QRB power requirements & simulation

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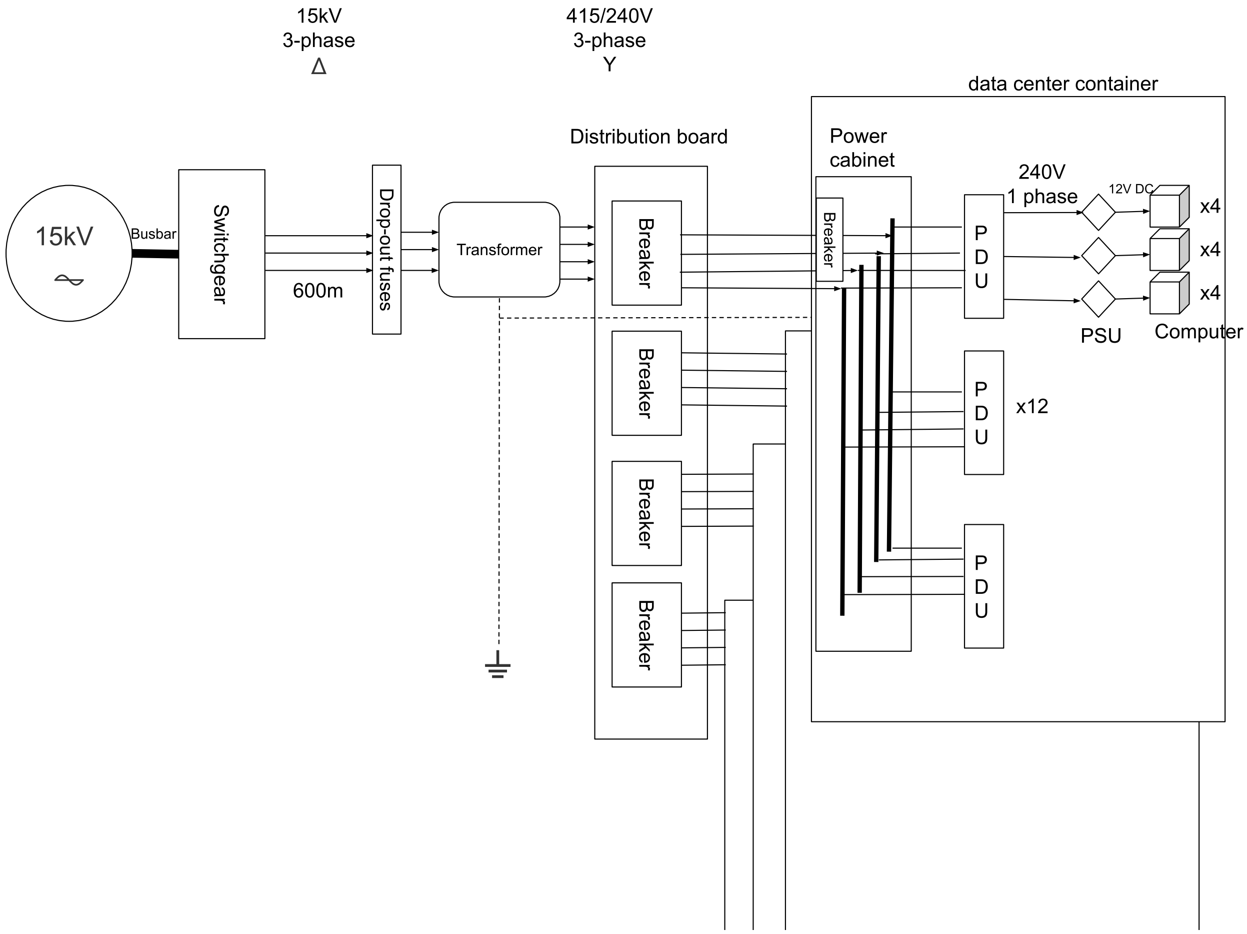
Objective

Specify high-level power system requirements and simulation of modular data centers in an electrical substation.

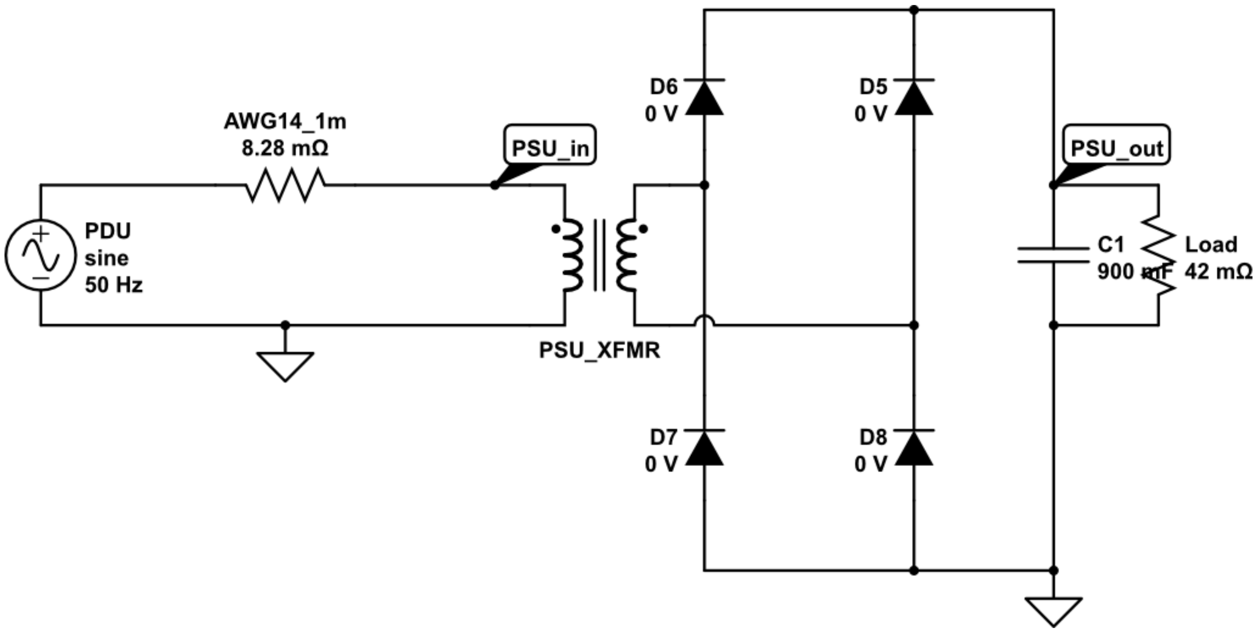
Background

QRB Labs deploys modular data centers for energy-intensive computation.

- Data center modules are containers deployed in power transmission substations
- Power supplied is AC 3-phase Δ configuration (3-wire) at 15kV, 50Hz.
- Each container holds 144 computers (12 shelves x 12 computers each).
- Each shelf is supplied by a 3-phase power distribution unit (PDU)
- Computers run on 12V DC, drawing 3-4kW via power supply units (PSUs) drawing 10-20A at 240V.
- Transformer steps down to AC 415/240V Y (4-wire)
- Each phase supplies 1/3 of the computers

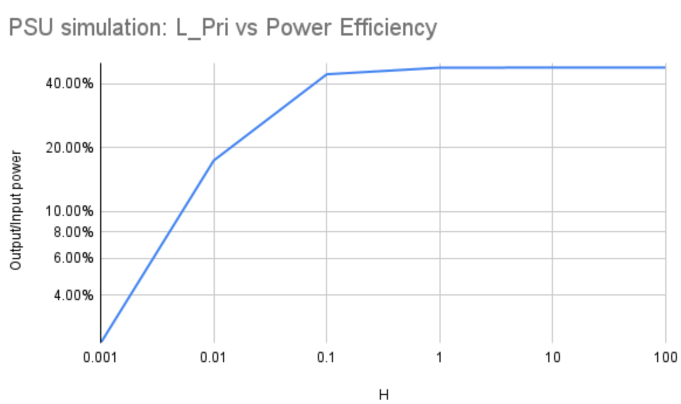


Single machine circuit model

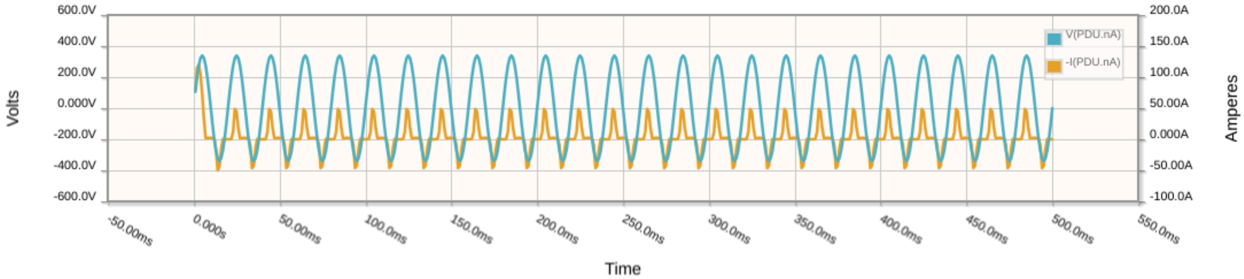


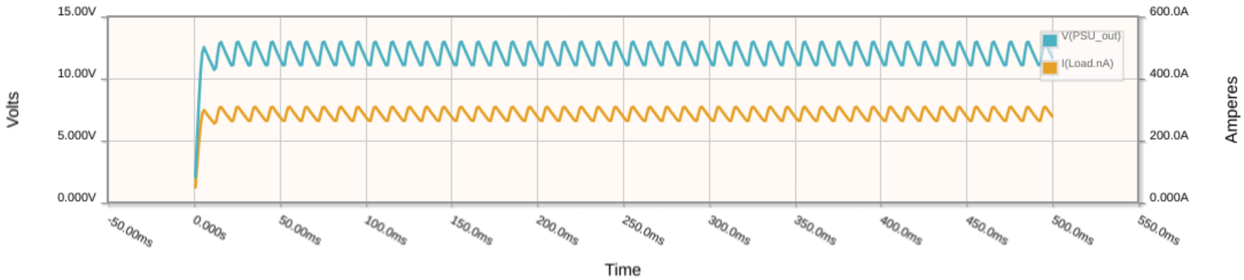
A single machine (computer+PSU) can be modeled by this circuit model

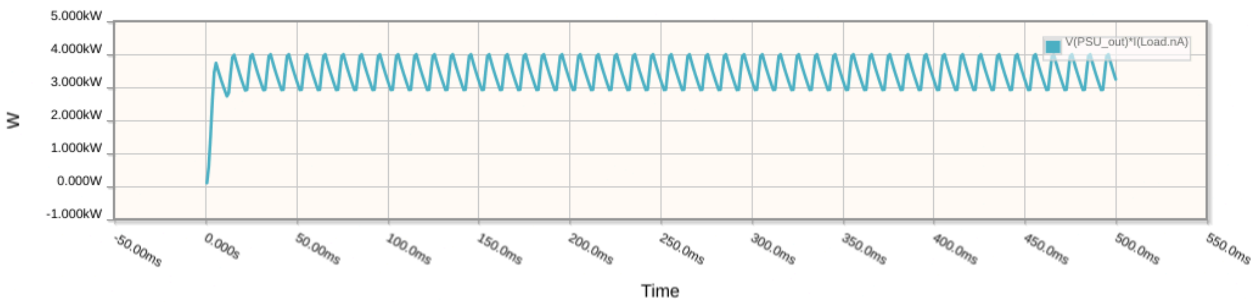
- PSU input :
  - 240V AC single phase, 12V DC output
  - Power cord: AWG14 (2mm²), resistance 8.282 Ω/km
- Load:
  - Expect 3400W power consumption
  - Model the load as a pure resistance R_{load} = 12*12/3400 = 0.042 Ω.
- PSU simulation parameters:
  - N = 24 turns; resistance R_{PRI} = 0 Ω, R_{SEC} = 0.0012 Ω; inductance L = 1H; Capacitance C = 0.9F.
    Higher C => less “ripple” but lower power efficiency (more energy loss)
    Lower L => high current on primary and lower power efficiency.

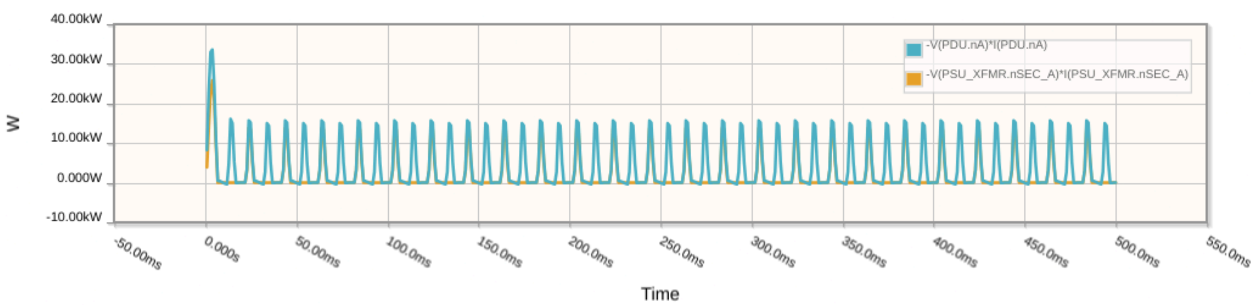


Note: With these parameters, the efficiency (output/input power) of the simulated PSU is 48%. Real PSUs achieve 80-90% efficiency. Since we are calibrating the simulation to the output power (per machine consumption), the input power will be potentially overestimated by ~2x.









Single data center 3-phase power system (Δ-Y)

- Supply: f=50Hz, 3-phase 15kV
- Transmission: 700m x 150mm^2 All Aluminum Conductors - equiv to copper 2/0 AWG, 0.2555 Ω/km
- Transformer: delta-wye configuration step down transformer
- Delta primary: input amplitude is 15000√2 = 21,213V (line to line)
- Load per dc container: 240V single phase, 144 machines, 48 on each phase
- Load: 48 machines x 3.4kW each = 163.2kW per phase.
- PDU: one for every 12 machines
- Busbar in the data center: 50x15 mm, 23 µΩ/m
- Cables from busbar to PDUs: AWG2 (33.6mm^2), 0.513 Ω/km
- Transformer Rating: 2500 kVA
- Phase current Delta-Wye (see reference)
  - Primary phase current = line current/√3 = (2500/3)/(15√3)/√3 = 18.5A (rms) = 26.2A amplitude
  - Secondary phase current = line current = (2500/3)/(0.240√3) = 2005A (rms) = 2835A amplitude

Transformer model parameters

Basic parameters

Windings ratio (for Delta-Wye, the ratio of line voltage is √3 times greater than the nameplate ratio of 15/0.415):

$$N = 15/0.240 \approx 62$$

Transformer Inductance (Delta-Wye):

$$L = (V/I)/2\pi f = (15000/18.5)/(2\pi * 50) = 2.58H$$

Transformer load-loss (percent impedance)

- Data from actual 2500 kVA transformer
  - 20670/2500000=0.8% loss
  - 5.77% impedance voltage (percent of the rated primary voltage required to induce rated currents in both windings when secondary is shorted)
- Simulate with 5.77% of primary voltage (1224 V amplitude) and short circuit on secondary.
- Load-loss simulation circuit
- Adjust parameters so rated current in primary is approximately achieved (26.2A amplitude)

$$R_{pri} = 32\ \Omega$$

$$R_{sec} = 0.0038\ \Omega$$

Transformer no-load loss (iron loss)

- Data from actual 2500 kVA transformer
    - 2253/2500000 = 0.1% loss
    - No load current 0.19%
- Simulate with 240V (339V amplitude) on secondary and open circuit on primary.
- No-load loss simulation circuit
- Adjust parameters to exciting current of 0.19% of rated = 2835*0.0019 = 5.39A amplitude achieved.

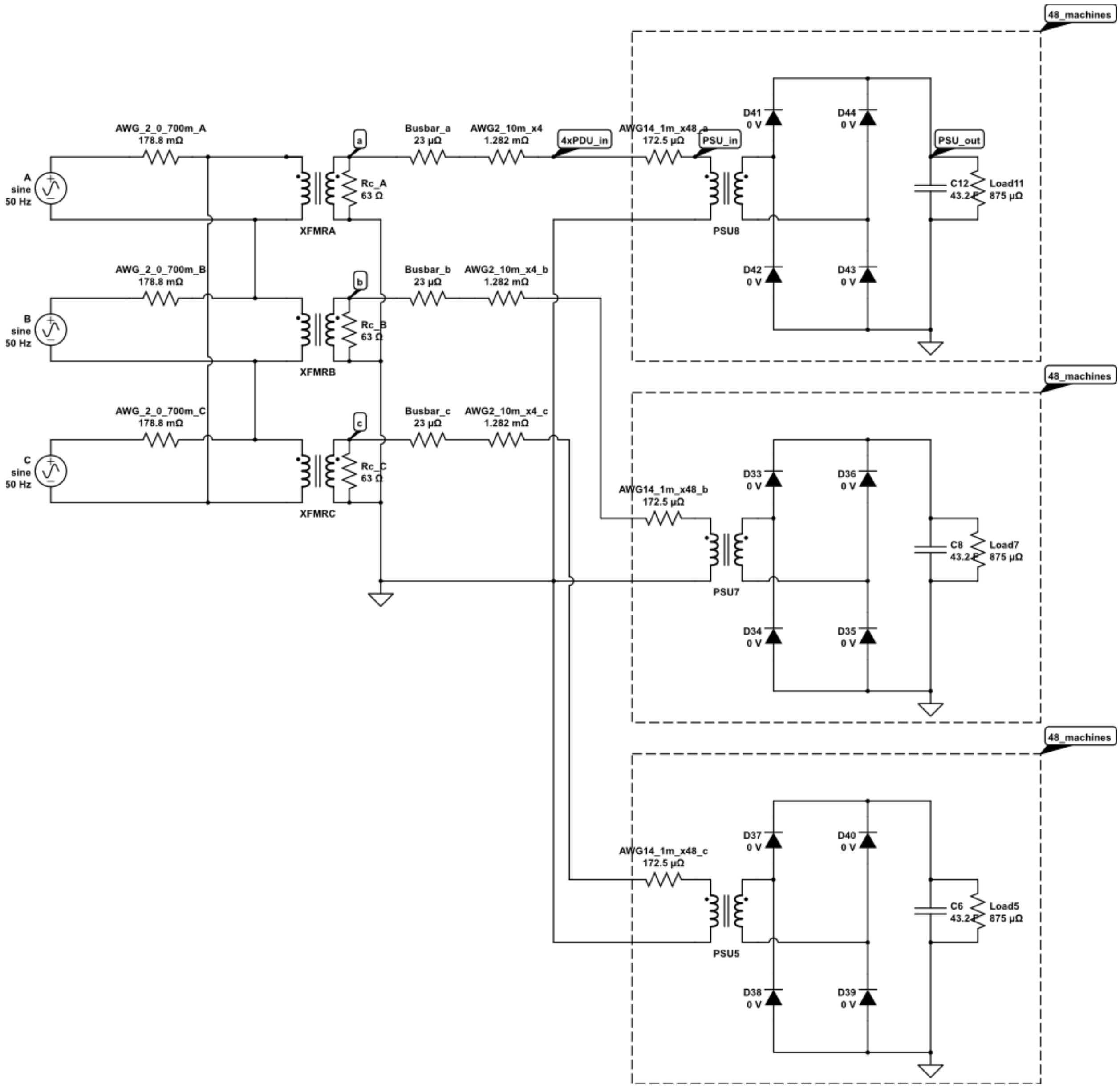
$$R\_c = 339/5.39 = 63\Omega$$

Data center module simulation

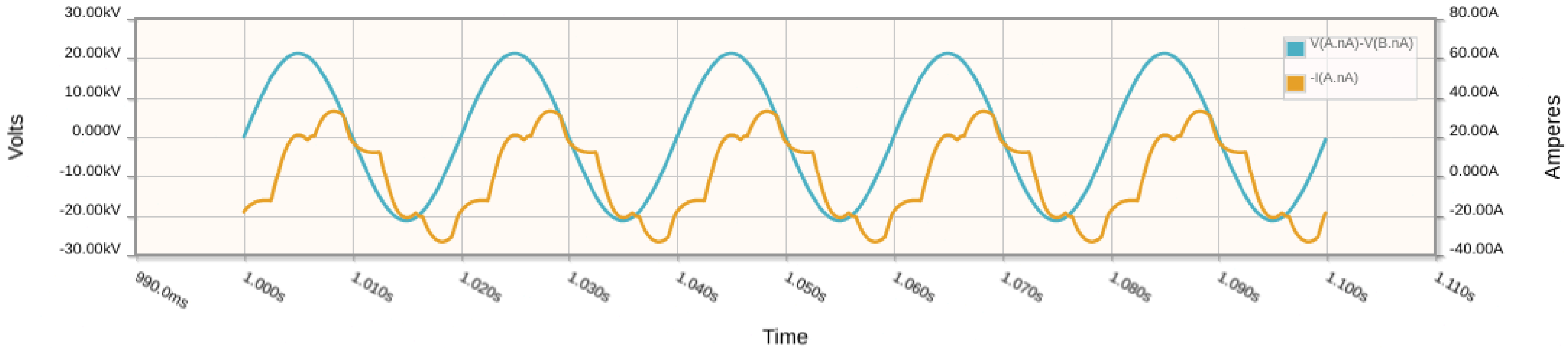
Equivalent circuit for 48 machines

A single data center module has 144 machines, 48 on each phase. Rather than simulating each machine individually, we can use an equivalent circuit for 48 machines. They are connected in parallel, so we want voltage to remain the same and current to be 48x. So in the equivalent circuit, we use the single machine values of R_{load} , R_{PRI} , R_{SEC} and L divided by 48, and C multiplied by 48.

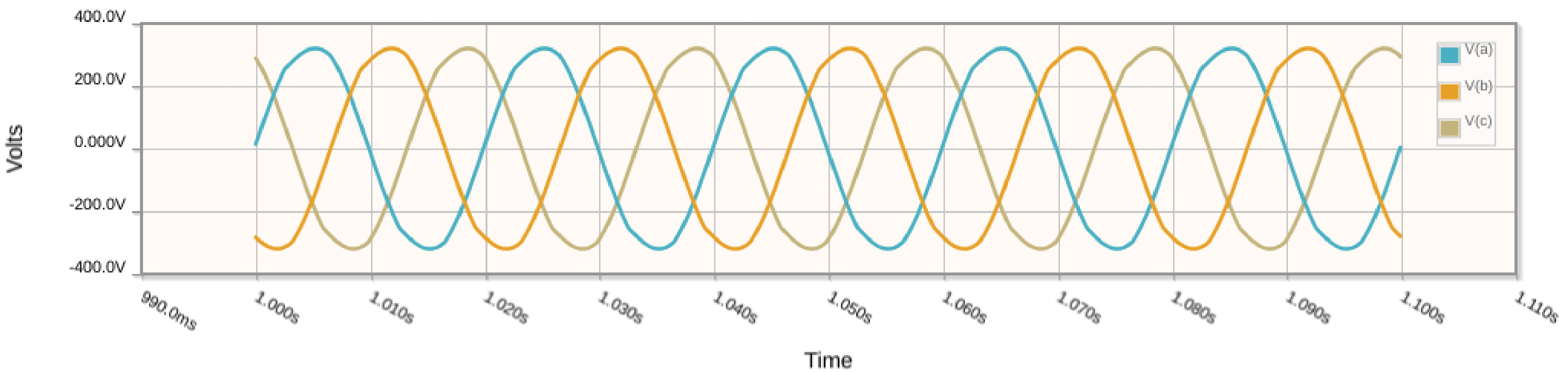
Simulation circuit

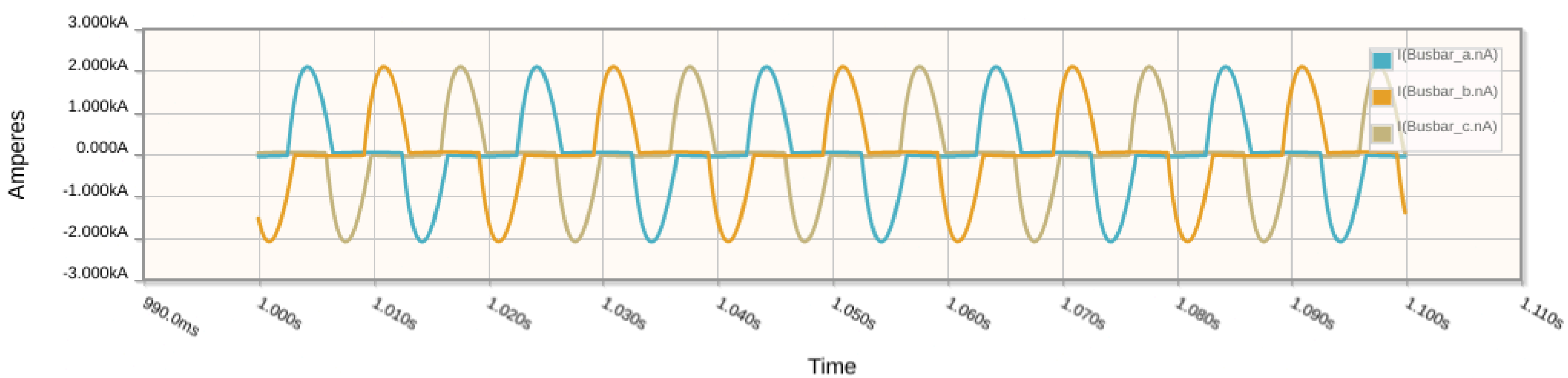


Input line voltage and current (one phase)

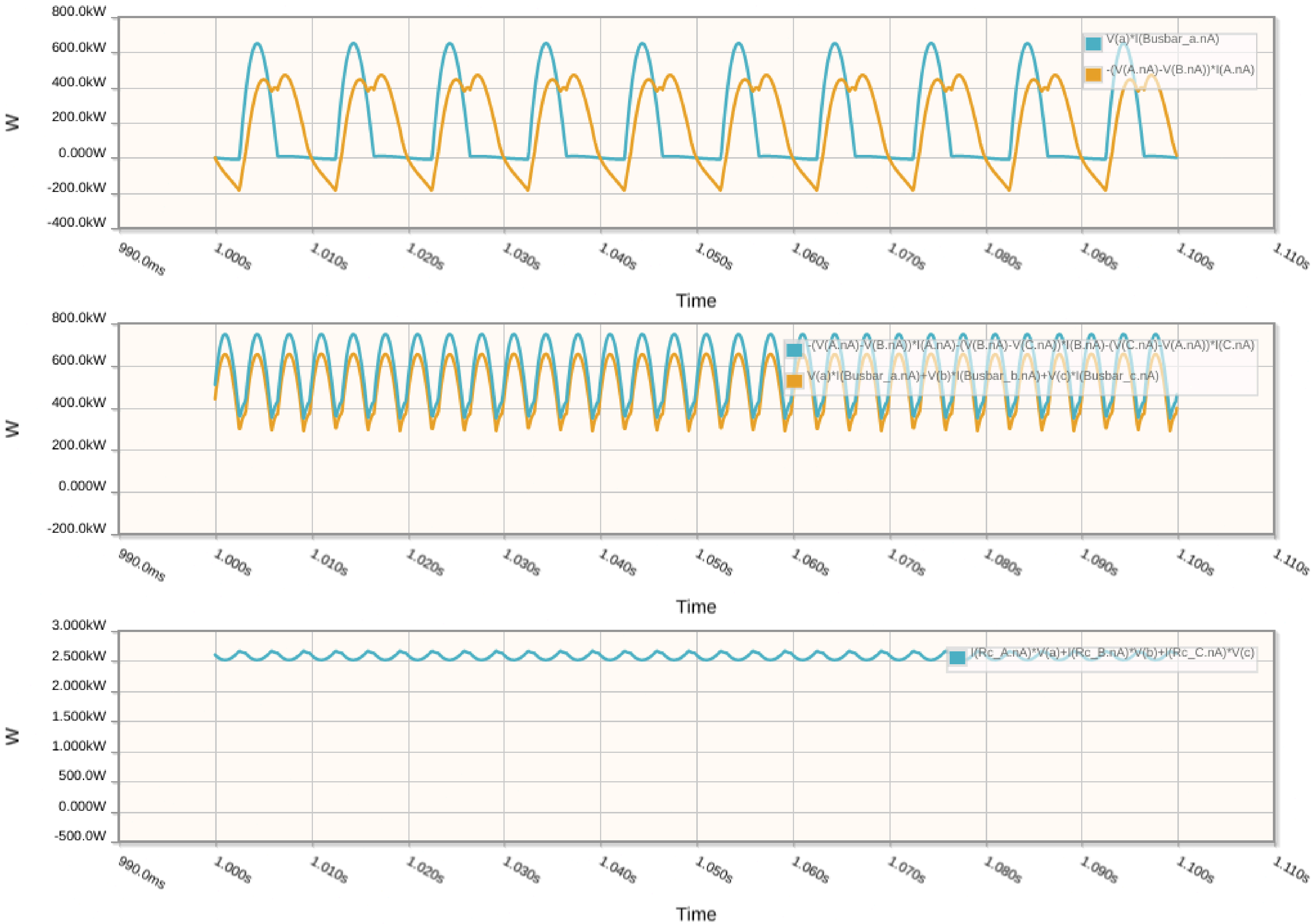


Transformer output voltages and currents (3-phases)

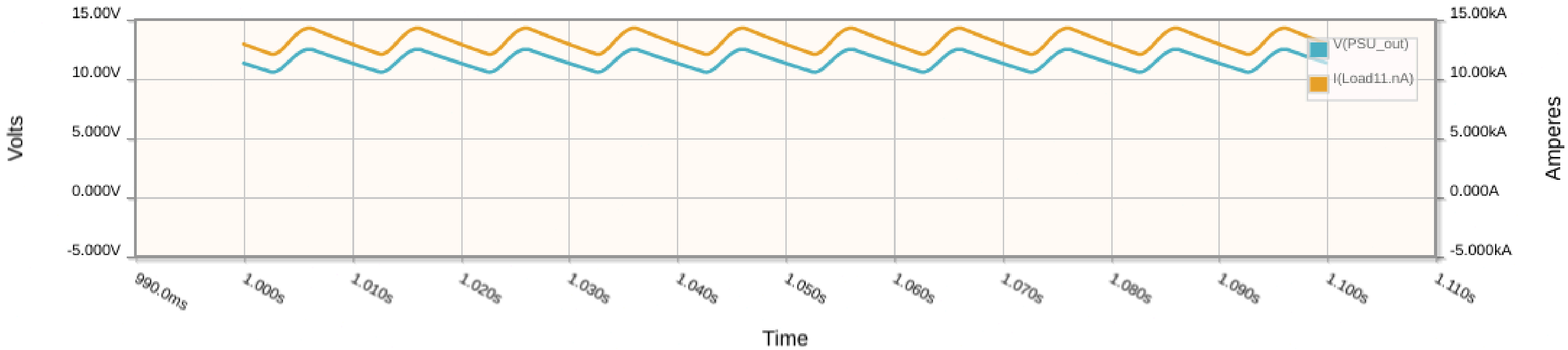


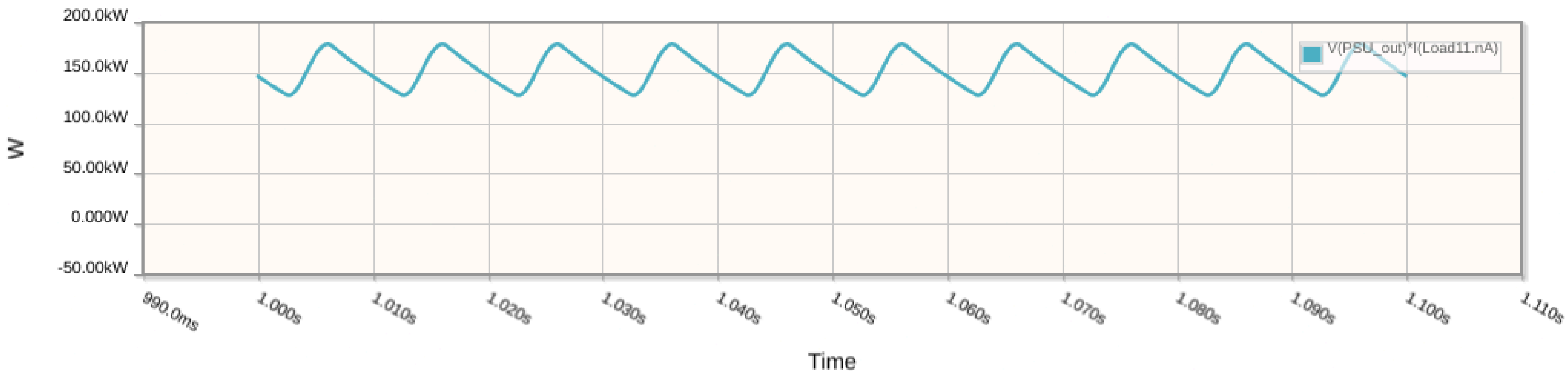


Transformer input and output power (one phase, sum of 3 phases) and core losses (sum of 3 phases)



48 machine load voltage, current and power





Simulation summary

Input voltage	15,004	V
Input current (per phase)	22	A
Input power (per phase)	309,130	W
Input power (sum of 3 phases)	624,359	W
Single data center module		
Container input voltage	233	V
Container input current (per phase)	977	A
Container input power (one phase)	296,424	W
Container input power (sum of 3 phases)	529,980	W
PDU Input power	44,165	W
Load power (per 48 machines)	153,056	W
Load power (144 machines)	459,169	W

Recall that our single machine circuit model overestimates PSU power losses so the input power and current levels simulation are upper bounds, suitable for safety and capacity planning, but not accurate for cost purposes.