QRB power requirements & simulation

Revised: 2024-09-24

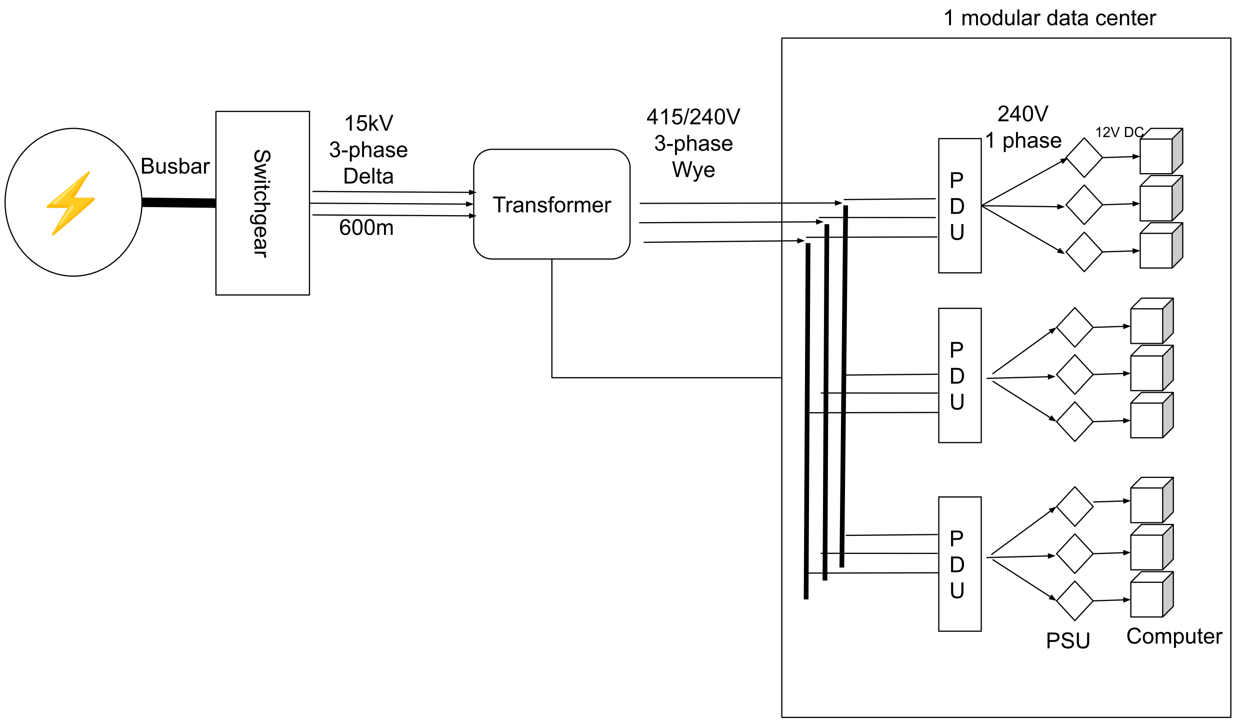
Objective

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

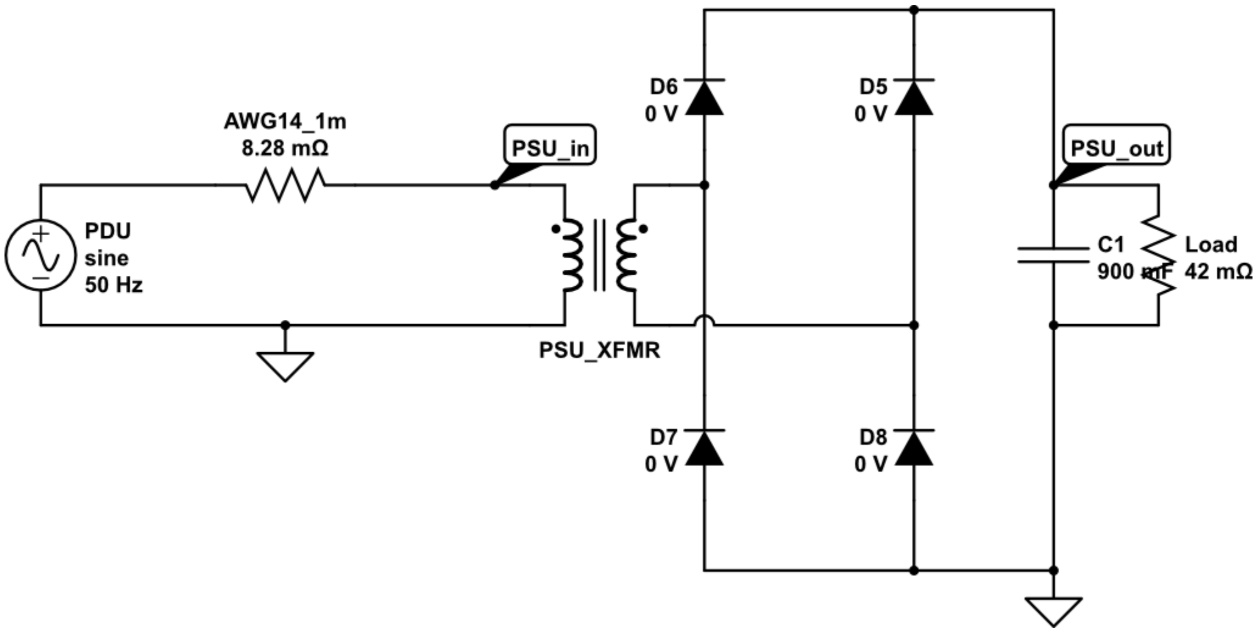
Background

QRB is deploying modular data centers for energy-intensive computation.

- Each module is a shipping container, loaded with 100-300 high power computers.
- The computers run on direct current 12V DC, drawing 3-4kW. They come with power supply units (PSUs) drawing 10-20A at 240V.
- Datacenter modules are deployed in electrical network substation compounds.
- Power supplied is AC 3-phase Δ configuration (3-wire) at 15kV, 50Hz.
- Transformer steps down to AC 240V Y config (4-wire): three 240V circuits plus neutral.
- Via switchboard, each circuit feeds 1/3 of the machines in the datacenter
- The machines are on shelves, each shelf is supplied by one power distribution unit (PDU)

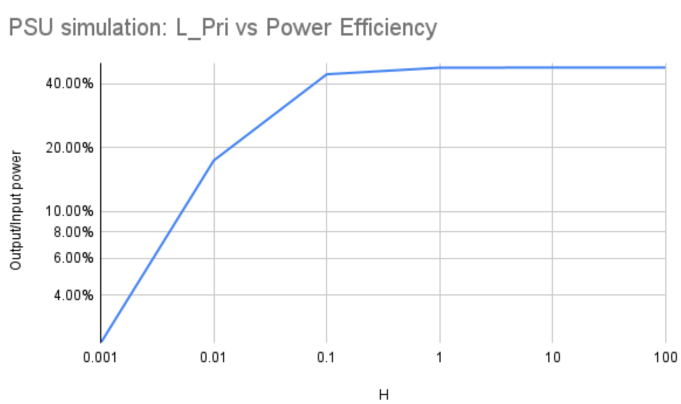


Single machine circuit model

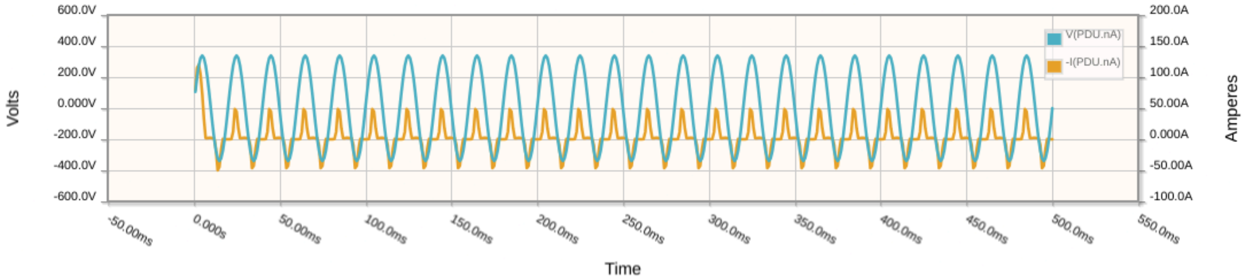


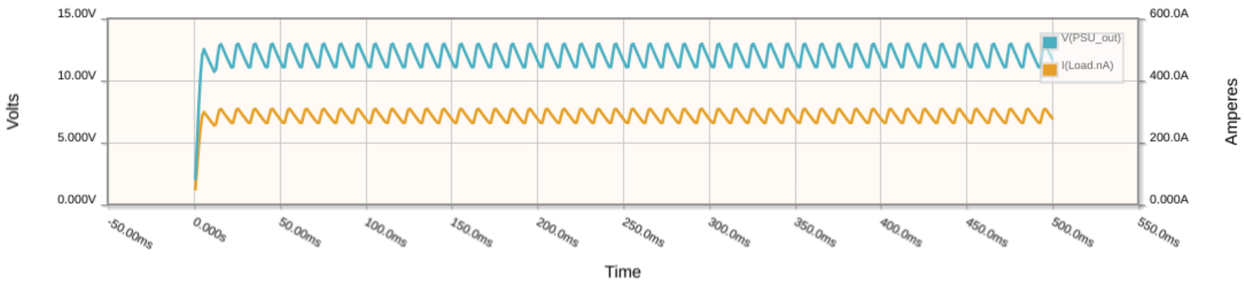
A single machine (computer+PSU) can be modeled by this circuit model

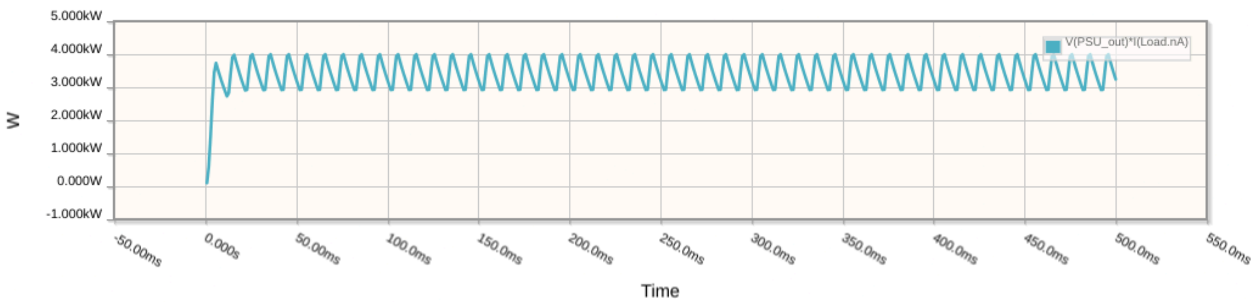
- PSU input :
  - 240V AC single phase, 12V DC output
  - Power cord: AWG14 (2mm²), resistance 8.282 Ω/km
- Load:
  - Expect 3400W power consumption
  - Model the load as a pure resistance R_{load} = 12*12/3400 = 0.042 Ω.
- PSU simulation parameters:
  - N = 24 turns; resistance R_{PRI} = 0 Ω, R_{SEC} = 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.

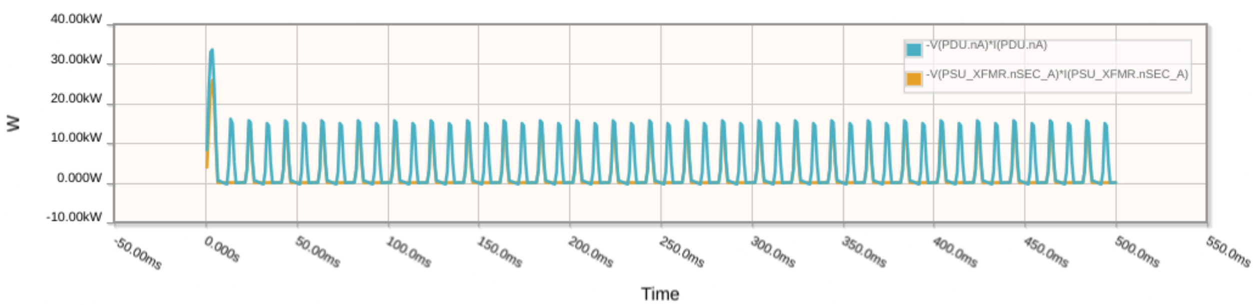


Note: With these parameters, the efficiency (output/input power) of the simulated PSU is 48%. Real PSUs achieve 80-90% efficiency. Since we are calibrating the simulation to the output power (per machine consumption), the input power will be potentially overestimated by ~2x.









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.

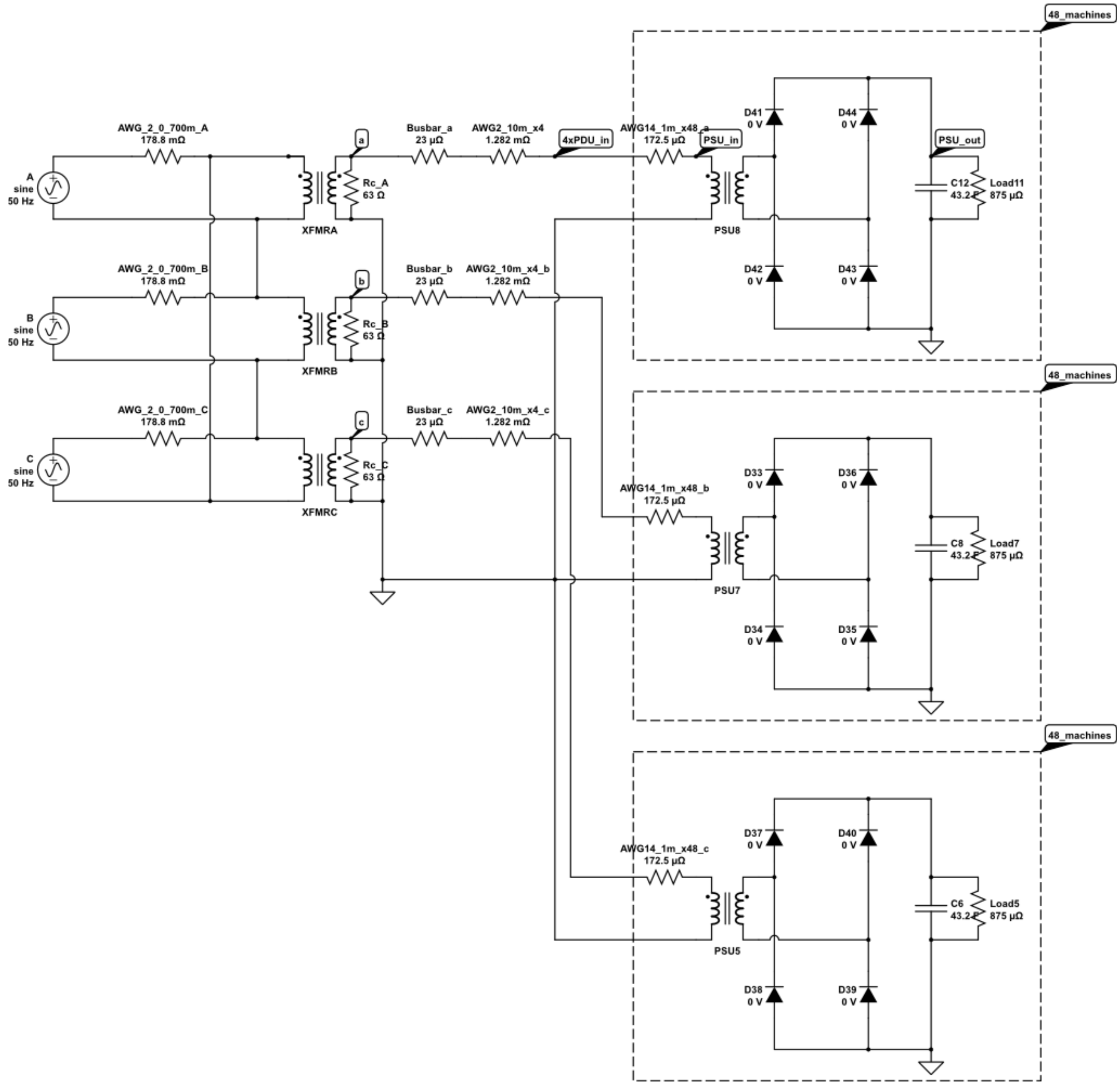
$$R\_c = 339/5.39 = 63\Omega$$

Data center module simulation

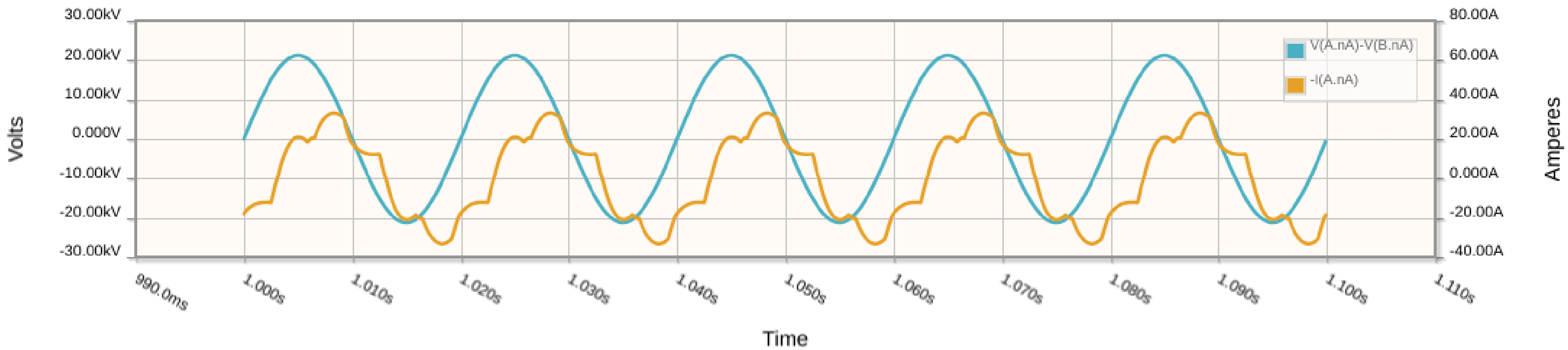
Equivalent circuit for 48 machines

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.

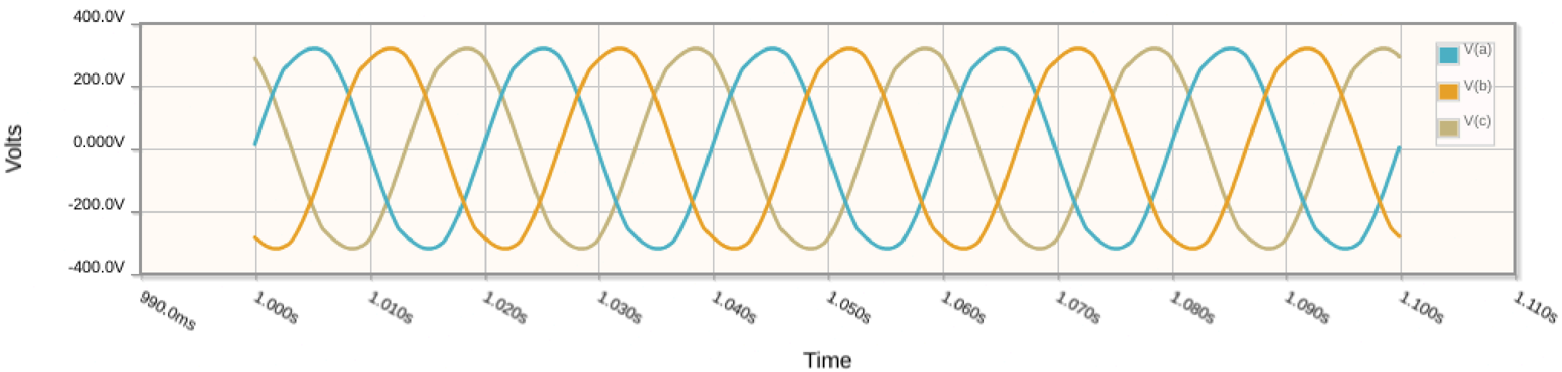
Simulation circuit

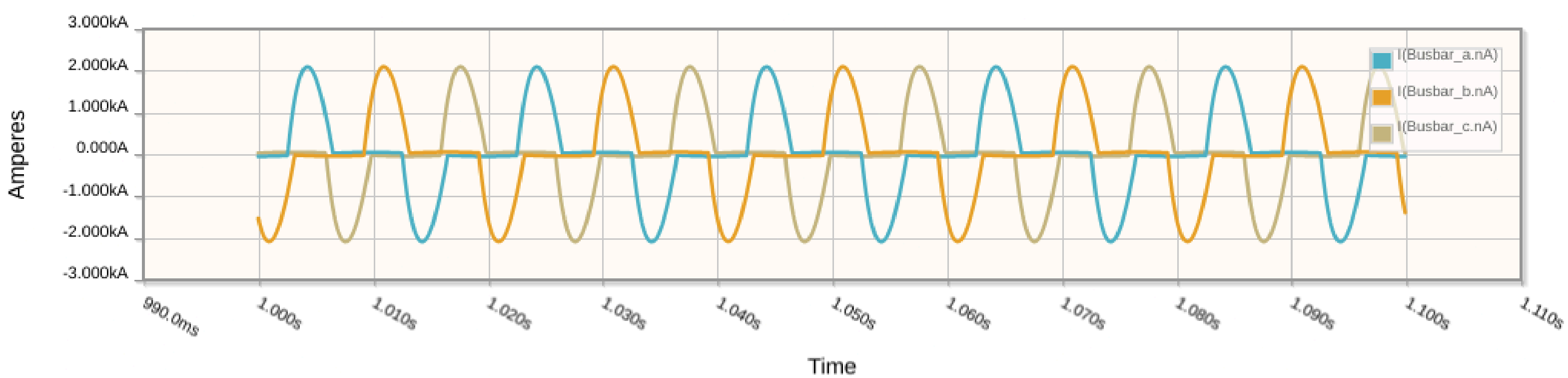


Input line voltage and current (one phase)

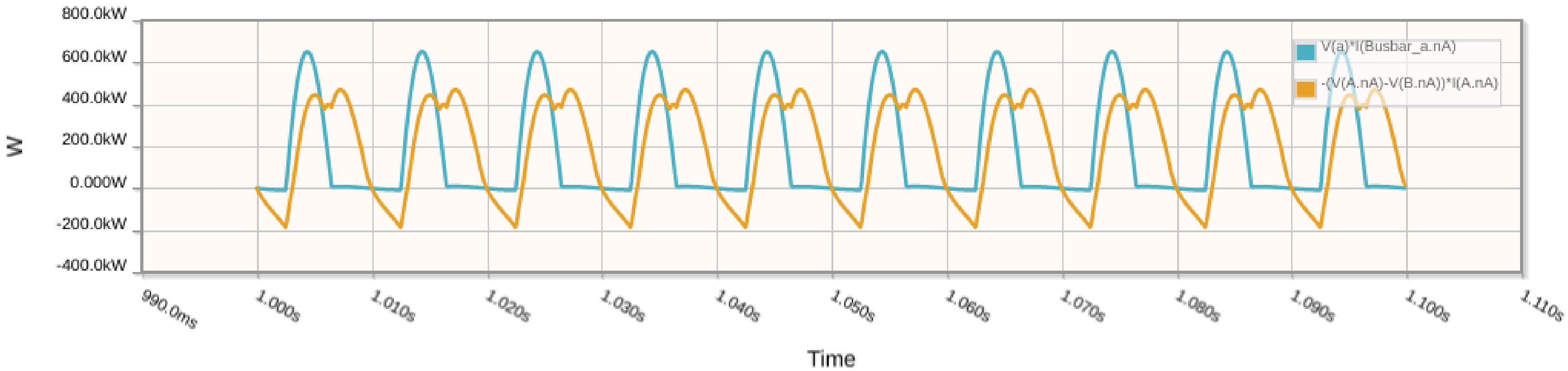


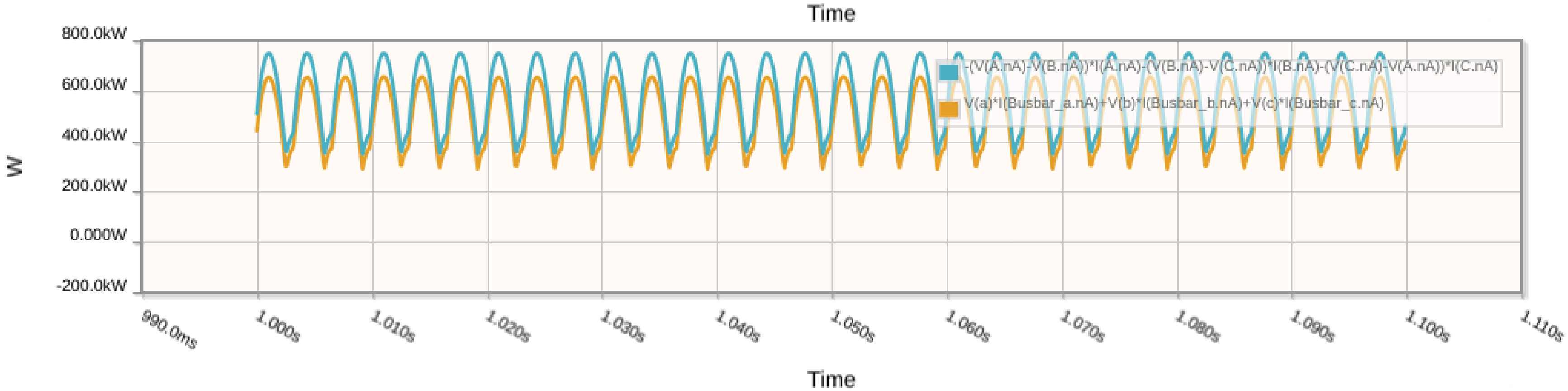
Transformer output voltages and currents (3-phases)

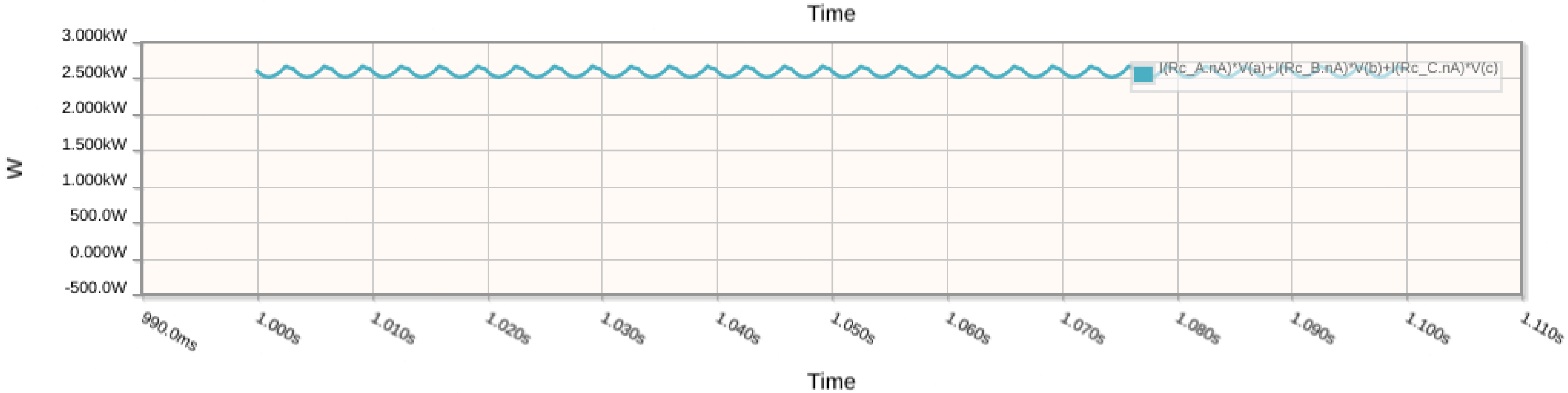




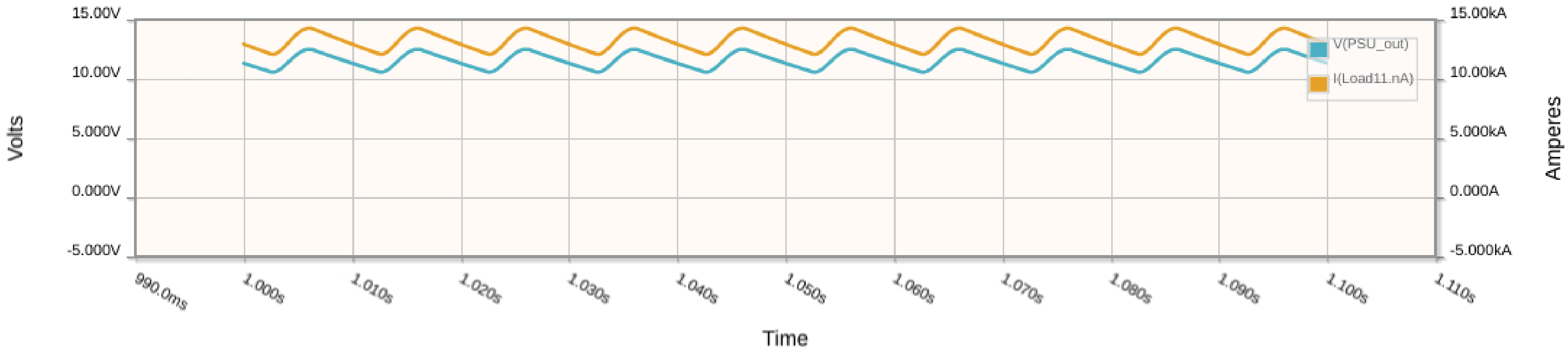
Transformer input and output power (one phase, sum of 3 phases) and core losses (sum of 3 phases)

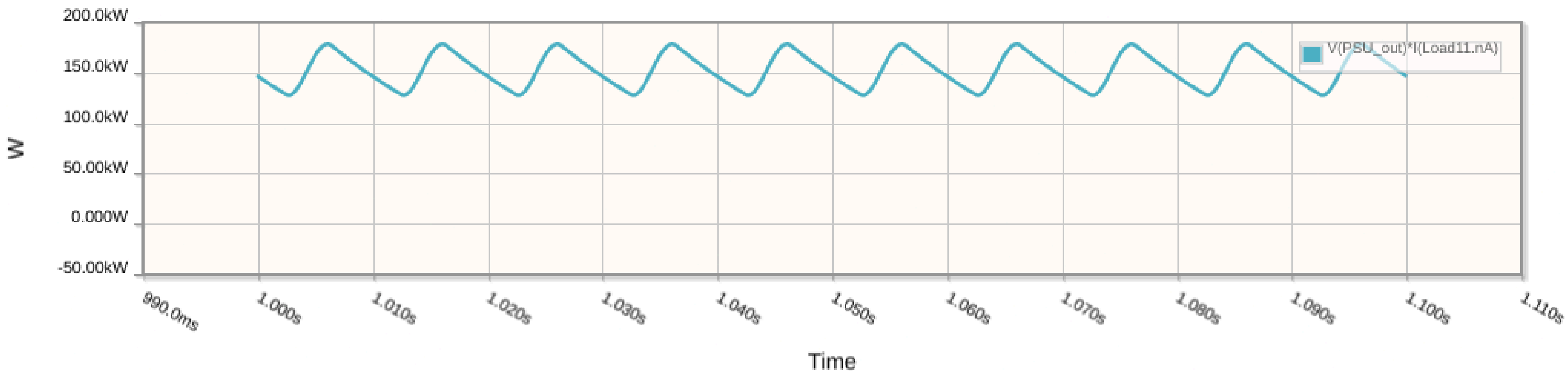






48 machine load voltage, current and power





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.

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

- Supply: 50Hz, 3-phase 15kV
    - Y (Wye) primary: input amplitude is 15000√2/√3=12,247V line-to-neutral)
- Load: 240V single phase, 120 machines, 40 on each phase
- Transformer: Y-Y (Wye-Wye) configuration step-down transformer
- Windings ratio:
    - Y-Y: N = 15000/√3/240 = 36
- Output: 40 machines x 3.4kW each = 136kW per phase.
- Rating: Assuming power ratio = 0.8 => rating 136/0.8 = 170kVA per phase (510kVA total)
- Phase current
    - Primary: 170kVA/(15kV/√3) = 19.6A (rms) = 28A amplitude
    - Secondary: 170kVA/240V = 708A (rms) = 1kA amplitude
- Inductance: L= (V/I)/2πf = (12247/28)/(2π*50)= 1.4H
- Transformer load-loss/Impedance: Assuming 5% loss
    - Simulate with 5% primary voltage (612.4 V amplitude) and short circuit on secondary. Rated current in primary (28A amplitude) achieved when $R_{primary}$ = 11 Ohms and $R_{secondary}$ = $R_{primary}/N^2$ = 0.0085 Ohms
    - Load-loss simulation circuit
- No-load loss: Assuming 2%
    - Simulate with 240V on secondary and open circuit on primary. Exciting current of 2% of rated = 708*0.02 = 14.16A (rms) = 20A amplitude achieved when R_c = 17 Ohms on secondary, or equivalently, R_c = 17*36² = 22032 Ohms on primary.
    - No-load loss simulation circuit

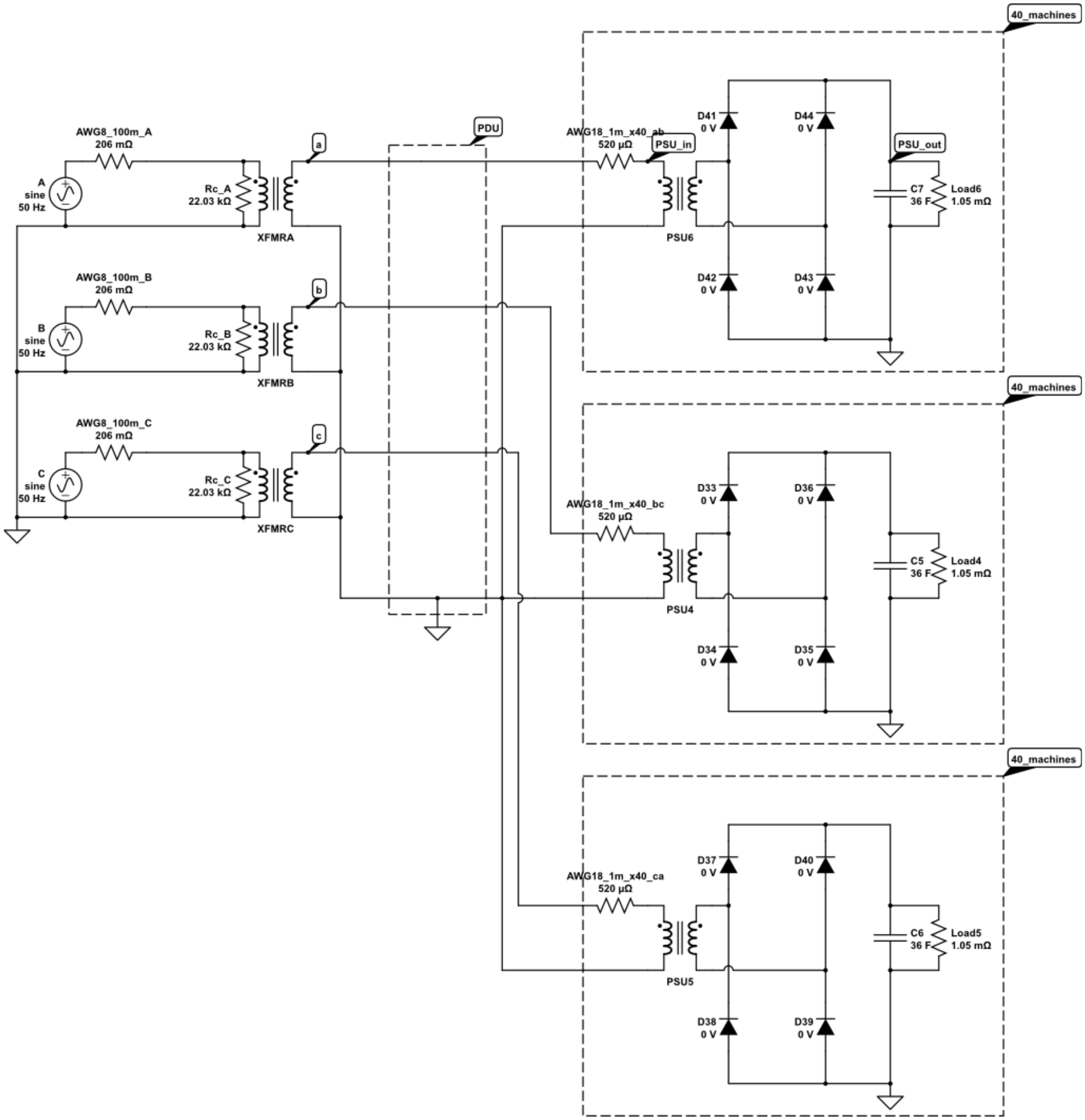
Simulation summary

Circuit model and simulation

Voltage	Primary	15kV	(3 phase RMS)	
	Secondary	228V	(per phase line-to-line RMS)	
Current	Primary	27A	(per phase RMS)	
	Secondary	750A	(per phase RMS)	
	Per machine	19 A		
Power	Primary	182 kW (per phase)		546 kW (Total)
	Secondary	160 kW (per phase)		480 kW (Total)
	Per machine	3.4 kW		
	Total output	416 kW		

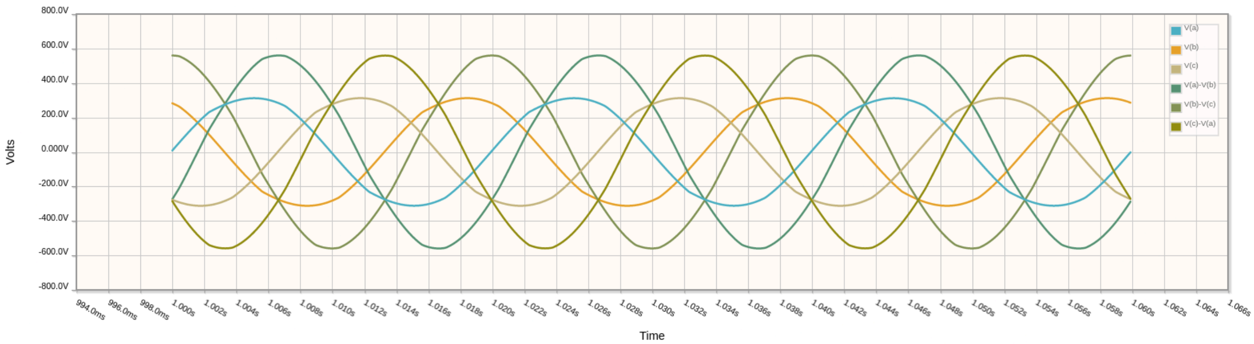
qrb power simulation

Circuit model

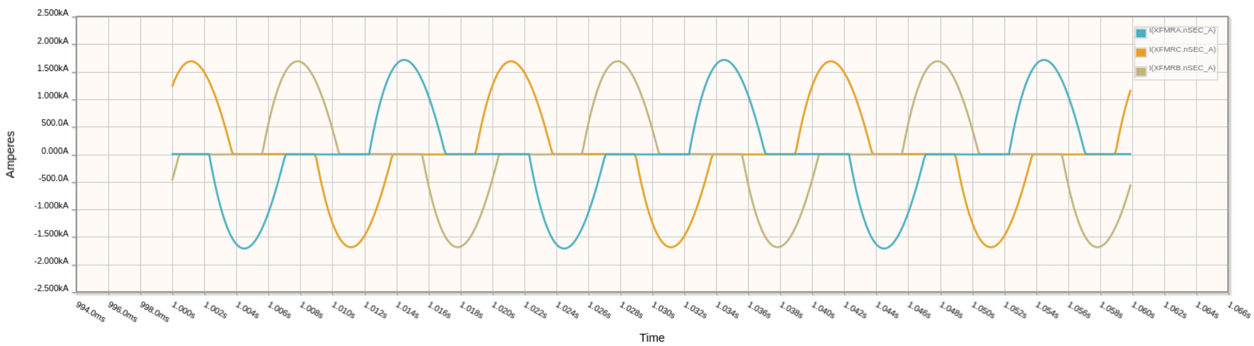


Simulation graphs

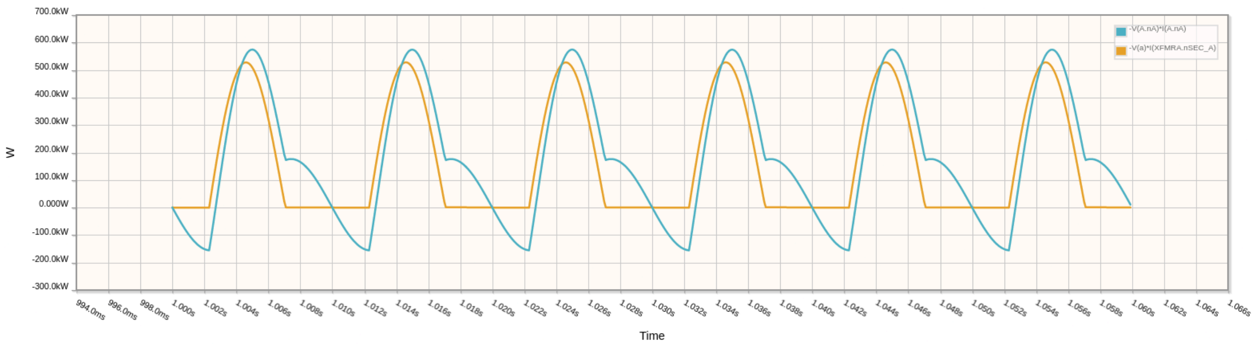
Transformer output voltage per phase



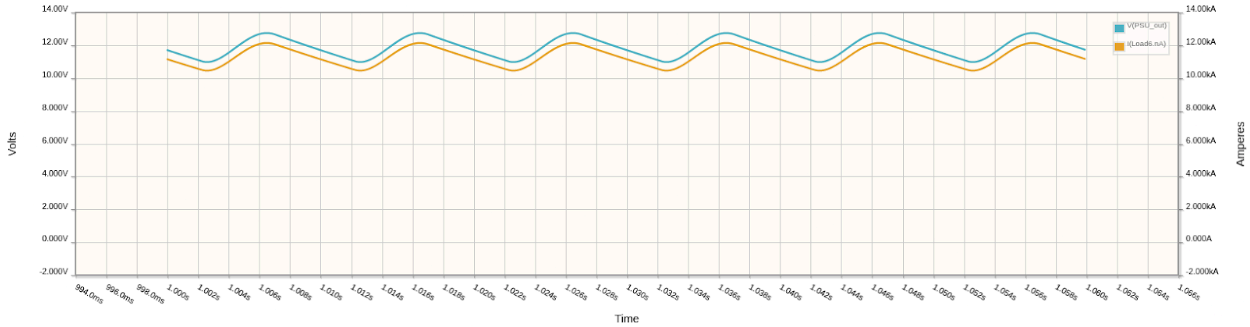
Transformer output current per phase

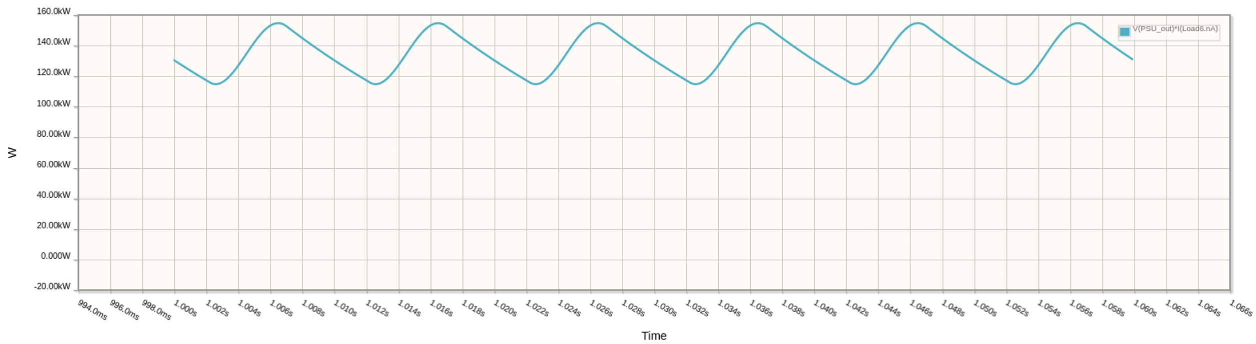


Transformer input and output power (per phase)

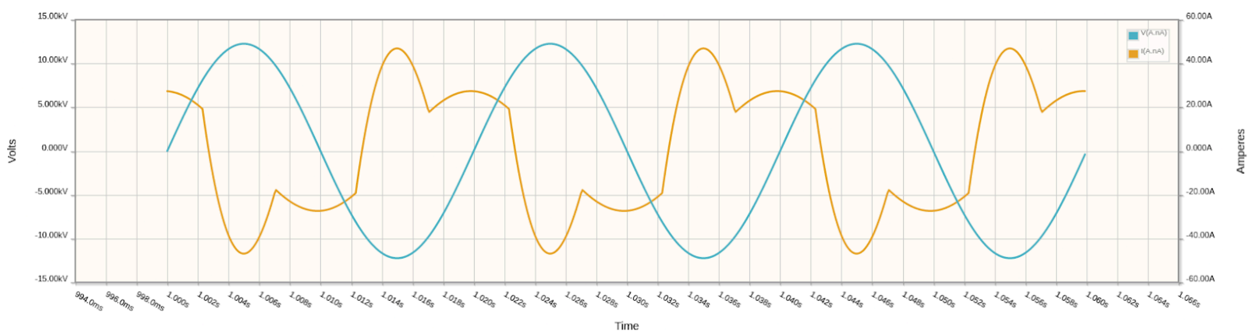


40 machine output voltage, current and power





Transformer primary (per phase) voltage and current



Notes

From: 132kV 50Hz
To: 415/240V AC 3 phase 60Hz (Blockstream MMU)(AI: check re: "other voltage configurations")

schneider
Cooling medium Oil
U1r = 132 kV +/- 10 % with 550 kV BIL
U2r = 11 kV
Sn = 40 MVA (transformer rated apparent power)
Connection group: Dy11
NLL = 25 kW (no load losses)
LL = 158 kW (transformer on load losses)

https://hmveng.ie/project/uk-132-kv-data-centre/
132 kV AIS equipment,
132/11 kV transformers, and the
11 kV modular switchgear building

https://www.betaengineering.com/projects
- Impedance level to optimize capex vs efficiency
- GIS (Gas insulated) vs AIS (Air-insulated switchgear): GIS costs 10%-40% more up front but easier to maintain

Busbar: in substation ~ 2000 mm^2
3MW / 132 kV = 23-32A
3MW / 240 V = 10-15 kA,
10-15A x 1000 miners

15kV/33kV to 415V/240V transformer, indoor or outdoor, need 3,000 kVA E.g.
- https://www.eaton.com/us/en-us/catalog/medium-voltage-power-distribution-control-systems/envirotran-three-phase-pad-mounted-transformers.technical.html
- https://stevenengineering.com/tech_support/PDFs/45TMEDVOLT.pdf
- https://www.larsonelectronics.com/product/150984/1000-kva-transformer-15000v-delta-primary-480y-277-wye-n-secondary-nema-3r-oil-cooled
- https://www.larsonelectronics.com/product/151079/500-kva-pad-mount-transformer-15000v-delta-primary-240v-delta-w-120v-center-tap-secondary

https://electrical-engineering-portal.com/res/Design-of-132-33KV-Substation.pdf

For a given core material, cross section and frequency, there's a maximum volts per turn. If you want to use the winding at a certain voltage, then you need enough turns to support that voltage.

https://electronics.stackexchange.com/questions/571566/does-the-number-of-turns-in-turns-ratio-matter-in-transformers

Peak Power Modeling for Data Center Servers with Switched-Mode Power Supplies
Provisioning power infrastructure for data centers is extremely costly; typical installations incur $10-$20 per provisioned watt [3]. A large fraction of this cost is associated with installing power distribution units (PDUs), which provide power to groups of servers. Often, total PDU capacity is overprovisioned [6, 8, 12].

Power supply can be modeled as RC circuit with switch-diode

Simulator https://en.wikipedia.org/wiki/LTspice

15kv to 240V transformer should be close to load to minimize voltage drop
Assume 15kv source -- (100m) -- xformer 240V -- (1m-5m) - PSUs
Transformer resistance: secondary resistance ~= primary resistance / N^2
where N is turns ratio
https://sound-au.com/articles/psu-simulation.htm#intro

1 machine
PSU in: 3404W/220V = 16A
For 40, 640A R = 240/640 = 0.34375 Ohms
PSU wire gage AWG 18= 0.0403 inches diameter
6.385 Ohms/1000ft
20.8 Ohms/km
PSU out: 3404W/12V = 285A
Load R = 12V/285A = 0.042 Ohms

Phase 1: 1 container with 116 x M31S

15kV input
395kW => 395kW/15kV = 26A
Full dc xfmr in: 1MW/15kV => 67A
Xmfr out: 1MW/220V => 4.5kA
Power line wire gage AWG 8 = 0.12849 inches diameter
http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/wirega.html
0.6282 Ohms/1000ft
2.06 Ohms/km

Copper resistivity: 1.724 x 10^{-8} Ohms m
Feeder line should support 8 DC containers up to 8MW
8MW/15kV = 533A => 180A per phase

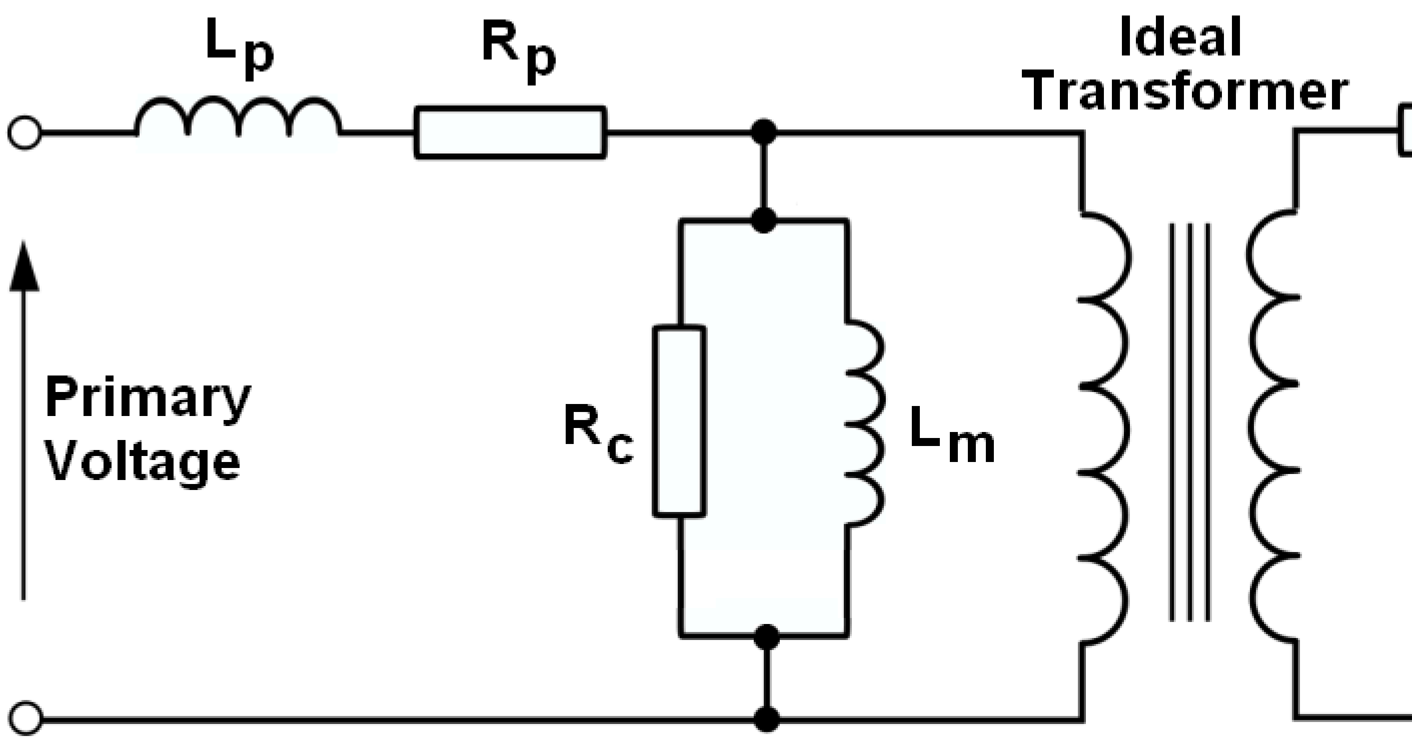
wire gauge
For copper https://precmfgco.com/wire-gauge-sizes-guide/:
00 (2/0), 0.3648inches diameter, 67mm^2 area (0.1045 sq in),
0.2555 Ohms/km

For aluminium: https://nvlpubs.nist.gov/nistpubs/Legacy/hb/nbshandbook109.pdf
Gauge 250,000, 126 mm^2
0.22 Ohms/km at 20C, 0.25 Ohms/km at 50C

Determining impedance (see percent impedance test

- https://www.eaton.com/us/en-us/products/medium-voltage-power-distribution-control-systems/transformers/medium-voltage-transformers--fundamentals-of-medium-voltage-tran.html
- https://www.landisgyr.com/webfoo/wp-content/uploads/2012/09/TLCpaperLG1.pdf
- Assume 5.75% @ 1000kVA Medium Voltage Transformers Specification Guide
- Short-circuit low-voltage side
- 5.75% of input voltage is such that ~~*secondary*~~ primary current = rated current (FLA)
- FLA: 1000kVA/240V/ sqrt(3) = 2624A line to line or 1515A line to neutral
- (https://www.alfatransformer.com/downloads/reference/medium_voltage_transformers_full_load_amp_chart.pdf)
- 5.75% impedance => 15kV * sqrt2 * 0.0575 = 862.5V x sqrt2 = 1219.75V amplitude

Transformer equivalent circuit http://www.stades.co.uk/



PSU - higher inductance L = 10H => better rectified shape, flat bottom, more constant DC

Low-voltage side details:
Distribution transformer feeds the low voltage switchgear and switchboards that provide the final utilization voltages to the data center power racks.
https://www.flex-core.com/engineering-resources/using-current-and-voltage-transformers-in-data-centers/

PDUs: 415/240V 1000kVA
https://www.deltapowersolutions.com/en-us/mcis/data-center-power-distribution-cabinet-specifications.php

https://www.raptorpowersystems.com/resources/crypto-mining-with-415v

https://raptorpower.us/support/blog/crypto-power-guide

- 415V/240V 3 phase wye power configuration. This power configuration provides the highest efficiency and has the lowest circuit breakers costs in your main panel and the branch breakers in your PDUs. A 415/240V 3 phase wye configuration will have 240V single phase line at the outlet of your PDU.
- Main disconnect
- Circuit breaker panel
  - freestanding for > 1000kVA
  - Wires or busbar: current level
  - magnetic/hydraulic breaker to avoid dependency on ambient temperature
  - Rated for +20% of actual current
- PDUs: 3-phase input Y configuration 415V, output single phase 240V
  - 0U vertical, one per rack
  - IEC C-13 or IEC-C19 outlets
  - Derate by 20%

Delta-primary/Y-secondary
- delta connection provides path for third harmonic currents to flow
- delta: voltage per phase will be = line voltage, and current will be 1/sqrt(3)
- High-voltage side is not grounded, full insulation required
- Less current -> lower cost of copper on HV side
- Three wires instead of 4 on HV side, lower cost of power lines
- Y secondary beneficial to get single phase and neutral to loads

Switchgear


Indoor metalclad AC metal-enclosed switchgear
Type KYN28-24
Rated Voltage 15 kV
Rated Current 400/800 A
Rated Power-frequency Withstand Voltage 50 kV
Rated Lightning impuse Withstand Voltage 145 kV
Rated Short-Time Withstand Current 31.5 kA
Rated Peak Withstand Current 80 kA
Rated Duration of Short Circuit 3 s
Rated Frequency 50 Hz
Mass 1500 Kg
Protection Degree IP 4X
Serial No. 1709048
Date of Production 2017.09
Standard IEC62271
Daqo JIANGSU DAQO CHANGJIANG ELECTRIC CO.,LTD.
Property of EEP
EEP00018234