MTS DYNAMIC POSITIONING CONFERENCE
Houston 2018

Modelling and Simulation of HVDC Distribution System DP Ships

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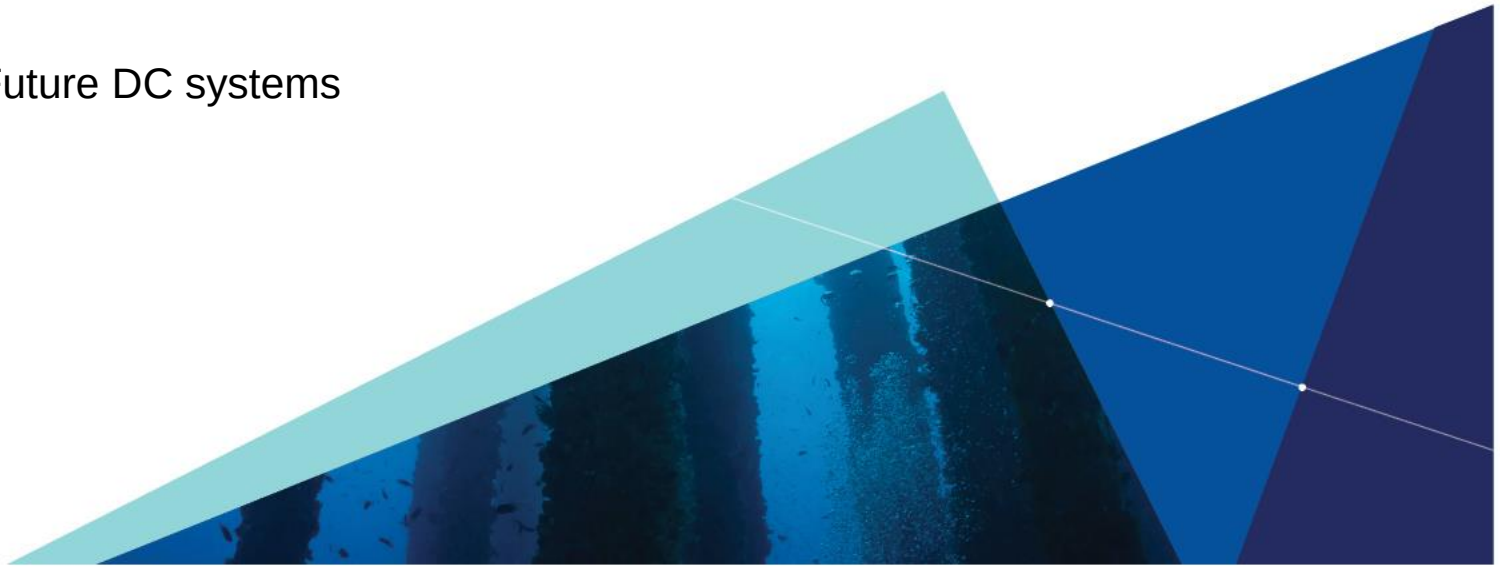
09 October 2018

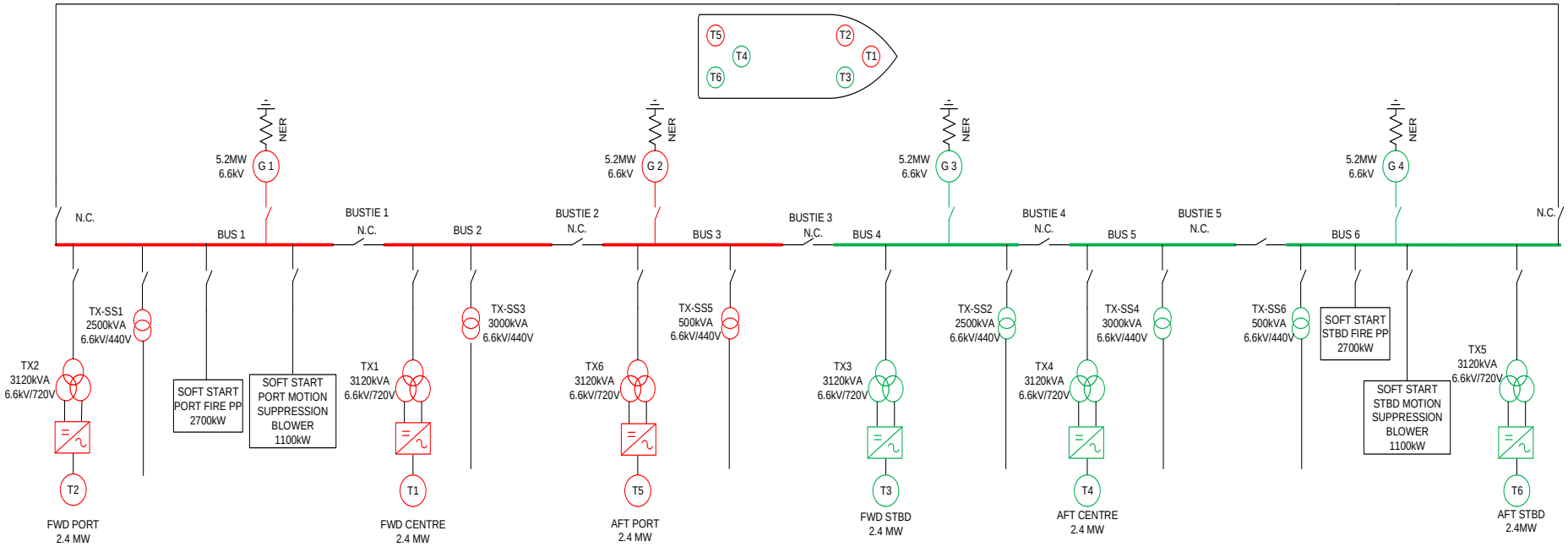
Introduction

- Conventional AC Distribution Systems
- Currently available DC distribution systems
- Voltage Source Converter for HVDC
- Modelling and Simulation of VSC
- Comparison of AC, Current and Future DC systems
- Conclusion



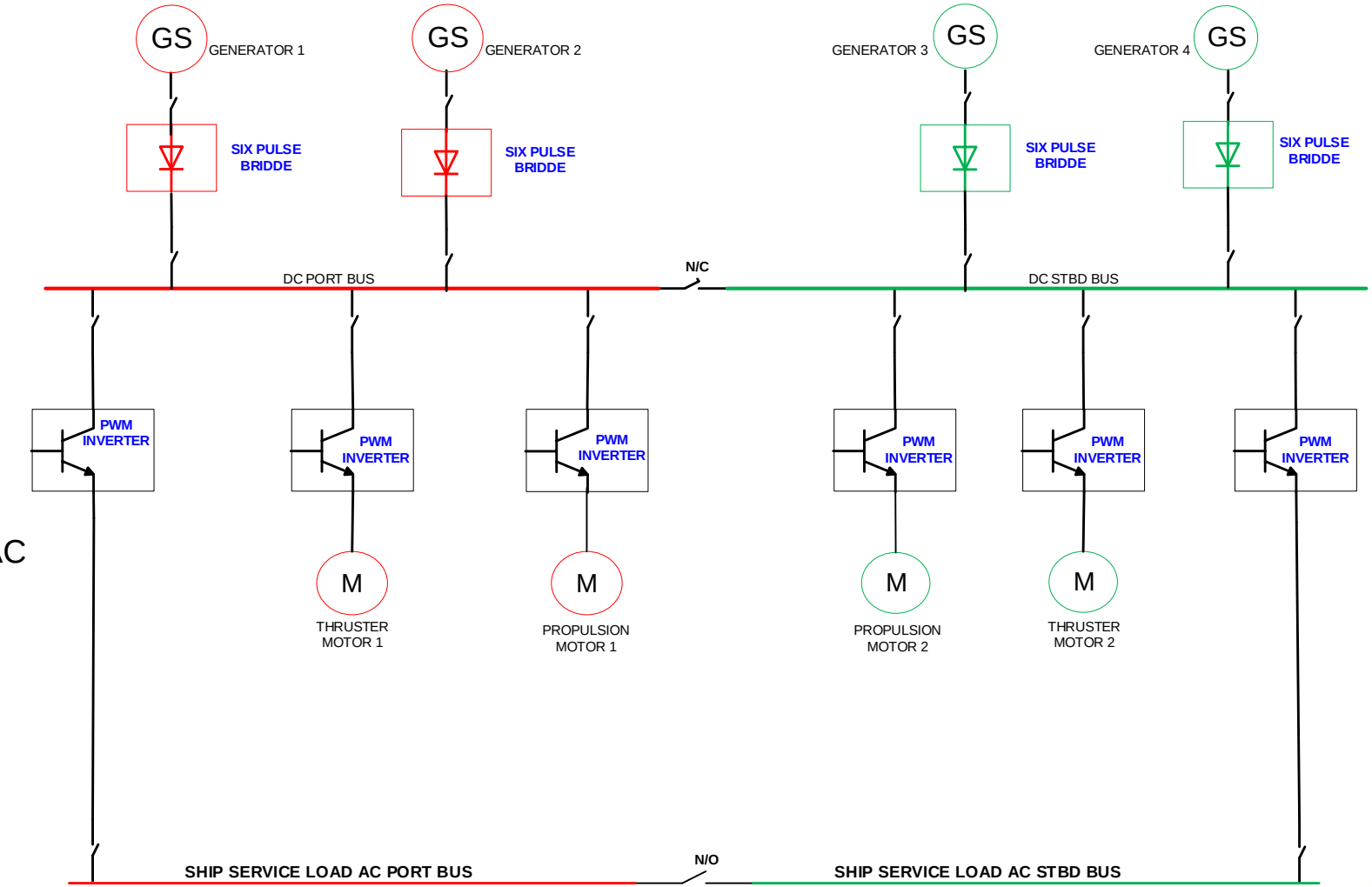
Conventional AC Distribution Systems

- Total generator power 20.8 MW
- Total thruster power 14.4 MW
- Some more VFD driven motors
- VFD DC power 69% +
- Advanced protection for ring bus operation



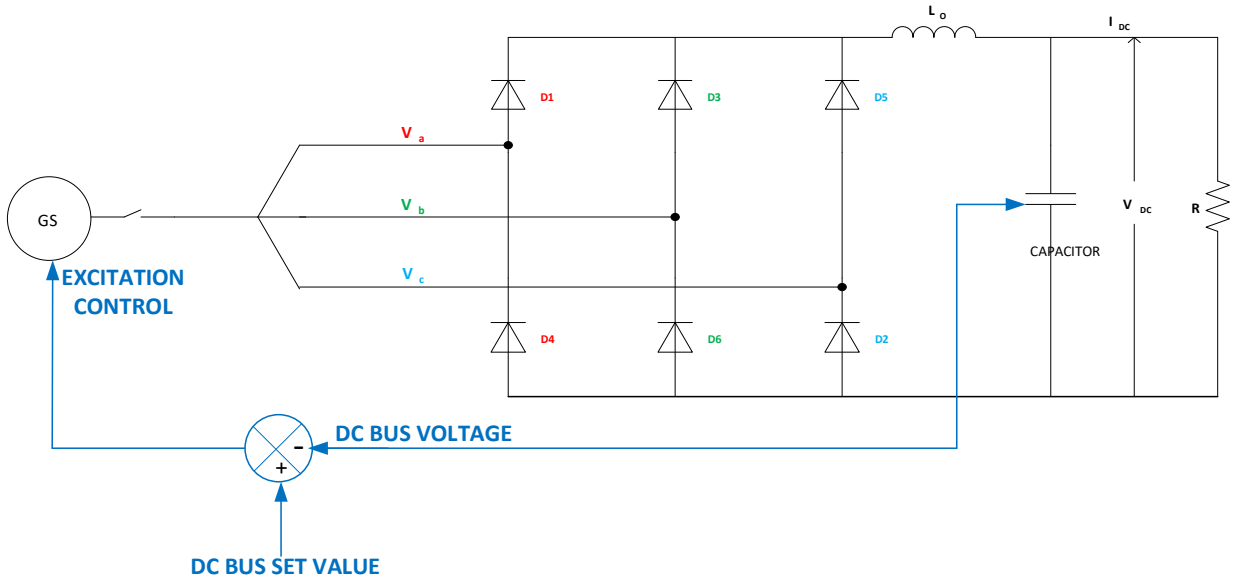
Currently Available DC Distribution Systems

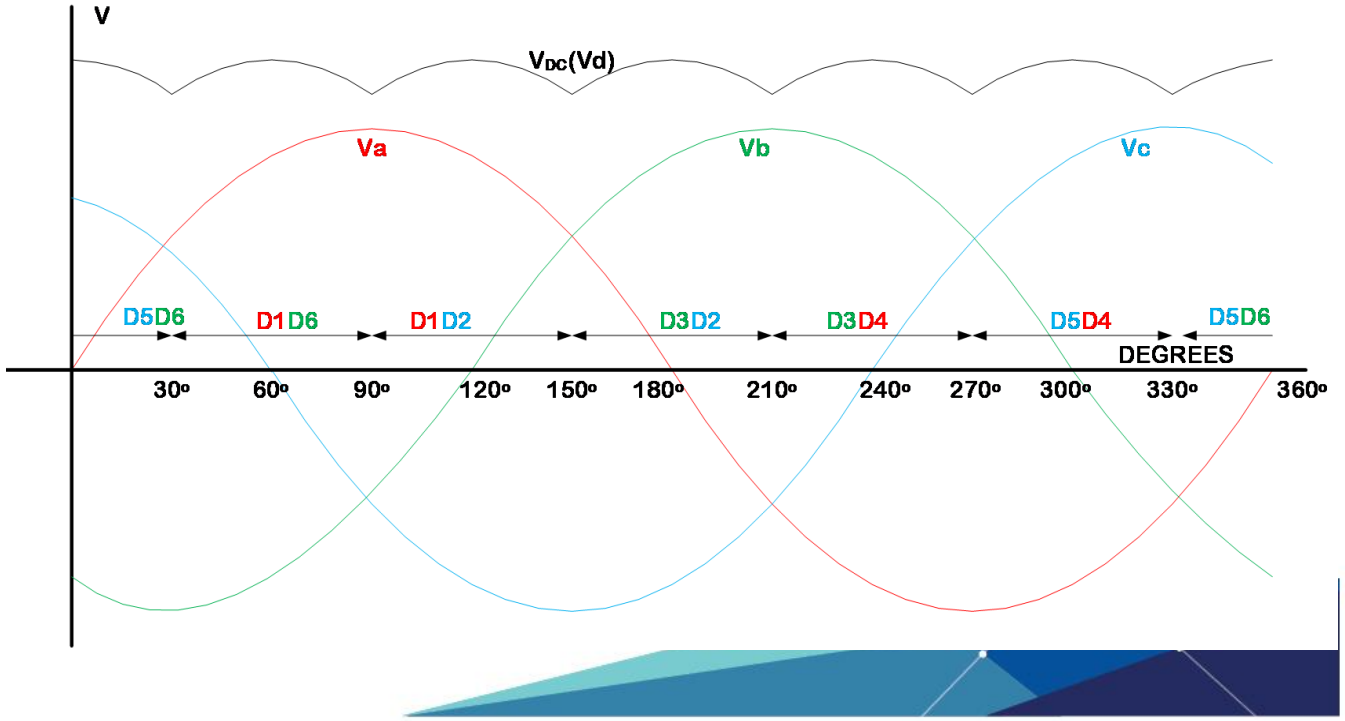
- Extension of multiple DC links that already exist in VFDs
- AC components with a new smart DC distribution
- Rectification using Six Pulse Diode Bridge
- Elimination of transformers
- Generators operating at optimised speed
- Addition of inverters operating at 60Hz for AC service load
- Governor/AVR failures limited to individual generator
- Control of excitation to maintain DC bus stability
- Less problems associated with harmonics



Six-Pulse Diode Bridge

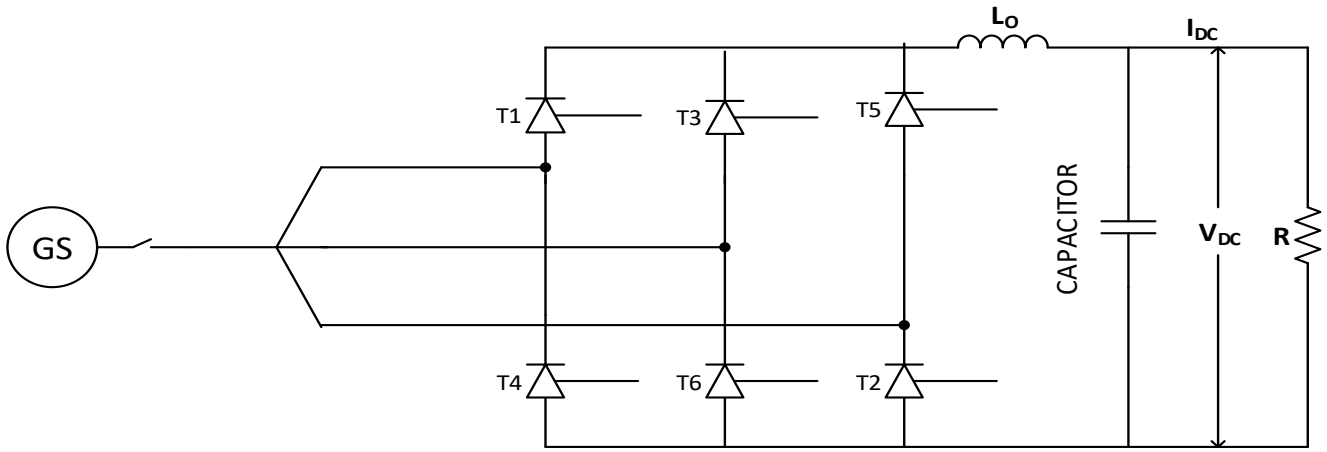
- Natural commutation of diodes
- Two diodes conduct always (opposite legs)
- Output DC voltage is regulated by control of excitation of generator
- Maximum output Voltage is 1.35 x Input Voltage
- Dominant odd harmonics 5th , 7th , 11th and 13th etc.
- Even harmonics cancelled – symmetry of the bridge
- 12 pulse rectifier (series or parallel) cancels 5th and 7th harmonics and so on

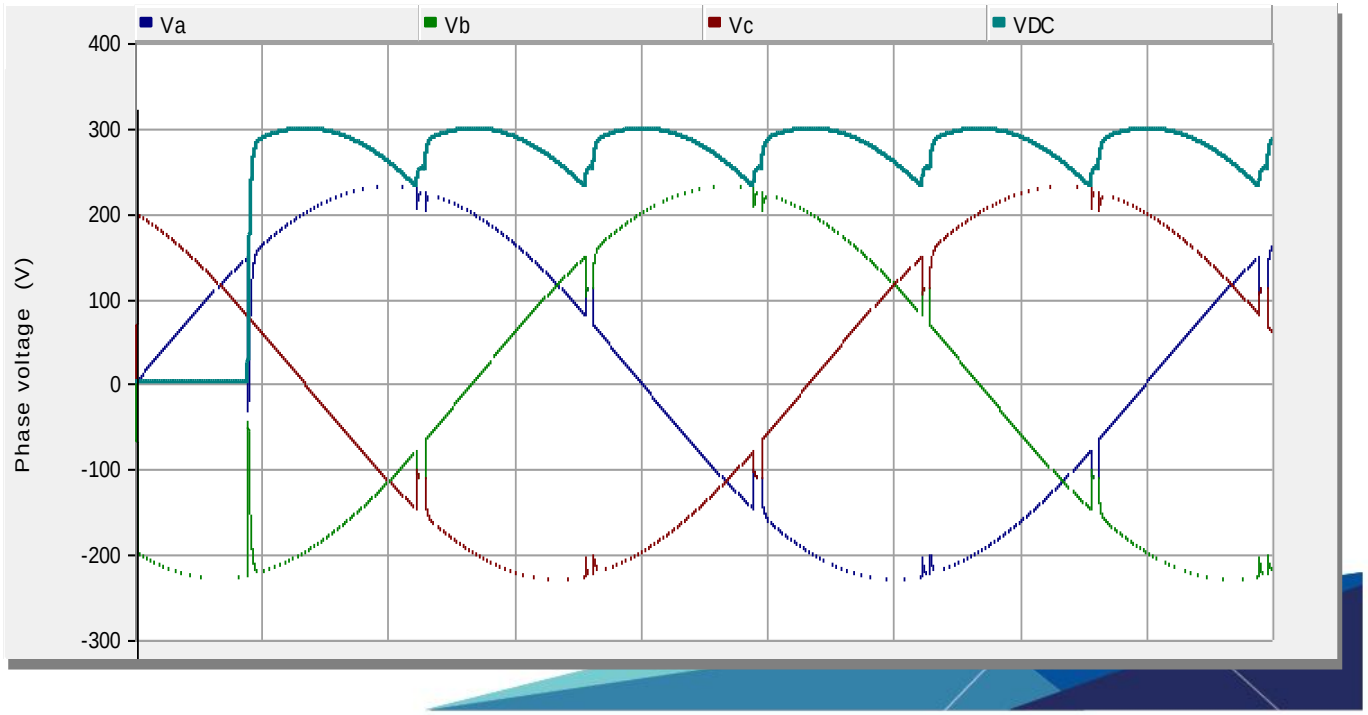




Thyristor Rectifier

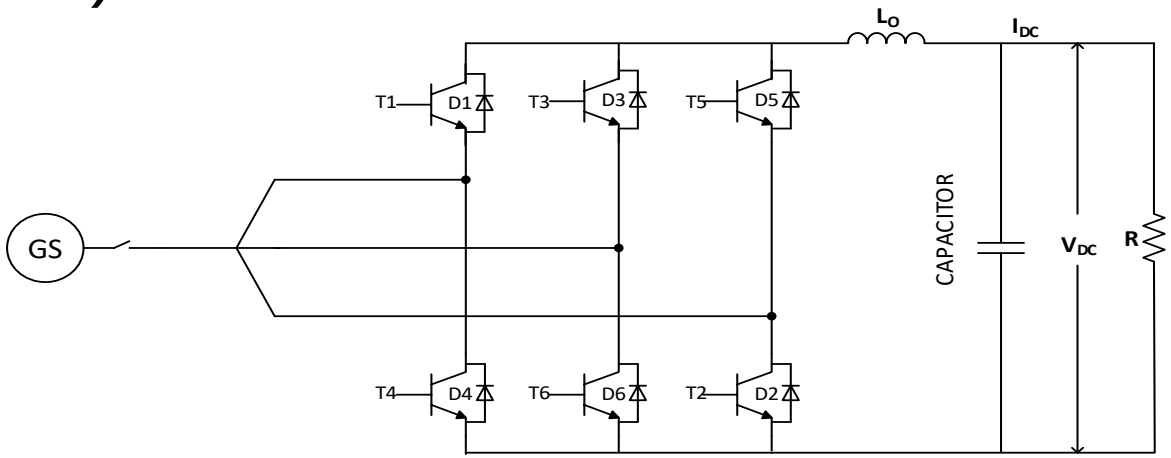
- Thyristers need trigger pulsus for conduction
- Output DC voltage is regulated by controlling the firing angles of the thyristors
- $(\mathrm{VDC})\mathrm{V_d} = 1.35 \times \mathrm{V_{LL}} \times \mathrm{Cos}\alpha$
- Maximum output voltage is 1.35 x Input Voltage when firing angle is zero
- Produces commutation notches, non-characteristic harmonics (Inter-harmonics and Sub-harmonics)
- Used in
  - Load Commutated Inverters (LCI)
  - DC motor drives
  - HVDC transmission lines - Line-Commutated Converter(LCC)

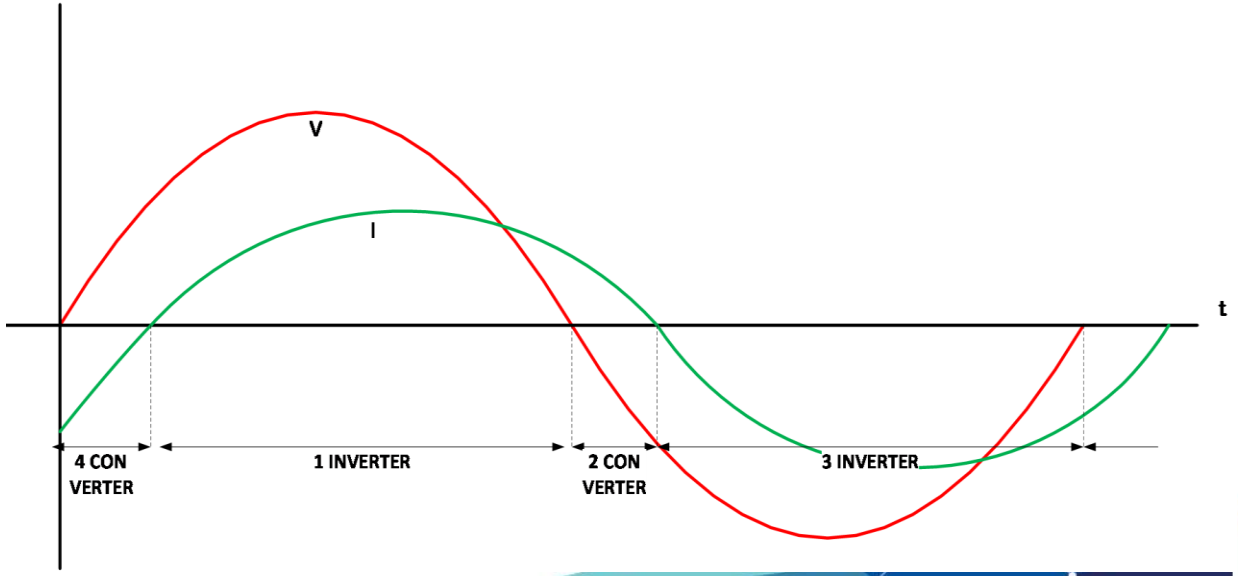




Voltage Source Converter (VSC)

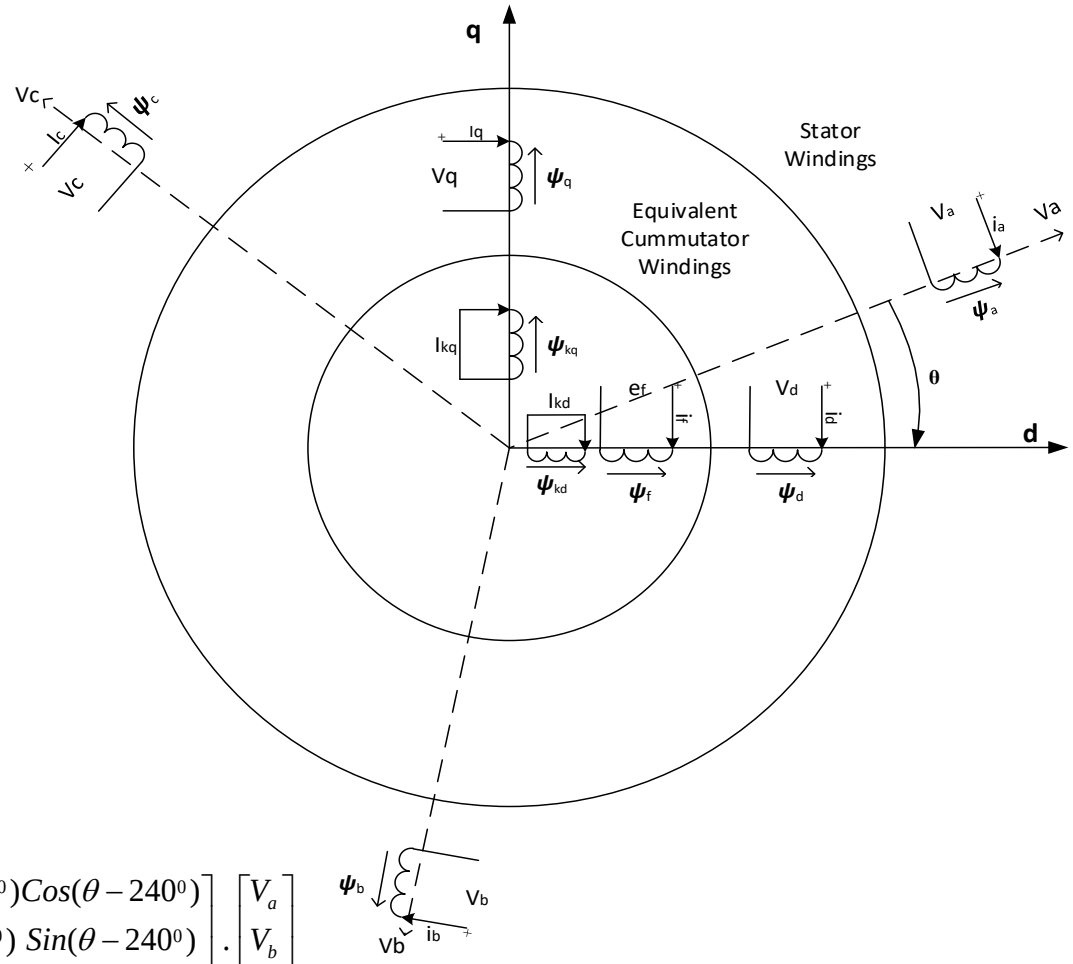
- Operates in 4 quadrants
- Power flows from source to load and load to source
- Operates in PWM (Sinusoidal, Hysteresis and SVM etc.)
- SVM improves output voltage – two times the input voltage
- Draws reactive power from the source unlike diode rectifier
- Complex control system – cascade with outer voltage and inner current control
- Independent control of active and reactive power
- Stable system for all range of load variation
- Reactive power drawn from the source is maintained at zero





System Modelling – Synchronous Generator

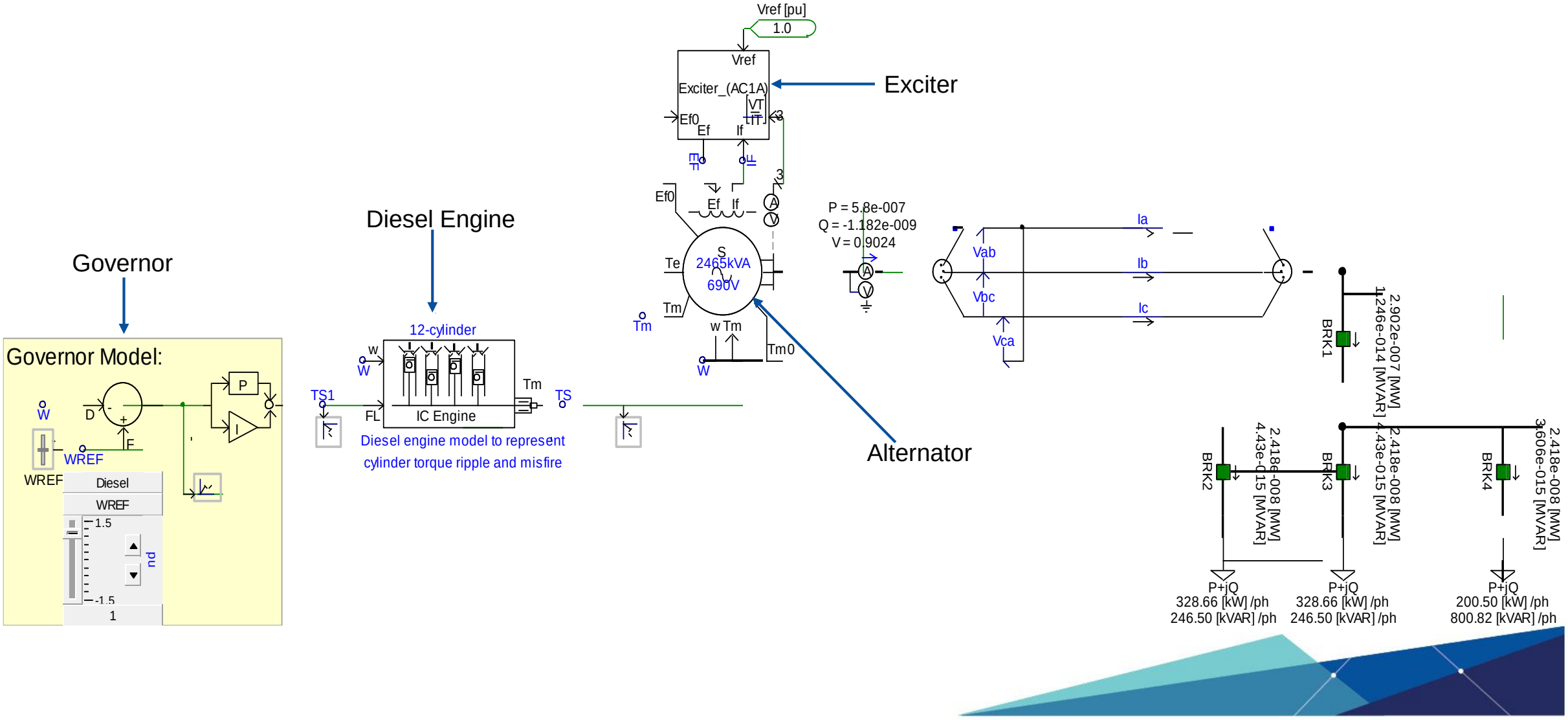
- Use of electromagnetic transient simulation software PSCAD/EMTDC for system modelling
- Used the validated 5th order synchronous generator in PS-CAD
- Used the validated diesel engine in PS-CAD
- Used validated IEEE Std 421.5-2005 exciter model AC1A in PS-CAD
- Developed a governor control system and verified the performance of the generator against class rules (ABS)



ψ_f = *Flux produced by the field winding*
ψ_{kd} = *Flux produced on the direct axis by Amortisseur windings*
ψ_{kq} = *Flux produced on the quadrature axis by Amortisseur windings*
ψ_d = *Flux produced on the direct axis (rotor) by stator magnetic field*
ψ_q = *Flux produced on the quadrature axis(rotor) by stator magnetic field*
ψ_a = *Flux on the phase A winding of the stator*
ψ_b = *Flux on the phase B winding of the stator*
ψ_c = *Flux on the phase C winding of the stator*

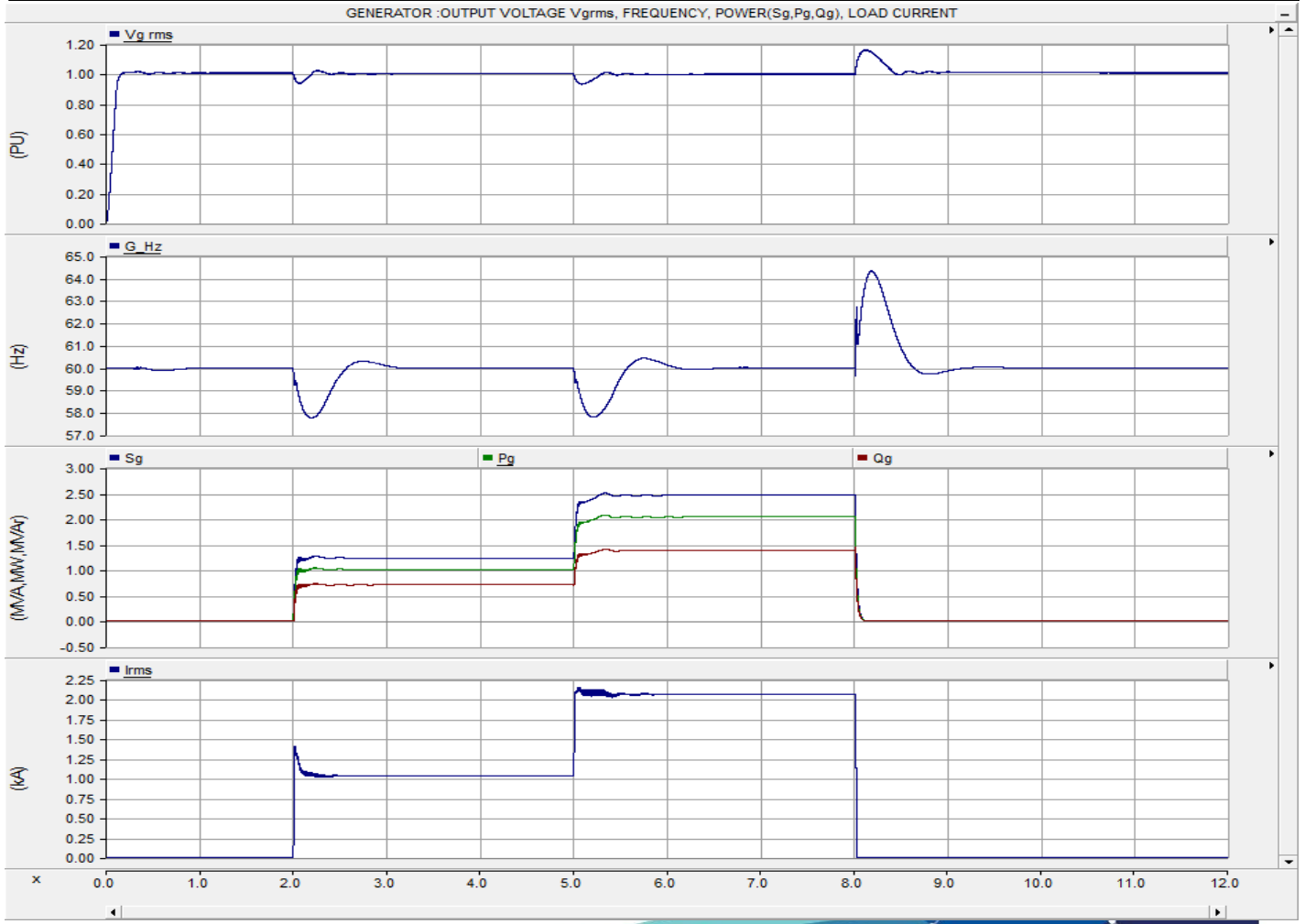
$$\begin{bmatrix} U_d \\ U_q \\ U_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos(\theta) & Cos(\theta-120^0) & Cos(\theta-240^0) \\ Sin(\theta) & Sin(\theta-120^0) & Sin(\theta-240^0) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Complete System Model of Generator



Simulation Results

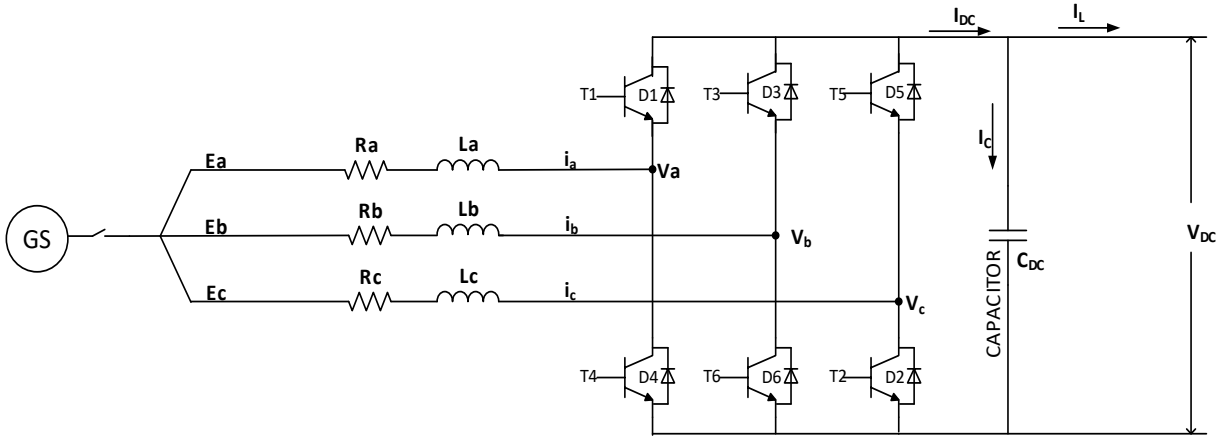
STATUS	VRMS VOLT	OUTPUT POWER, kW, kVAR, mVA			FREQUENCY Hz	LOAD CURRENT RMS A
		ACTIVE	REACTIVE	APPARENT		
No Load	691.00	0	0	0	60	0
50% Load	689.67	1007.87	707.87	1231.68	59.99	1031.21
Full Load	688.56	2033.55	1381.58	2462.48	59.99	2062.39



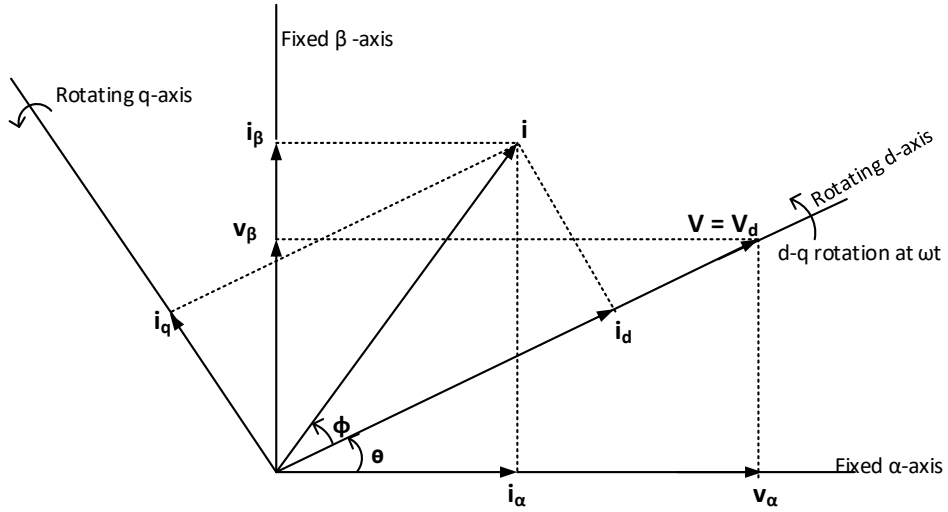
- The first overlay – Generator terminal voltage
  - Generator terminal voltage at rated voltage 690V
  - Minor voltage dips when step load is thrown on
  - A swell when 100% load is thrown off
- The second overlay – Frequency in Hz
  - Rated frequency (60Hz) maintained except during step load change but within acceptable limits
- The third overlay - Three graphs Sg, Pg and Qg
  - No load - 0
  - Step load 50% on
  - 100 percent of the generator capacity
- The fourth overlay - Line current

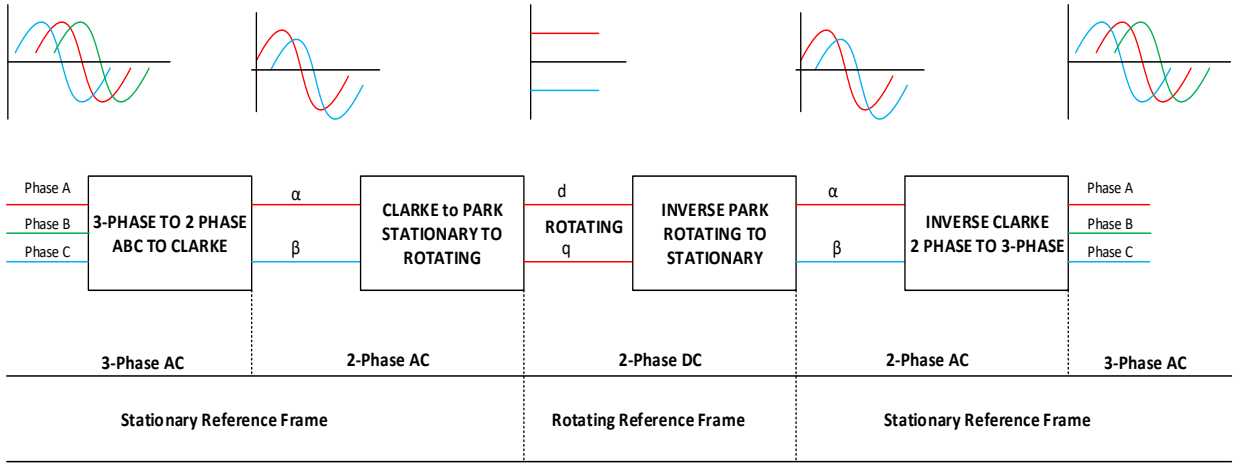
VSC Modelling

- VSC – Generator, I/P Impedance, IGBTs with antiparallel diodes and center capacitor
- Voltage equation - Standard Kirchhoff's voltage law
- Transformation of axes in vector control
- Transformation of reference frames – ABC-αβ-dq-αβ-ABC
- ABC to synchronous rotating dqo



$$E_{abc} = L\frac{d}{dt}i_{abc} + V_{abc} + Ri_{abc}$$

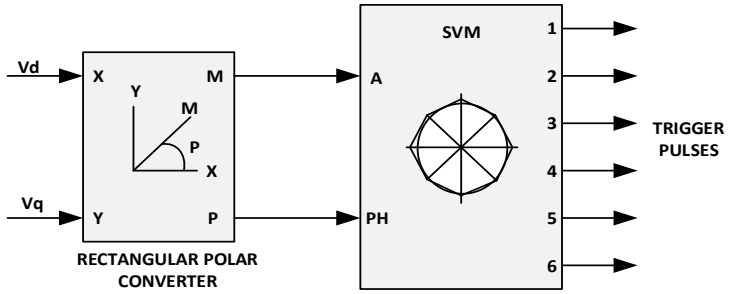


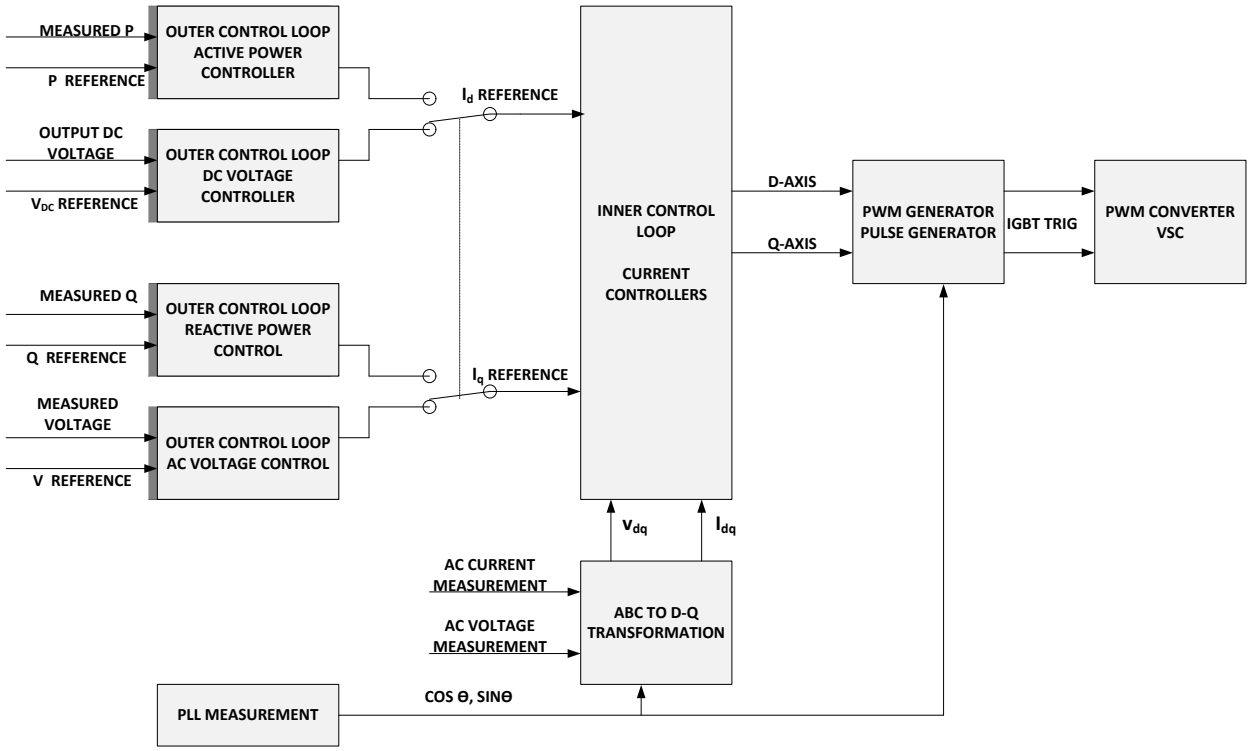


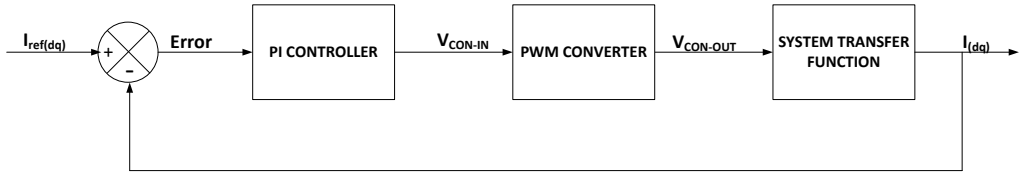
$$\begin{bmatrix} d \\ q \\ o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos(\theta) & Cos(\theta-120^0) & Cos(\theta-240^0) \\ Sin(\theta) & Sin(\theta-120^0) & Sin(\theta-240^0) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Control Methodology of the PWM

- Complete cascade control – Trigger pulse generation
  - Outer control loop voltage - AC and DC OR
  - Outer control loop power - P and Q
  - Functional block - Inner current control – Id and Iq
  - PI controller - Inner current control
- Generates rectangular voltage in d and q axes – Vd and Vq
- Converts rectangular to polar – Amplitude and phase
- SVM generates trigger pulses for IGBTs in VSC
- Vary width of pulses to regulate the DC output when load changes



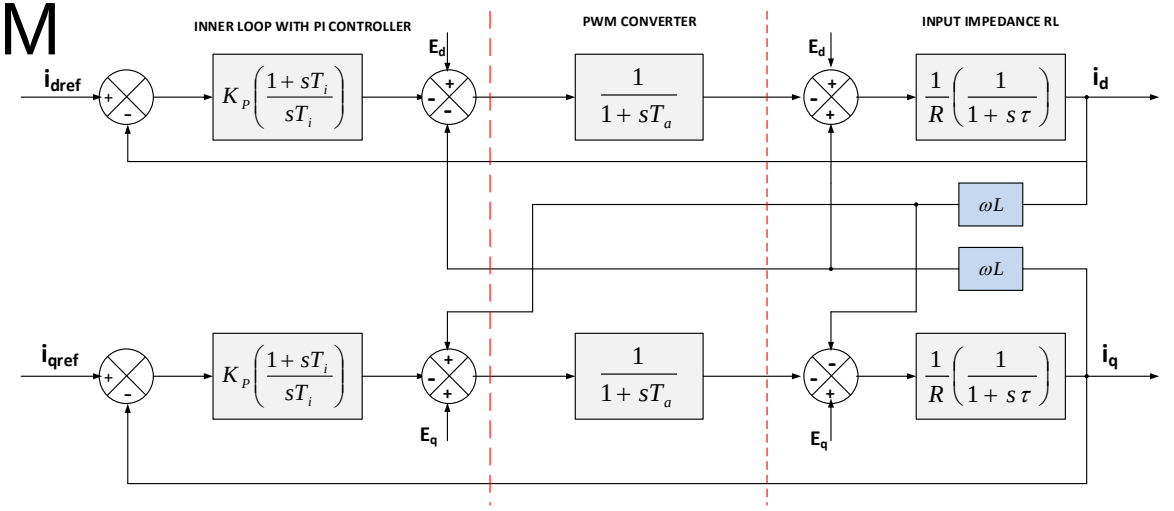




$$PI(s) = K_P + \frac{K_i}{s} = K_P\left(\frac{1+T_i\,s}{T_i\,s}\right)$$

Control Methodology of the PWM

- PWM converter input - Output of the PI controller
- Transfer function of the PWM converter
  - PWM converter - A transformer with a time delay
  - Delay equals to half of the period of switching frequency
- Output of the PWM Converter
- Complete system model

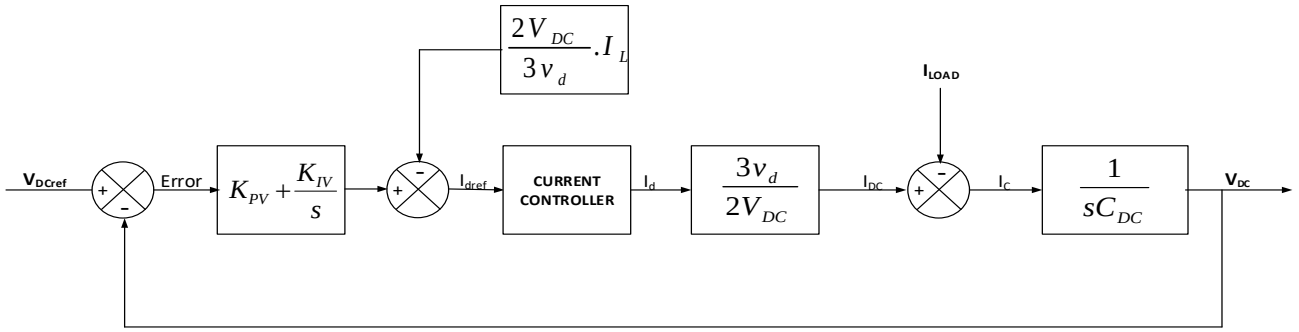


$$V_{CON-IN}(s) = \left[I_{ref}(s) - I(s)\right].K_P\left(\frac{1+T_i s}{T_i s}\right)$$

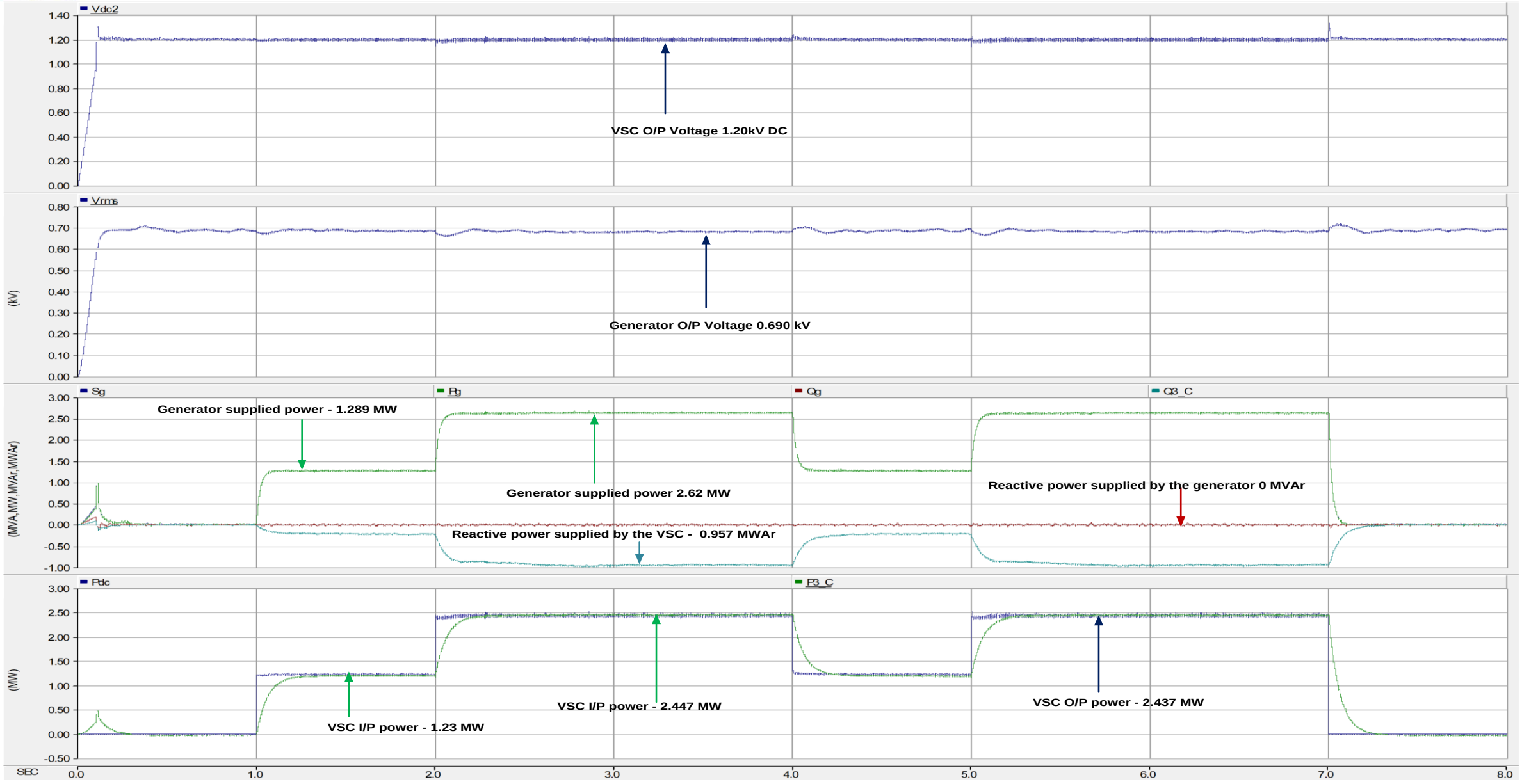
$$Y(s) = \left(\frac{1}{1+T_a s}\right)$$

$T_a = T_{swtch}/2$, T_{swtch} *is the period of switching frequency* (f_{switch})

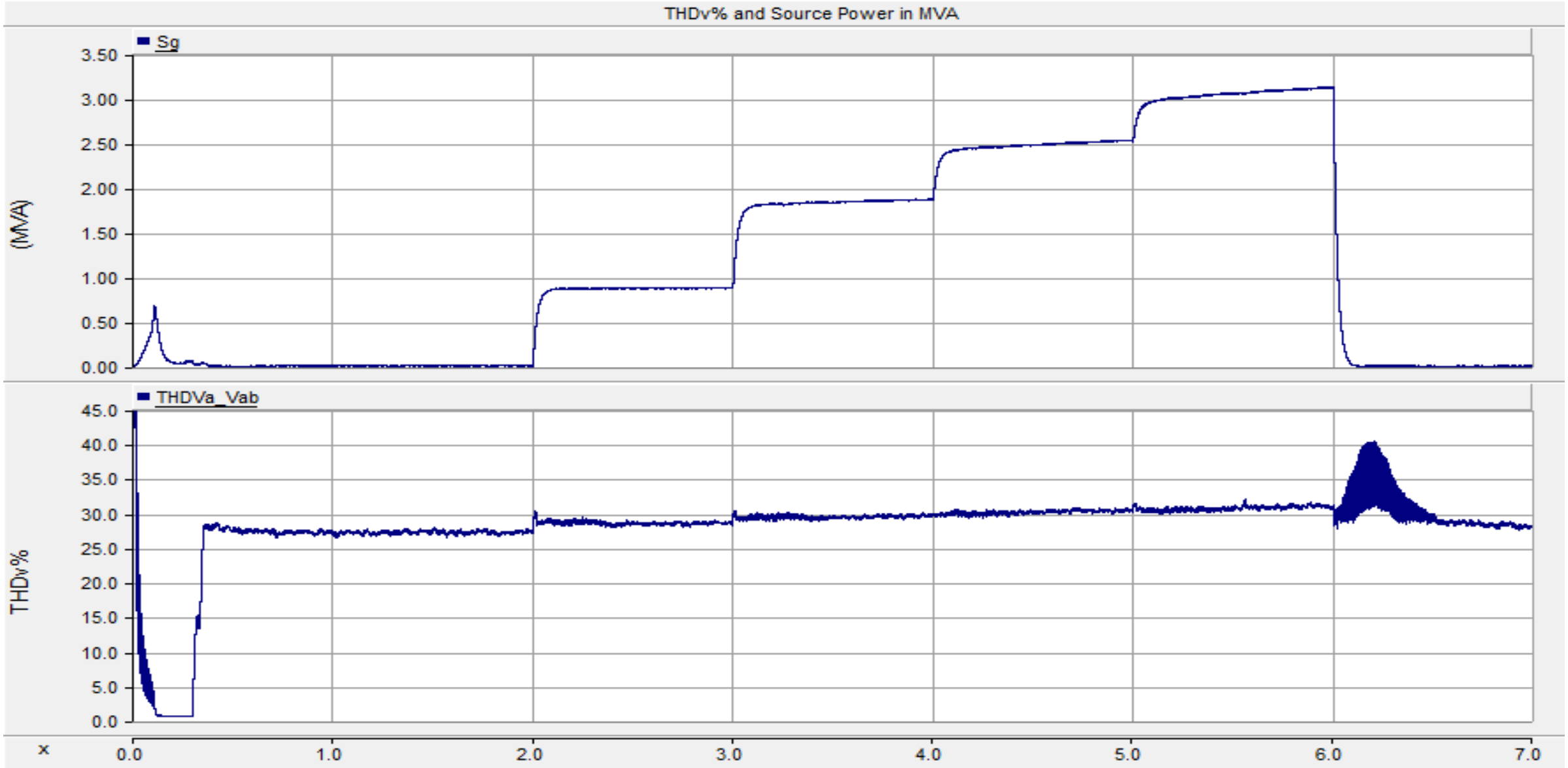
$$V_{CON-OUT}(s) = \left[I_{ref}(s) - I(s)\right].K_P\left(\frac{1+T_i s}{T_i s}\right).\left(\frac{1}{1+T_a s}\right)$$



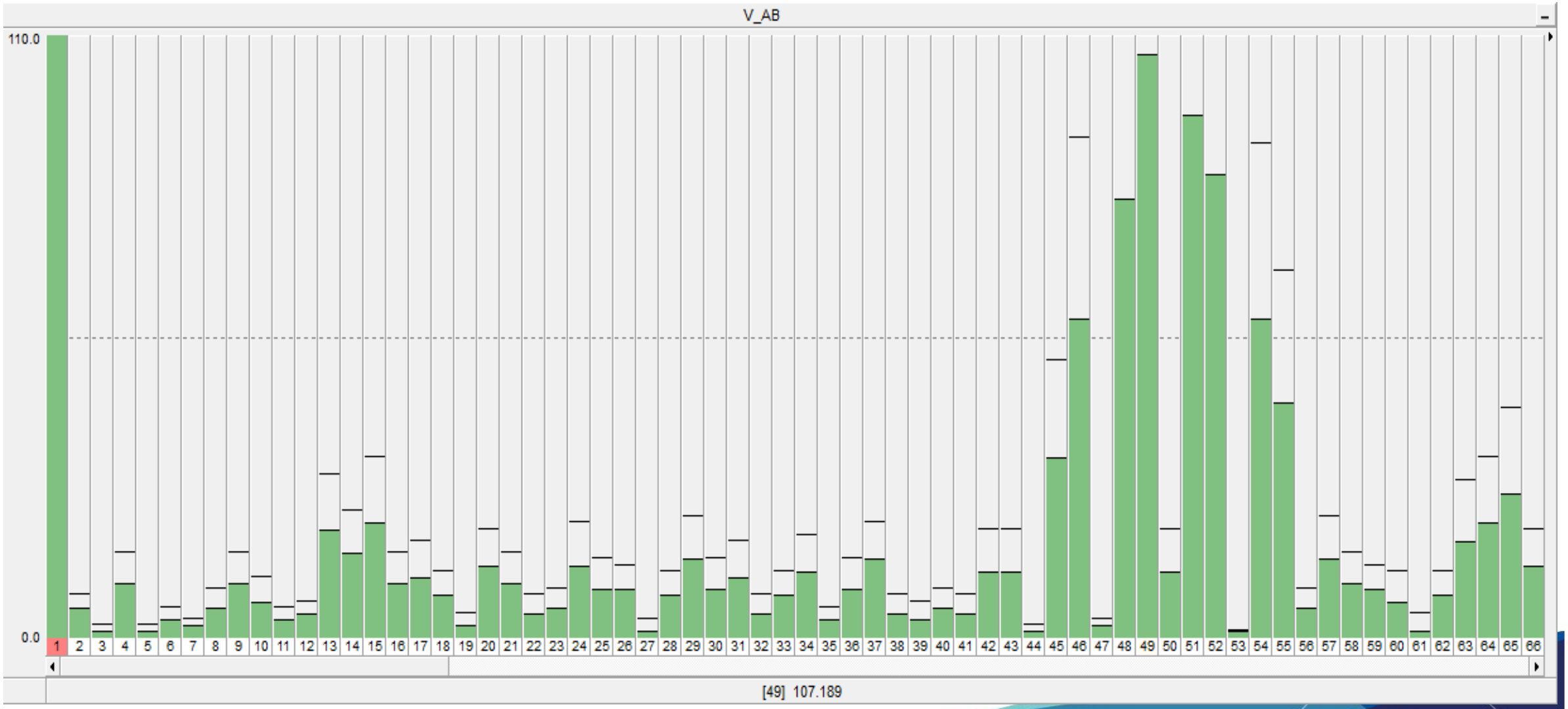
Simulation Results - VSC



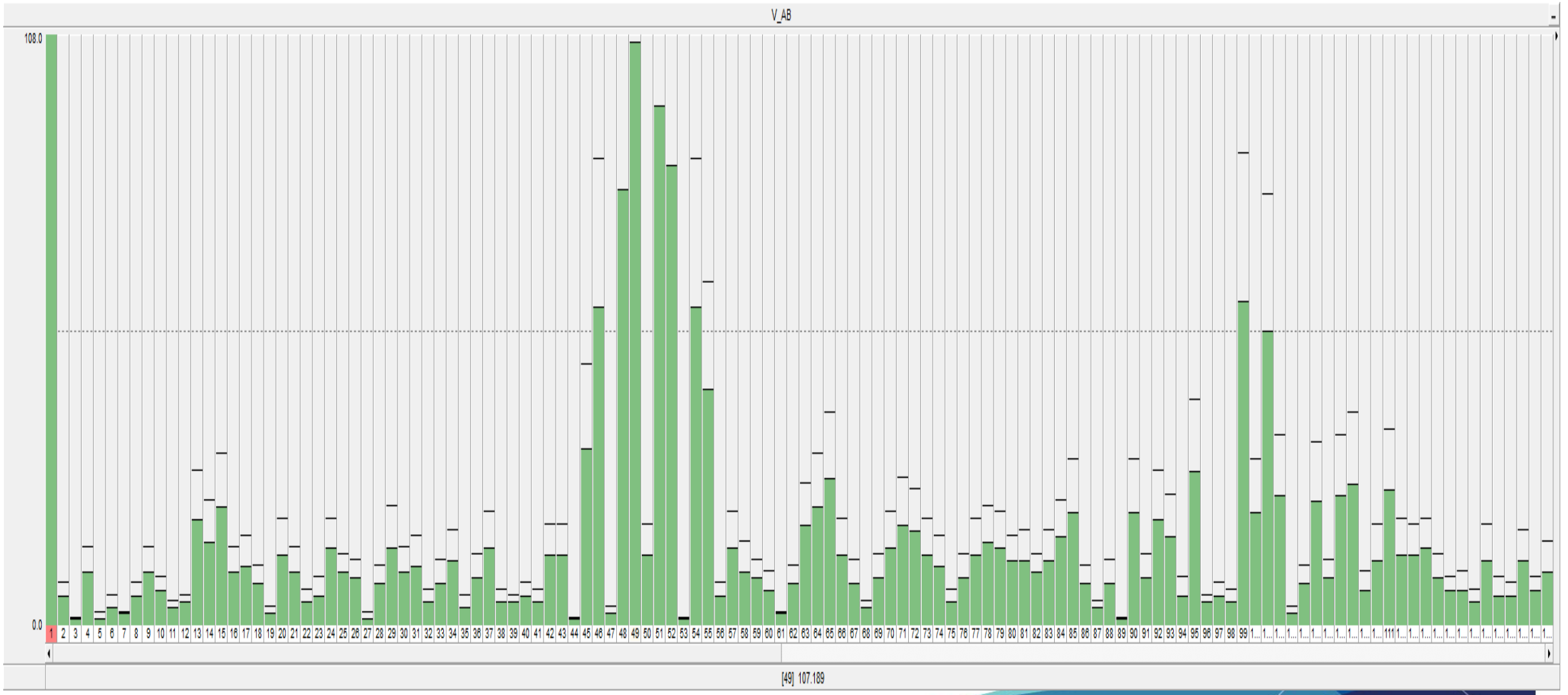
Simulation Results – THDv without L-C-L Filter



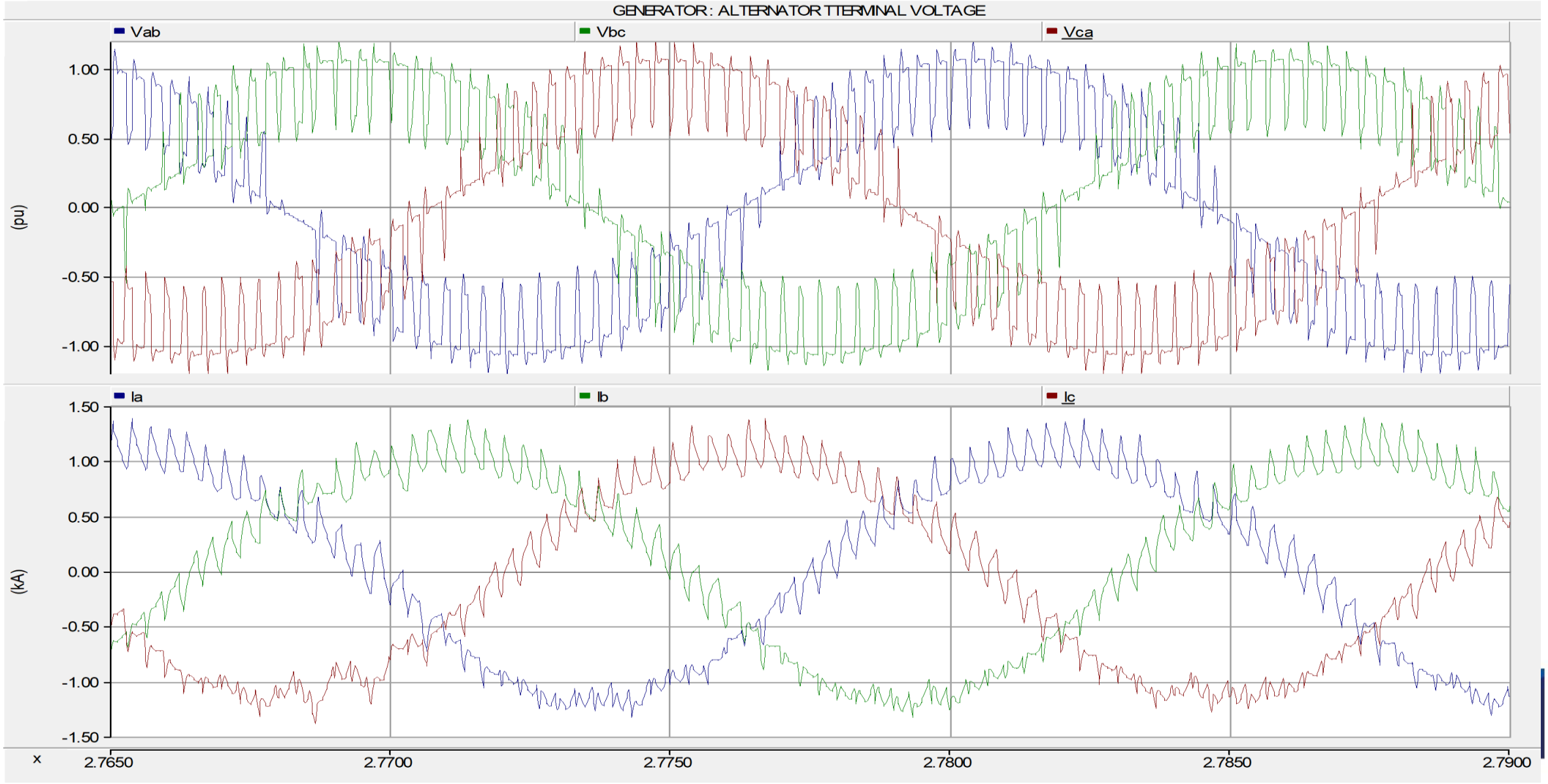
Single order Harmonics without L-C-L Filter



Single order Harmonics without L-C-L Filter

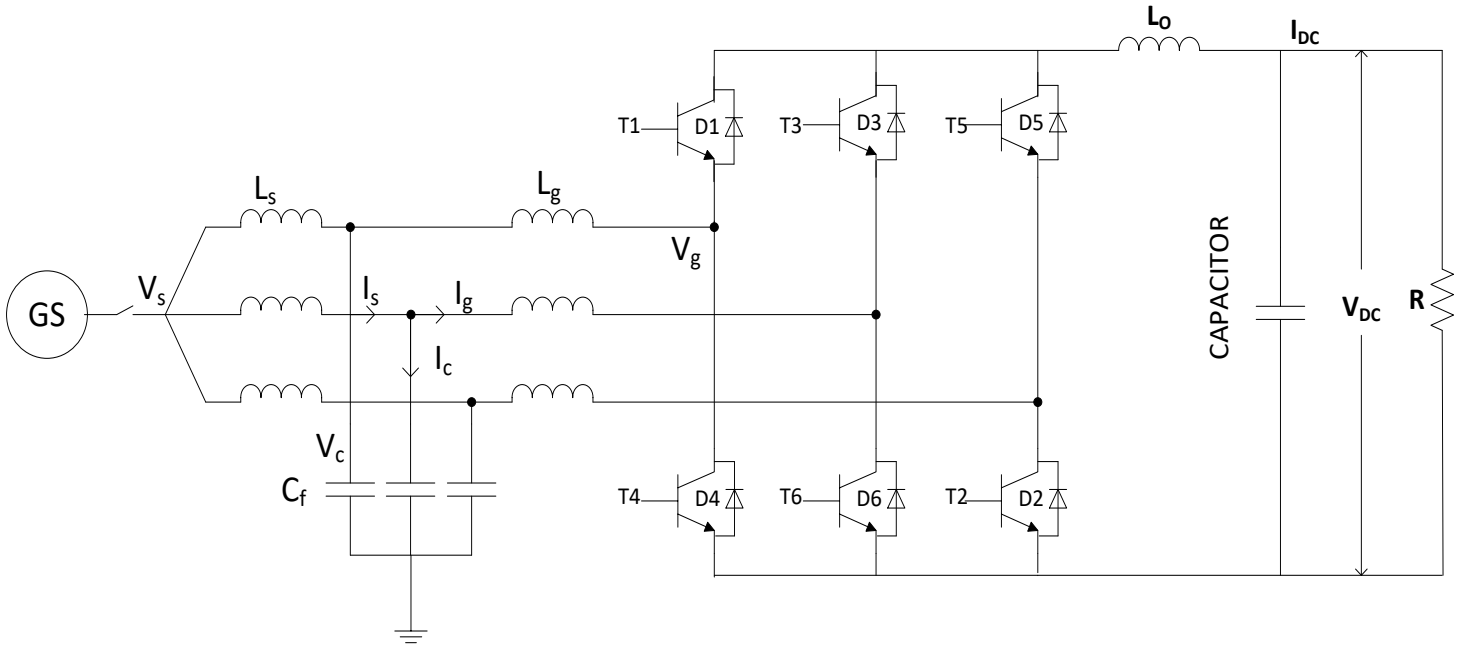


Simulation Results – Generator Voltage with Harmonics



Simulation Results - Harmonics

- VSC with L-C-L implemented
- Transfer function of the L-C-L Filter
- Calculation of resonant frequency of the filter
- Active damping - Transfer function of the low pass filter used in the control loop

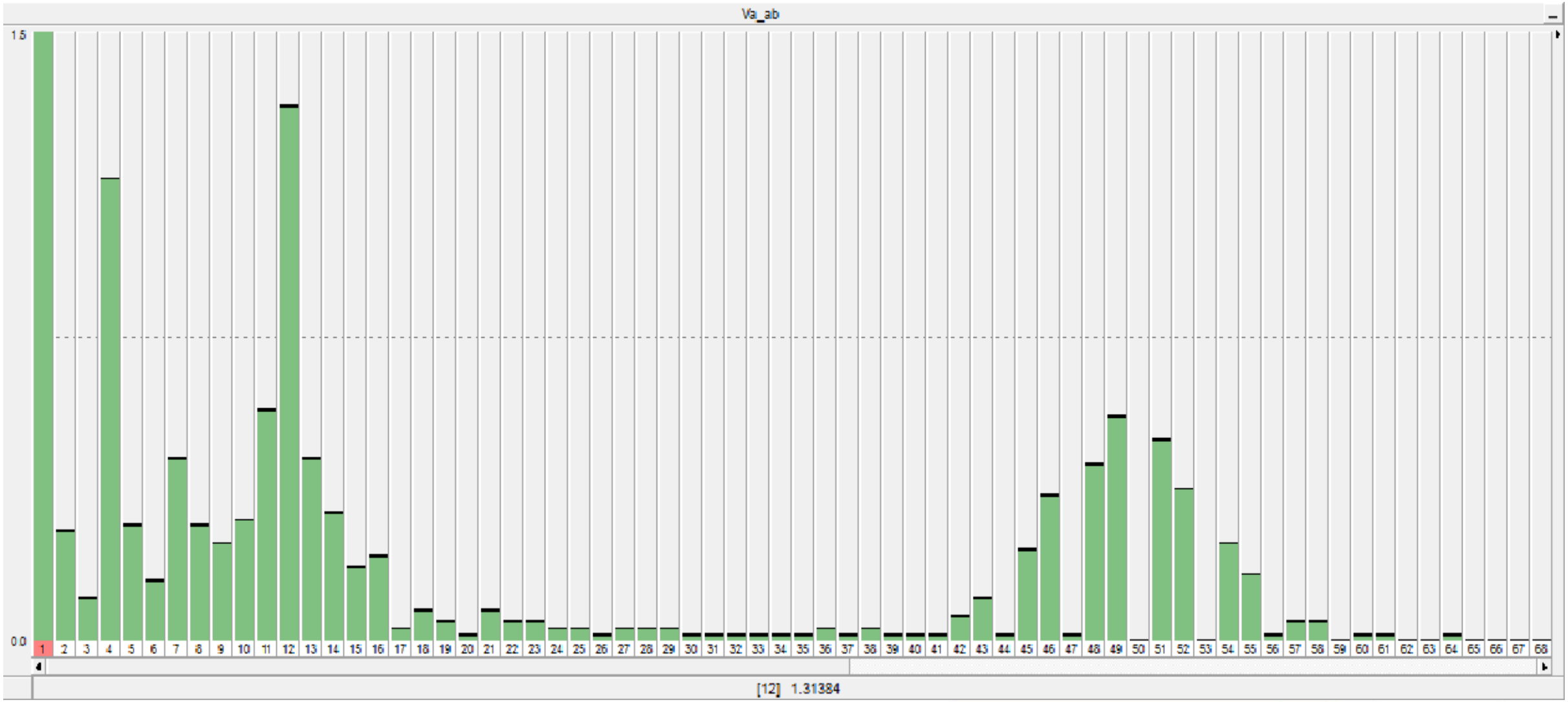


$$H_{LCL} = \frac{I_g(s)}{V_S(s)} = \frac{sC_fR_d + 1}{s^3L_gL_SC_f + s^2C_fR_d(L_S + L_g) + s(L_S + L_g)}$$

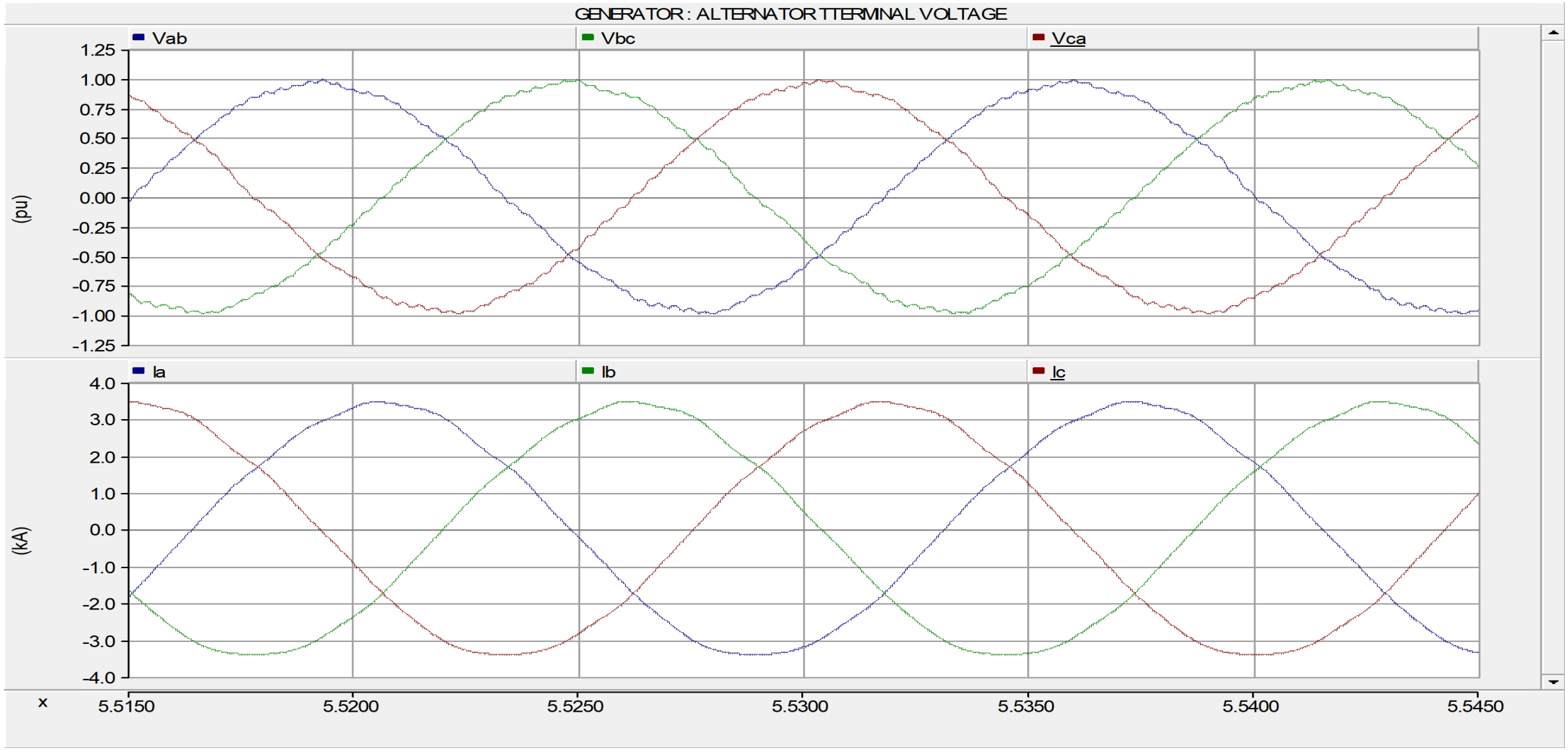
$$\omega_{res} = \sqrt{\frac{L_S + L_g}{L_SL_gC_f}}$$

$$H_{LPF} = \frac{G}{1 + sT}$$

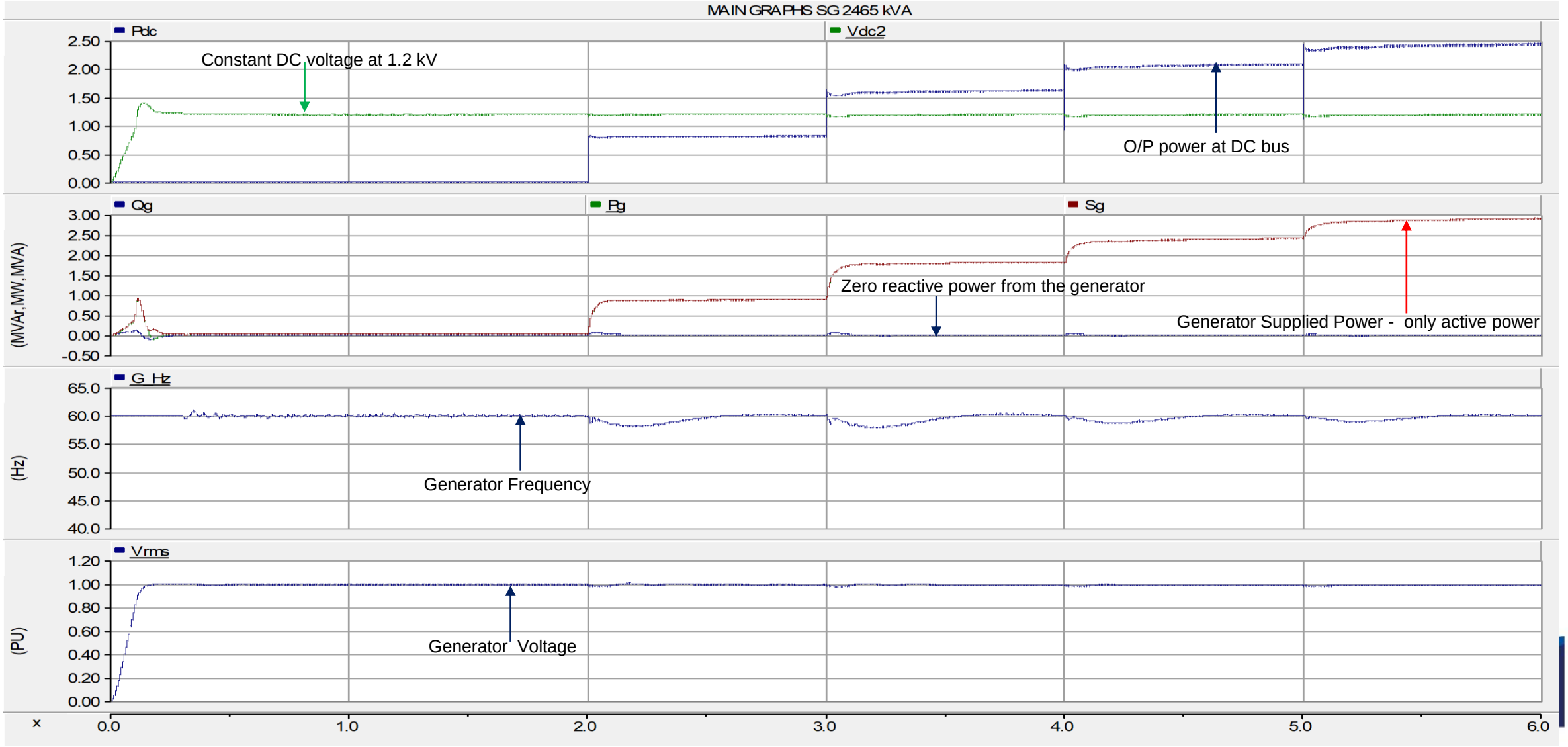
Simulation Results – Single order harmonics with L-C-L filter



Simulation Results – Generator voltage and Current waveforms after Filter Installed

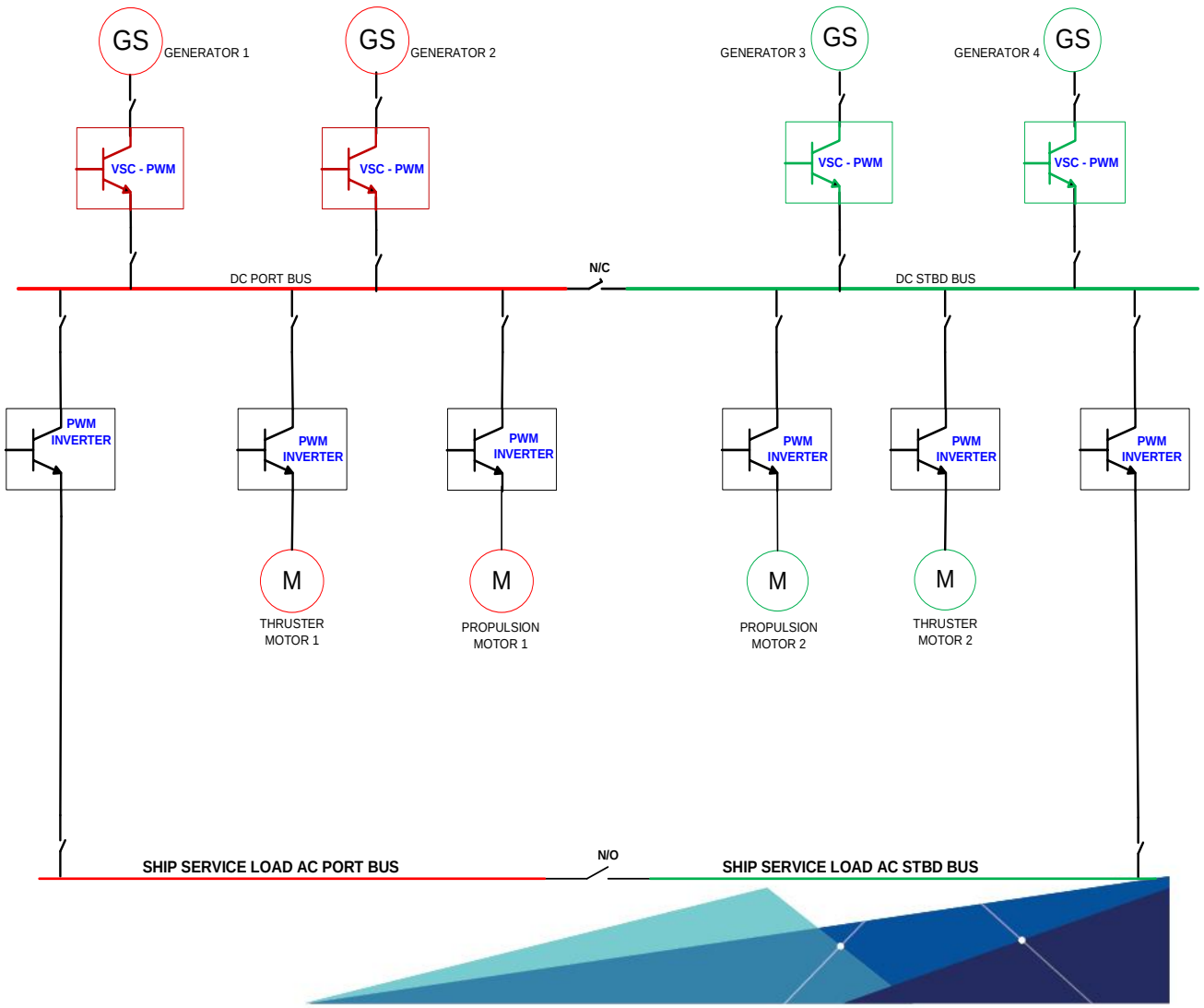


Simulation Results – Frequency and power level after Filter installed



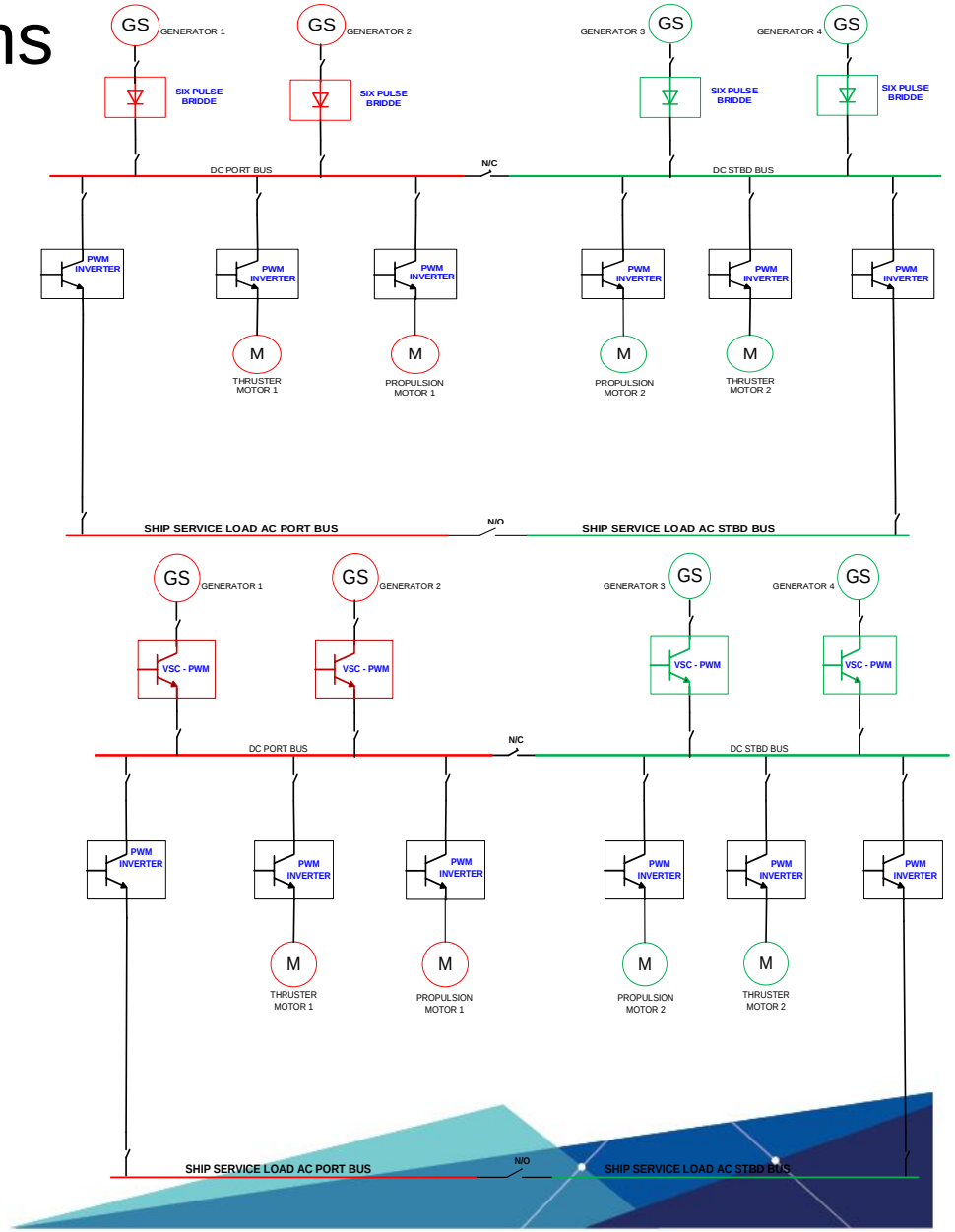
Implementation of VSC in DP Ships

- Six pulse diode bridge is replaced by VSC
- DC bus voltage can be raised to twice the generator voltage
- Rapid reconfiguration of the power system after a fault
- Independent control of DC bus voltage irrespective of the status of the generator
- Synchronous generators with excitation control can be replaced with;
  - Permanent Magnet Synchronous Generators (PMSG)
  - Shaft Generators (SG)
  - Brushless Double-Fed Generators (BDFG)
- Stable DC bus voltage through wide range of load variation
- Generators can be operated at unity power factor.



Discussion on DC Distribution Systems

- Both six pulse bridge and VSC are suitable for DC systems on DP ships
- DC systems help of fuel saving as diesel engines can be operated at optimum speed
- Both the systems help space savings
- Ability to integrate with power storage devices;
  - batteries
  - super capacitors
  - fuel cells
  - fly-wheels
  - wind/solar power
- Fast reconfiguration after a fault
- Solid state bus tie circuit breaker
  - galvanic isolation between the bus bars (DC-DC converter)
  - power electronic current limiting
- Difficulties in failure analysis of power electronic systems
  - VSC
  - Solid-state circuit breaker
- Identifying the safe methods of testing them



Conclusion

- DC distribution systems offer benefits over AC distribution systems
- DC systems can be designed stable and robust
- Reduces fuel consumption and support low carbon emission
- DC systems contribute to space savings of ships
- Integration of different power sources make possible to have multiple input and multiple out put systems
- Flexible, reconfigurable and stable systems
- Failure analysis and effects of power electronics should be understood
- Competence in safe testing and proving the cause of failures and their effects
- LOC will include process for developing competence in Competence Assurance Framework

Thank you

Questions ?