# WEBINAR AND DEMO: Real-time Simulation of Aircraft Electrical Systems with the RTDS Simulator

RTDS Technologies

RTDS.COM

# AGENDA

- Intro to real-time simulation for aircraft electrical systems
- Presentation on AES modelling –
  system characteristics, technical considerations, modelling library
- RSCAD screenshare demonstration
- Q&A

# About RTDS Technologies


- Headquarters in Winnipeg, Canada
- Pioneered real-time power system simulation in the 1980s
- The RTDS Simulator is the industry standard for real-time simulation and closed-loop testing, used by utilities, manufacturers, research and educational institutions, and consultants worldwide
- Learn more at www.rtds.com or the large library of videos on the RTDS Technologies YouTube channel

# More Electric Aircraft (MEA)

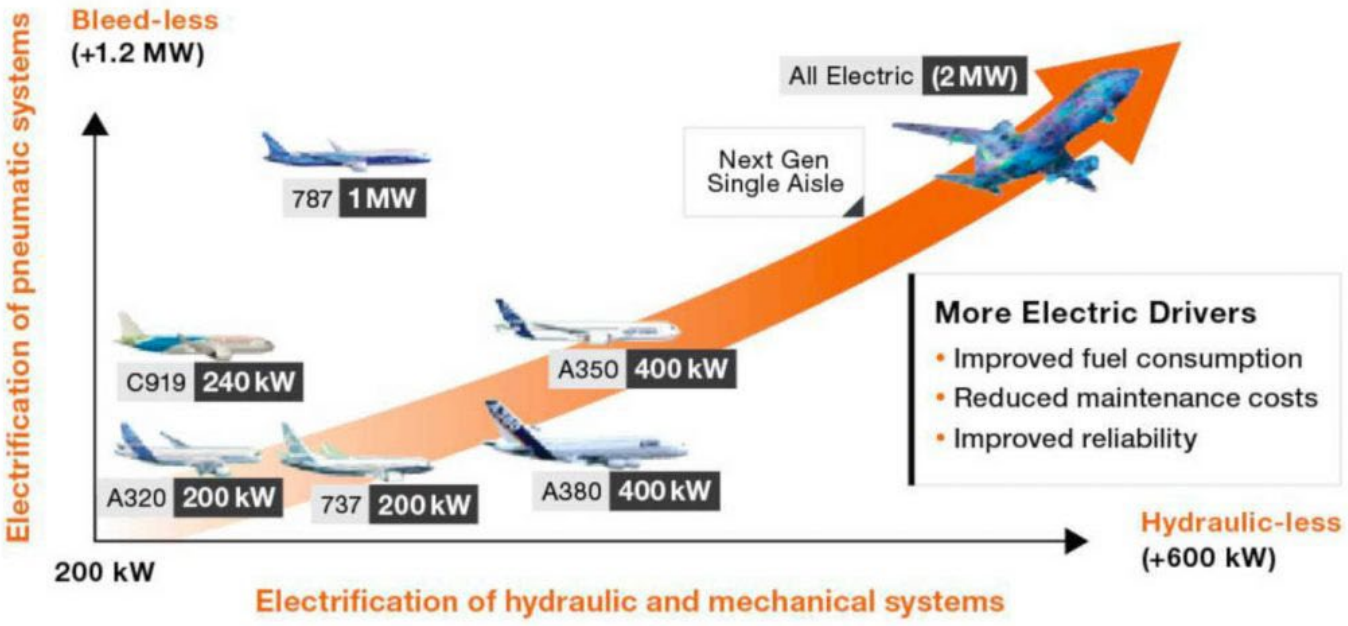


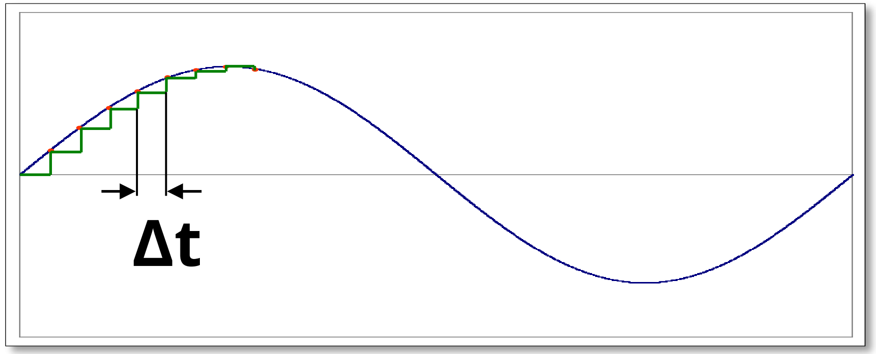

***Figure 1**- Increasing onboard electrical equipment demand in commercial aviation.*

*Source: CleanTechnica via United Technologies*

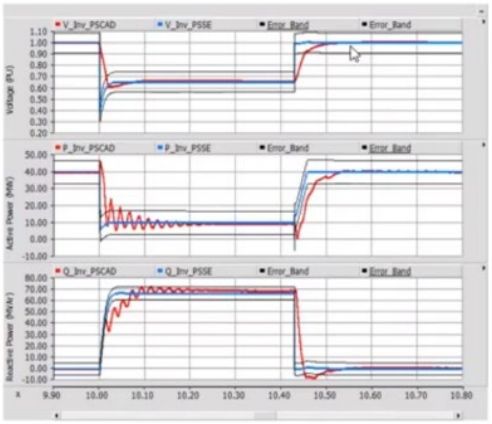
- MEAs feature bleedless engines, specialized design for generation and distribution systems, and more electric loads (braking, A/C, anti-icing)
- Power electronics are a key enabling technology for MEA
- Reducing risk and anticipating vulnerabilities (power quality issues, control misoperation) before deployment is critical

# EMT Simulation for Aircraft Electrical Systems

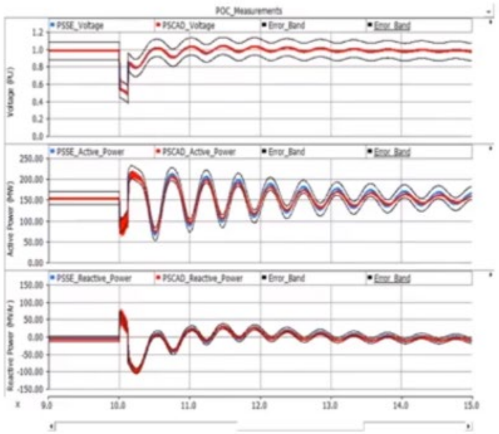
- Allows for a greater depth of analysis than phasor domain (RMS) representations
- Varying timesteps allow for representation of faster and slower dynamics throughout the AES
- Detailed power electronics models are key – representation of harmonics and switching transients at high frequencies, potential instabilities in complex fast-acting controls




Wind farm fault ride through

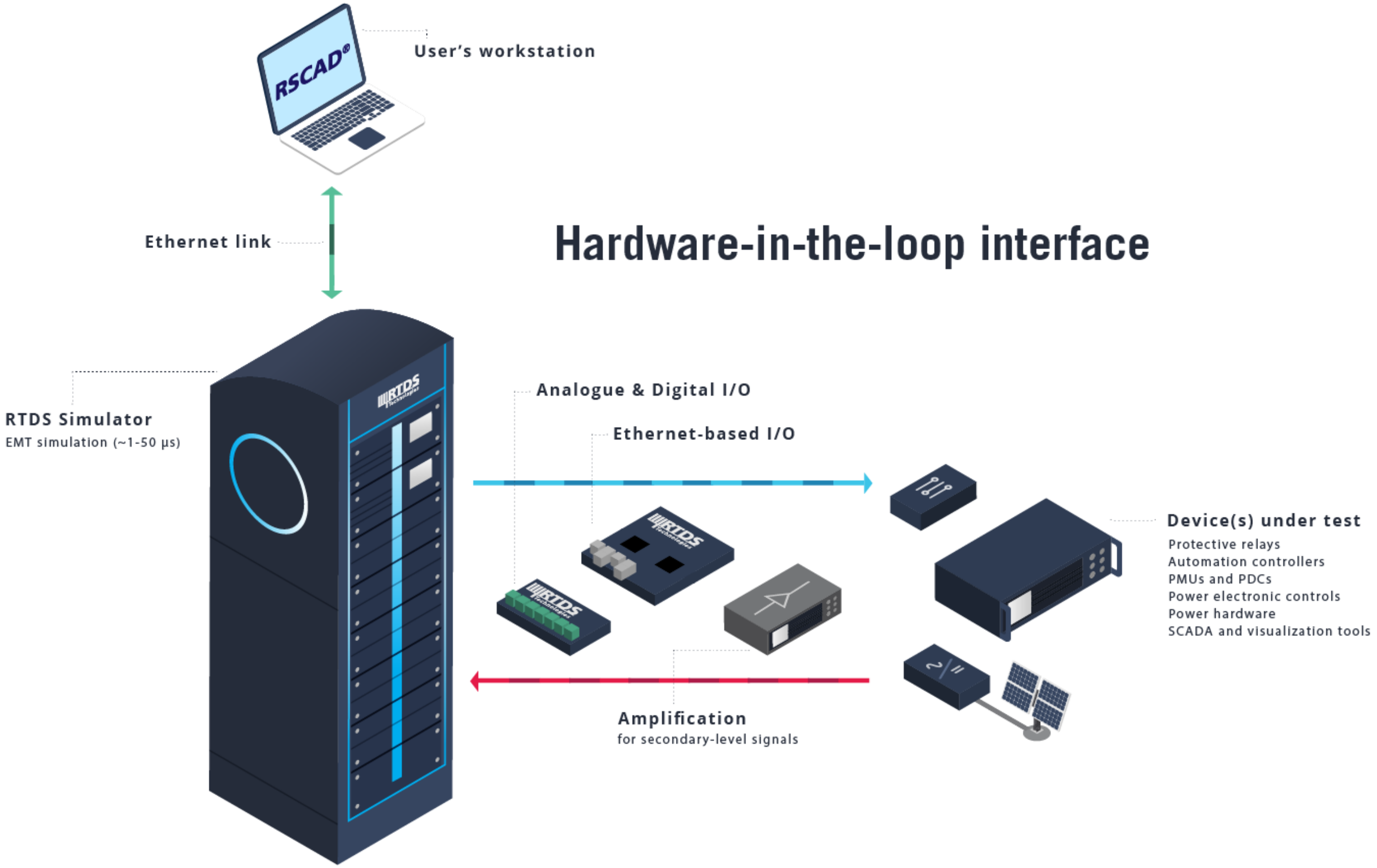


Synchronous generator fault ride through



# HIL Testing for Aircraft Electrical Systems

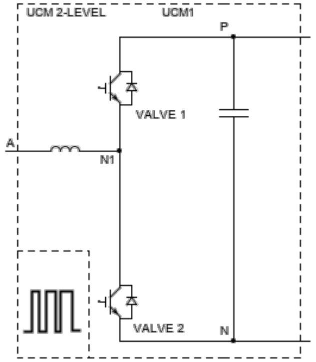
- Real-time simulators allow for hardware-in-the-loop testing of control and protection equipment
- Connect AES controls to the simulated network in a closed loop
    - APU control
    - ECS control
    - Engine control
- Options for analogue, digital, and communication protocol-based I/O

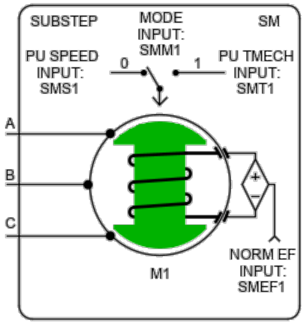


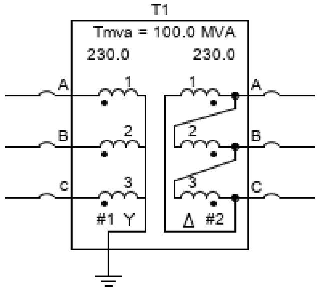
# Modelling Library

- Flexible environment for configuring AES model – no limitation on architecture

- Sherry's presentation will go into more detail on modelling the generators, TRUs, converters, batteries, loads, etc.

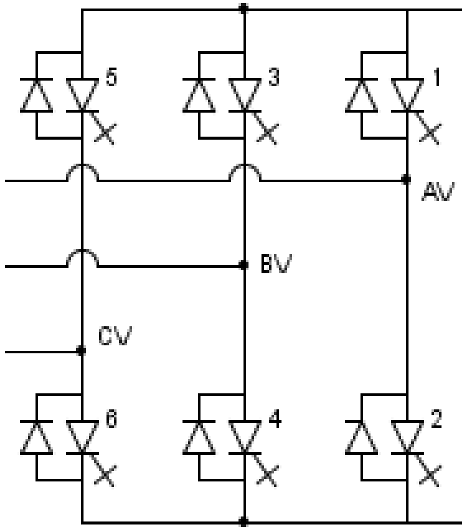


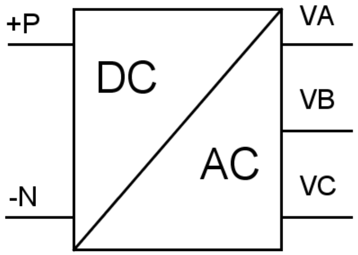

# Power Electronics Modelling

## Fully-switched models




- Consider the switching topology, switching characteristics of the converter, characteristic harmonics
- Allows for low level control testing (firing pulses)
- **May be modelled with resistive switching or L/C switching**
- **May or may not be decoupled/interfaced**
- **Higher computational burden**

## Average value models




- Replaces detailed models with controlled voltage and current sources
- Modulation waveforms from the same current controller can be used to strategically control the sources such as to reproduce an averaged version of the high frequency switching transients
- **May or may not be decoupled/interfaced**
- **Lower computational burden**

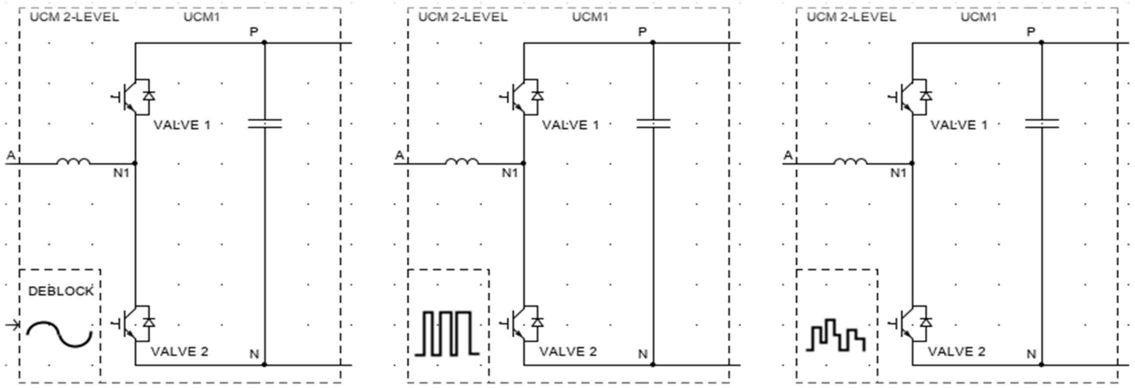
# Universal Converter Model (UCM)

## Motivation

- Demand for converter modelling and simulation with higher switching frequency (>30 kHz)
- Research found that average modelling may be used to achieve high resolution of firing
- Other average model implementation is decoupled on the DC bus – can cause instability

## Solution: Universal Converter Model

- Available for 2-level, NPC (ANPC), T-type, boost and buck
- Multiple input (control) types
- Can be used in Mainstep OR Substep
- Improving performance and reducing computational burden
- **No decoupling / interface lines**




*2-level UCM*

# UCM

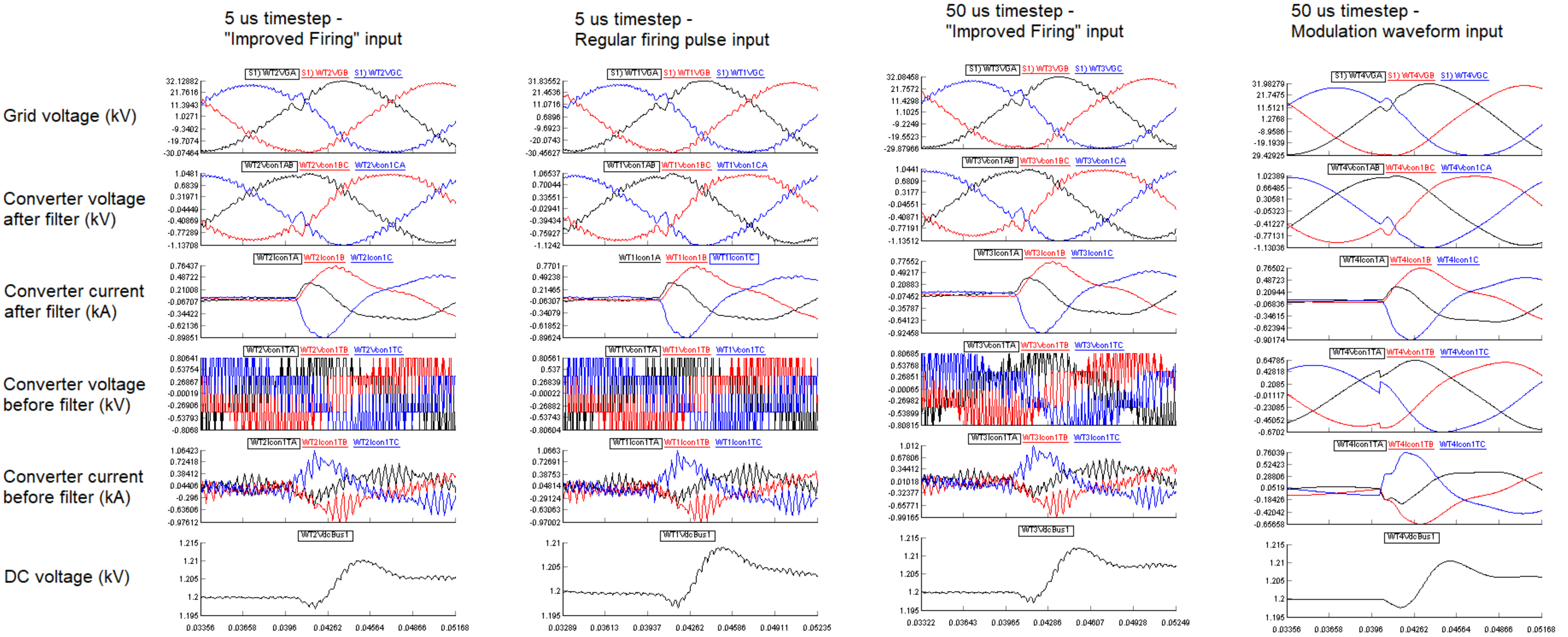
## Substep Environment (<10 us)

- Full Firing Pulse Input
  - Similar to existing resistive-switching Substep models
- Modulation Wave Input
  - Similar to average model, but with improved performance
  - Proper transition between blocked and de-blocked states
- Improved Firing Input
  - Accurately represents converter performance with PWM firing **>150 kHz**

## Mainstep Environment (30-50 us)

- Modulation Wave Input
- Improved Firing Input
  - Accurately represents converter performance in the **3 kHz range**
  - 10 load units per converter

# UCM Performance



# Thank you!

RTDS Technologies

RTDS.COM

# Aircraft Electrical System Modelling in RTDS

# CONTENT

- Introduction
- AES Modelling in RTDS
- Simulation Demonstration
- Conclusion and Future Development

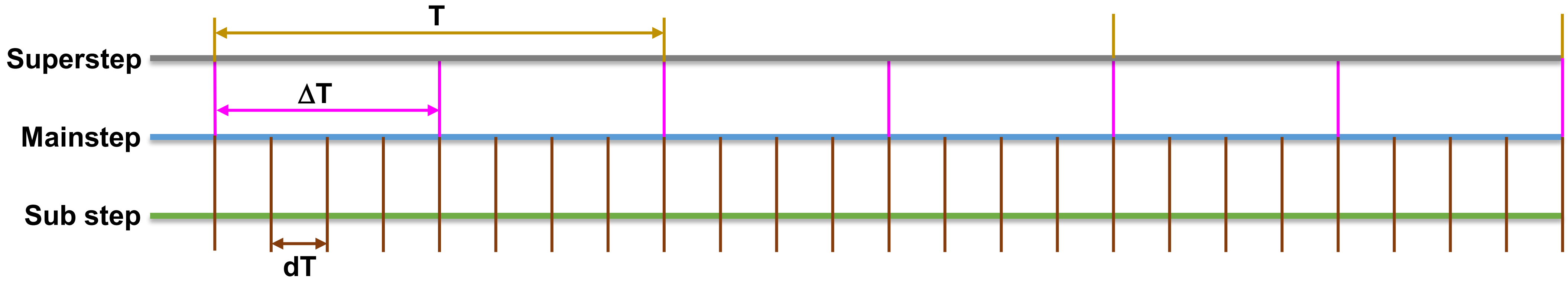
# Introduction

RTDS Technologies

# Introduction

New generation product: NovaCor

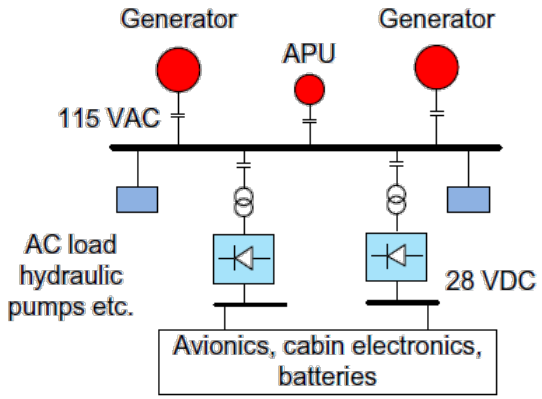

- **Simulation Capabilities**
  - IBM's state of the art POWER8™ processor
  - 10 powerful cores running at 3.5 GHz
- **Precise**
  - Higher precision simulations with timesteps reduced by up to 50%
- **Scalable**
  - Scalable access through the licensing of 1~10 cores per chassis
  - Overall system expansion and full connectivity up to 144 chassis
- **RTDS provides three simulation modes to set different simulation timesteps.**



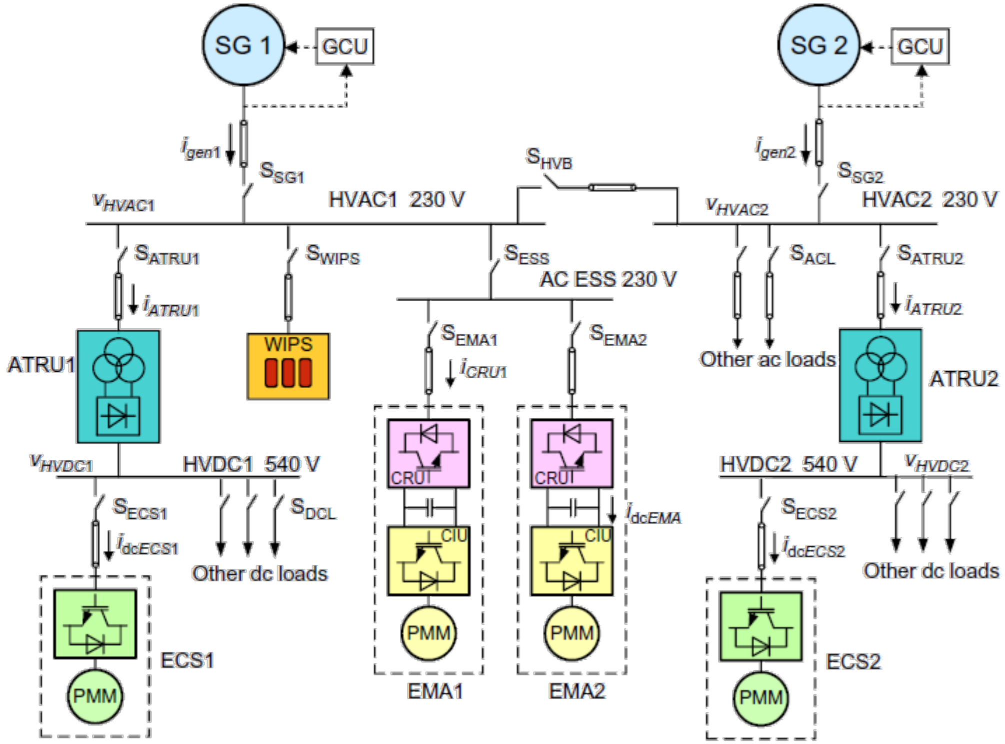

- **RTDS provides various models for converters, transformers, machines, cables etc. to meet different application needs.**

# Introduction

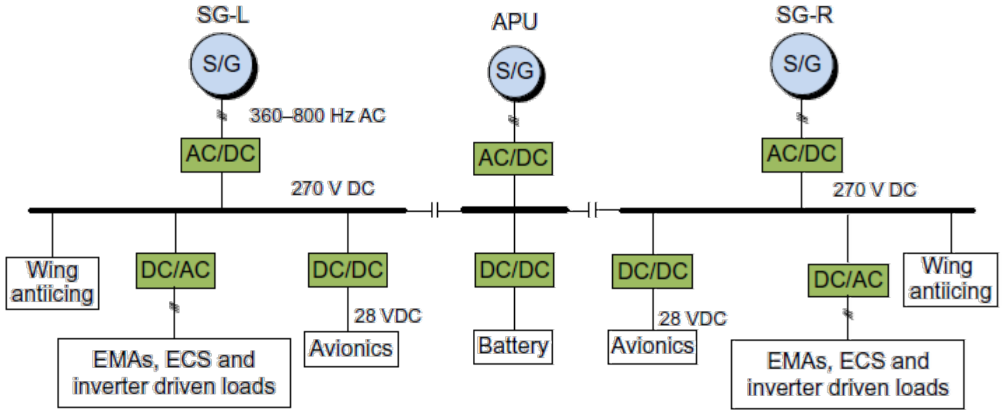
***Key components***: **TRU (ATRU), AC-DC converters, DC-AC converters, DC-DC converters, transformers, machines, batteries, etc.**




**Conventional Architecture [1]**




**MOET Architecture [1]**
**(More-Open Electrical Technologies)**



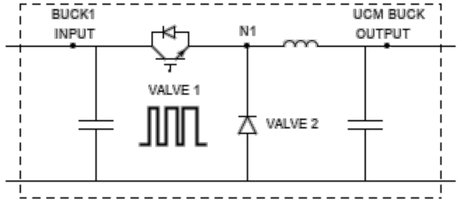

**MEA Architecture [1]**
**(More-Electronic Aircraft)**

[1] Frede Blaabjerg, “Control of Power Electronic Converters and Systems”, UK, Academic Press, 2018.

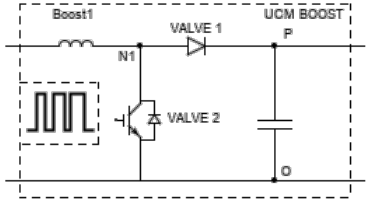
# Various Converter Types in RTDS

**Universal Converter Models (UCMs)**

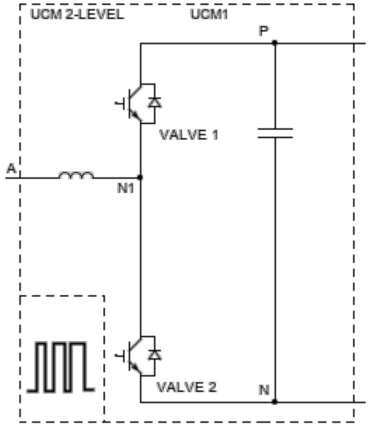
- Various topologies, such as Buck, Boost, 2L-VSC, 3L-NPC, 3L-T-type, 3L Flying Capacitor, etc.
- Resistive switching models
- Various control input, such as improved firing pulse, modulation waveform / duty cycle
- Switching frequency up to 221.5 kHz for 2 μs Sub-timestep



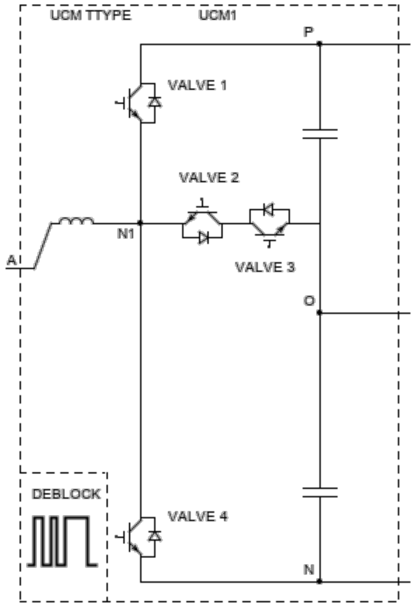

Buck



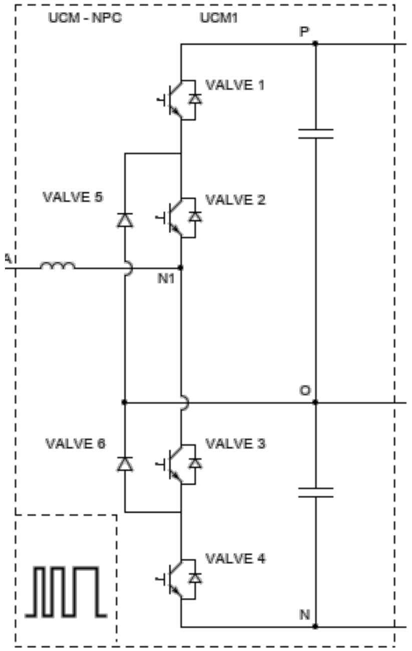

Boost



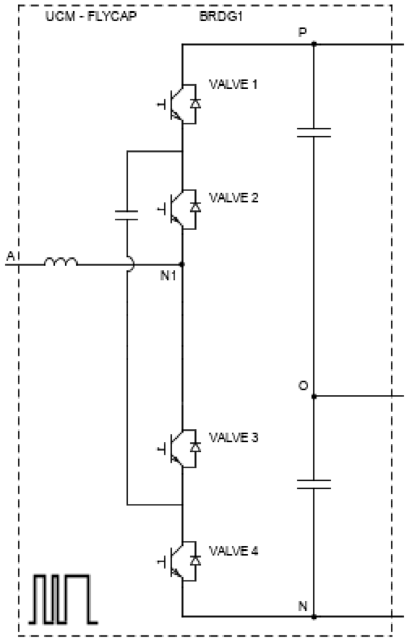

Two-level VSC




Three-level T-type



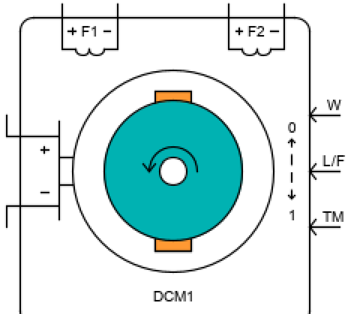

Three-level Diode Clamped NPC



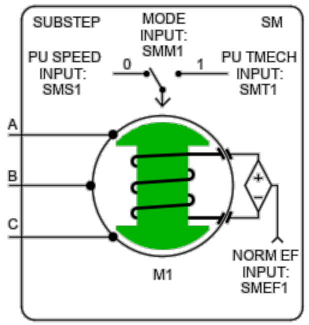

Three-level Flying Capacitor

# Various Machine Models

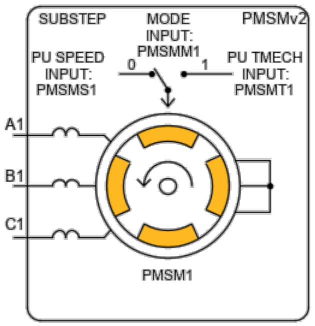
- Various machine types, such as DC machine, induction machine, synchronous machine, PMSM, etc.
- Various synchronous machines including transformer or internal faults
- Single-phase and multi-phase machines



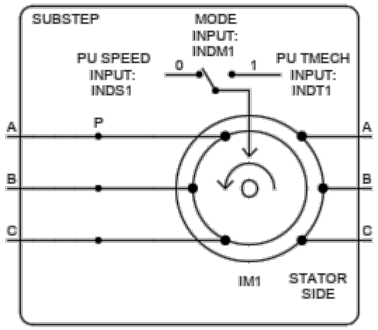
DC Machine



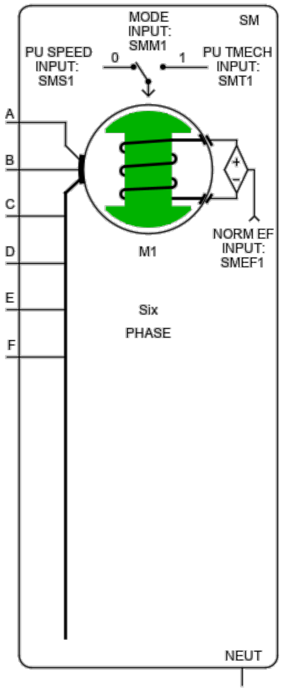
Synchronous Machine



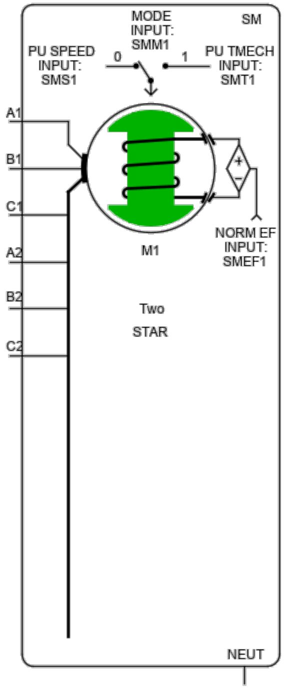
PMSM



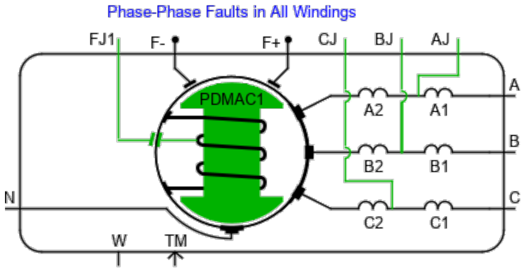
Induction Machine



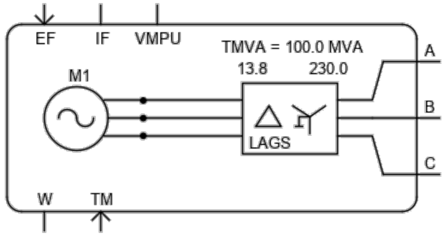
Multi-Phase Synchronous Machine



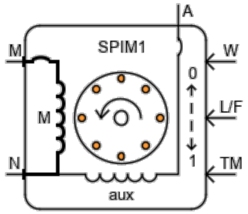
Multi-Star Synchronous Machine



Synchronous Machine with Internal Faults



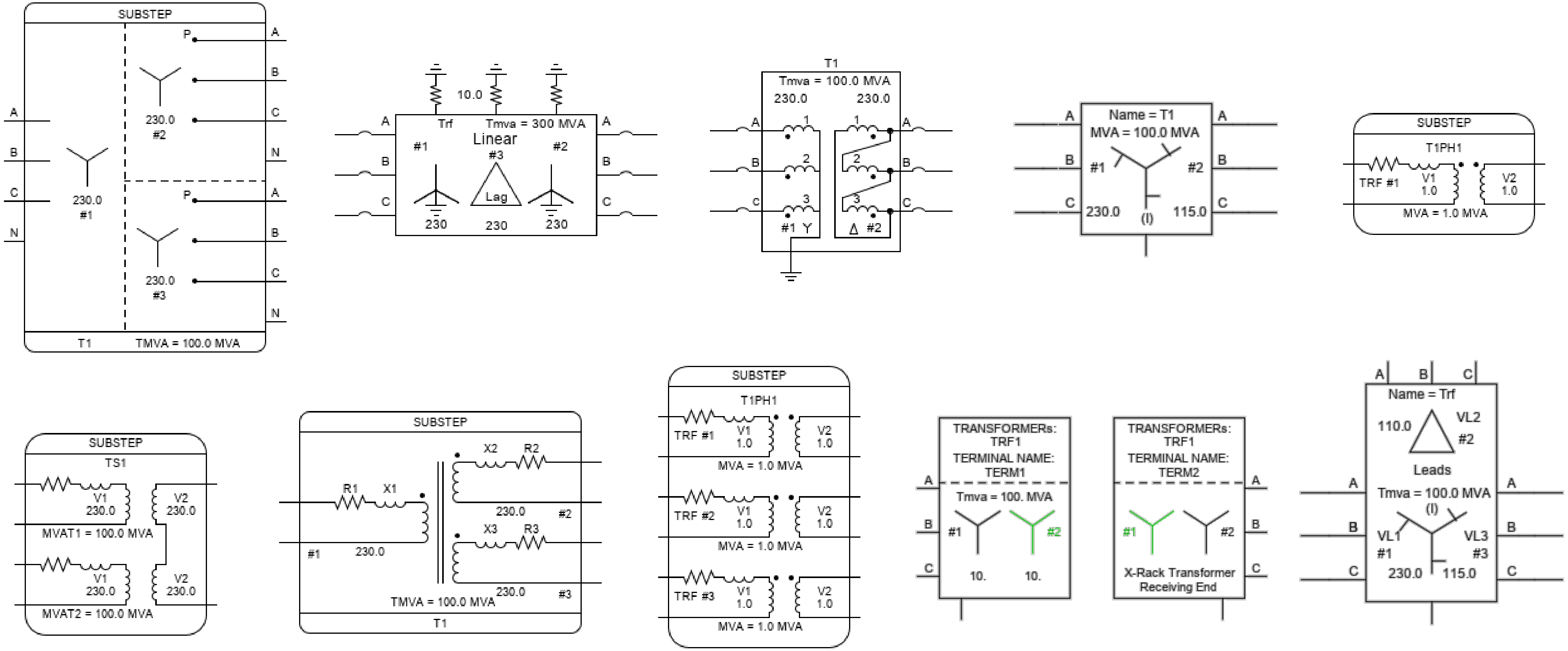
Synchronous Machine with Transformer

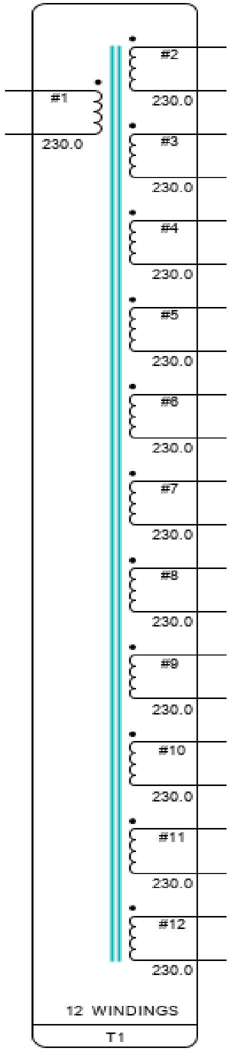


Induction Machine with Imbedded Breakers

# Various Transformer Models

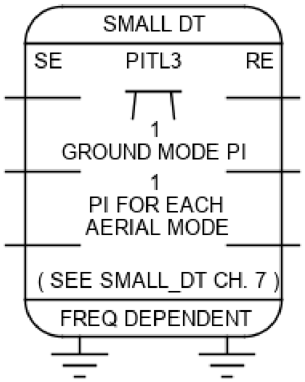
- Various transformer models, such as YYD type, single-phase, three-phase, multi-phase, etc.
- Some models include the saturation settings
- Some models consider the internal fault

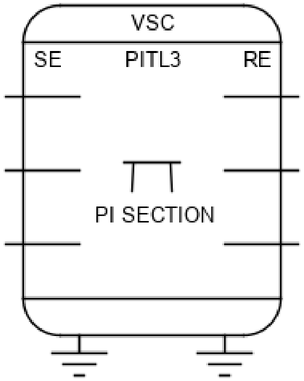


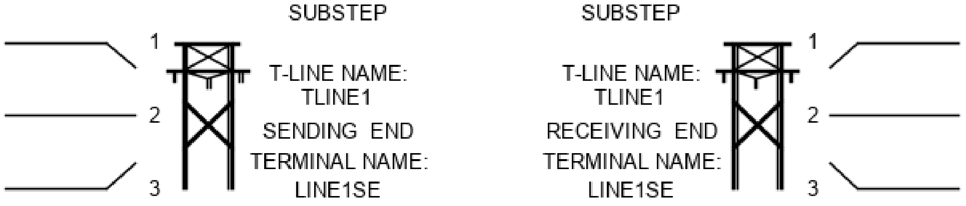



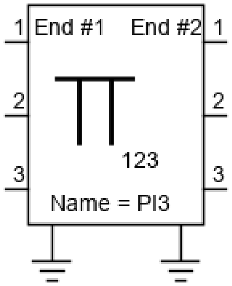
# Various Cable Models

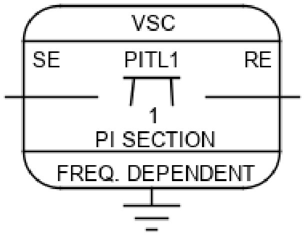
- Various cable models, including PI section and Tline, for example,
    - PI section, double PI section, and frequency dependent PI section
    - Bergeron Tline, and frequency dependent Tline

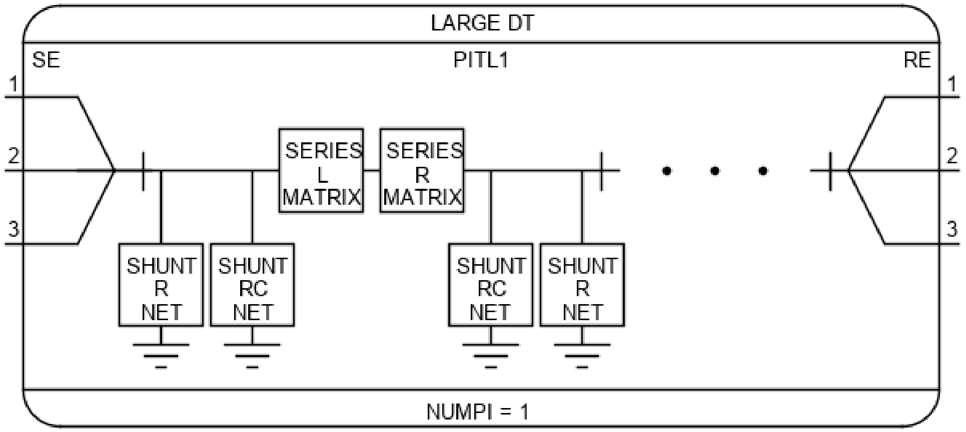


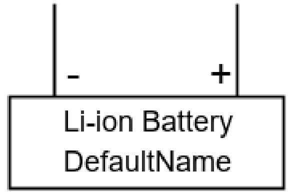



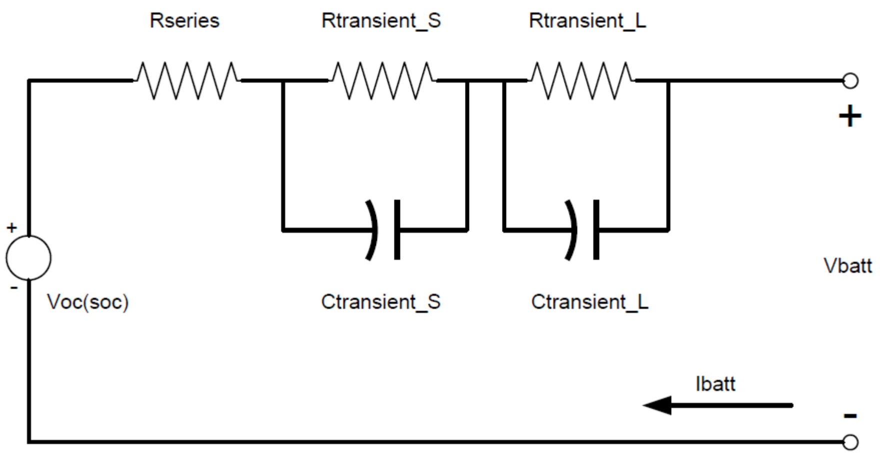



# Battery Models

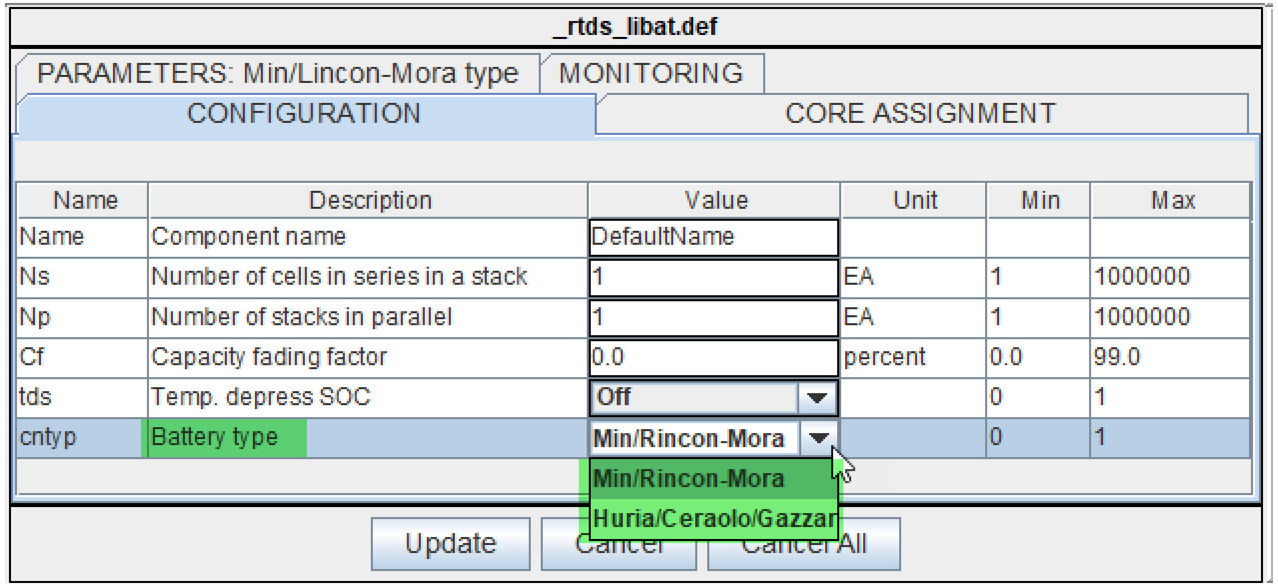
- **Li-ion battery is modeled in RTDS for two types:**
  - **(i) ‘Min/Rincon-Mora’ model: considering state of charge (SOC) influence on the parameters in the equivalent circuit;**
  - **(ii) ‘Huria/Ceraolo/Gazzarri/Jackey’ model: taking account of the temperature effect on the model dynamics.**




**Battery Model in RTDS**




**Equivalent Circuit used in the Battery Model**



# AES Modelling in RTDS

RTDS Technologies

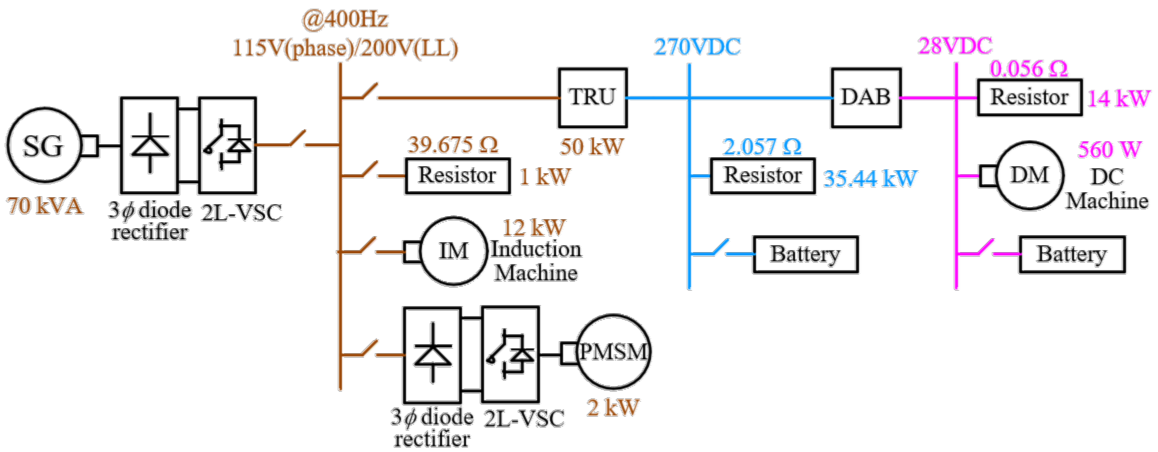
RTDS.COM

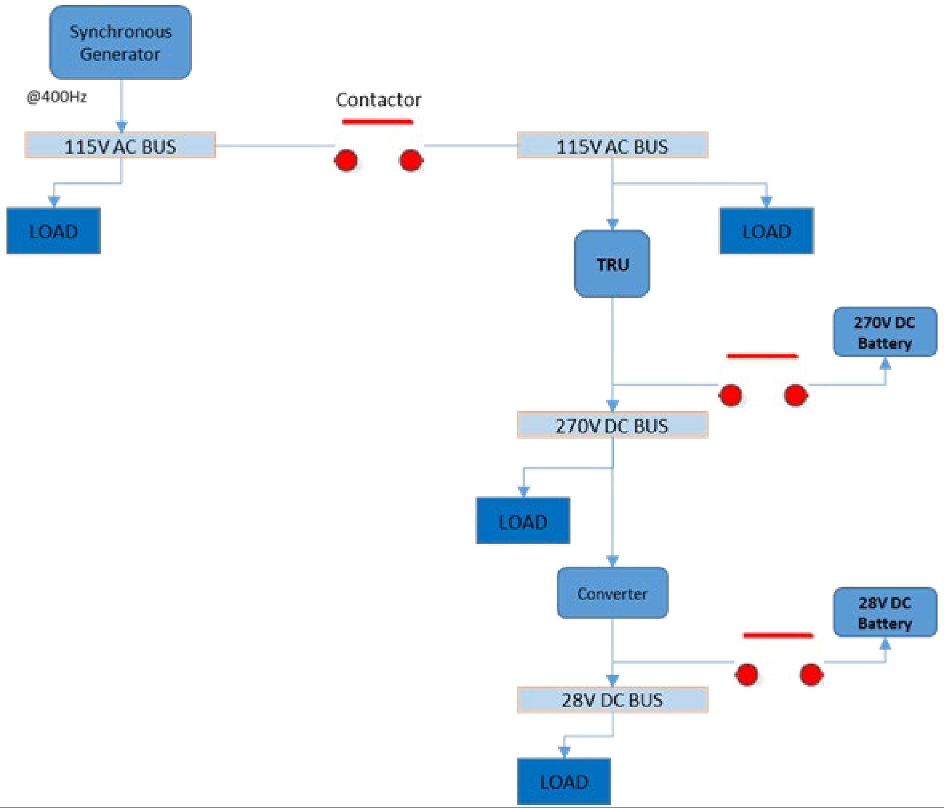
# AES Example Modelled in RTDS

- Split the large system to several parts and develop the parts step by step
- Combine the parts together to build a large case

**Taking the following architecture as example**

***Note RTDS can develop various architectures of aircraft electrical systems, not limited to this example one.***

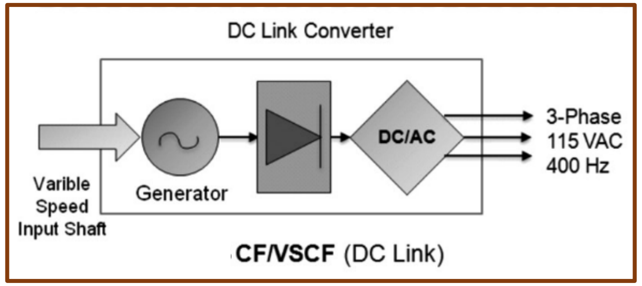



***Architecture Analysis for the AES Example***

- **Three buses:** 115V/400Hz AC bus, 270V DC bus and 28V DC bus.
- **SG with VSCF**: synchronous generator with variable-speed constant-frequency to generate the 115V AC bus fixed at 400 Hz
- **12-Pulse TRU:** to convert 115V AC bus to 270V DC bus
- **DAB:** dual-active bridge converter to converter 270V DC bus to 28V DC bus
- **Loads:** linear (e.g., resistive loads) and nonlinear loads (e.g., motor loads)
- **Battery:** 270V battery and 28V battery

# SG with VSCF Operation




## SG Parameters:

- Rated RMS line-to-line voltage: 200V
- Base angular frequency: 400Hz
- Rated MVA of the machine: 70kVA

## Controller:

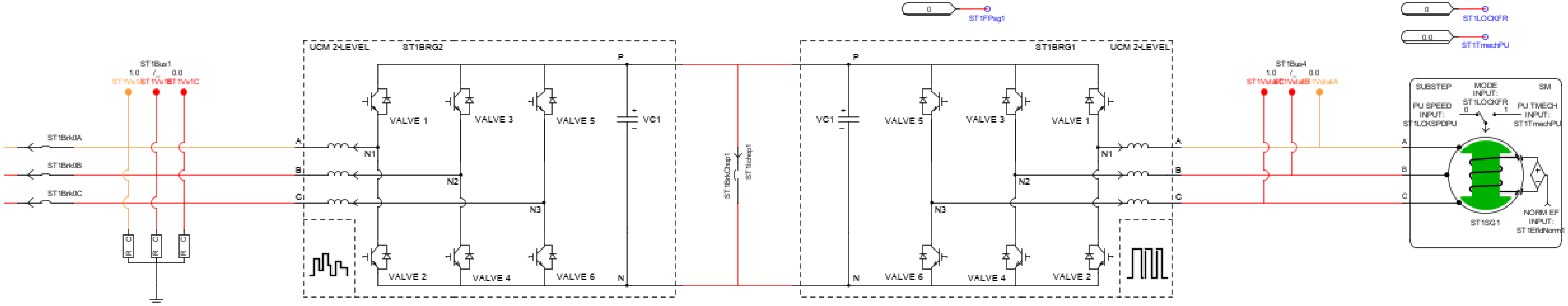
- Adjusts the field voltage for SG to control the dc-link voltage

## 2L-VSI Parameters:

- Switching frequency: 15kHz
- DC-link voltage: 320V
- AC-side filter (RLC): 28uH, 50uF and 0.25Ω

## Controller:

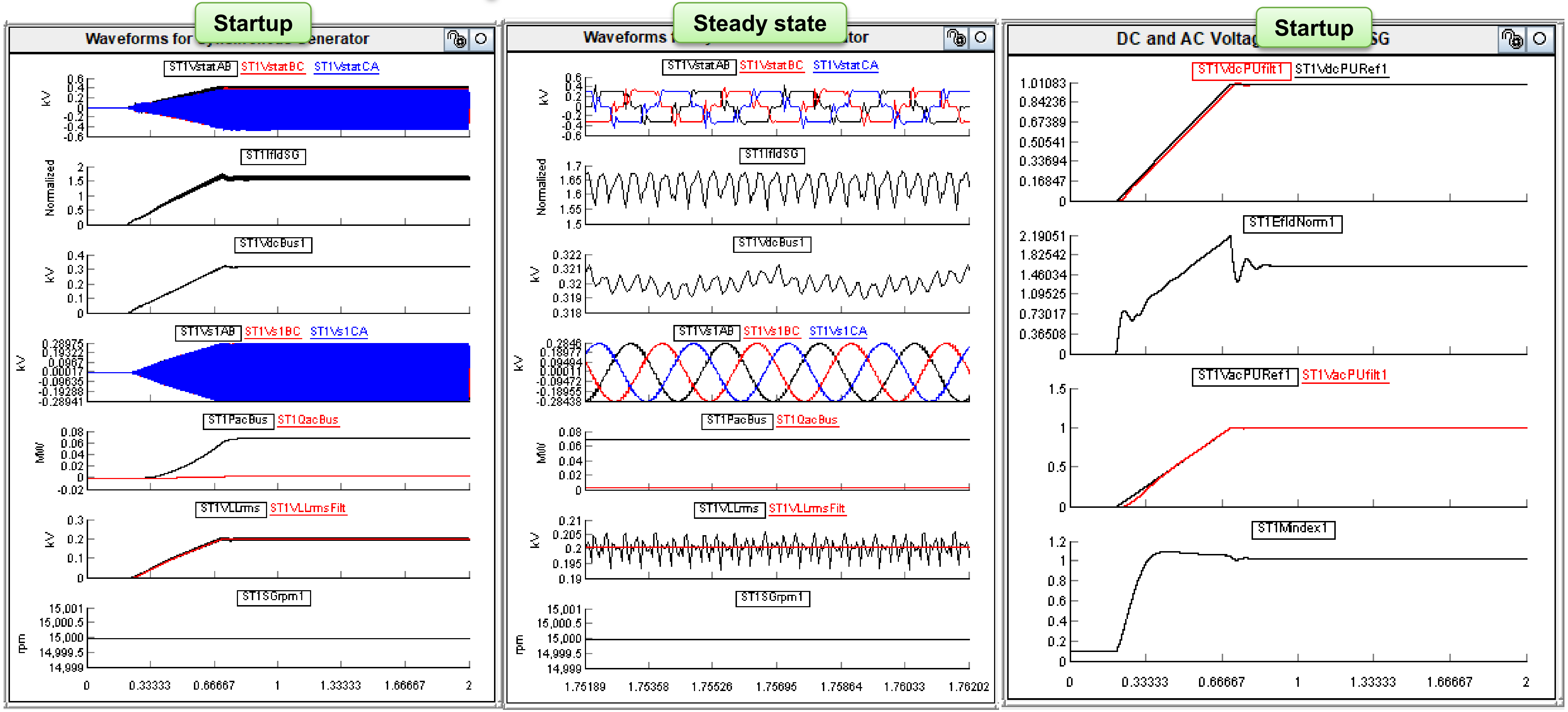
- Controls the inverter’s output voltage magnitude




115V/400Hz AC Bus ← 2L-VSC + Diode Rectifier ← SG

# SG with VSCF Operation

**Add resistive load (0.571 Ω) to test the SG + 2L-VSC Operation**




- The field voltage for SG is adjusted to regulate the dc-link voltage to 320V.
- The output ac voltage magnitude is controlled to be 115V (phase) or 200V (LL) at 400 Hz.

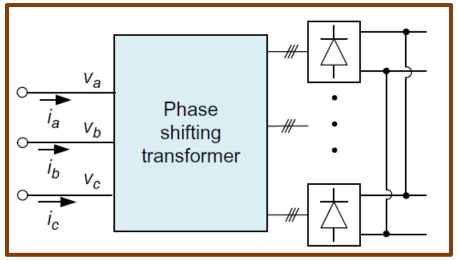
# 12-Pulse TRU Operation

**Transformer (Y-Y-Δ) Parameters:**

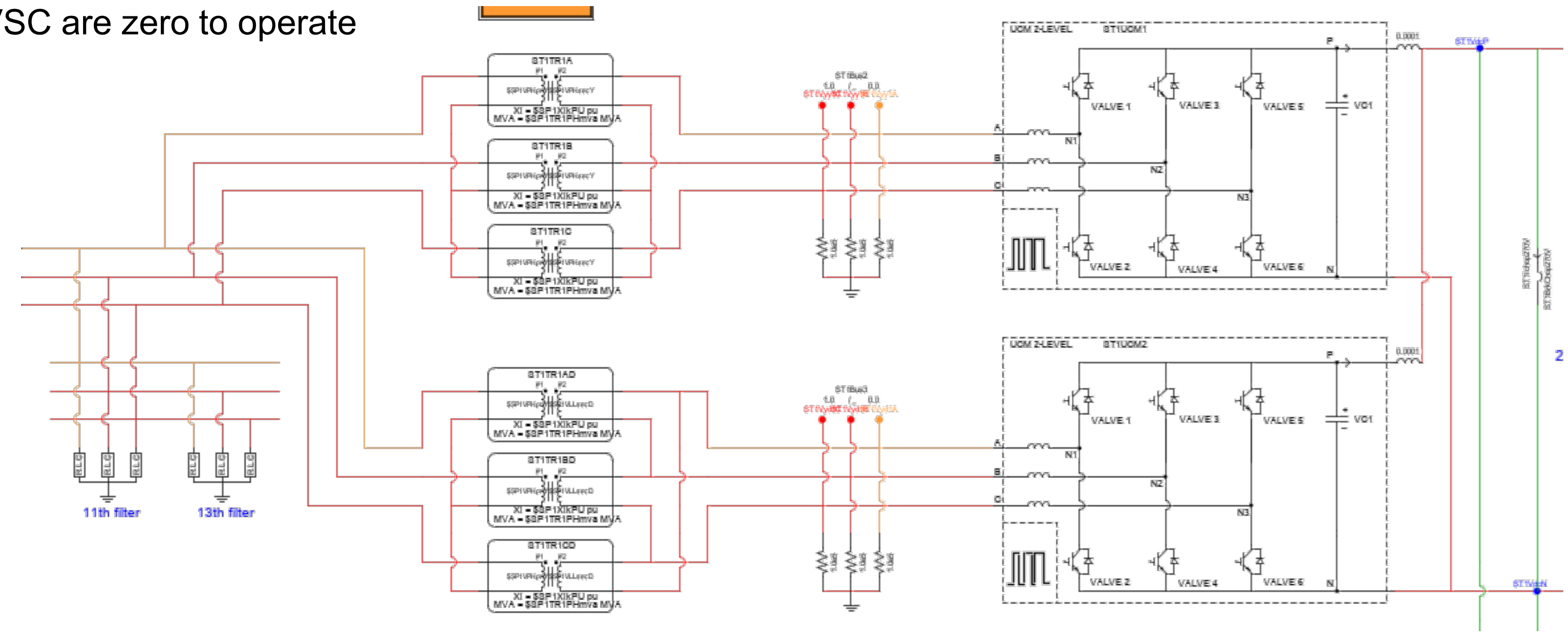
- Rated RMS line-to-line voltage Y: Y : Δ
  = 200V : 210V : 210V
- Base angular frequency: 400Hz
- Rated MVA of 3-phase transformer: 50 kVA
- Transformer leakage: 0.168 pu

**Converter Parameters:**

- DC bus capacitor: 3000uF
- Firing pulses for 2L-VSC are zero to operate as diode rectifiers



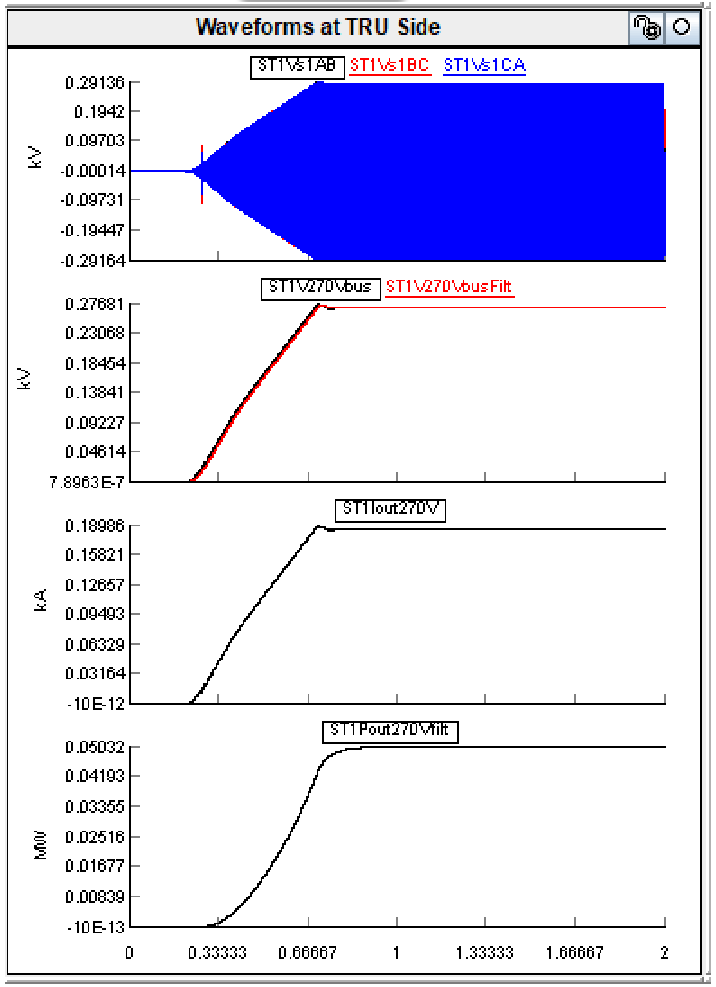

**115V/400Hz AC Bus → TRU (Output in Parallel) → 270V DC Bus**



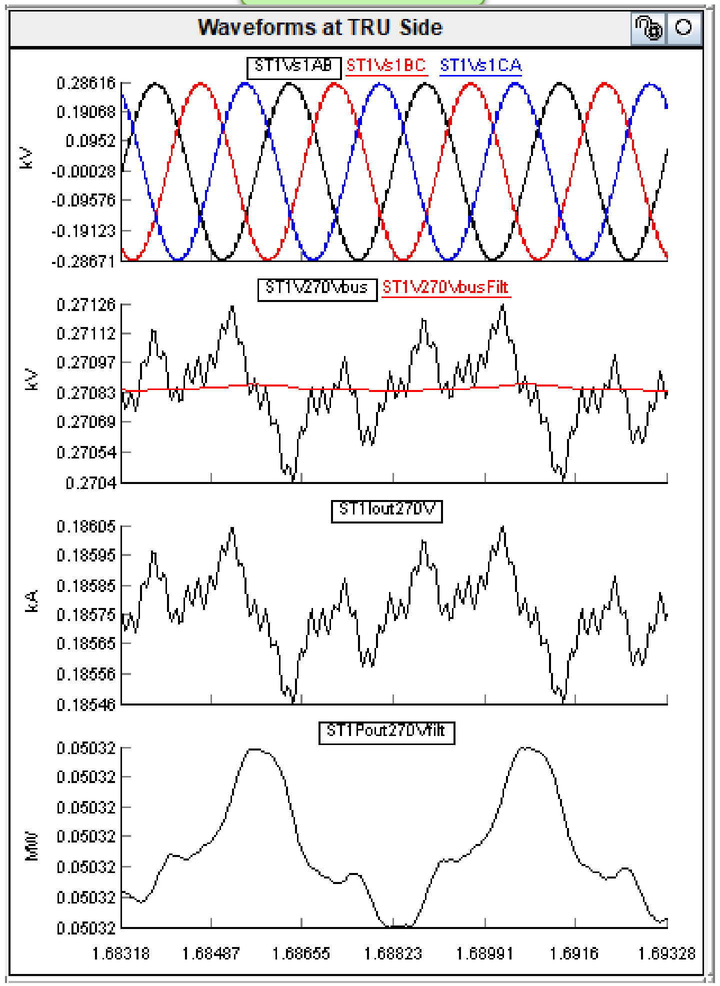
# 12-Pulse TRU Operation

**Add resistive load (1.458 Ω) to test the TRU Operation**

**Startup**




**Steady state**




- With proper main circuit parameter design, the output voltage of TRU stays at 270V in steady state.

# DAB Operation

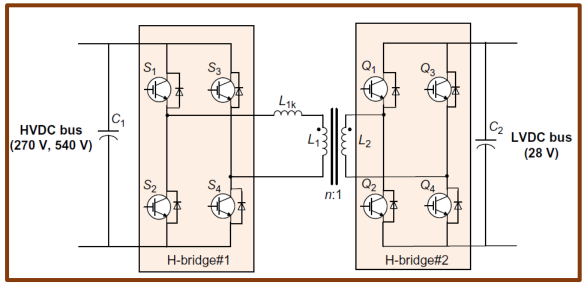
**DAB** provides galvanic isolation, high-power density, fast power reversal, and buck-boost operation with possibility of high step ratio. It is commonly used in aircraft electrical system for DC-DC conversion.

### DAB Parameters:

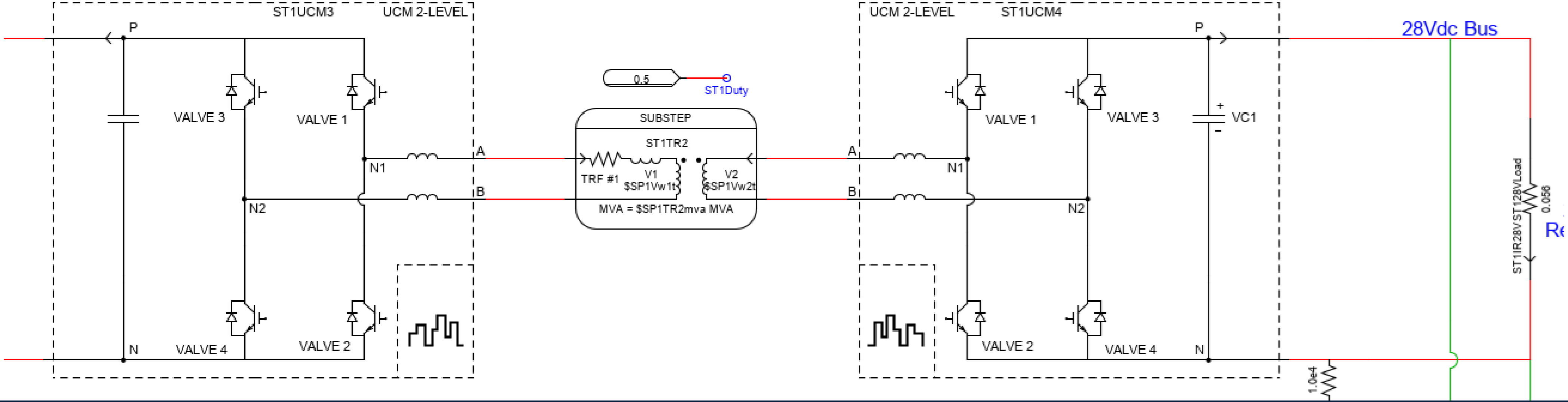
- Rated transformer's wing voltages = 270V : 28V
- Base angular frequency: 10kHz
- Rated MVA of transformer: 14 kVA
- Transformer leakage: 0. 294 pu
- 28V DC bus capacitor: 12000uF
- Converter switching frequency: 10kHz

### Controller:

- Controls the output voltage by adjusting the phase shift between the left and right-side square waves

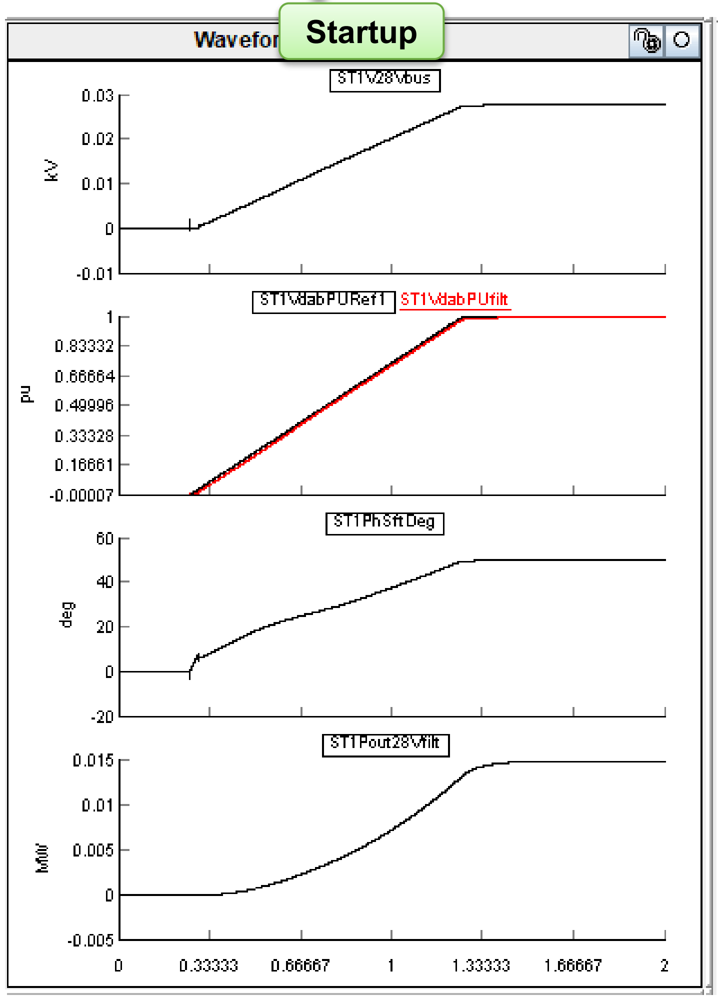


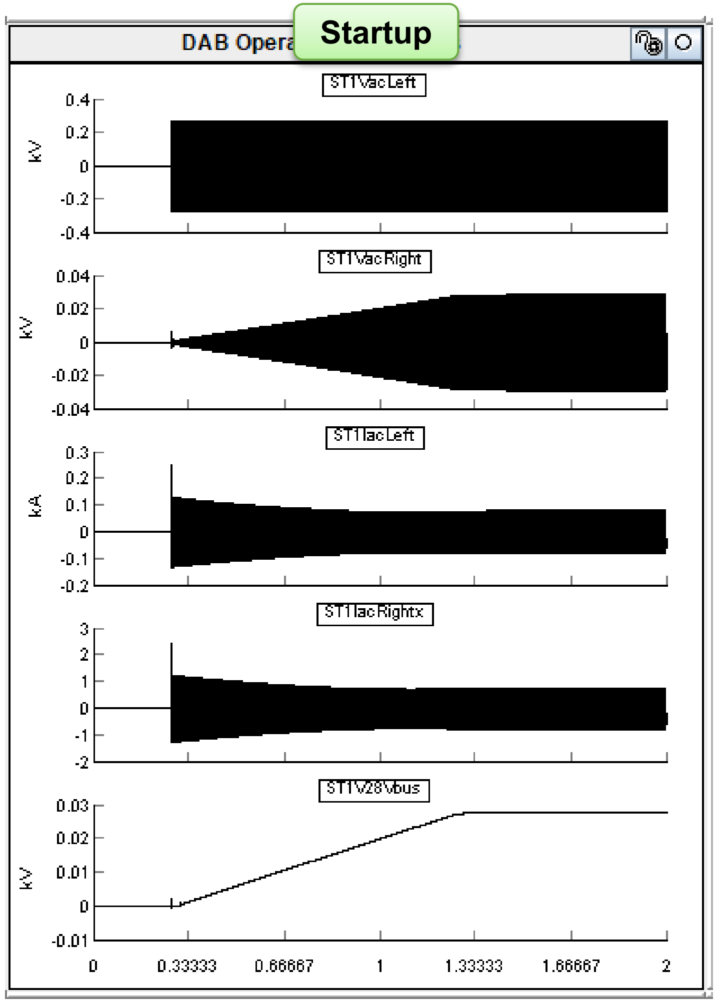

**270V DC Bus → DAB → 28V DC Bus**

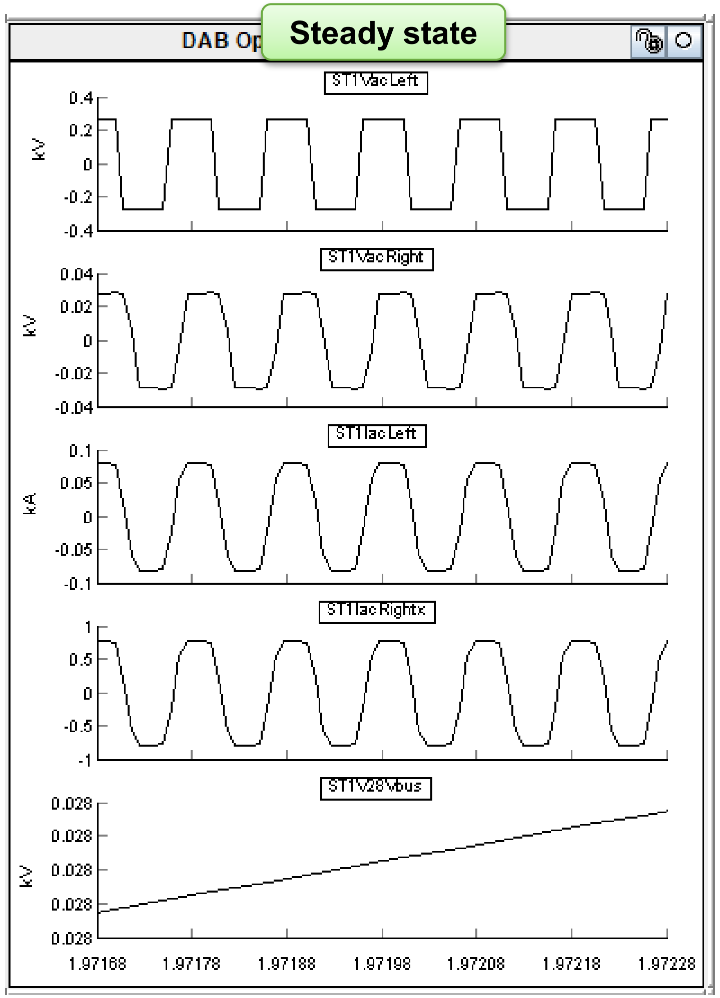


# DAB Operation

**Add DC source (270 V) as input to test the DAB operation**




- With improved firing pulse for UCMs, DAB operation can be precisely controlled by the phase shift between the left- and right-side converter's firing pulses.

# PMSM Load Operation

**Diode Rectifier Parameters:**

- Rectifier inductance: 546.8uH
- DC bus voltage: 260V
- DC bus capacitance: 3000uF
- DC chopper resistor: 8Ω

**2L-VSI Parameters:**

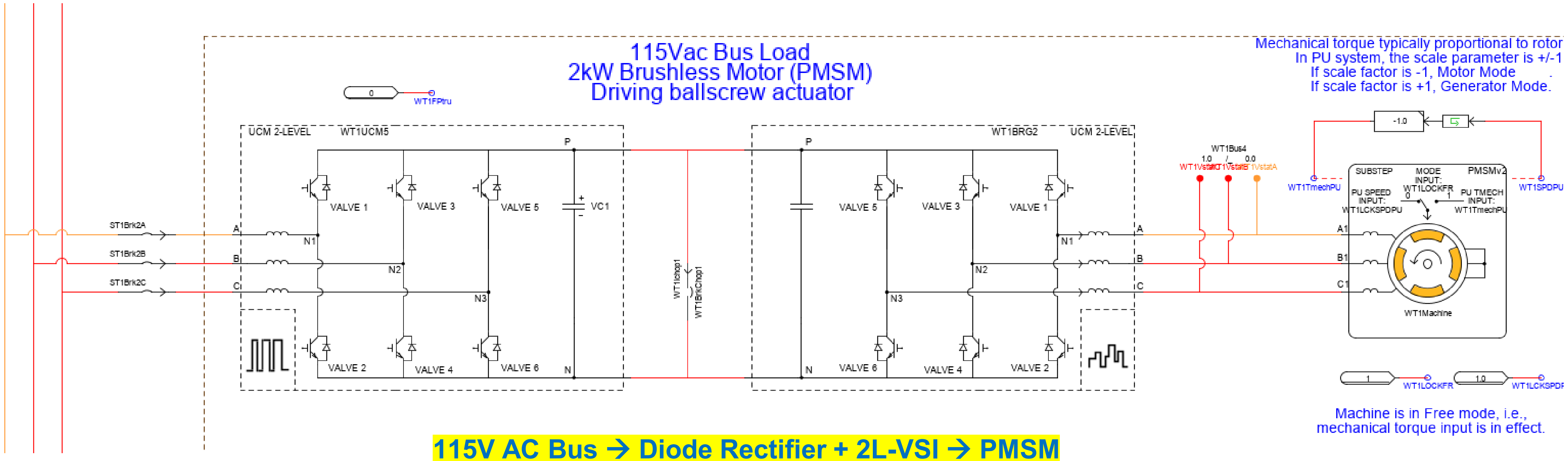
- Switching frequency: 4kHz

**Controller:**

- Controls PMSM speed to generate iq*
- Controls id* = 0 to minimize the line current

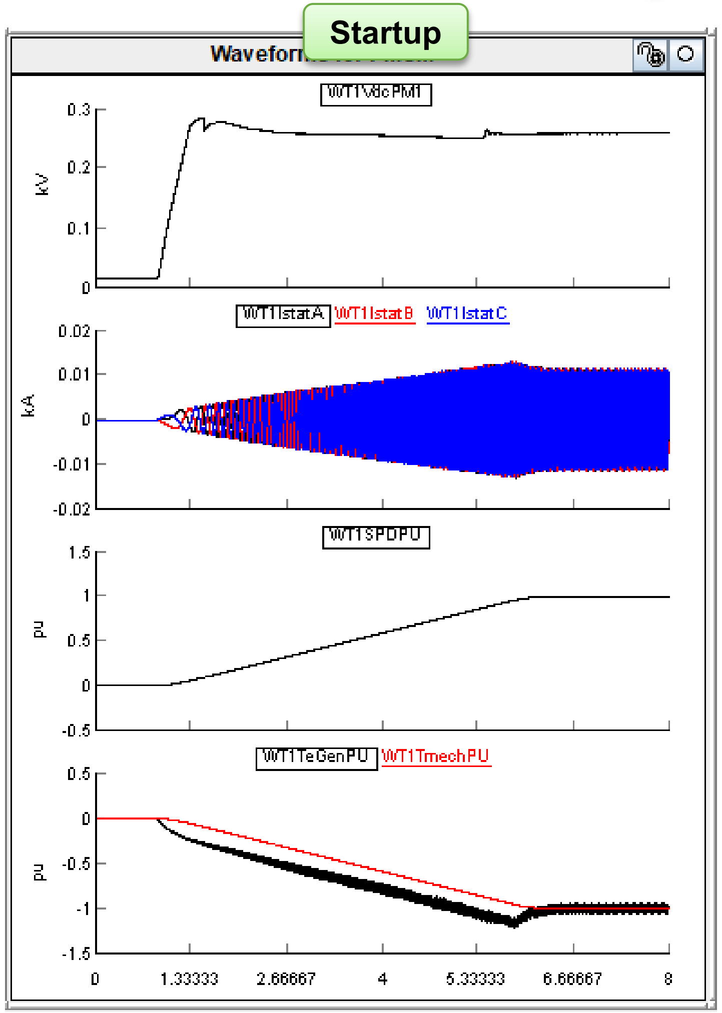
**PMSM Parameters:**

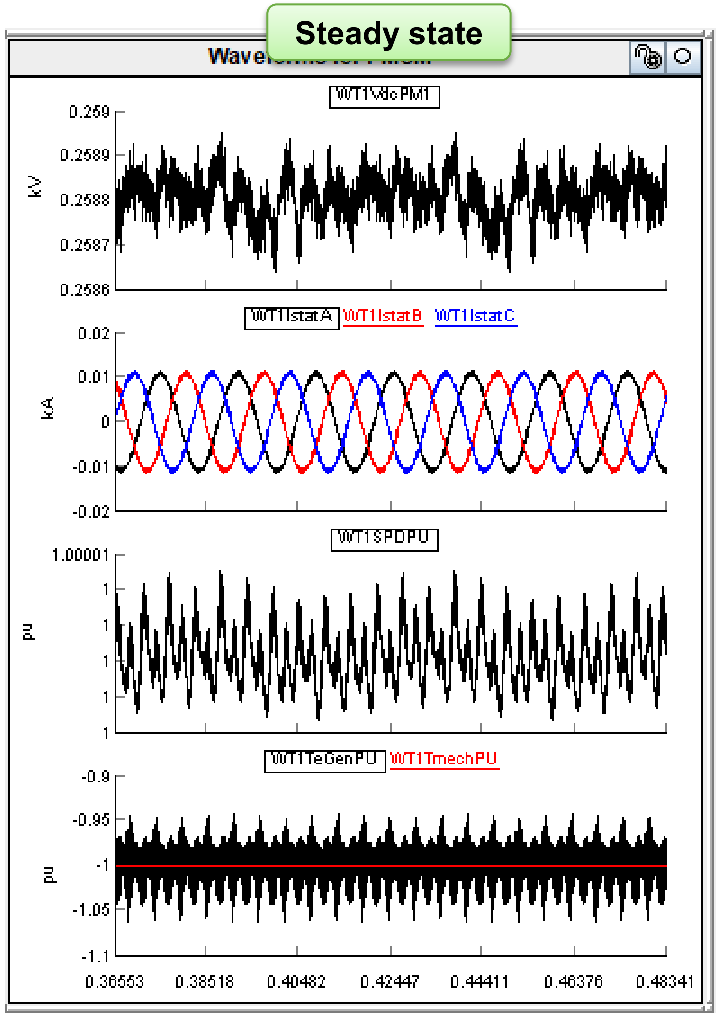
- Rated stator voltage: 150V
- Base frequency: 60Hz
- Rated MVA of machine: 2kVA
- Machine inertial constant (H): 0.5MWs/MVA
- Mode: speed mode

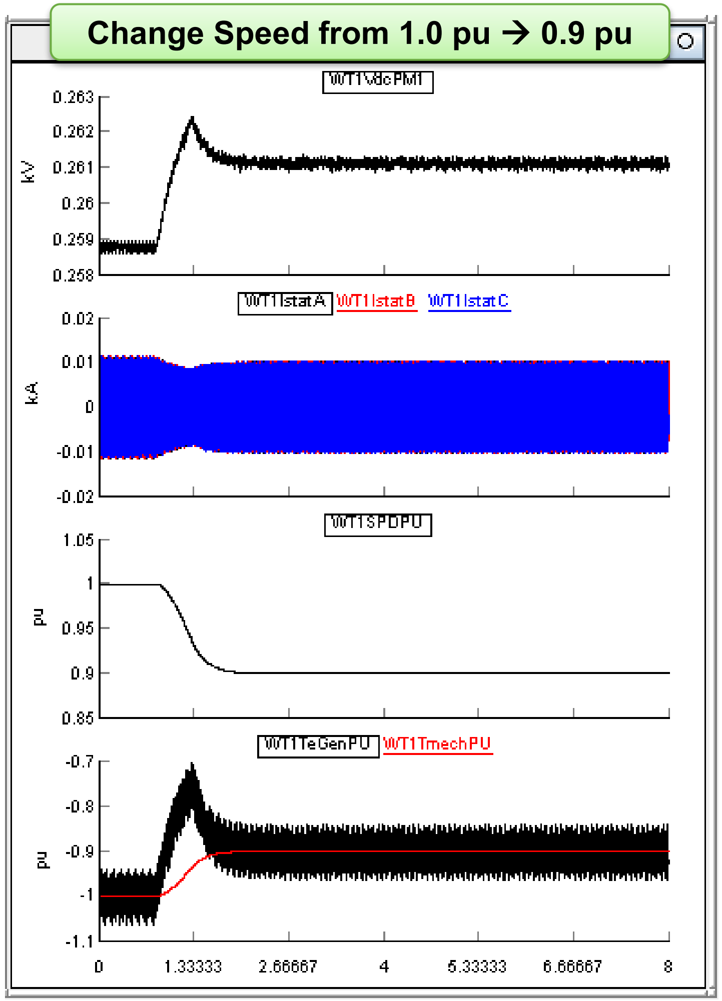



**115V AC Bus → Diode Rectifier + 2L-VSI → PMSM**

# PMSM Load Operation



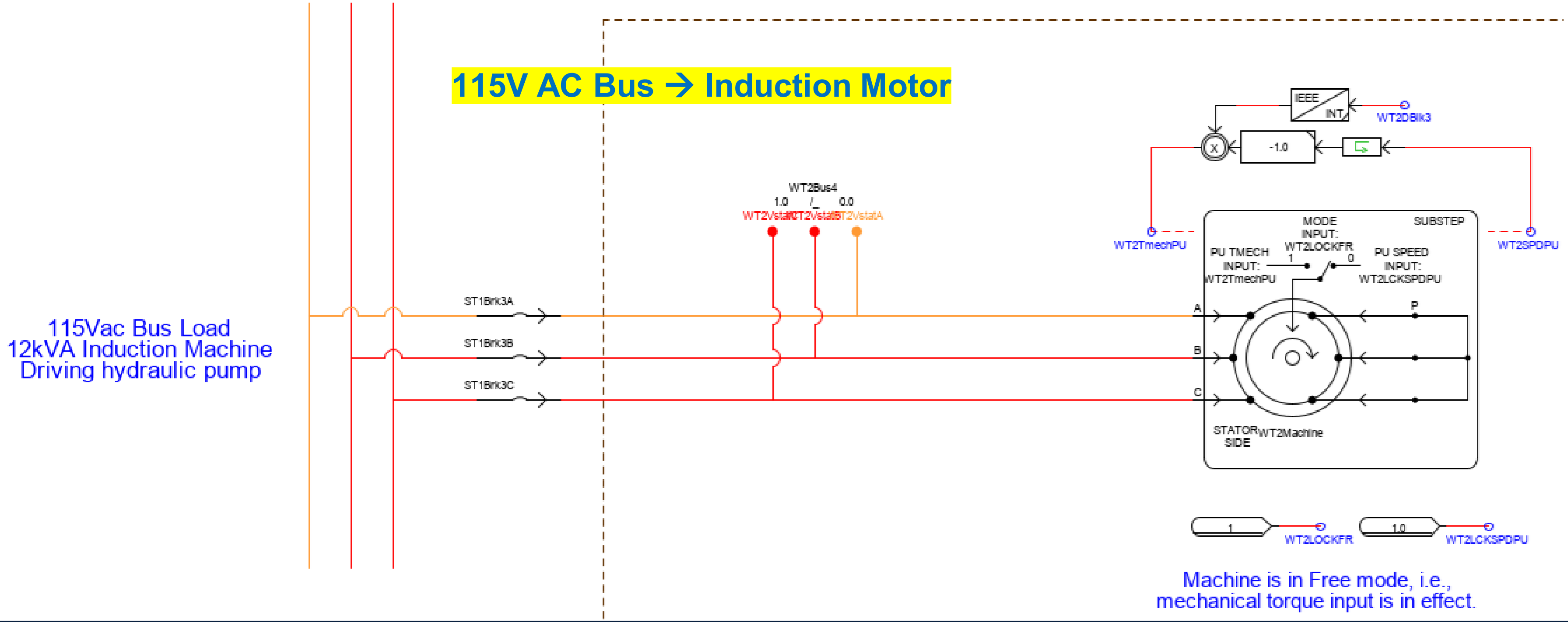




- PMSM starts up smoothly and the controller can track the speed reference very well.

# Induction Machine Load

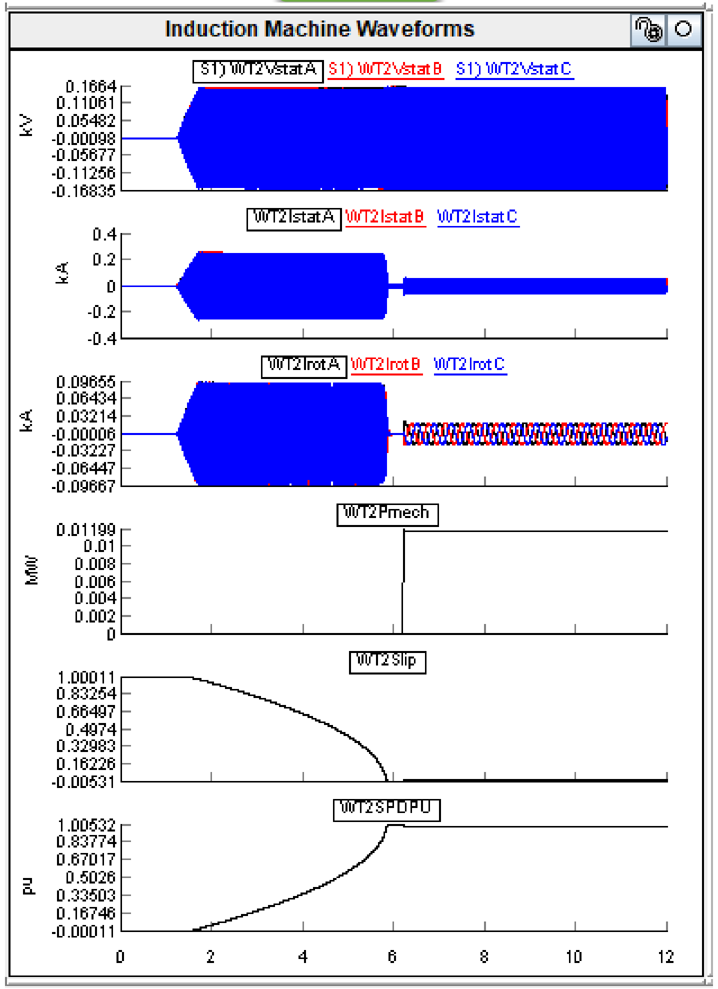
**Induction Machine Parameters:**

- Rated LL RMS stator voltage: 200V
- Base frequency: 400Hz
- Rated MVA of machine: 12kVA
- Turns ratio (roto to stator) 2.6377
- Machine inertial constant (H): 0.658MWs/MVA

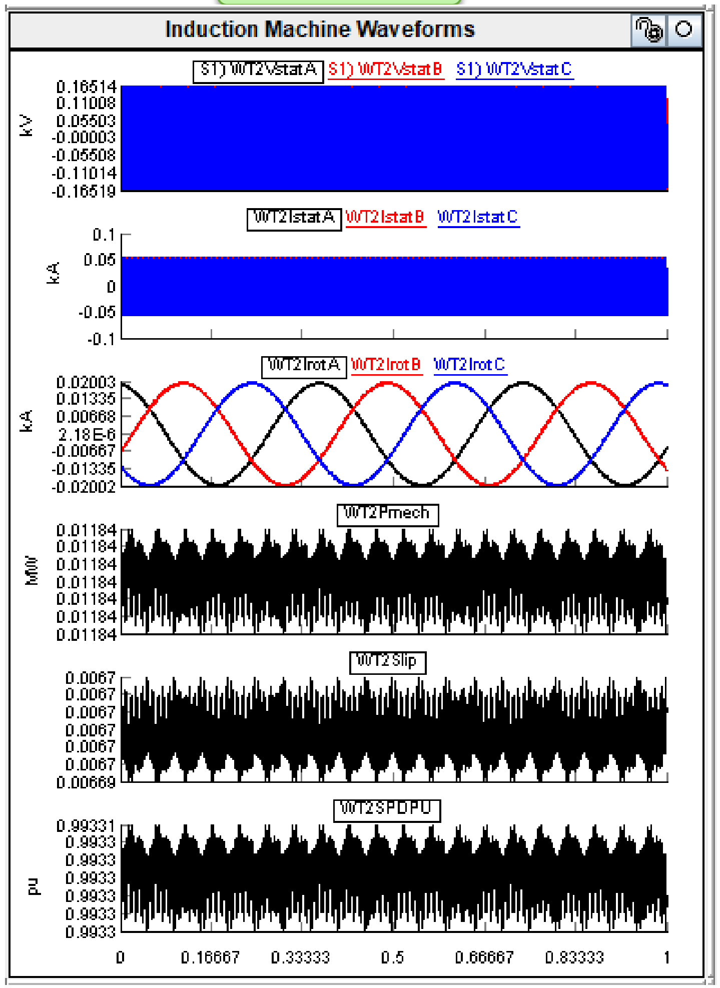


# Induction Machine Load

Startup




Steady state

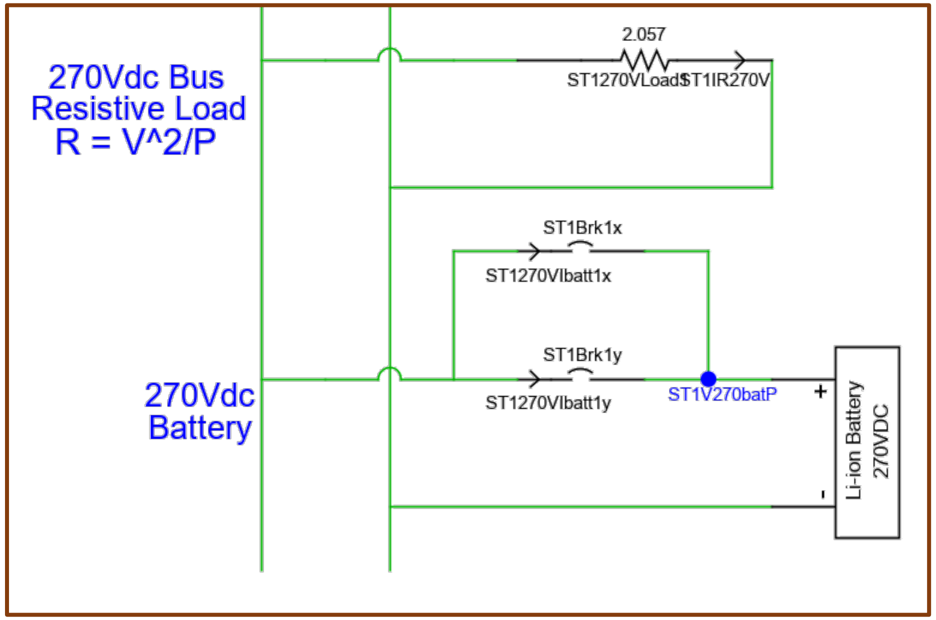


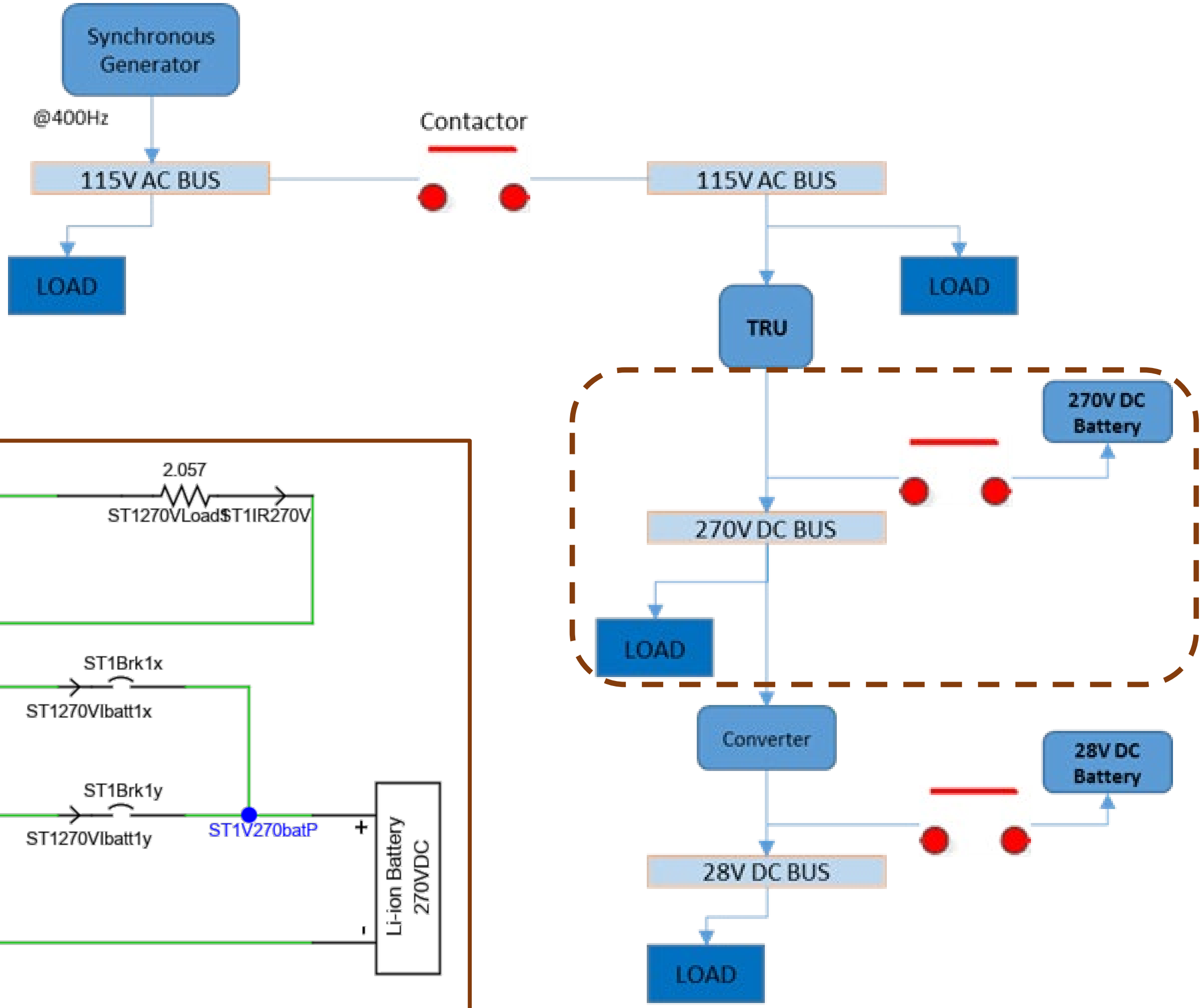
# 270V DC Bus Load

- Resistive load: on-board lamp
- Nonlinear load: battery

**In RTDS, 270V DC bus load**

- **36kW resistive load:** 2.057Ω
- **270V battery:**
  - 60 cells in series in a stack
  - 20 stacks in parallel
  - 0.85AH
  - Initial SOC = 100%



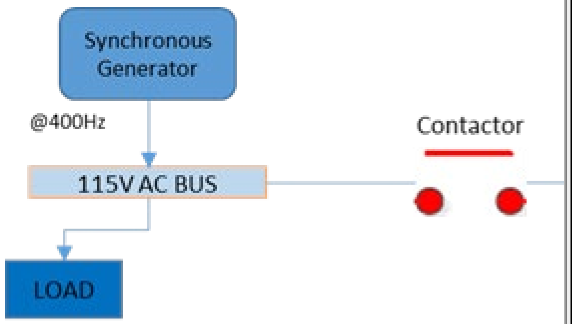



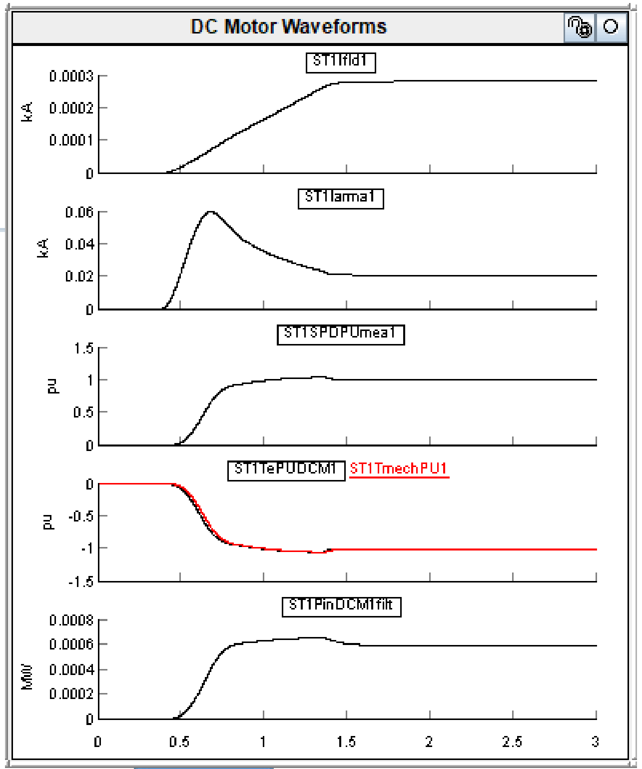
# 28V DC Bus Load

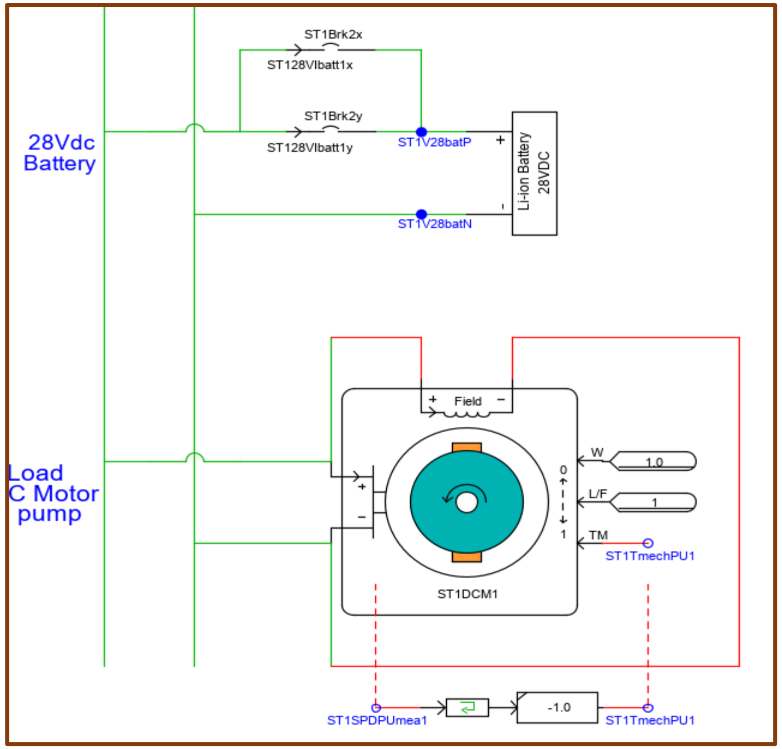
- Resistive load
- Nonlinear load: battery, dc motor driving a fuel pump and so on

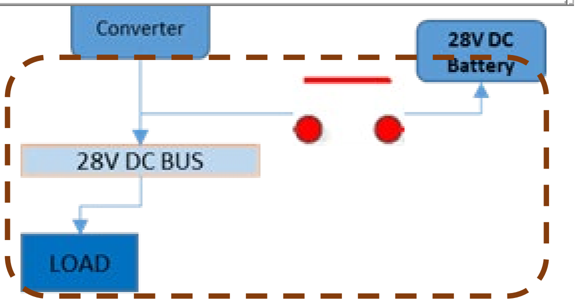
**In RTDS, 28V DC bus load**

- **14kW resistive load: 0.056Ω**
- **28V battery:**
  - 7 cells in series in a stack
  - 10 stacks in parallel
  - 0.85AH
  - Initial SOC = 100%
- **560W DC Motor**
  - Rated speed: 2000rpm
  - Rated armature voltage: 28V
  - Rated armature current: 20A
  - Rated field current: 0.37A
  - Motor inertial constant (H): 0.01MWs/MVA



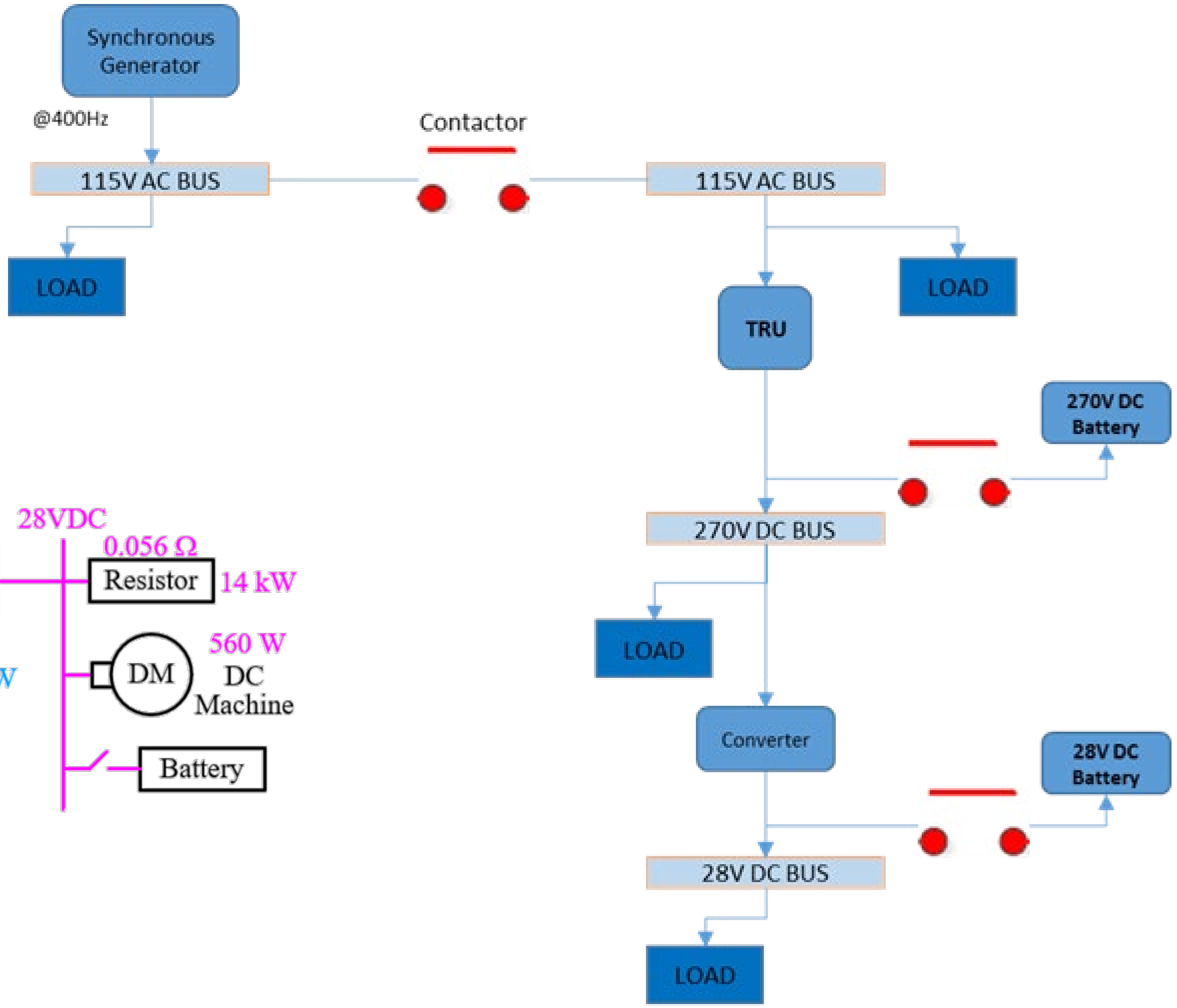



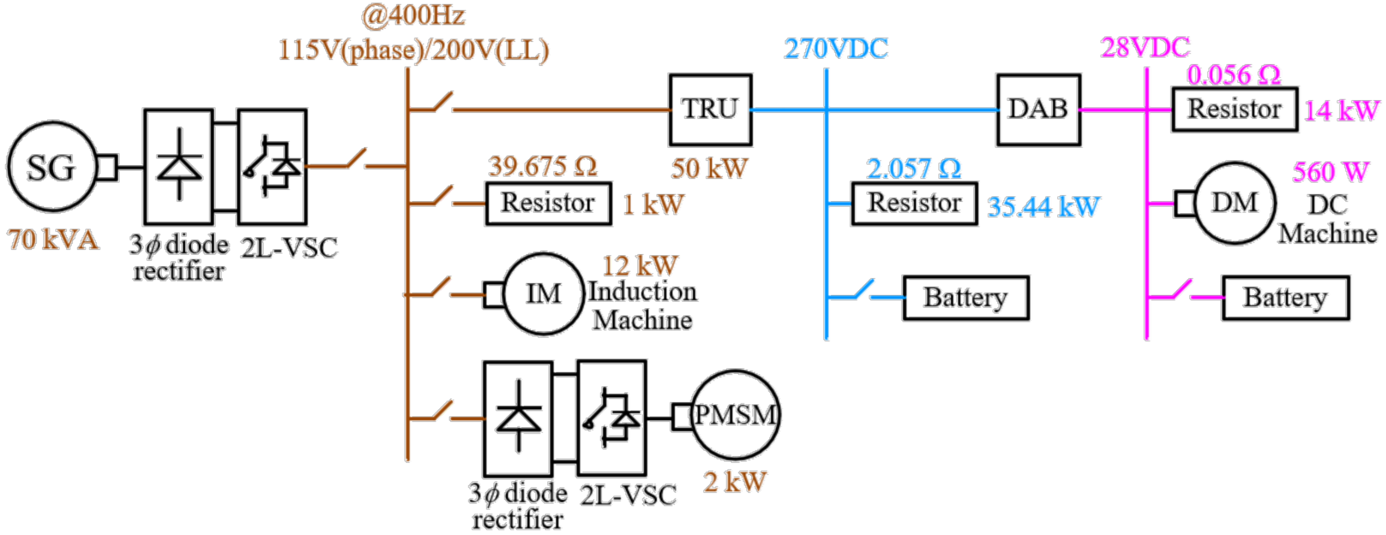
# Simulation Demonstration

RTDS Technologies

# AES Model in RTDS

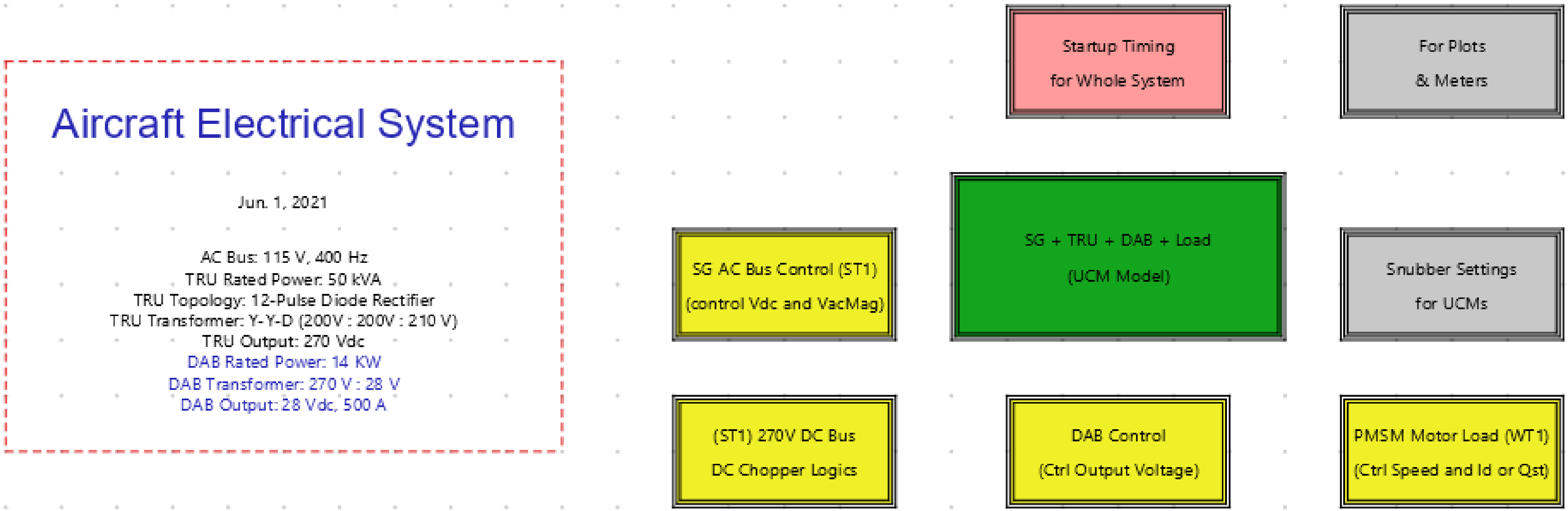
- SG is online when its speed is in the range of 10000~20000 rpm.
- If SG is offline, battery will be connected to power the load.
- Battery's initial SOC is 100%. When the battery's SOC decreases to 60%, the SG will be online (if applicable) to charge the battery




System Developed in RTDS

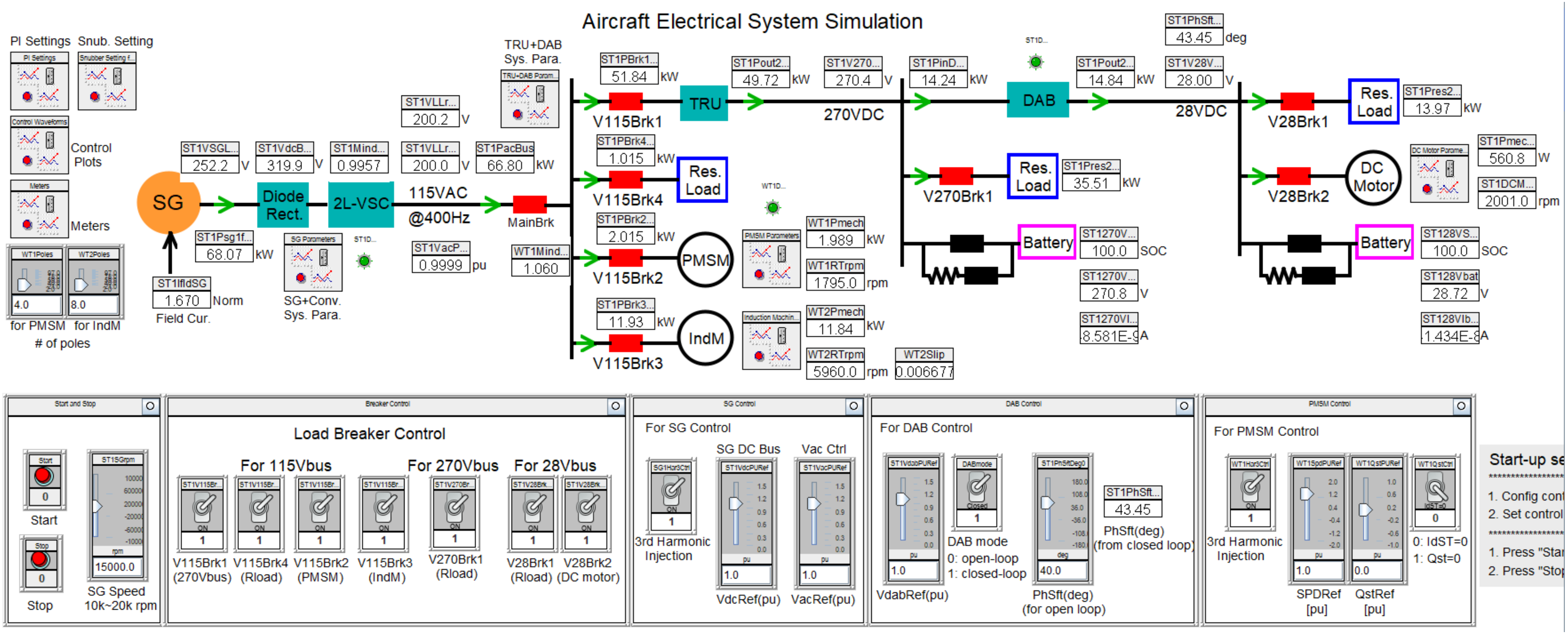
# Draft of AES in RTDS




- ❑ Sub-timestep: 50us/6 = 8.333 us
  - 8 UCMs
  - 5 three-phase breakers
  - 7 single-phase breakers
  - 7 single-phase transformers
  - 1 PMSM, 1 induction machine, and 1 DC motor

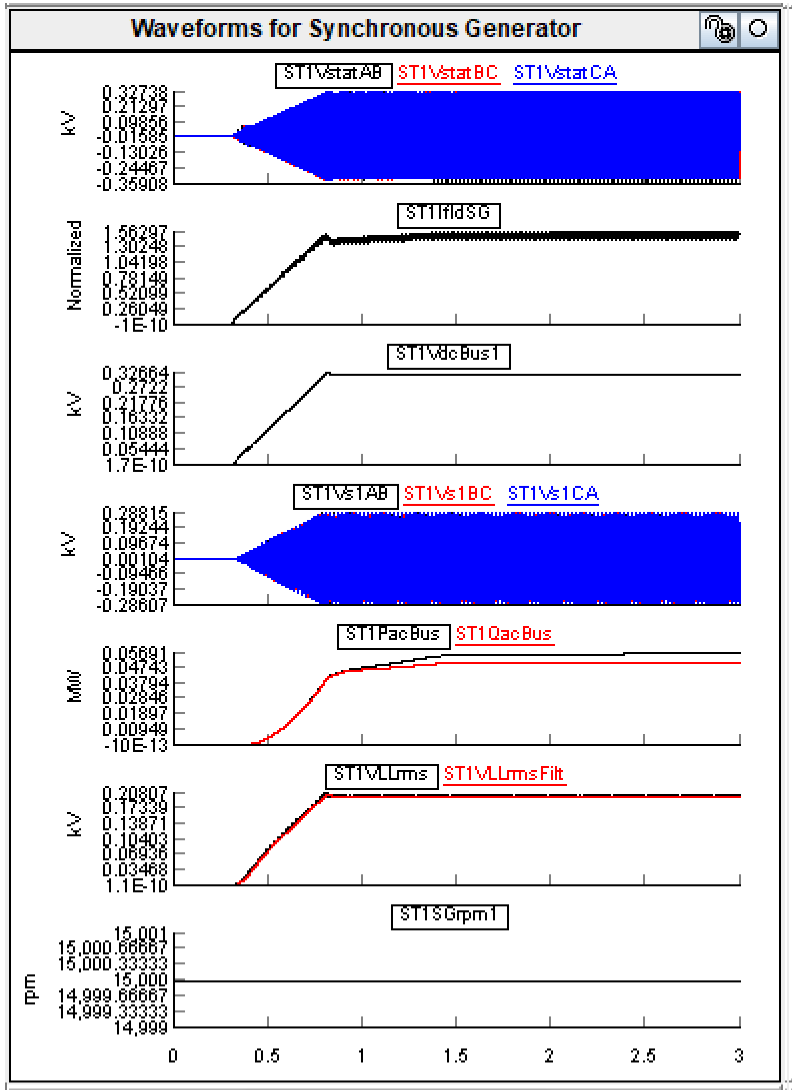
Switching frequency for power electronic converters:
- DAB: 10 kHz
- 2L-VSI for SG side: 15 kHz
- 2L-VSI for PMSM side: 4 kHz

# RunTime of AES in RTDS

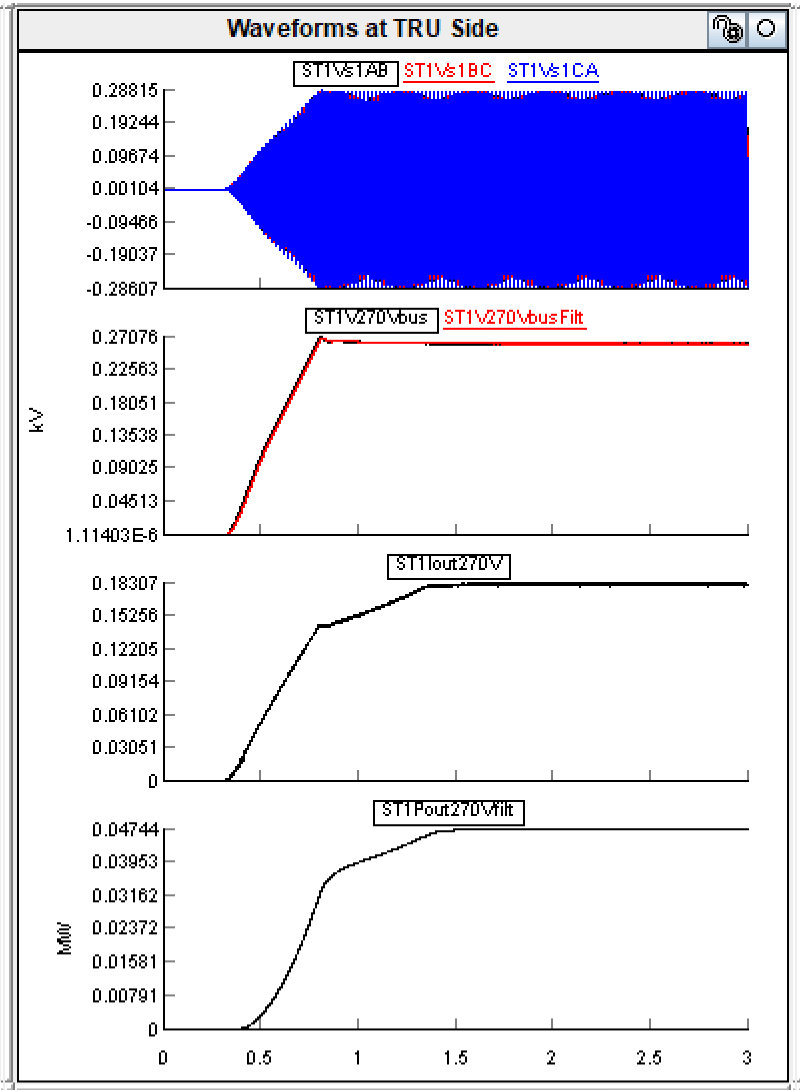


# Simulation Results

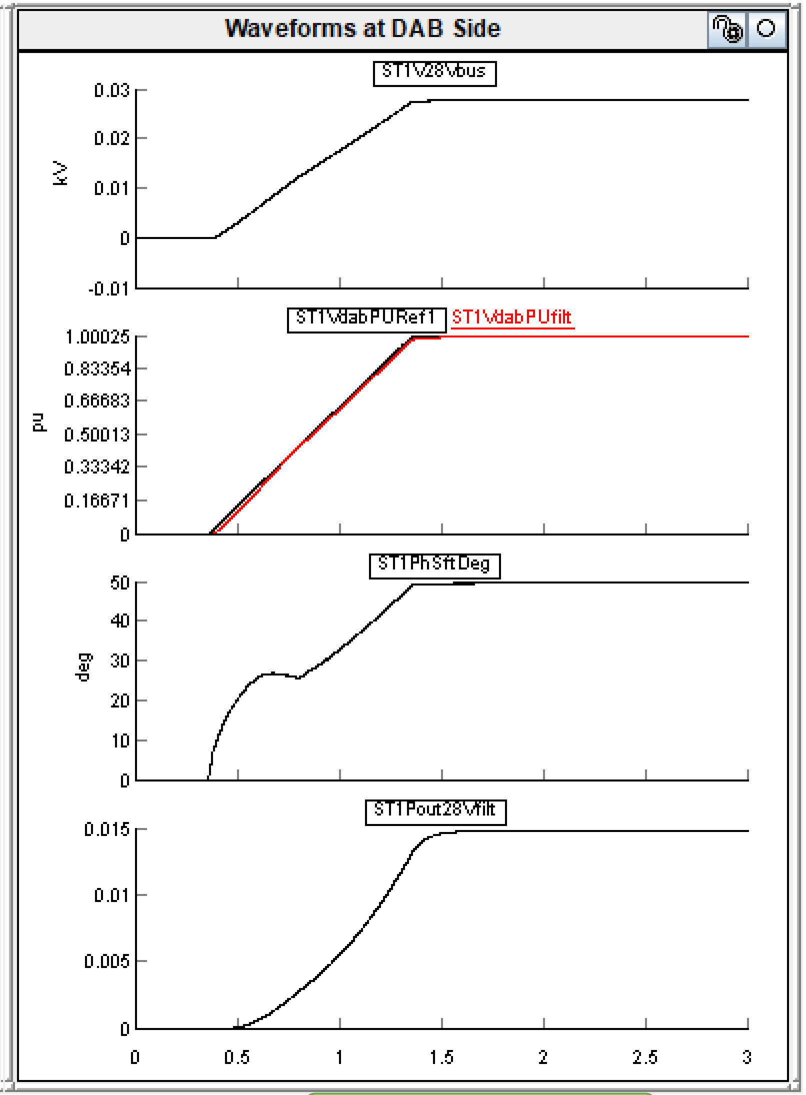
**System startup to the SG speed 15000 rpm**




**SG Operation**



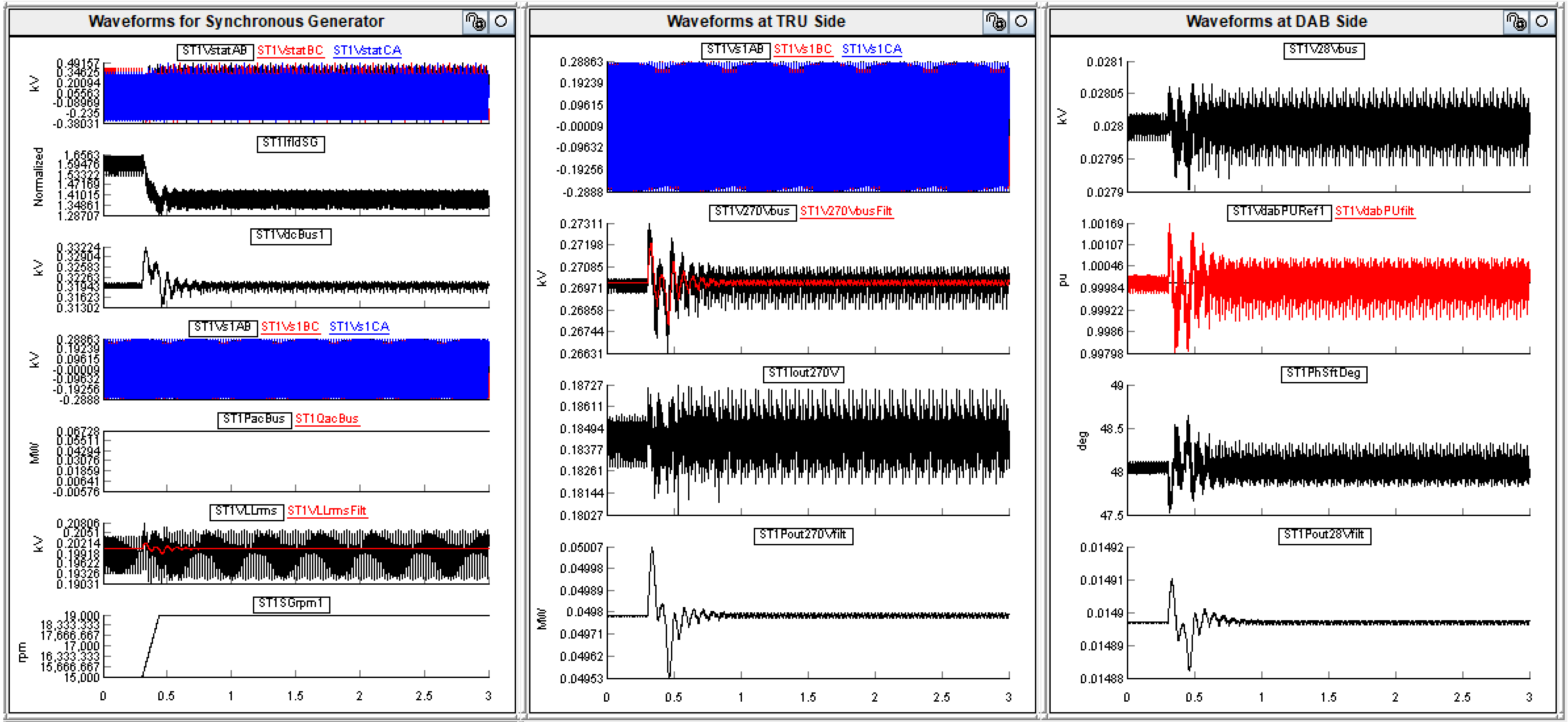

**TRU Operation**




**DAB Operation**

# Simulation Results

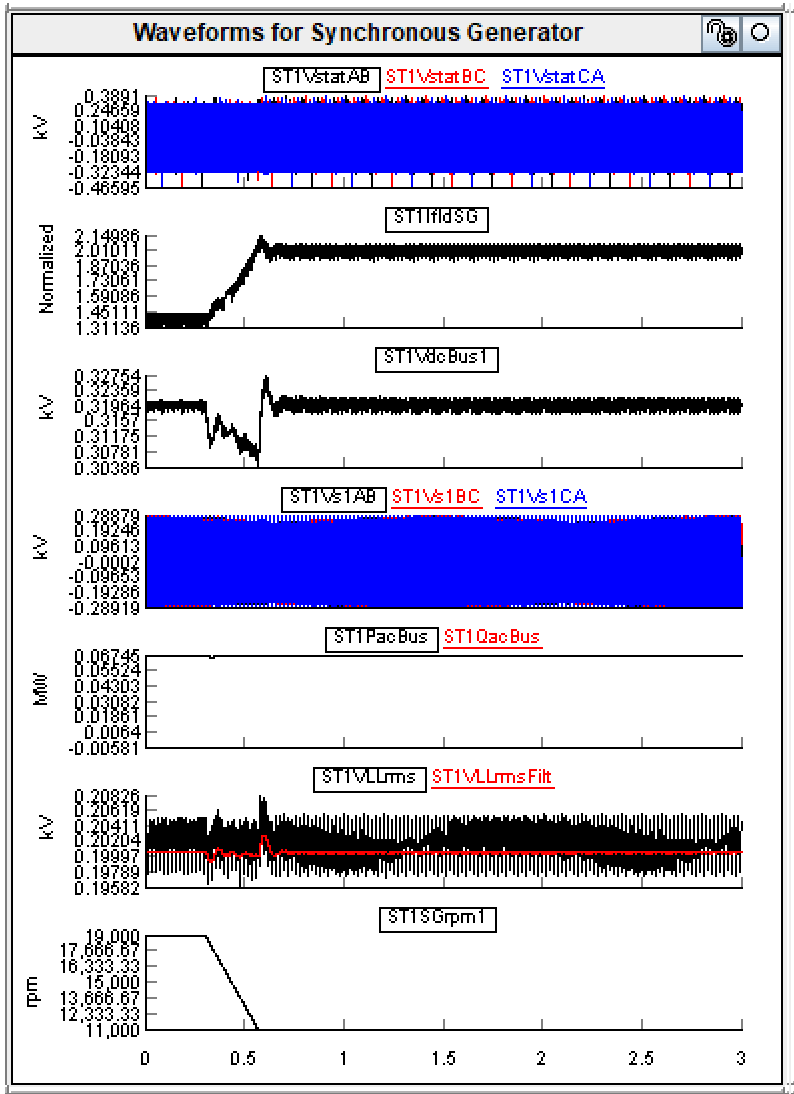
**Change SG speed from 15000 rpm to 19000 rpm**



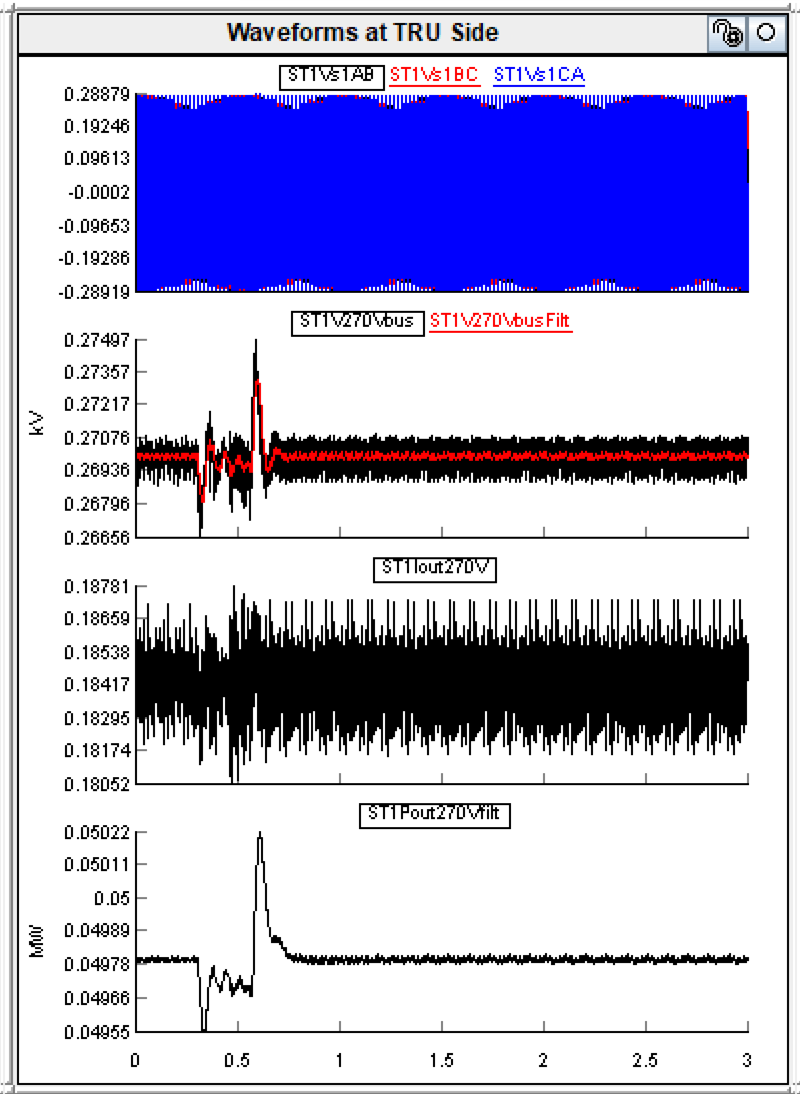

**SG Operation** **TRU Operation** **DAB Operation**

# Simulation Results

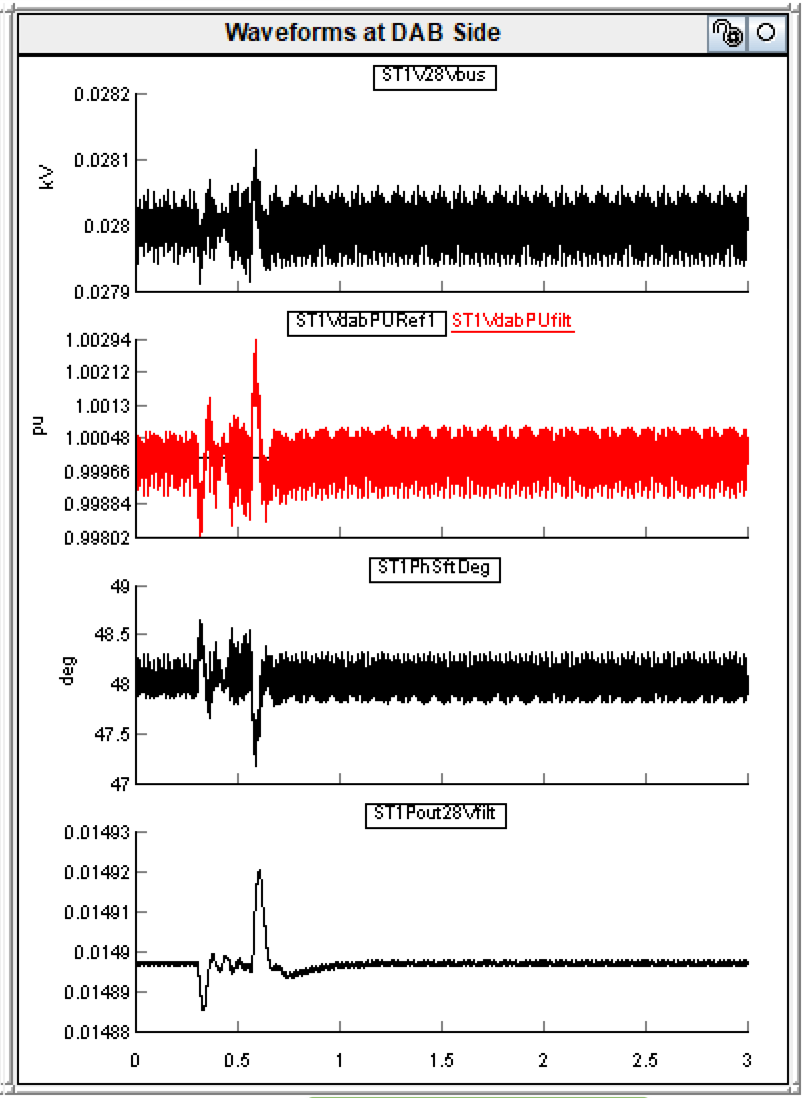
**Change SG speed from 19000 rpm to 11000 rpm**




**SG Operation**



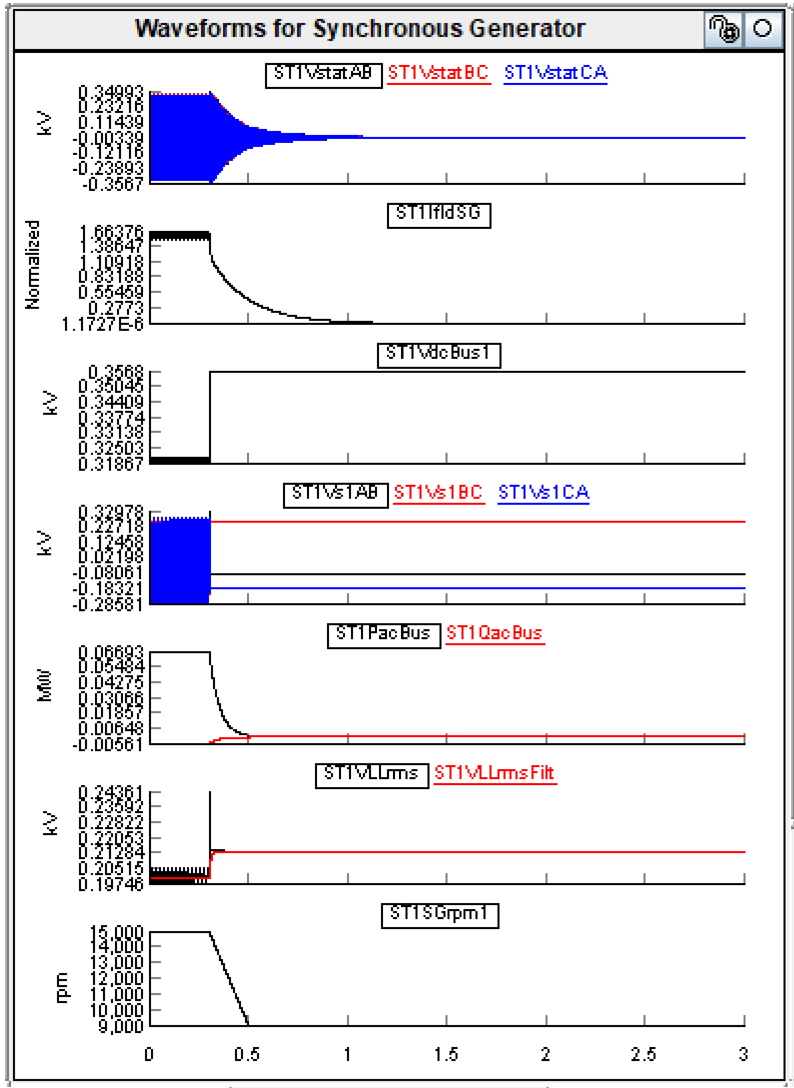

**TRU Operation**



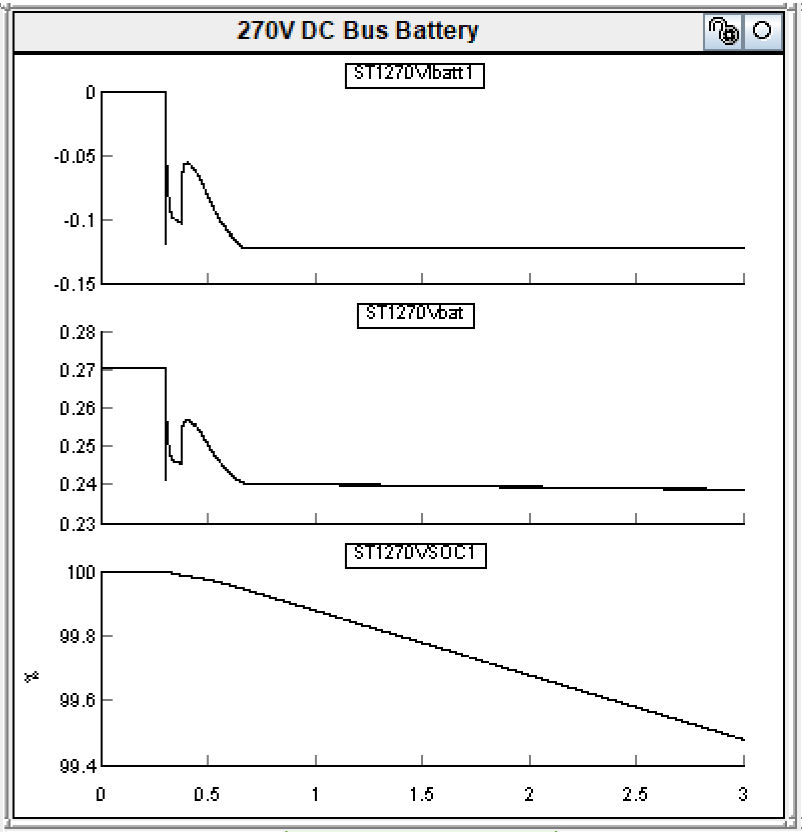

**DAB Operation**

# Simulation Results

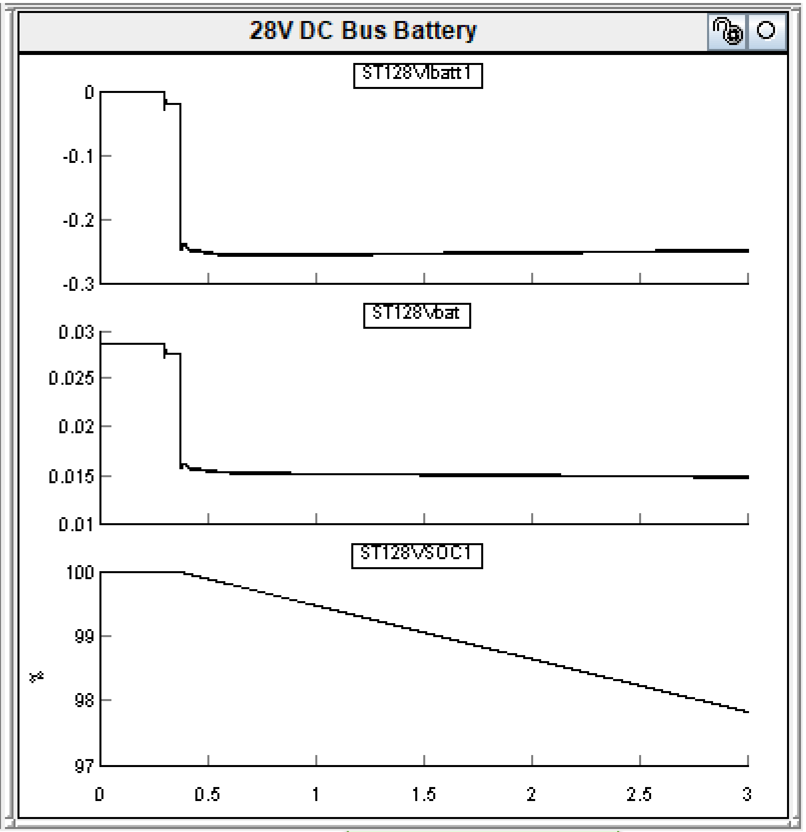
**Change SG speed from 15000 rpm to 9000 rpm**




**SG Operation**




**270V Battery**

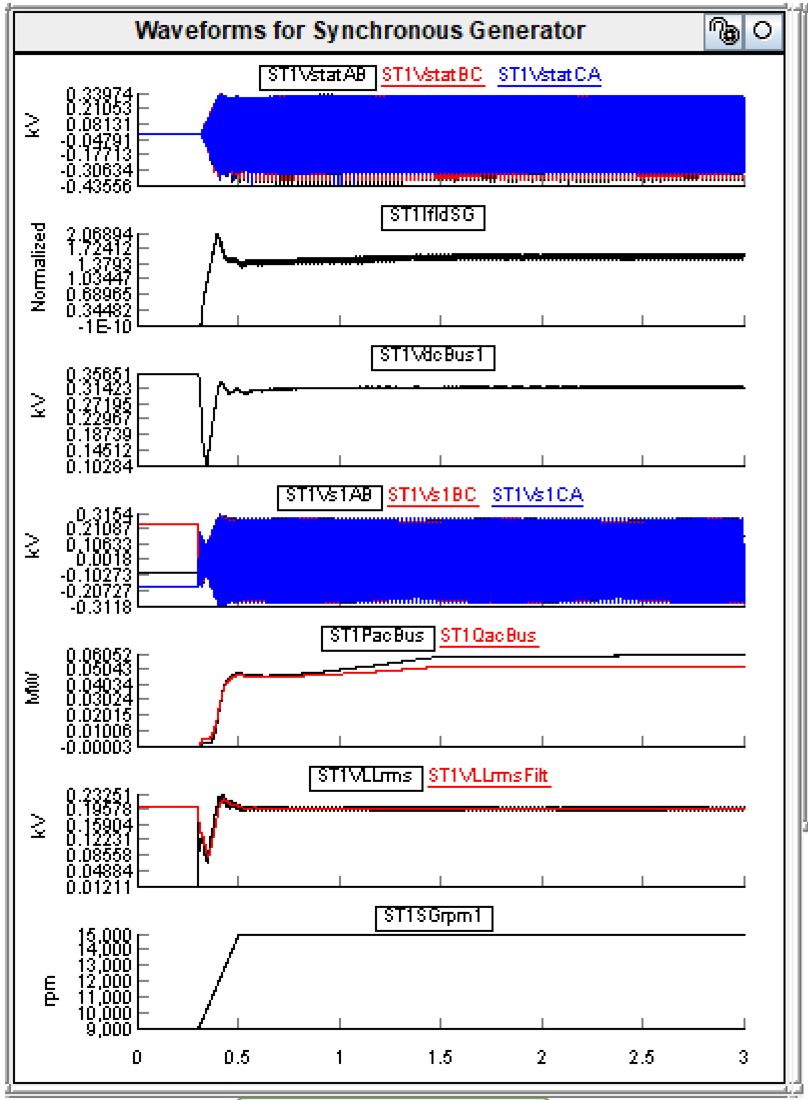



**28V Battery**

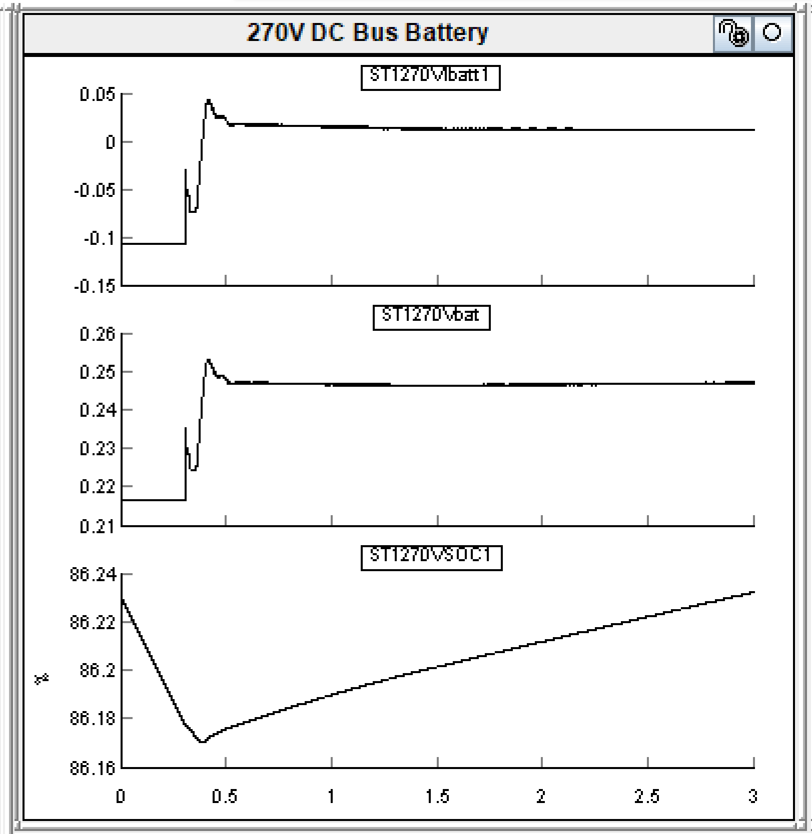
- SG is allowed to be online when its speed is in the range of 10000~2000 rpm.
- When SG speed is decreased to 9000 rpm, SG is offline and the 270V and 28V batteries are online to supply power to the load.

# Simulation Results

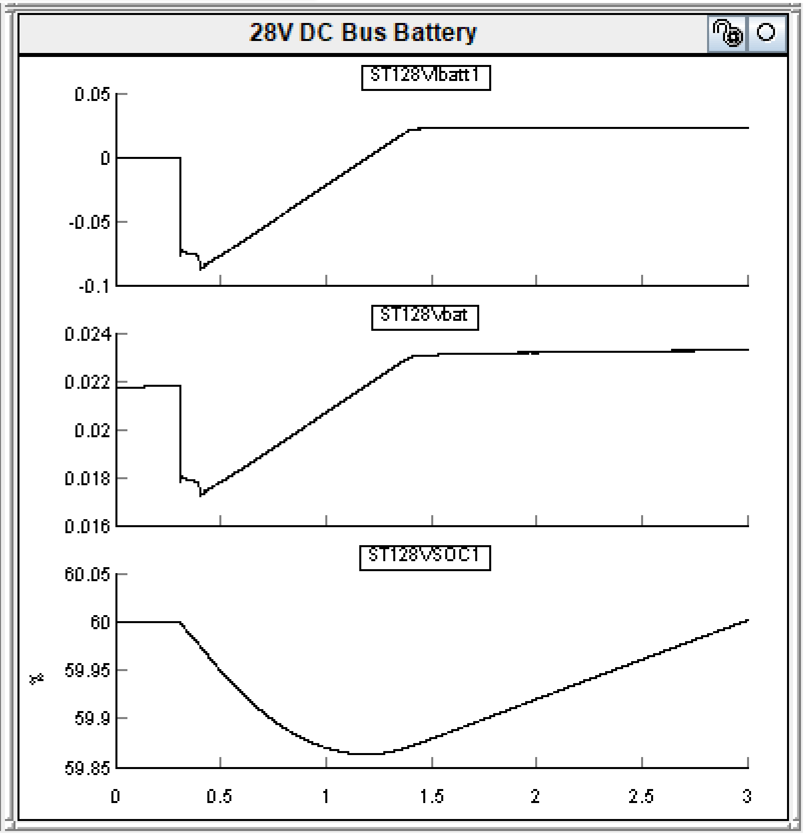
**Change SG speed from 9000 rpm to 15000 rpm**




**SG Operation**




**270V Battery**

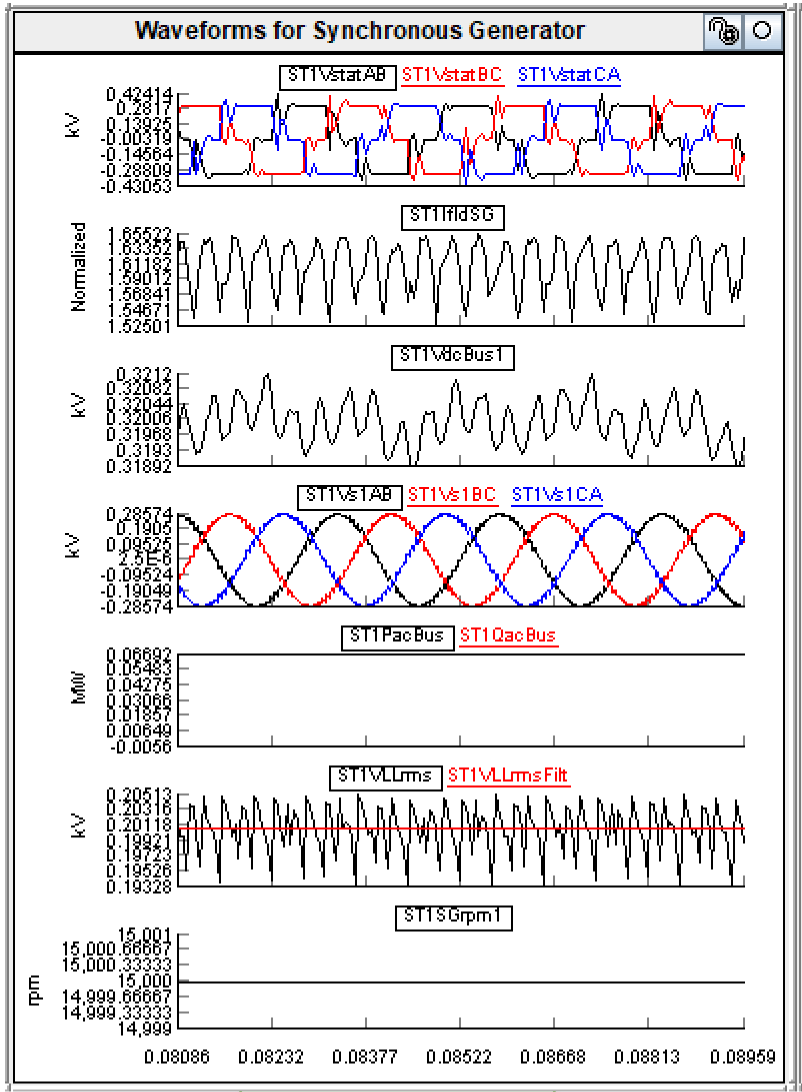



**28V Battery**

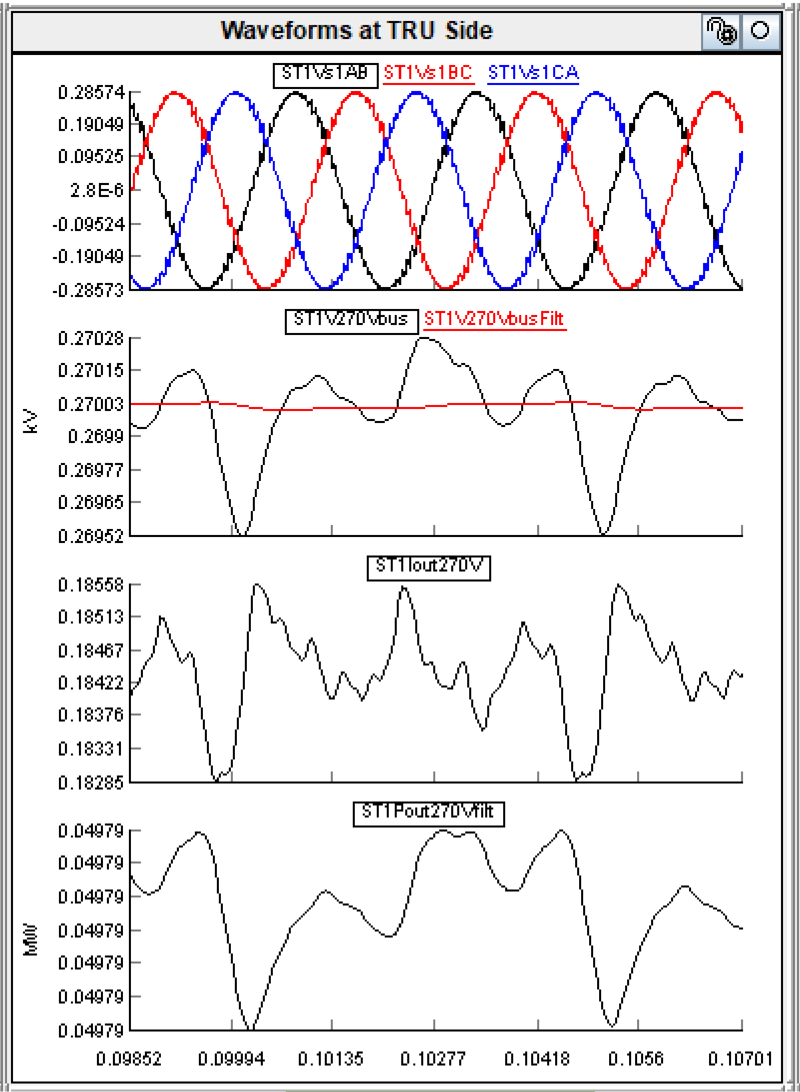
- When SG speed is increased to 15000 rpm, SG is online and the 270V and 28V batteries are online to be charged.

# Simulation Results

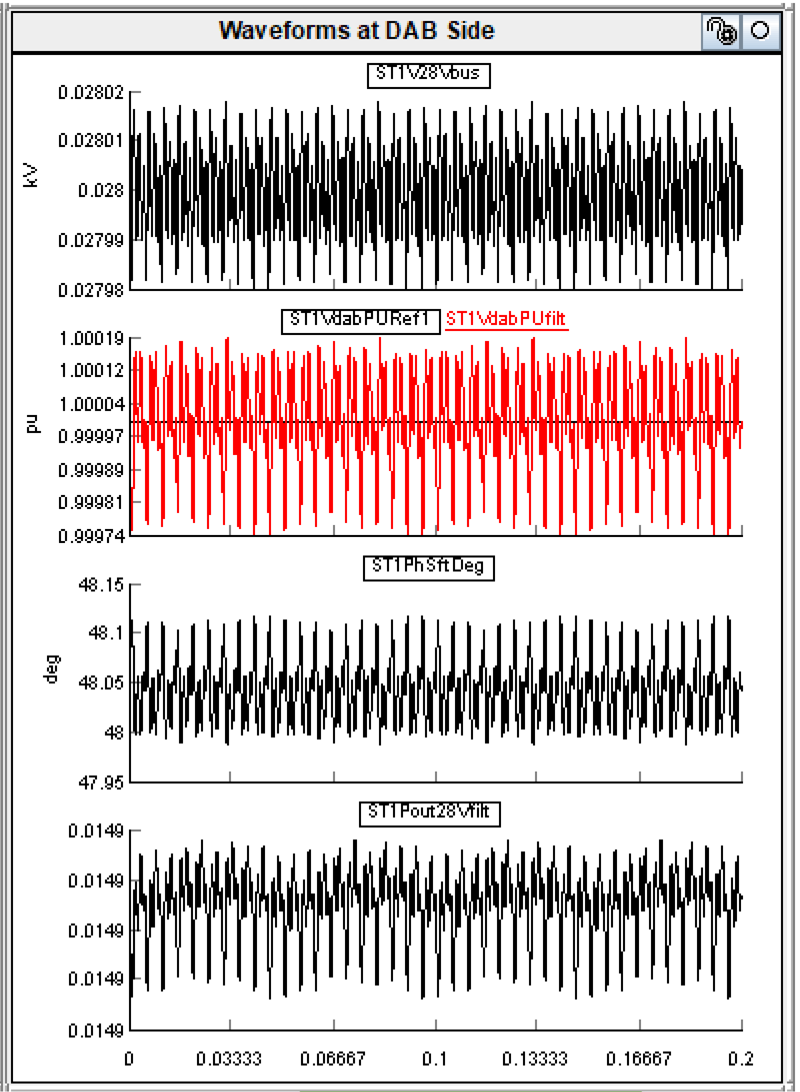
**Steady state operating waveforms under SG speed 15000 rpm**




**SG Operation**



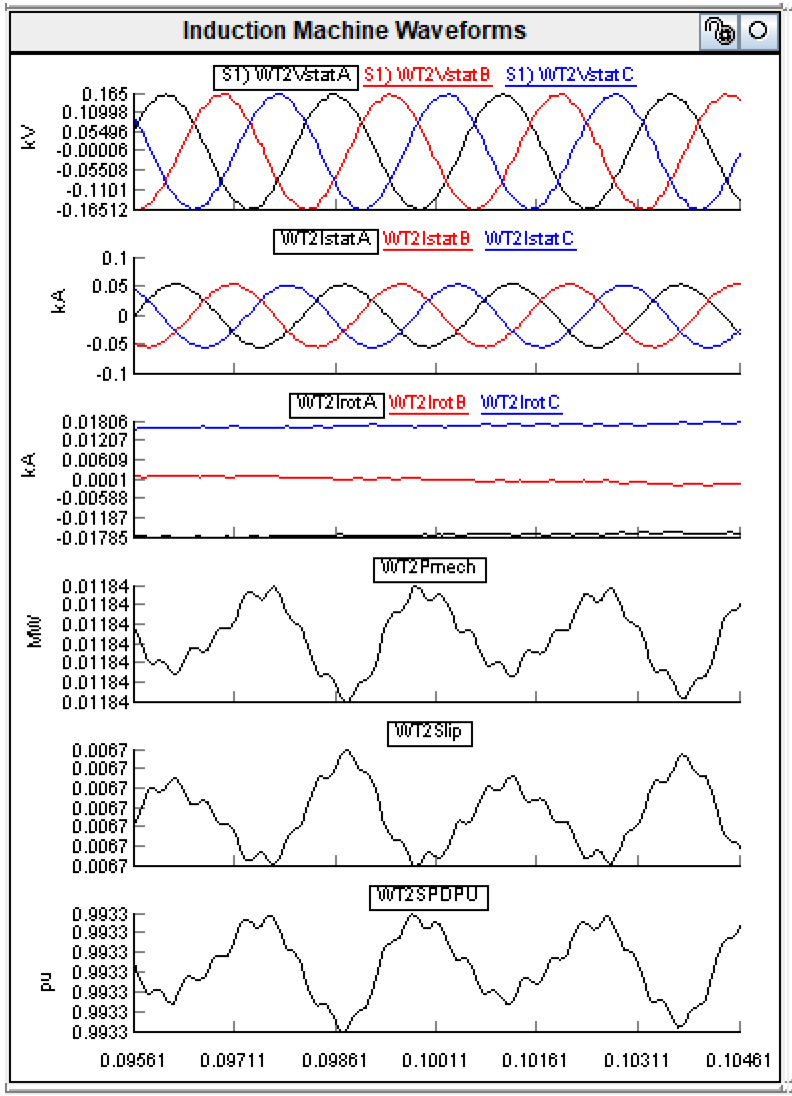

**TRU Operation**



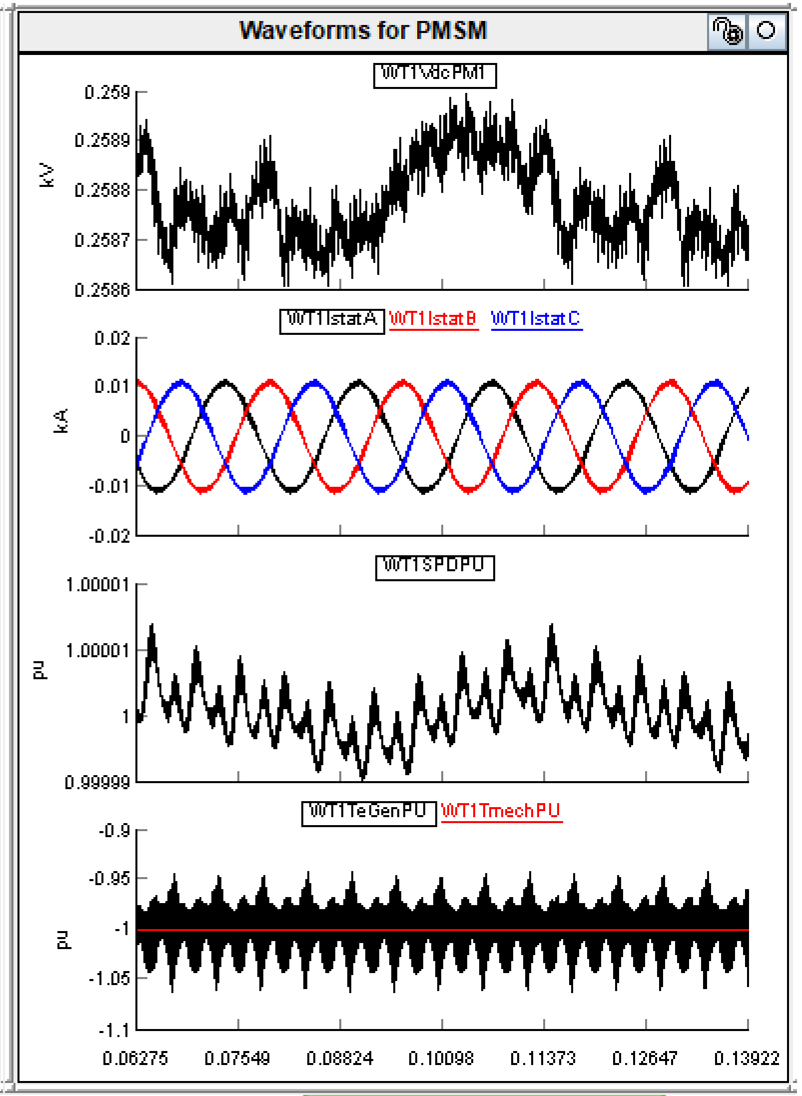

**DAB Operation**

# Simulation Results

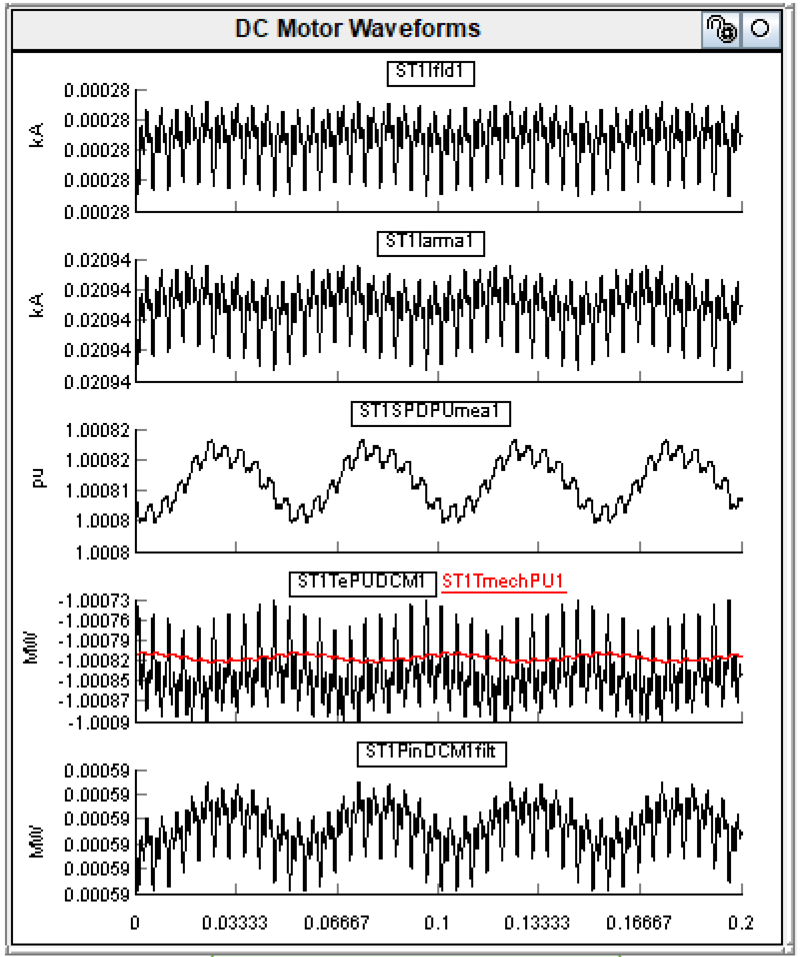
**Steady state operating waveforms under SG speed 15000 rpm**




**Induction machine Operation**




**PMSM Operation**

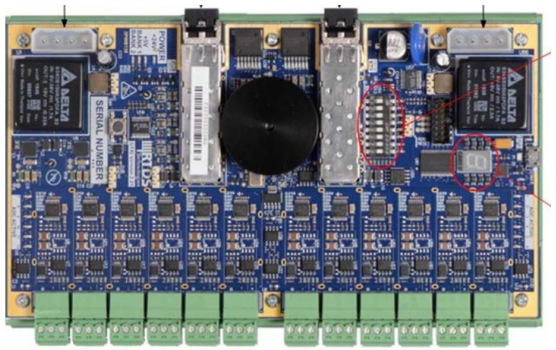



**DC Motor Operation**

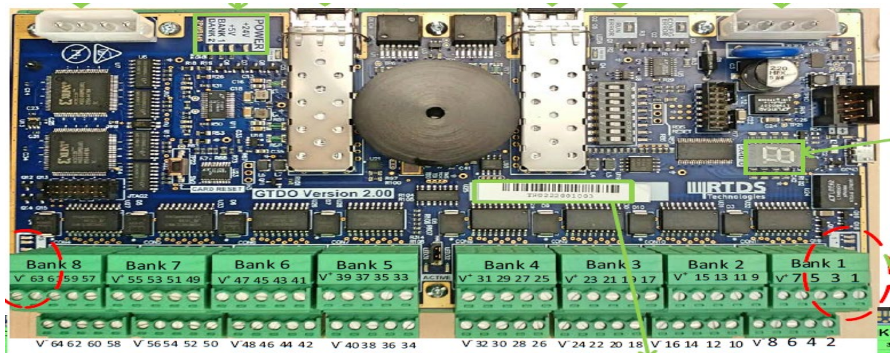
# Hardware Interface to Peripherals

RTDS Technologies

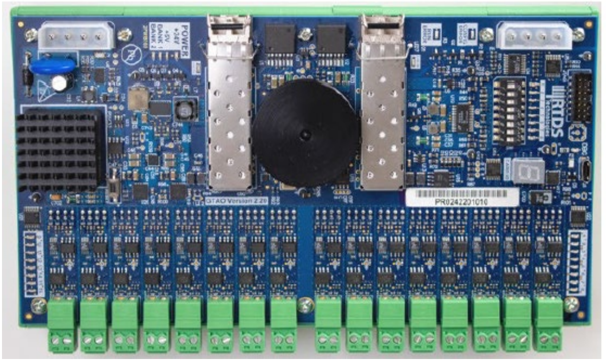
# GTIO Cards



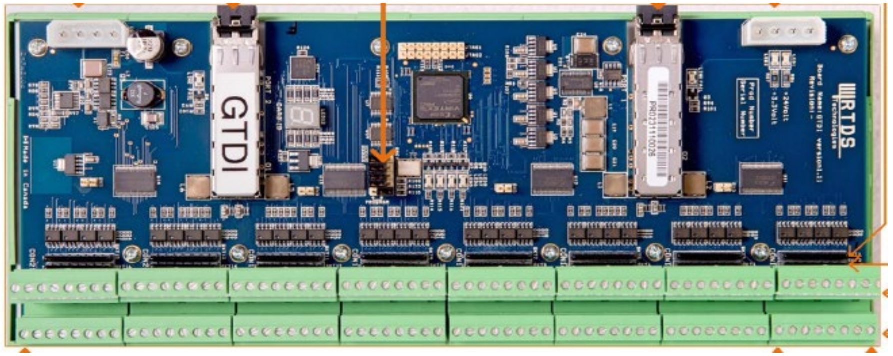
GTAI v2: 12 channels/card
+/- 10V range




GTDO v2: 64 channels/card, +5V ~ +30V range

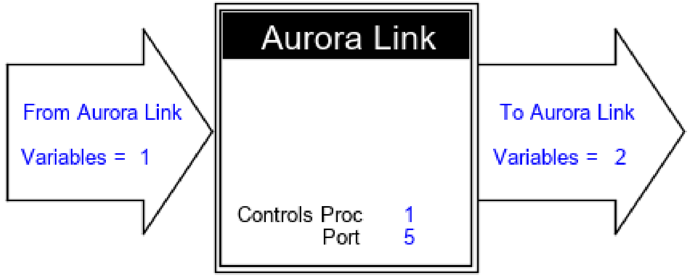


GTAO v2: 16 channels/card
+/- 10V range



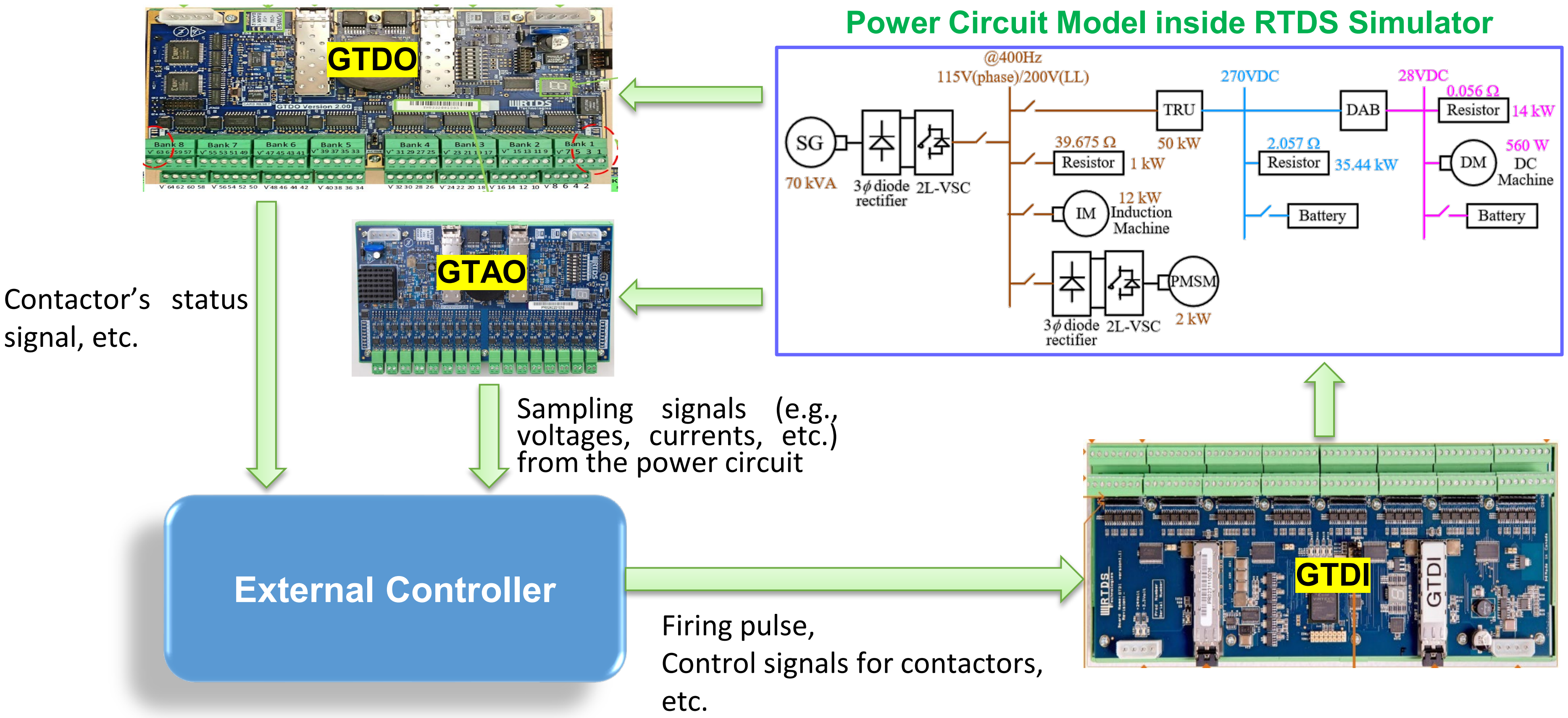

GTDI v2: 64 channels/card, +3V ~ +50V range

# Aurora Link




The Aurora protocol is a lightweight serial protocol developed by Xilinx suitable for high speed point to point communication links. This component provides a way to digitally communicate with the RTDS simulator using the Aurora Protocol.

# Example for Control-Hardware-In-Loop (CHIP) Test



# Conclusion and Future Development

RTDS Technologies

# Conclusion

- One example of aircraft electrical system (the architecture including 115V/400Hz AC bus, 270V DC bus and 28V DC bus) was successfully simulated with good performance.
- Thanks to UCMs, the simulation with high switching frequency can be done under relatively large timestep (e.g., 15 kHz with 8.333 us in this example, i.e., only 8 calculations for one switching period).
- RTDS provides various machine models to emulate the nonlinear motor load in aircraft electrical system.

# Future Developments

- More aircraft electrical systems will be modelled in RTDS as sample cases.

RTDS Technologies 25 YEARS

RTDS.COM

# THANK YOU!