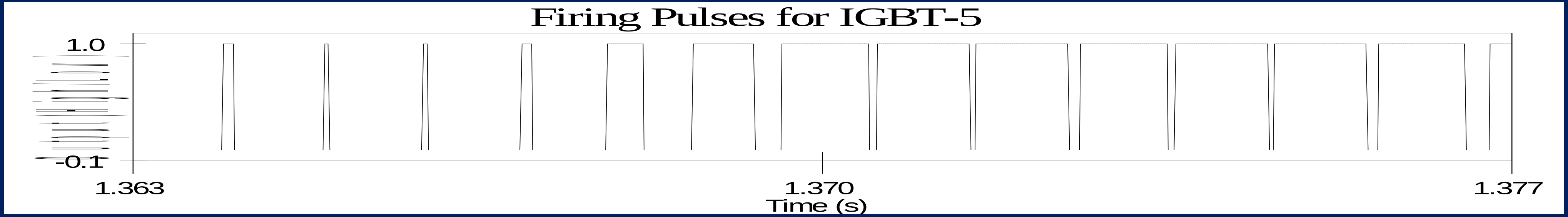


- 6 active states
  - 6 sectors between states
- 2 zero states at origin
- Rotating space vector from desired modulating functions
- Switch between adjacent active states and a zero state
  - High switching frequency
  - Only 1 switch transition at a time
  - Minimize losses and harmonics

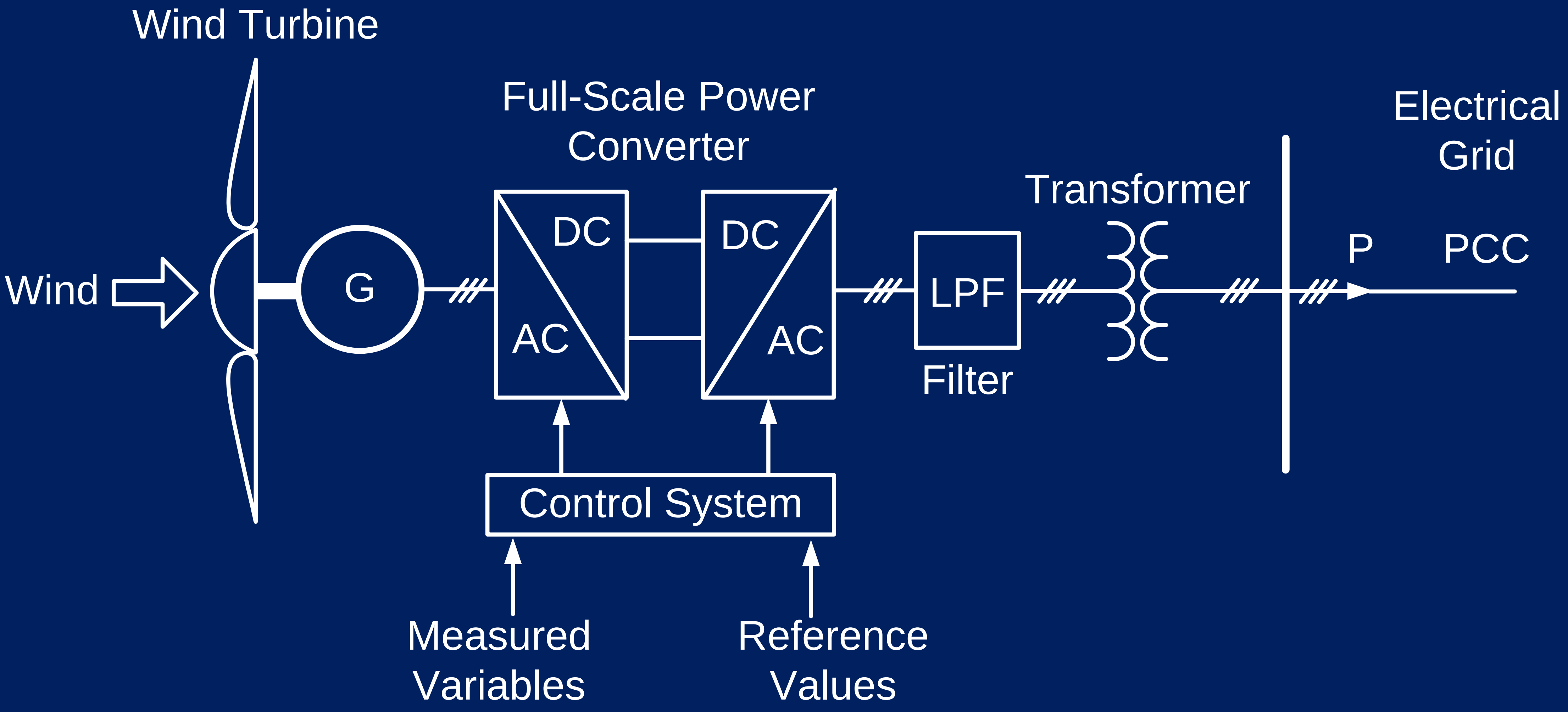
Example Space Vector PWM Pulses


Firing Pulse for IGBT-1

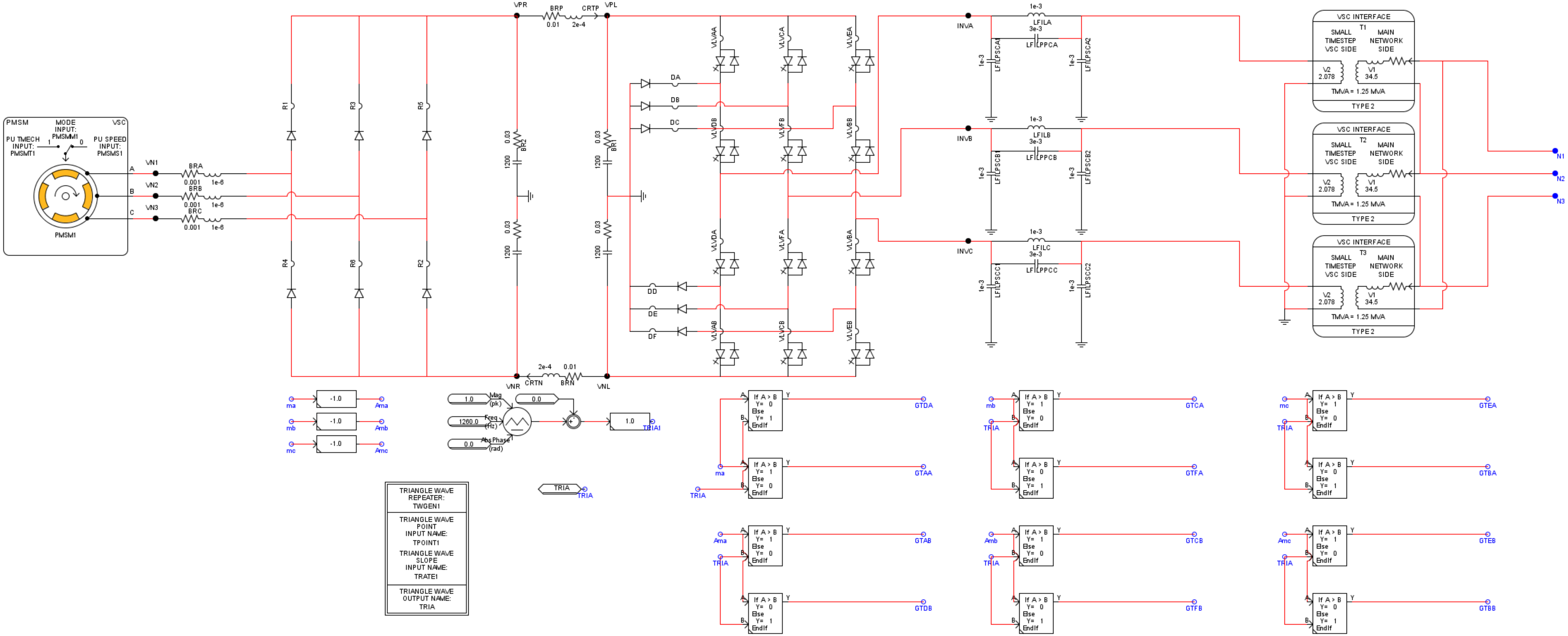

Firing Pulses for IGBT-3


Firing Pulses for IGBT-5

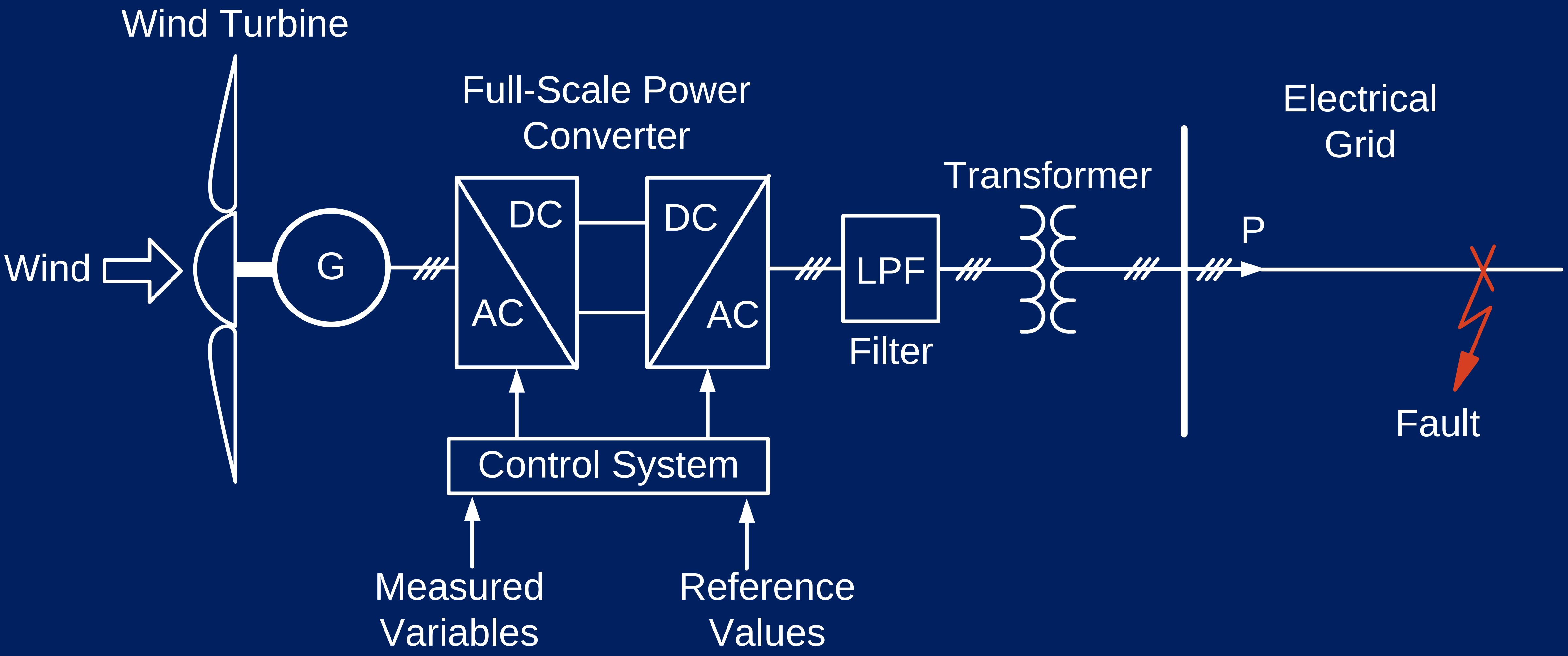
System Model



RTDS Implementation

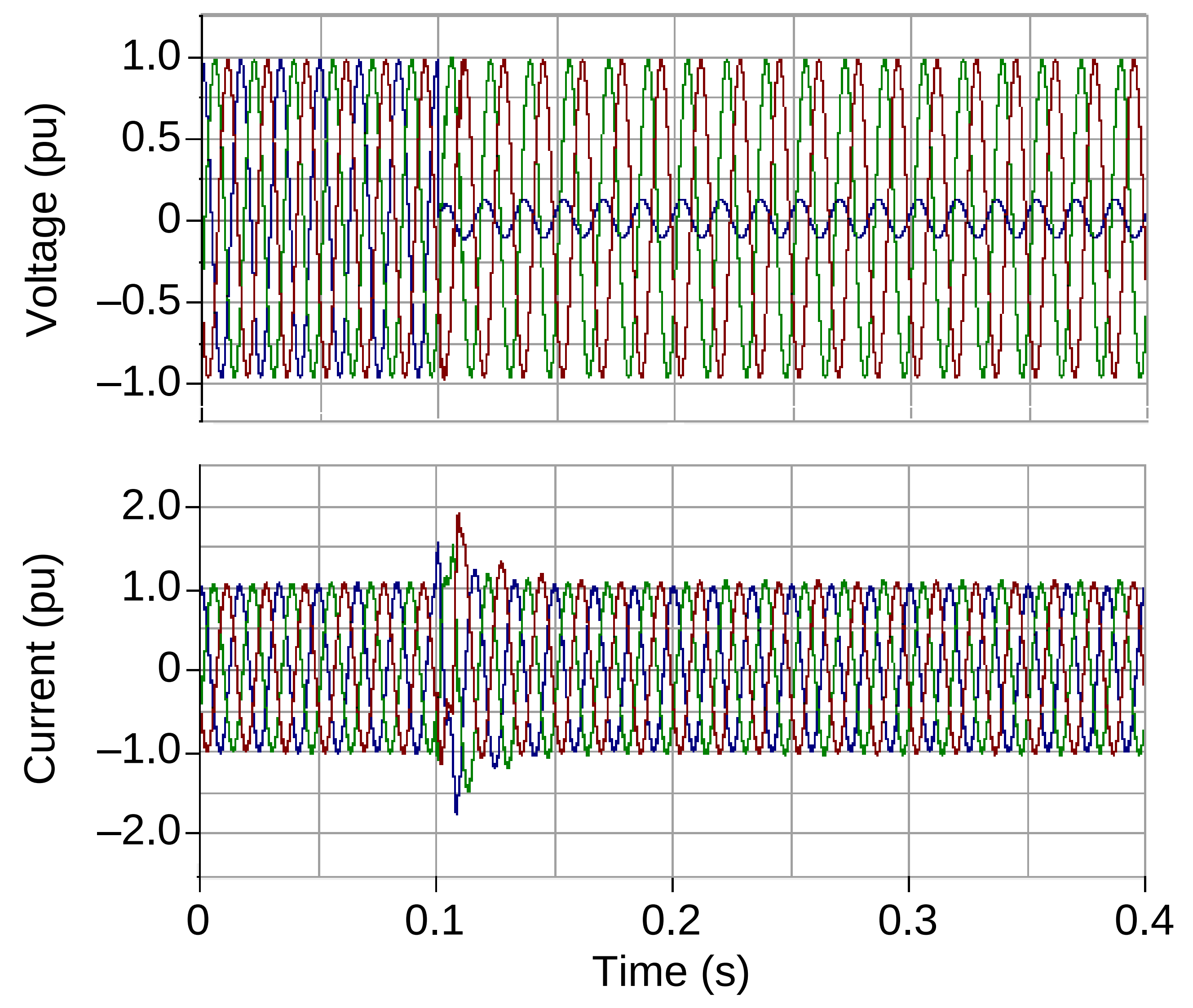


Fault Analysis



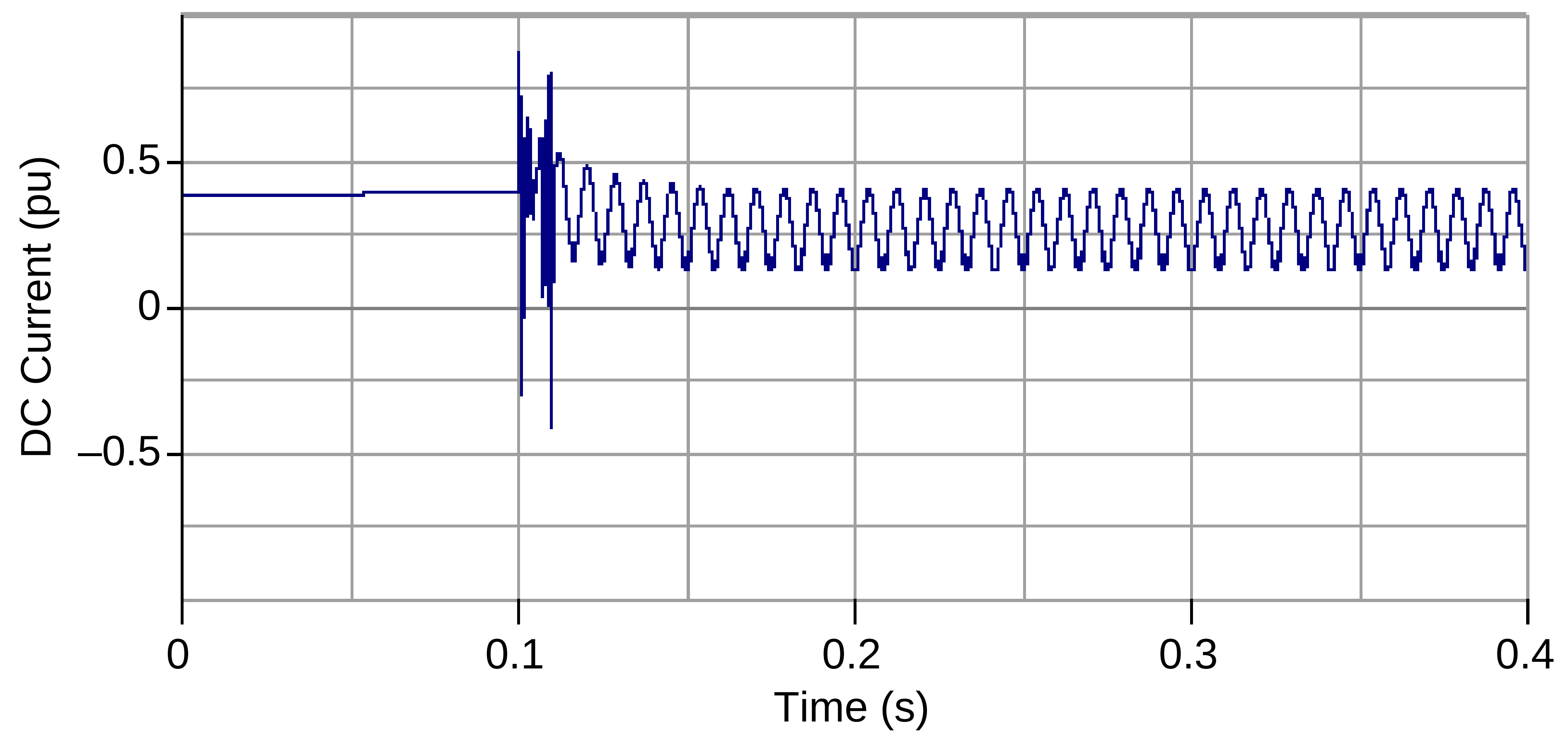
Close in AG Fault

(Voltage and Currents at PCC)



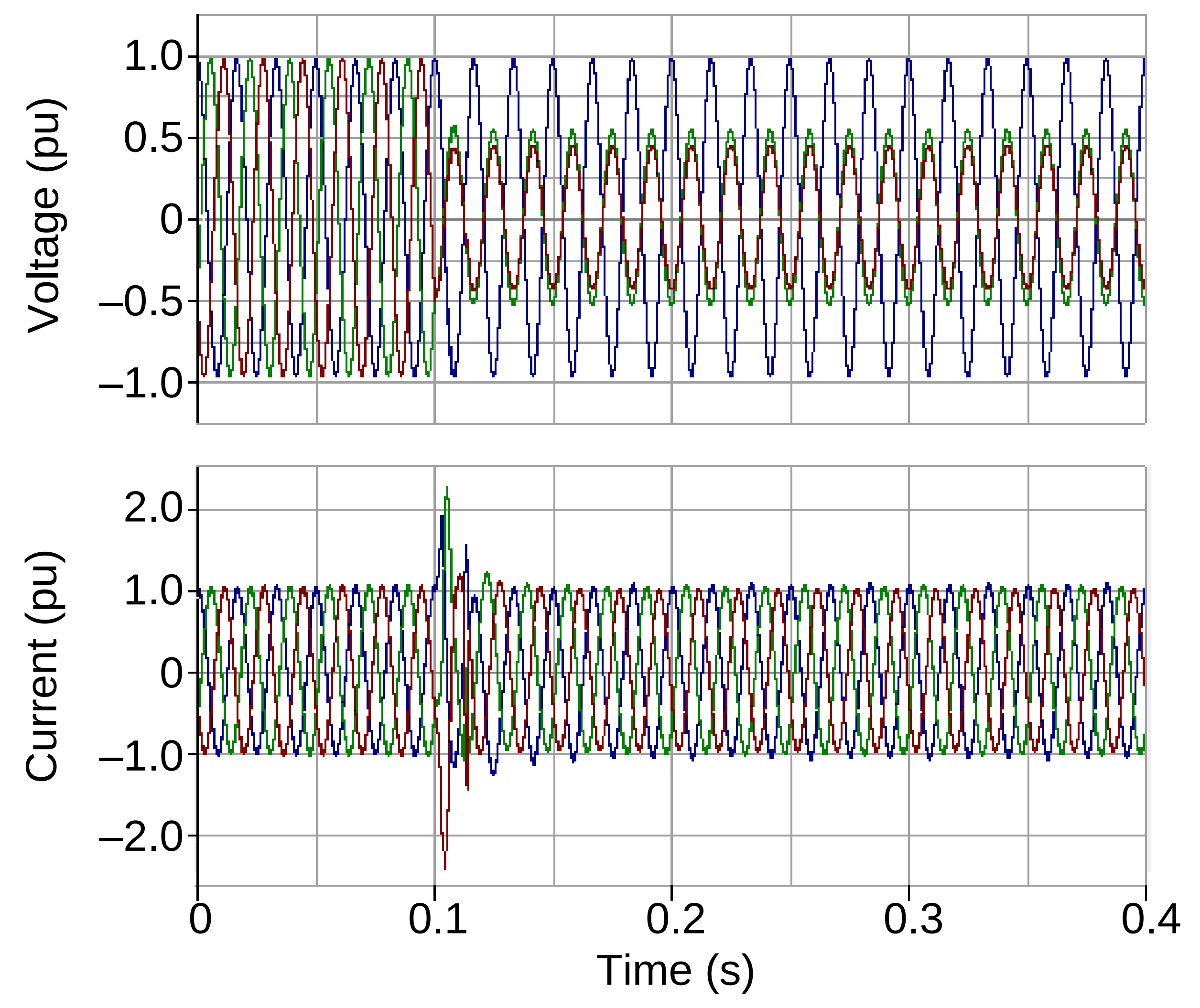
Close in AG Fault

(Current on the DC Bus)

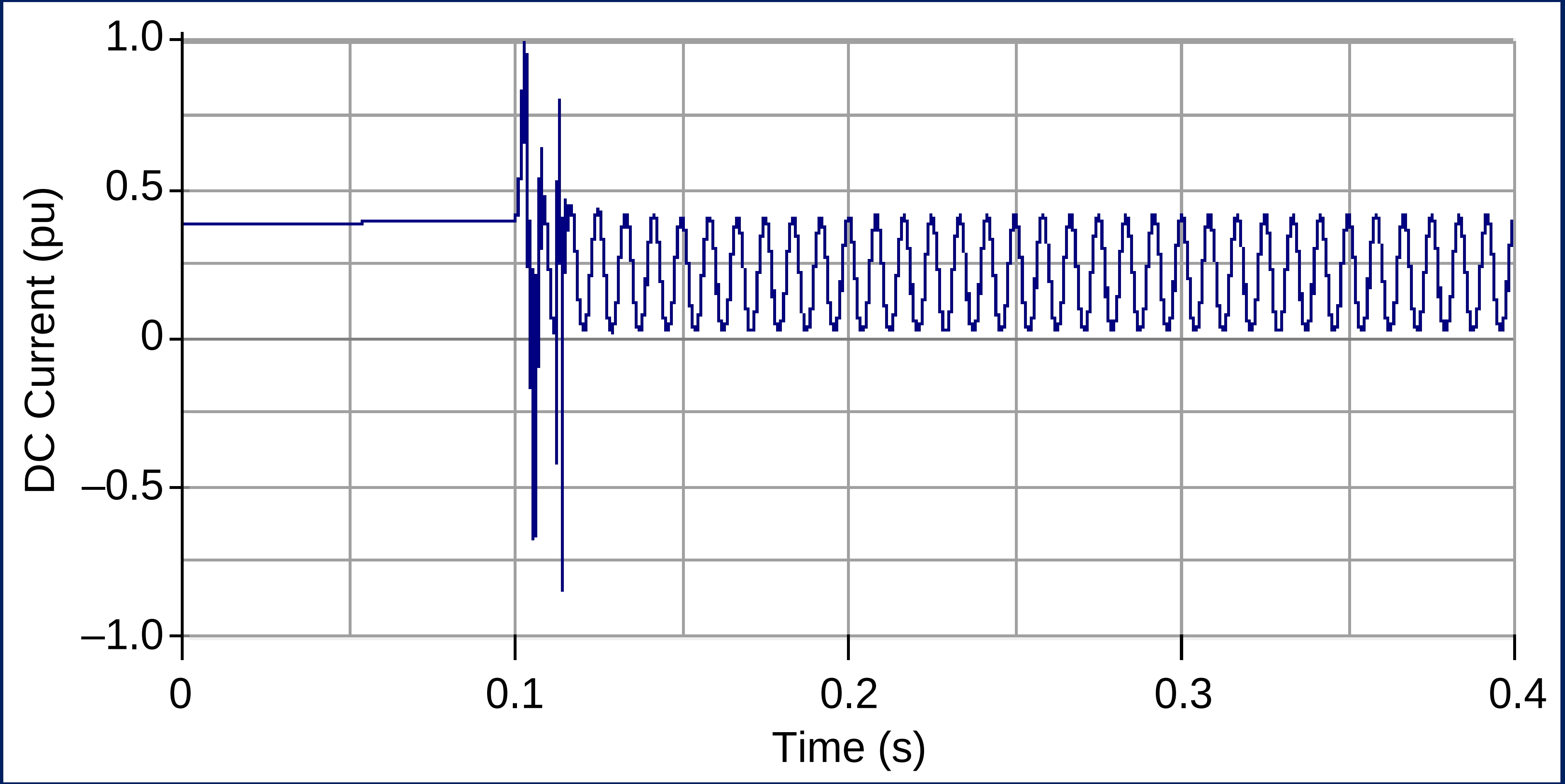


Close in BC Fault

(Voltage and Currents at PCC)

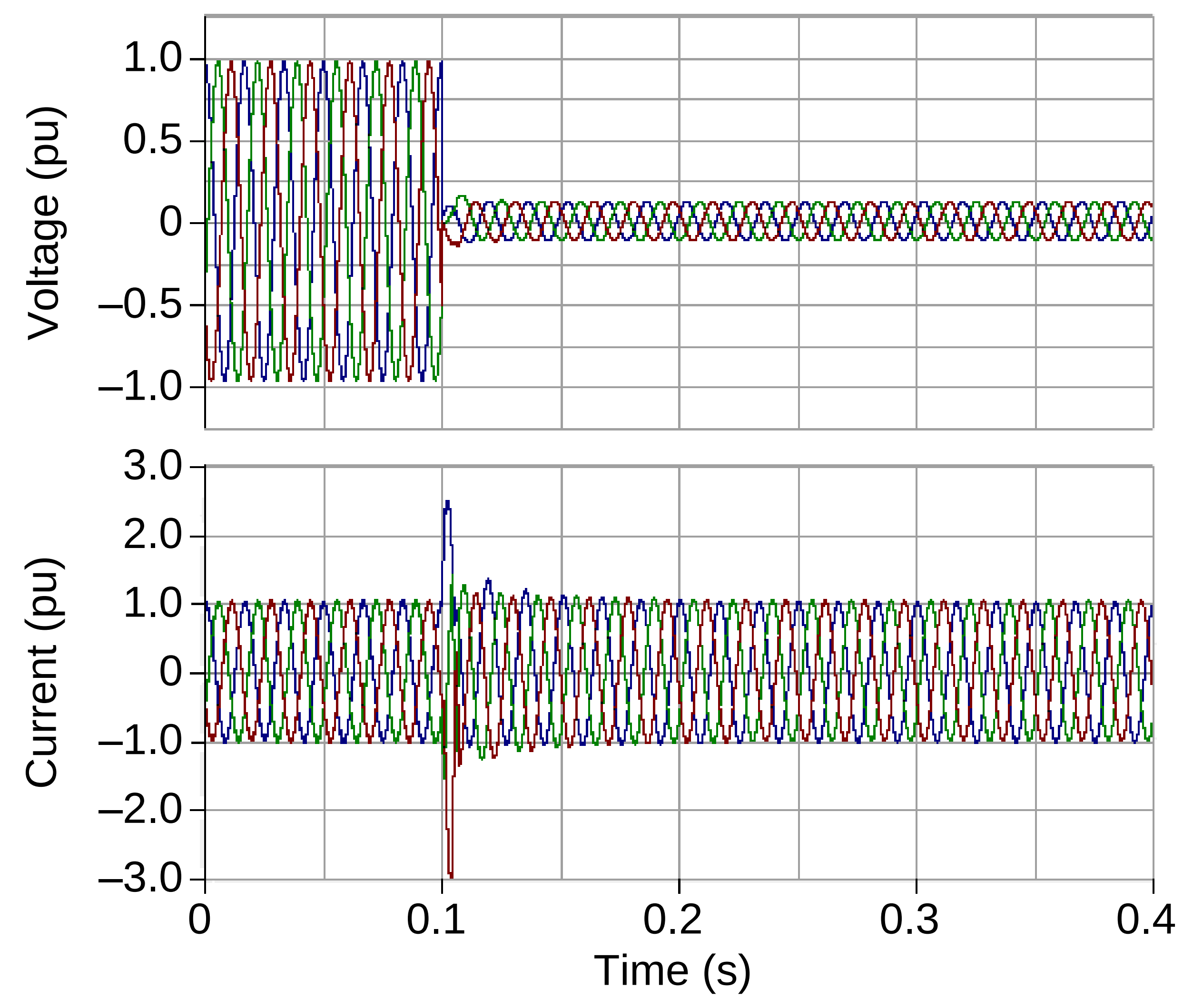


Close in BC Fault
(Current on the DC Bus)

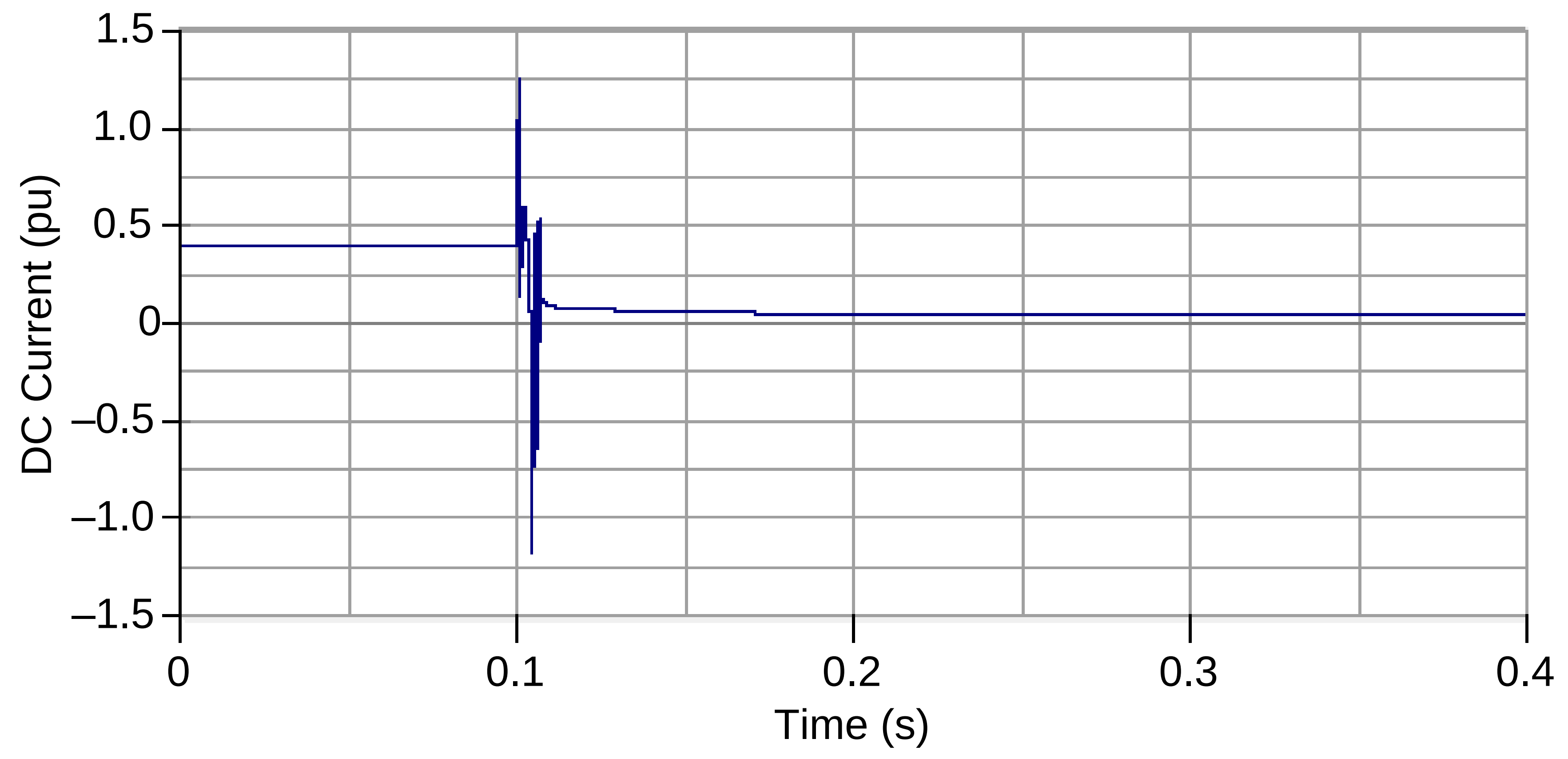


Close in 3 Phase Fault

(Voltage and Currents at PCC)

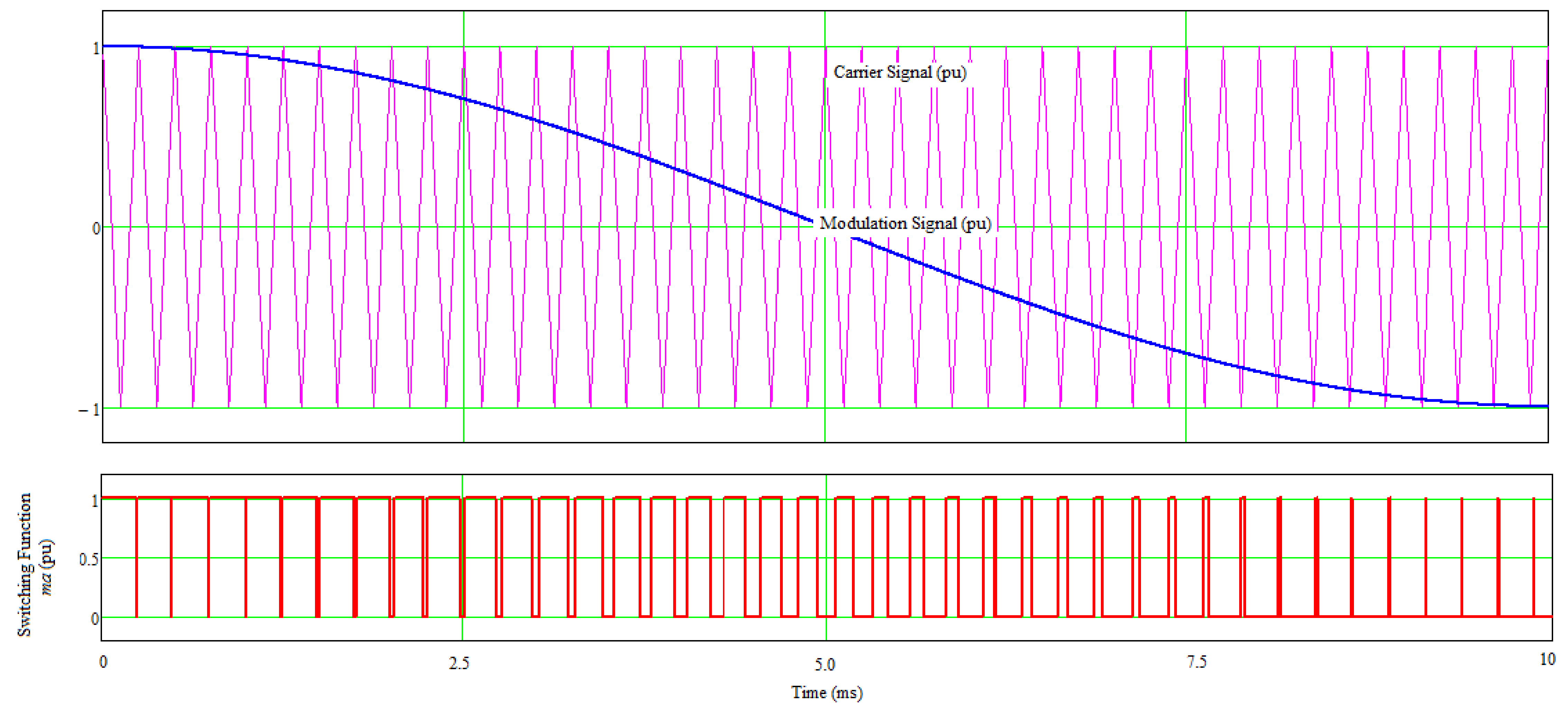


Close in 3 Phase Fault
(Current on the DC Bus)

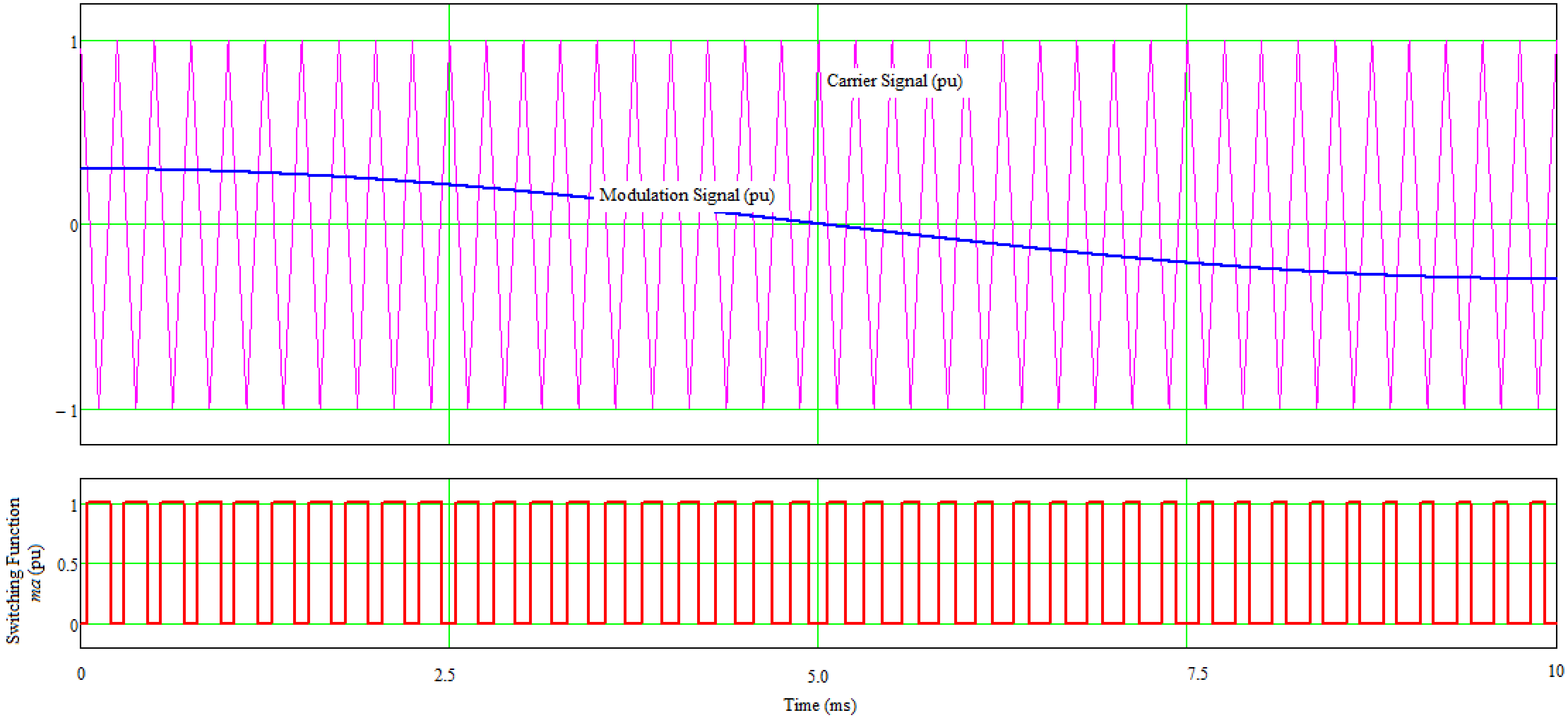


Proposed Protection Scheme

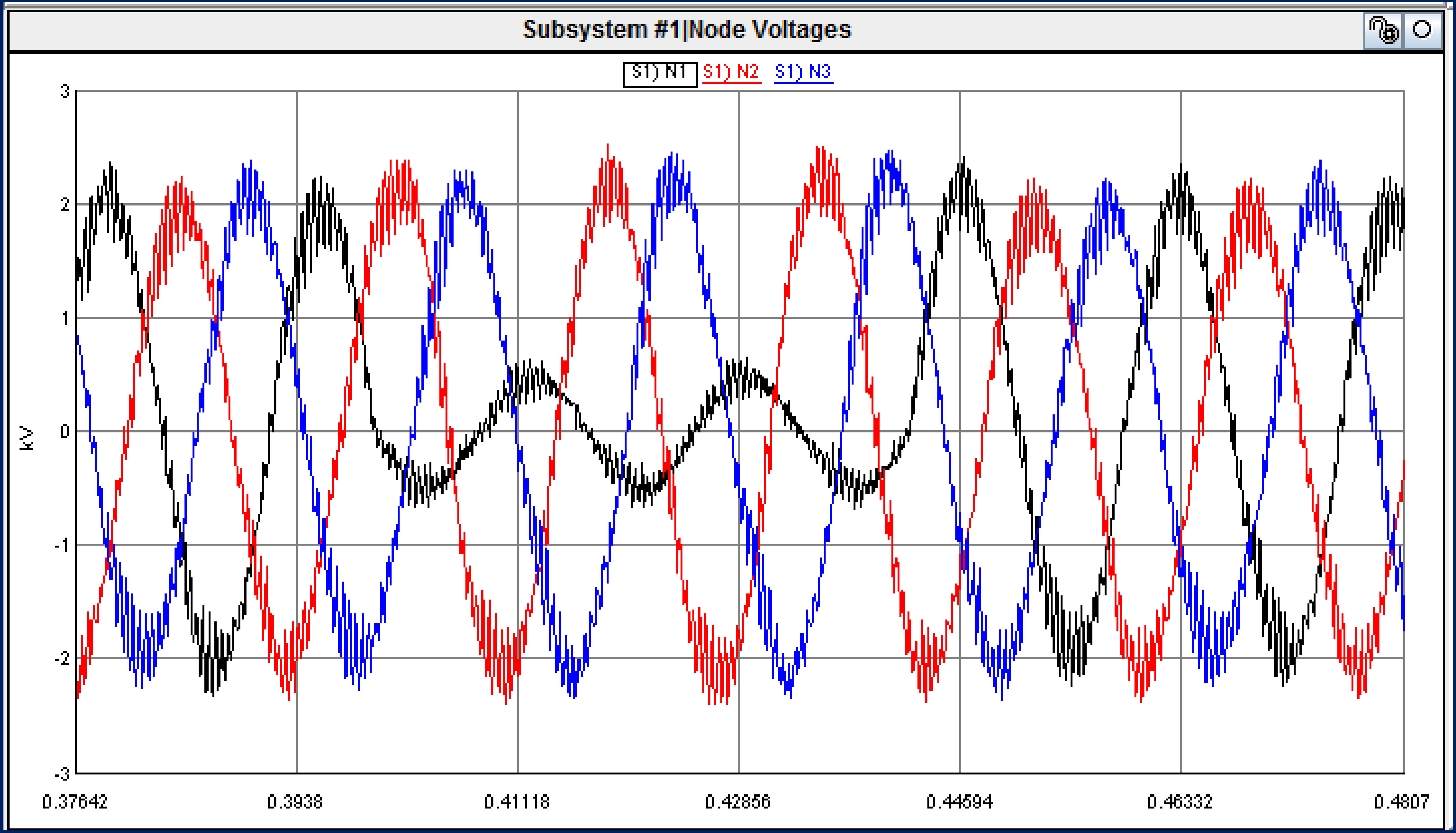
Modulation Signal and Switching Function *(Normal Operation)*



Modulation Signal and Switching Function *(Fault Condition)*

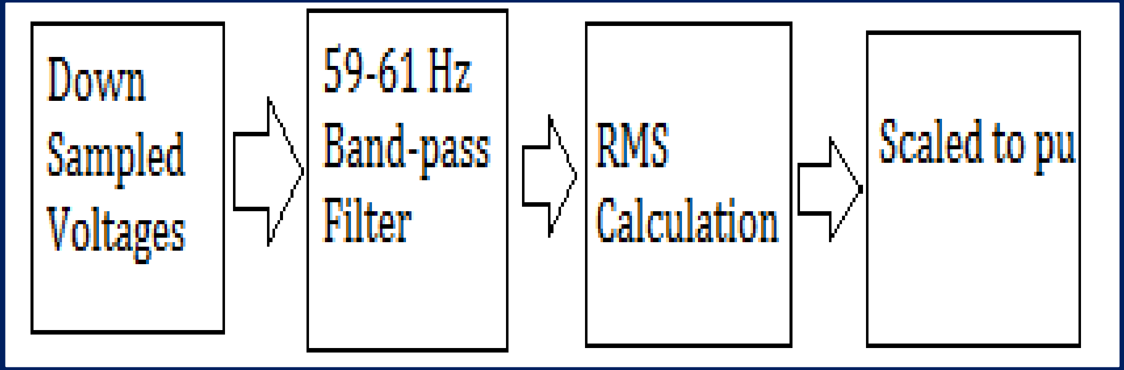


Voltage Waveforms for SLG Fault (AG)



Amplitudes of Modulating Voltage (m_a, m_b, m_c)

Calculated Indirectly From Voltage Waveforms for AG SLG Fault

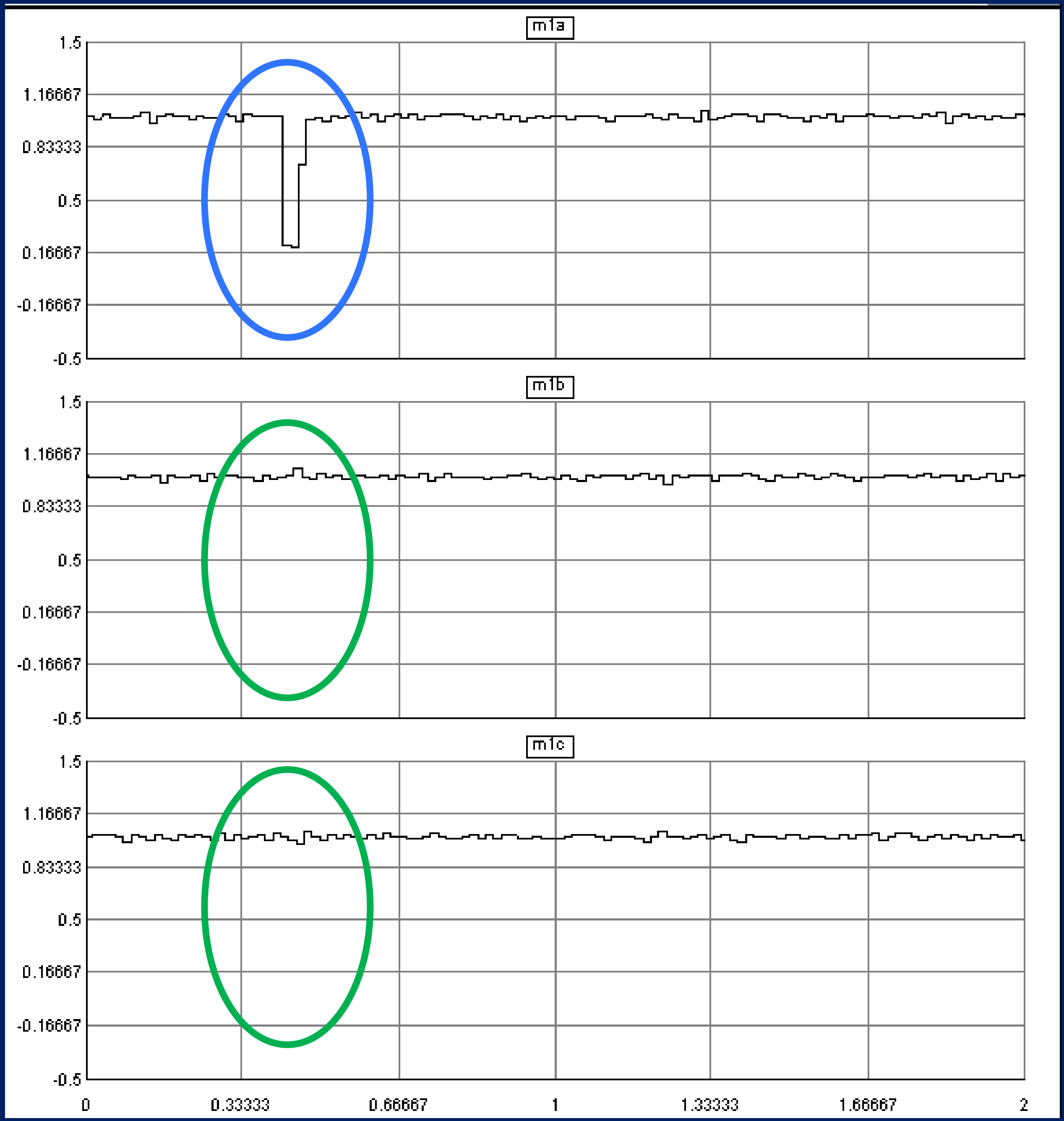


Down Sampled Voltages

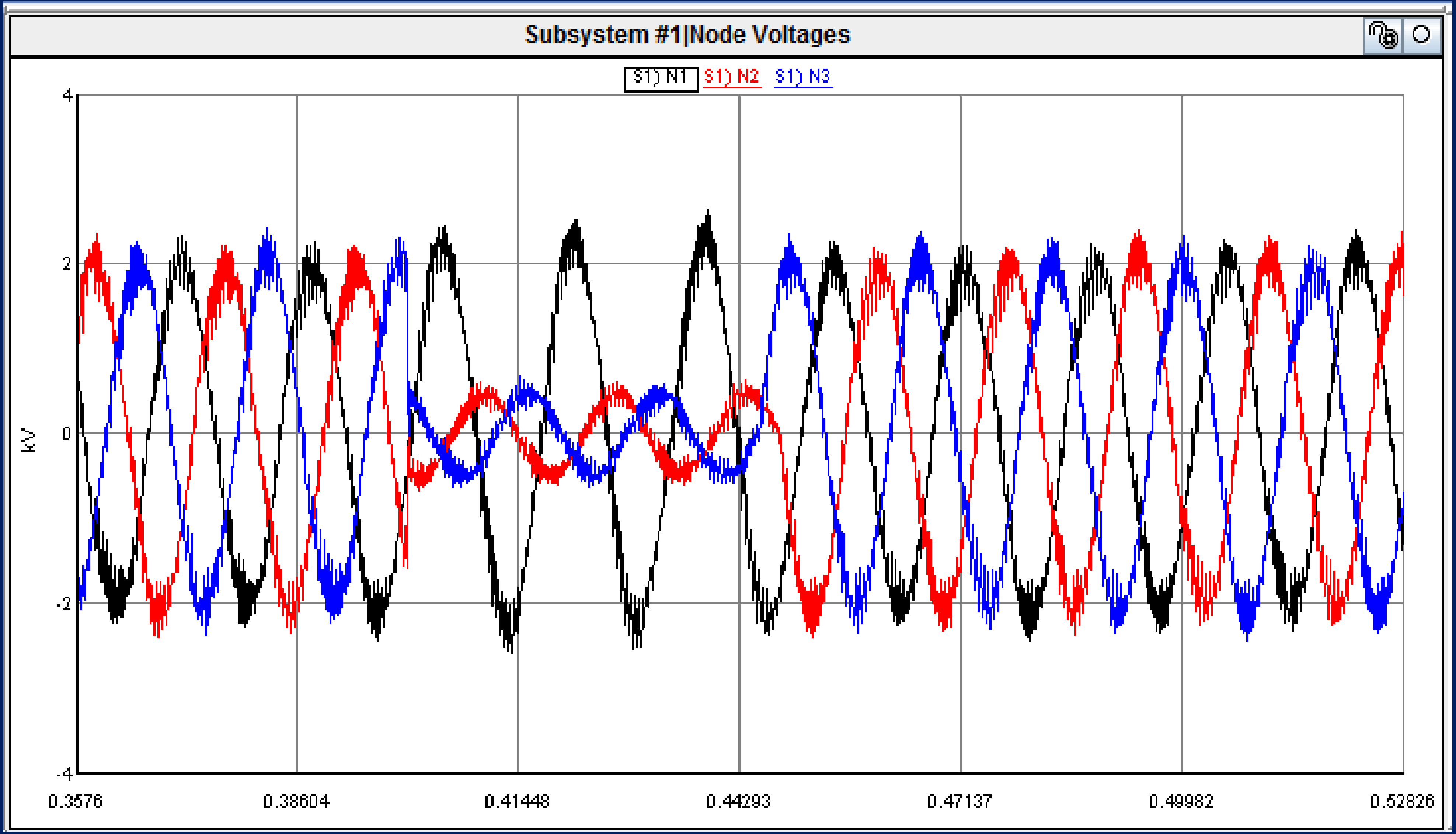
59-61 Hz Band-pass Filter

RMS Calculation

Scaled to pu

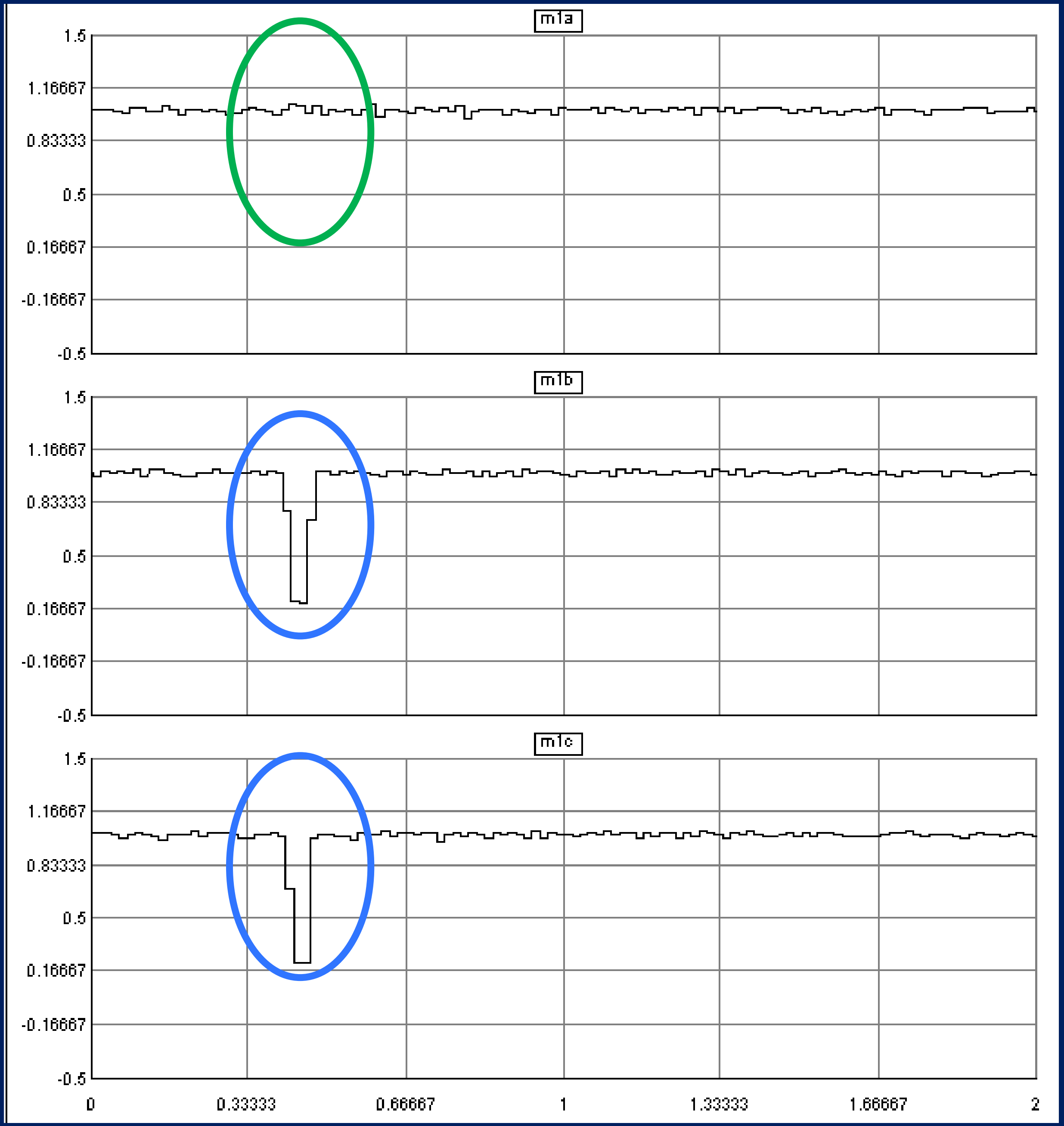


Voltage Waveforms for DLG Fault (BCG)



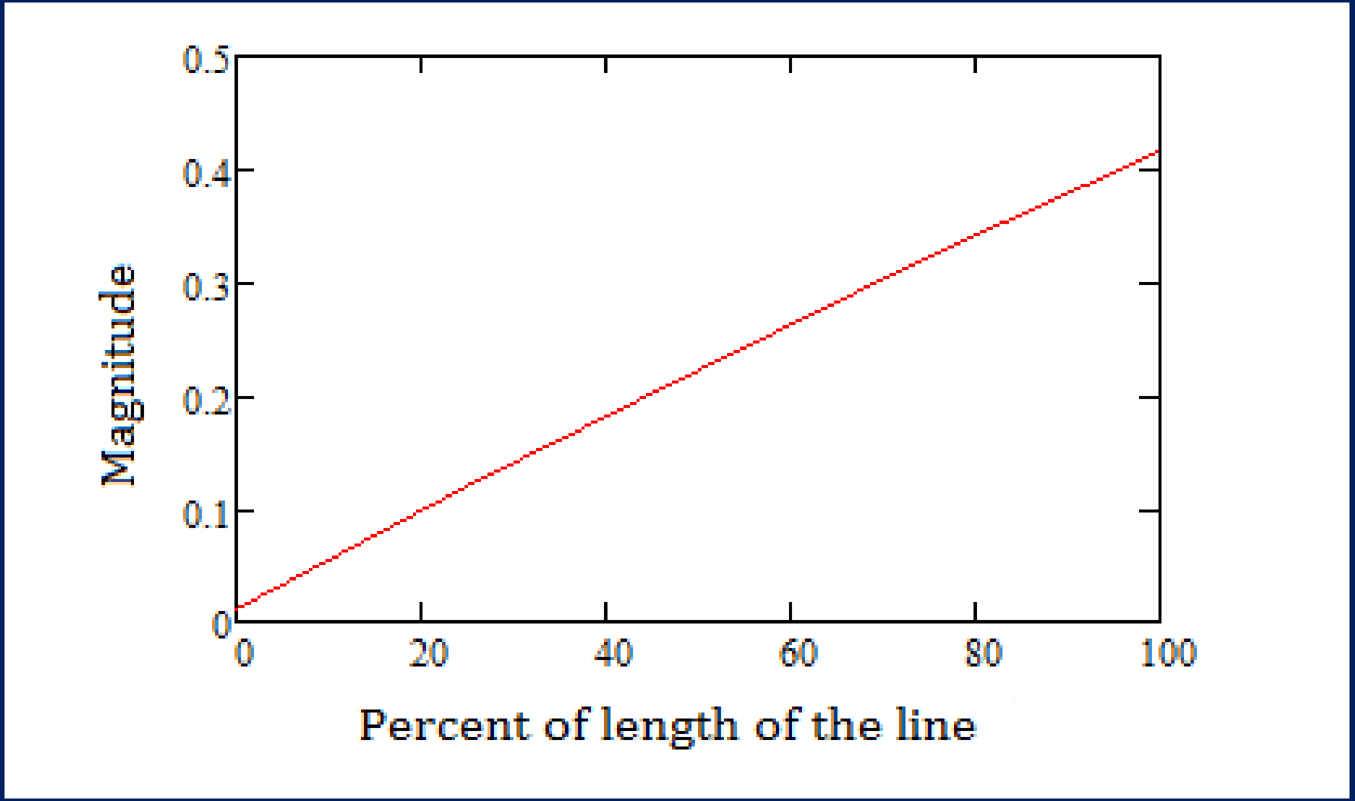
Voltage Magnitudes

Calculated Indirectly From Voltage Waveforms for DLG BCG) Fault



Variation with Fault Location

- Change in modulating voltage changes with location of fault.



Additional Advantages

- Unaffected even if wind input changes (independent of power input)
- Fault location (under investigation)
    - Need to characterize impact of transformer connection and other effects
- Only need present voltage and current data (do not need to store data)

Limitation

- Fault resistance sufficiently large – no considerable change in magnitude
- Fault resistance >24 ohms; change is <5%
- In process of developing algorithm for critical fault resistance value

Questions?