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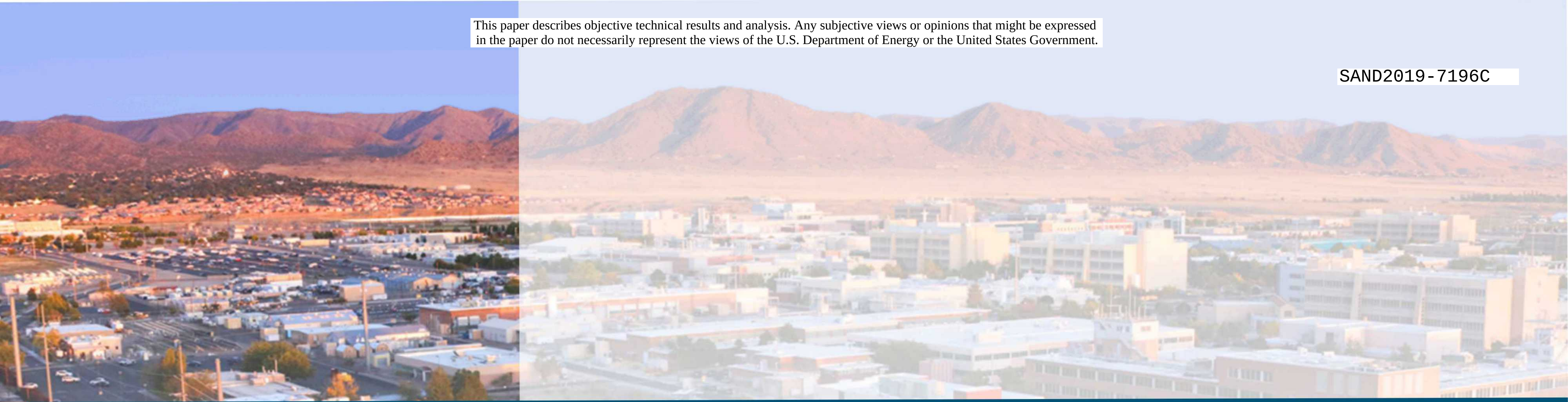

Fault Current Correction Strategies for Effective Fault Location in Inverter-Based Systems

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Standard Radial AC Feeder

Time overcurrent relay typically utilized

Energy comes from a single source

Closest breaker between energy source and fault should trip first

- Backed up by breakers in order of closeness to fault along fault path

Underlying assumption

- Sufficient energy is available to feed the fault
- Device settings allow for
  - Full load
  - Temporary overload (by some predefined percentage of full load)
  - Nonoperation during short transients

Integration of Renewable Energy Sources

Renewable energy sources such as solar and wind are stochastic in nature and require and additional power electronics interface.

- Solar energy: depends on weather/time of day
- Wind energy: depends on weather
- Both: Require energy storage for optimal operation

Energy output

- PV arrays: dc current generated
- Wind Farms: ac current of varying frequency is converted to dc before final ac conversion

Both require inversion to recouple to grid or distribute to customers

Current Limited Inverters

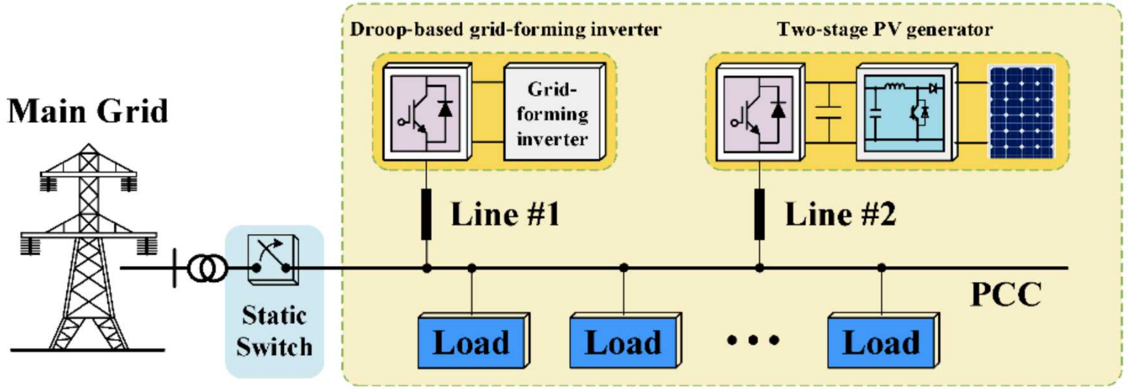
Consider a radial system with a dc source coupled to a distribution system through an inverter

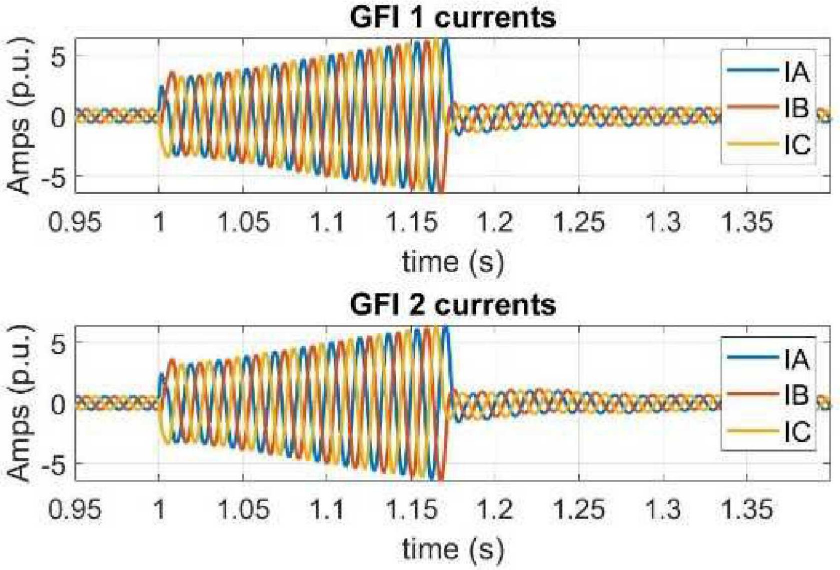
High power inverters are costly

- To protect this high cost equipment current is limited using programming
  - Peak current is immediately cut beyond inverter limit
  - Inverter will time out for a sustained fault

This may result in undesired operation throughout the system.

- Unnecessary loss of service to loads
- Distorted voltage dips during inverter overload





Options for Protection of Inverter Sourced Systems

(1) Develop protection schemes unique to these systems

- Pro: Will allow for solutions better tuned to the problem at hand
- Con: May require substantial research/development investment

(2) Repurpose traditional methods for application to inverter bases systems

- Pro: May not require purchase of any custom hardware
- Con: General solution may not allow for optimal operation

Here (2) is chosen primarily because repurposing existing equipment

- Can allow for reapplication of surplus equipment
- Can potentially reduce/eliminate additional training time for technicians

Problem Overview

Problem

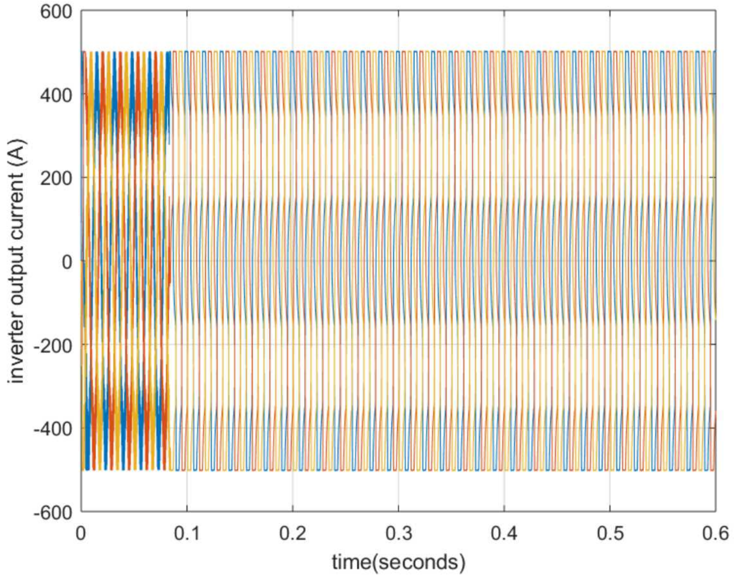
- Inverter sourced systems have a programmed current cutoff
- Cutoff may limit current too aggressively during a fault
- Cutoff may not be overridden as its purpose is avoid damaging the costly inverter
- Seek to use standard inverse time overcurrent protection for radial lines without having to develop or purchase more costly equipment

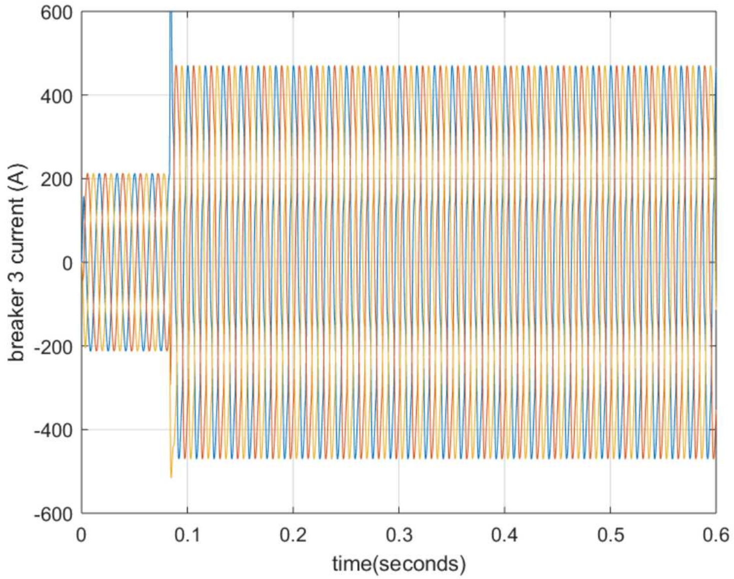
Proposed solution

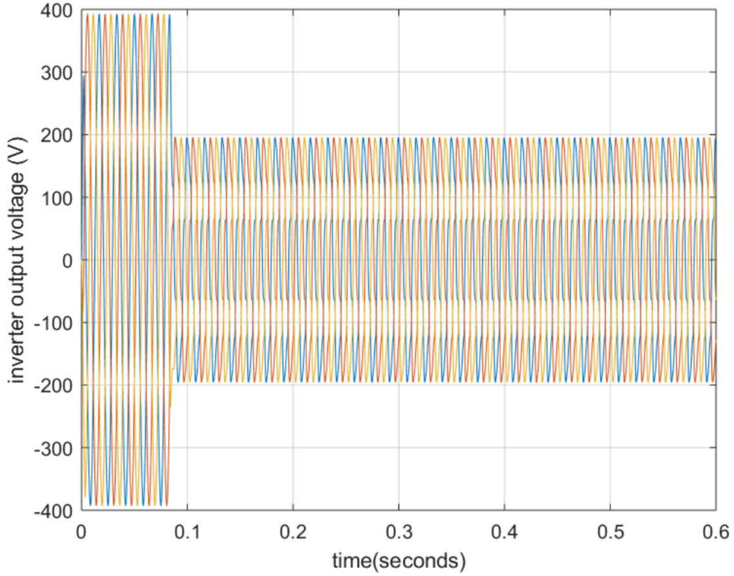
- Place small energy storage unit in parallel with limited source
  - Flywheel/Synchronous condenser
  - Supercapacitor

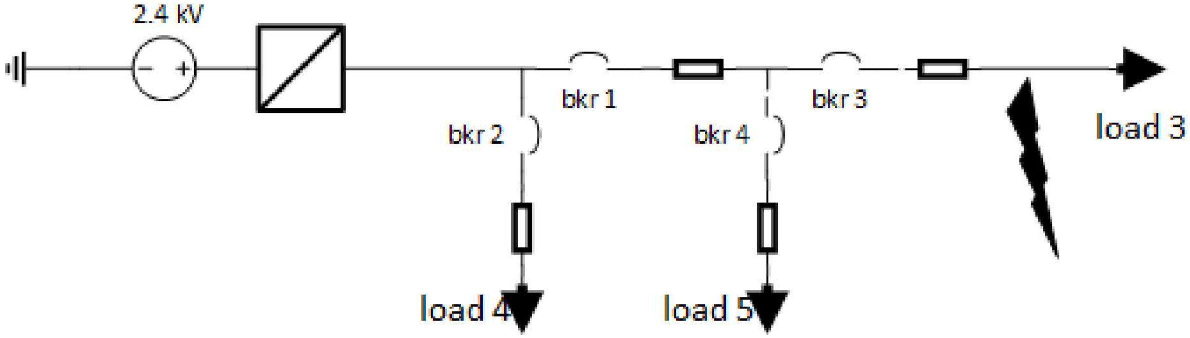
Simulation Results (Uncorrected Case)

- Inverter current clipped at programmed limit
- Designated breaker/backups cannot clear fault
- Bus voltage dips drastically and waveform becomes distorted during sustained fault





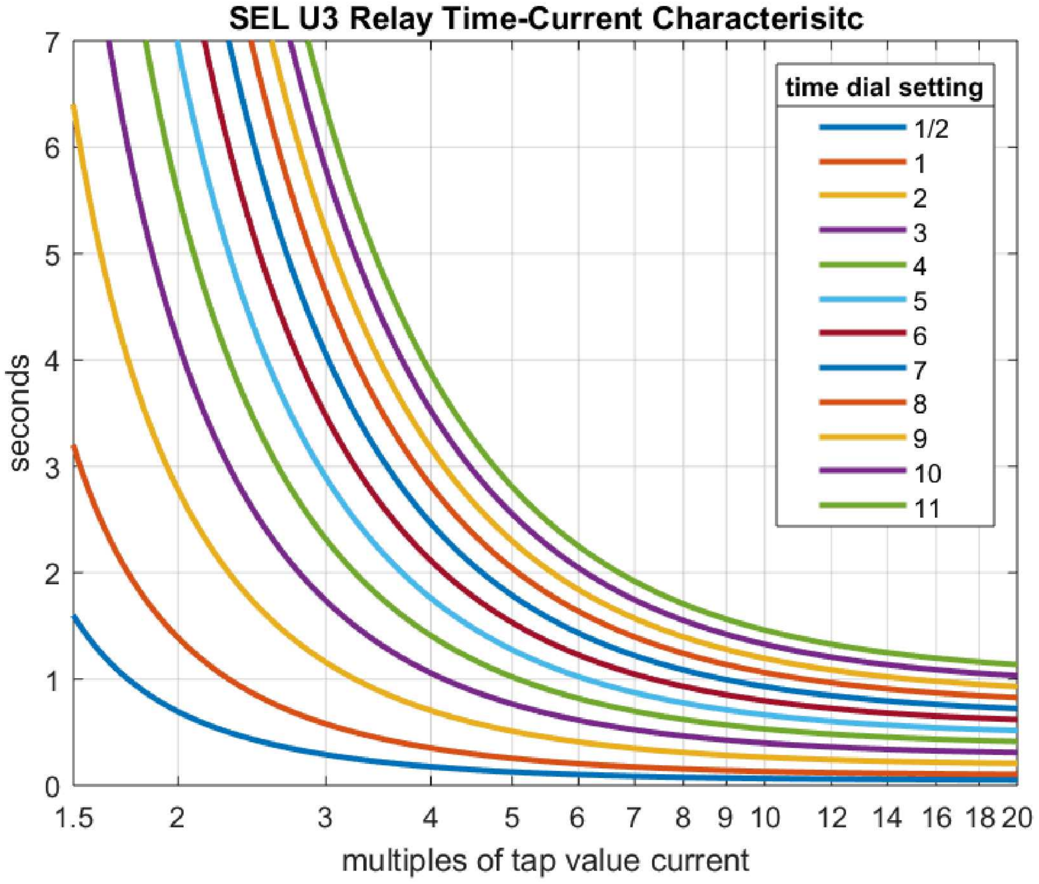




Modeling of Inverse Time OC relays

For this paper, the SEL U3 relay (very inverse) is modeled.

- The time-current characteristic (TCC) for the SEL U3 relay is
- $t_{relay} = TDS\left(0.0963 + \frac{3.88}{M^2-1}\right)$
  - TDS = time dial setting
  - M = multiples of tap current
  - t_{relay} = relay operation time
- The TCC for the SEL U3 is shown to the right (calculated)
- Each curve from bottom to top represents an increasing time dial setting (TDS)



Overall Relay Model

To model this phenomenon, the relay is modeled as a timer which can increment or decrement.

The flowchart to the right demonstrates this process

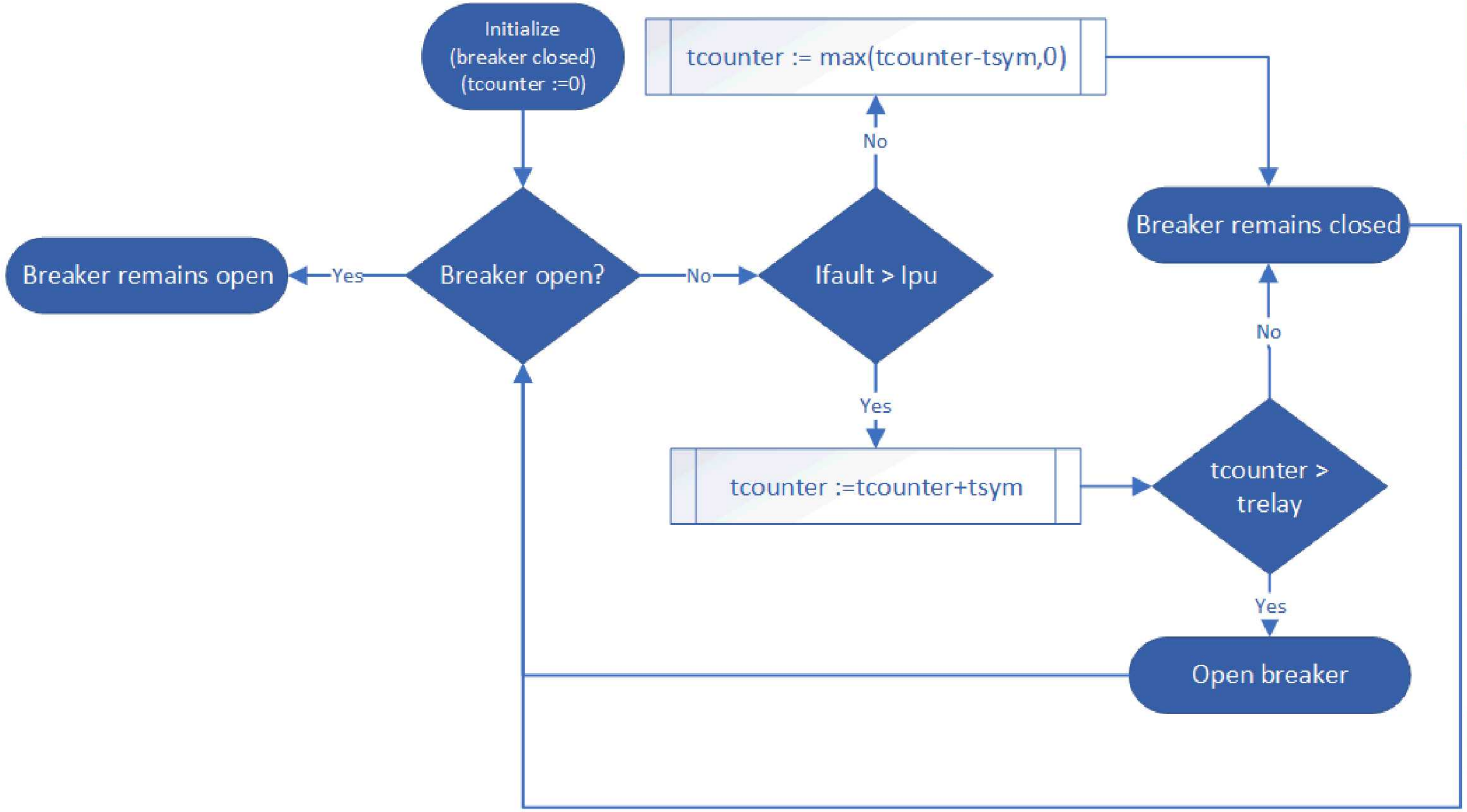
t_{relay} is as earlier defined

$t_{counter}$ is a timer

t_{sym} is the simulation step size

I_{fault} is time varying fault current

I_{pu} is the pickup current



Energy Storage Sizing: Supercapacitor

The energy stored in a capacitor is

- $E = \frac{1}{2} C v^2$

where C is the capacitance and v is the voltage across the capacitor. Differentiating yields

- $P = \frac{dE}{dt} = \frac{C}{2} \frac{dv^2}{dt}$

Assume

- The nominal voltage V_{nom} reduces by some fraction $\alpha \in (0,1)$ over some sufficiently short time interval Δt
- The "constant" power rate over this interval is $P_{energize}$
- Power is positive out of the capacitor
- Losses are neglected

The required capacitor size found from the time integral of v^2 is

- $C \geq -\frac{2 P_{energize} \Delta t}{(\alpha^2 - 1) V_{nom}^2}$

Energy Storage Sizing: Flywheel

The energy stored in the rotating inertia of the synchronous condenser is

- $E = \frac{1}{2} J\omega^2$

where J is the inertia and ω is the angular frequency. Differentiating yields

- $P = \frac{dE}{dt} = \frac{J}{2}\frac{d\omega^2}{dt}$

Assume

- The nominal frequency ω_{nom} reduces by some fraction $\alpha \in (0,1)$ over some sufficiently short time interval Δt
- The "constant" power rate over this interval is $P_{energize}$
- Power is positive out of the capacitor
- Losses are neglected

The required inertia found from the time integral of ω^2 is

- $J \geq -\frac{2P_{energize}\Delta t}{(\alpha^2 - 1)\omega_{nom}^2}$

Energy Storage Sizing

For both the flywheel and supercapacitor case, the goal is for the storage to deliver

- $P_{energize} = 1\text{MW}$ for $\Delta t = 0.5s$ with a drop from nominal (frequency/voltage) of $\alpha = 0.5$ (50%)

The nominal supercapacitor voltage is 2.4 kV

The nominal rotor speed is 60Hz

- An equivalent inertia may be maintained by reducing the inertia and increasing the speed via a drivebelt/gear to reduce the size of the flywheel.

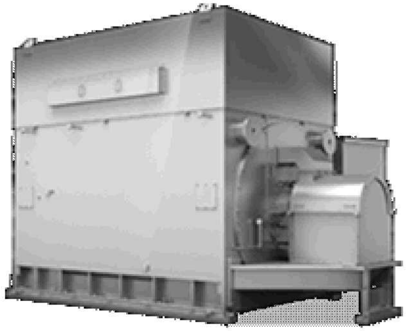
This results in

- $C \geq 0.2315$ F @ 2.4 kV
- $J \geq 21.2318$ kg m^2 @60 Hz

Cost Consideration (Flywheel: UPS v. Synchronous Condenser)

- Flywheel UPS
  - Commercially available units connect to dc bus
    - $200,000-400,000
  - Additional inverter required to connect to ac bus
    - ~$300,000

- Synchronous Condenser
  - Connects directly to ac bus
    - $10-40/kVAR
  - Maintenance cost
    - $0.4-0.8/kVAR annually
  - At worst
    - $40,000 purchase price
    - $800/year maintenance



- Assuming the most conservative cost estimate for the flywheel UPS
  - It would take 200 years for the flywheel cost to reach the cost of the commercial flywheel UPS unit.
    - And this doesn't even include the cost of the additional inverter
- This is why the synchronous condenser is selected over the UPS for use as the flywheel energy storage

Cost Consideration (Supercapacitor)

Limited to what sizes are available

Will likely have stack units in an array to get desired capacitance

At a common retailer, the largest supercapacitor is rated at 160V/5.8F

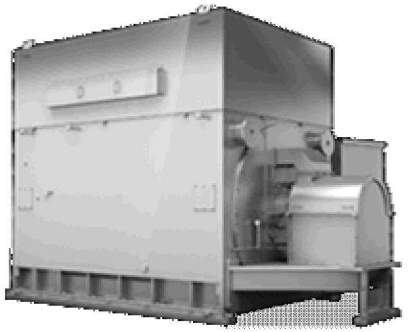
Stacking these in series to reach 2.4 kV

- Will require 15 units
- Reducing the capacitance to 0.3867 F.
- This is exceeds the desired minimum of 0.2315 F.

At a cost of $934.82 each, the total investment in supercapacitors would be $14,022.30.

Again, the 1 MW grid-ties inverter would be in the range of ~$300,000.

Cost considerations (Summary)



The most expensive case is the flywheel UPS/Inverter

The second most expensive is the Supercapacitor/Inverter

The most cost effective option seems to be the synchronous condenser based flywheel option.

Other considerations

- For more degrees of freedom in controls, the **supercapacitor/inverter** option is more ideal
  - The inverter can actively control the bus voltage during a fault
- The **synchronous condenser** is incapable of controlling active power
  - This may result in very poor voltage quality during fault ride-through

Storage: Active/Standby Modes

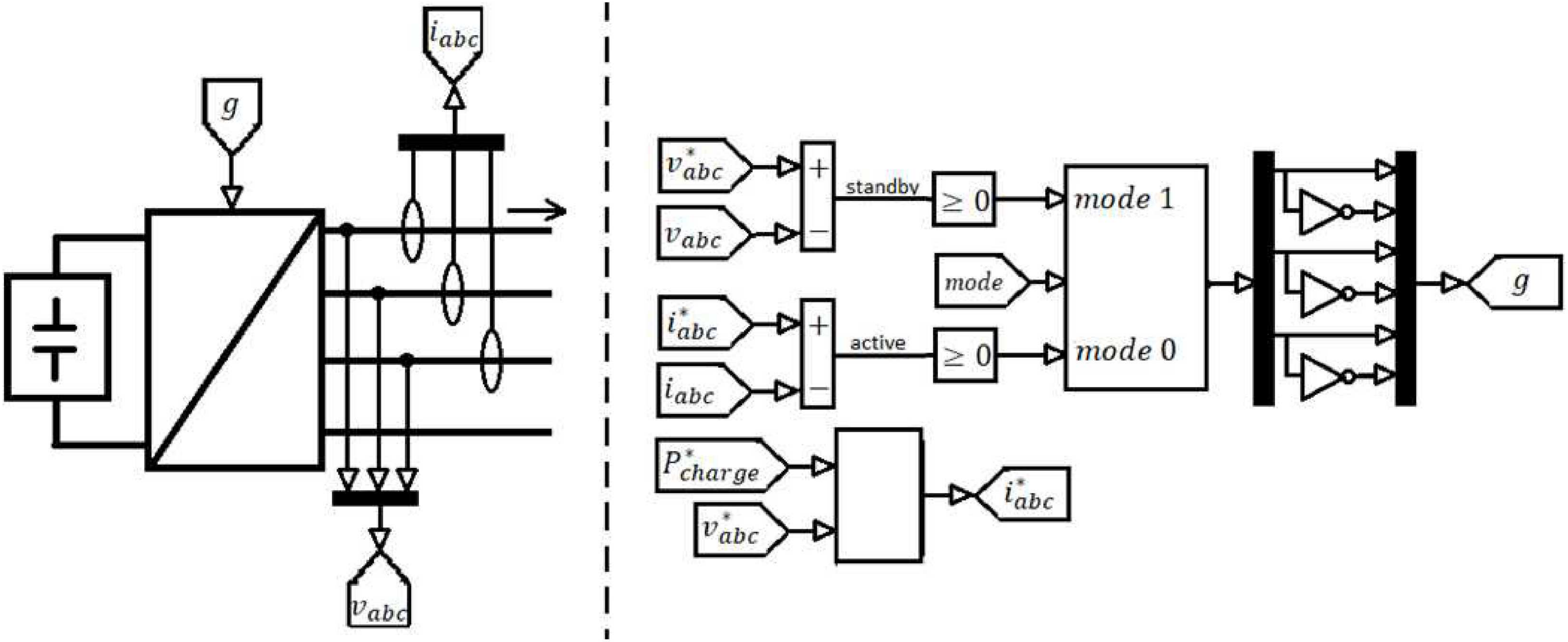
Active Mode

- Discharge storage
- Activates when rms bus voltage dips by some predefined percentage
- Hysteresis band used to avoid excessive switching between modes

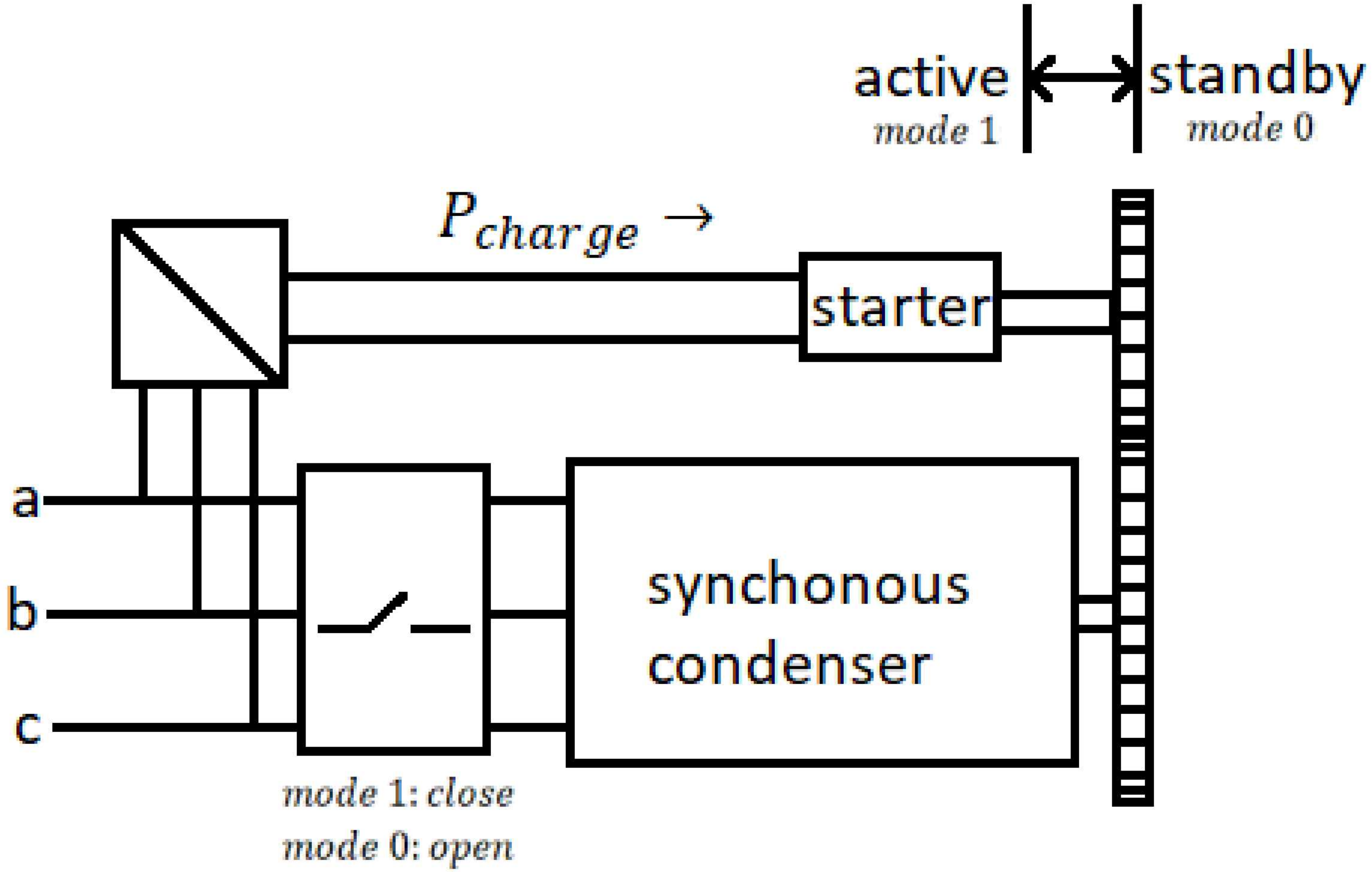
Standby Mode

- Charge storage
- Complementary to active mode
- Gradually charge storage at some predefined rate to avoid overload of source inverter
  - Inverter acts as rectifier to gradually charge supercapacitor
  - Starter motor gradually accelerates synchronous condenser to its nominal speed

Storage: Active/Standby Modes (Supercapacitor)



Storage: Active/Standby Modes (Flywheel)



Simulation Results

Single ideal dc energy source coupled to ac system through 3-phase inverter with neutral connection.

380 V bus voltage managed through closed loop pwm

The fault is assumed to be 3LG.

The reason for this is that this is the most difficult fault to clear

- Only 1/3 of the storage is available to energize each phase
- SLG faults are also easier to detect using zero-sequence overcurrent protection, which will still be available in inverter-based systems with appropriate grounding.

Simulation Results (Supercapacitor Backup)

Storage modes

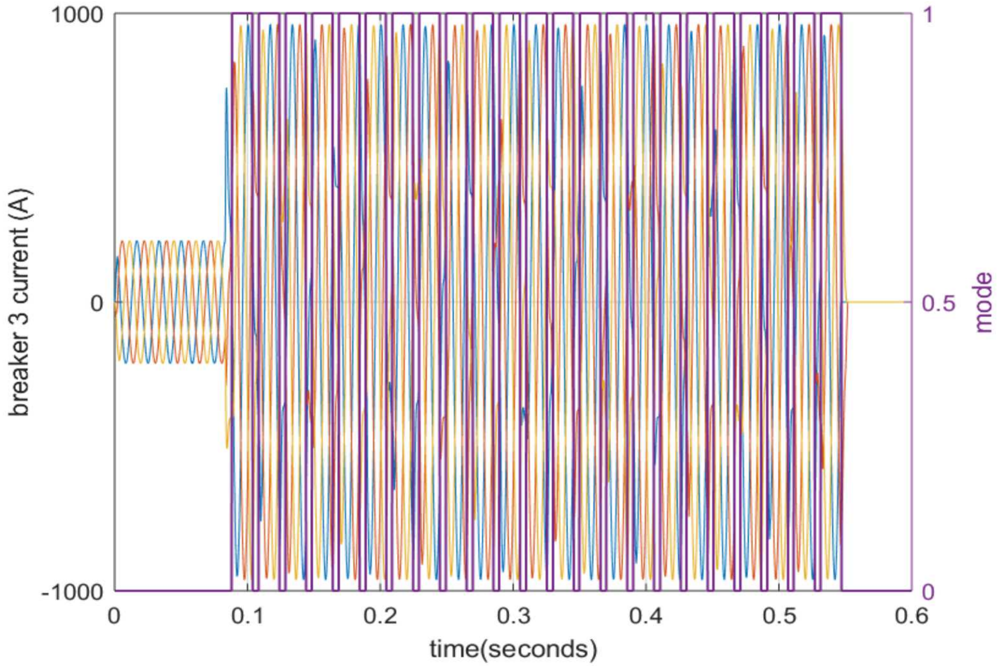
- 0 = standby (charging)
- 1 = active (discharge)

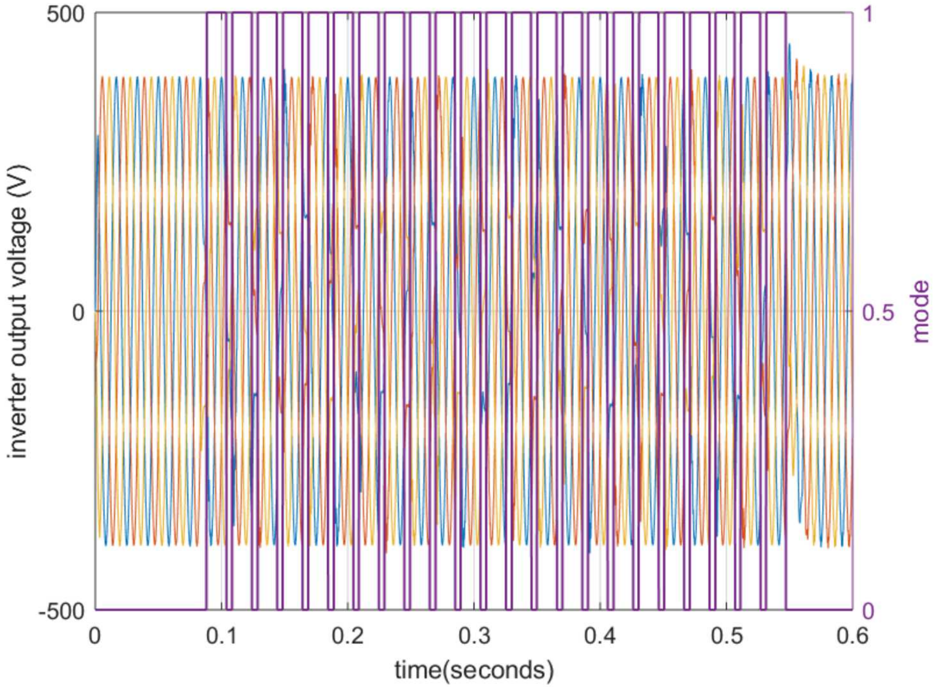
Pros

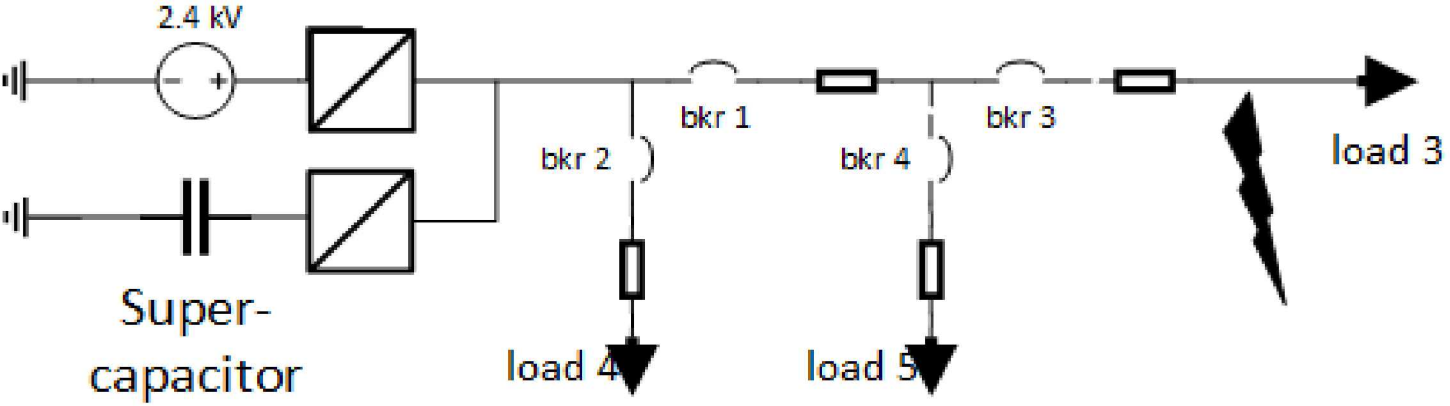
- Designated primary breaker clears fault successfully
- Voltage waveform maintained with minimal distortion dur fault

Cons

- Additional auxiliary inverter for storage will exceed cost of original source inverter due to drastically increased current requirements







Simulation Results (Supercapacitor Backup)

Breaker 3 clears fault in about 0.4s

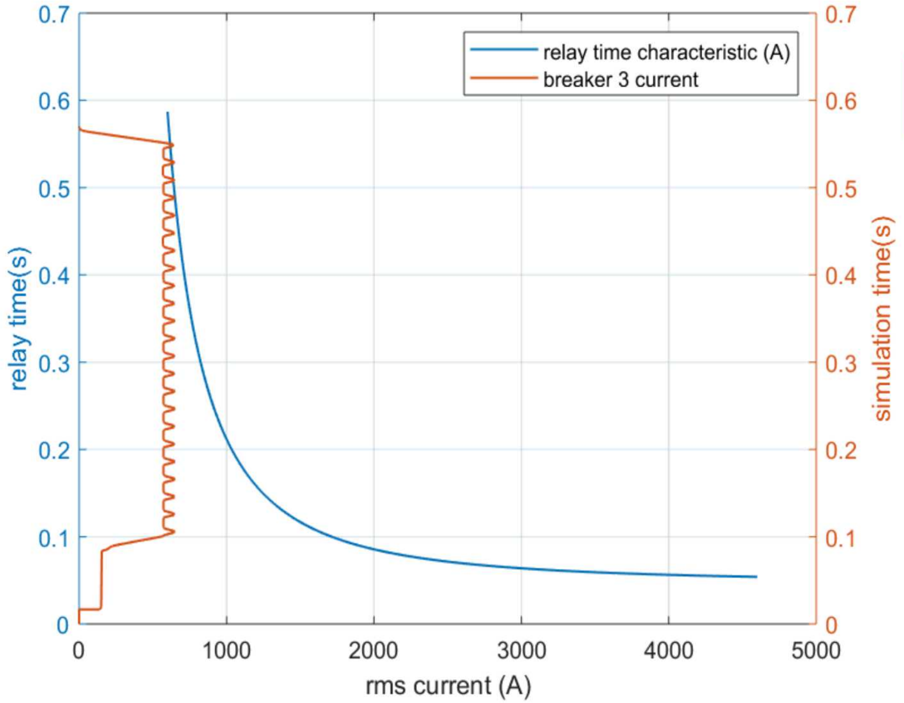
- Oscillating fault current as backup storage switching between active and standby mode

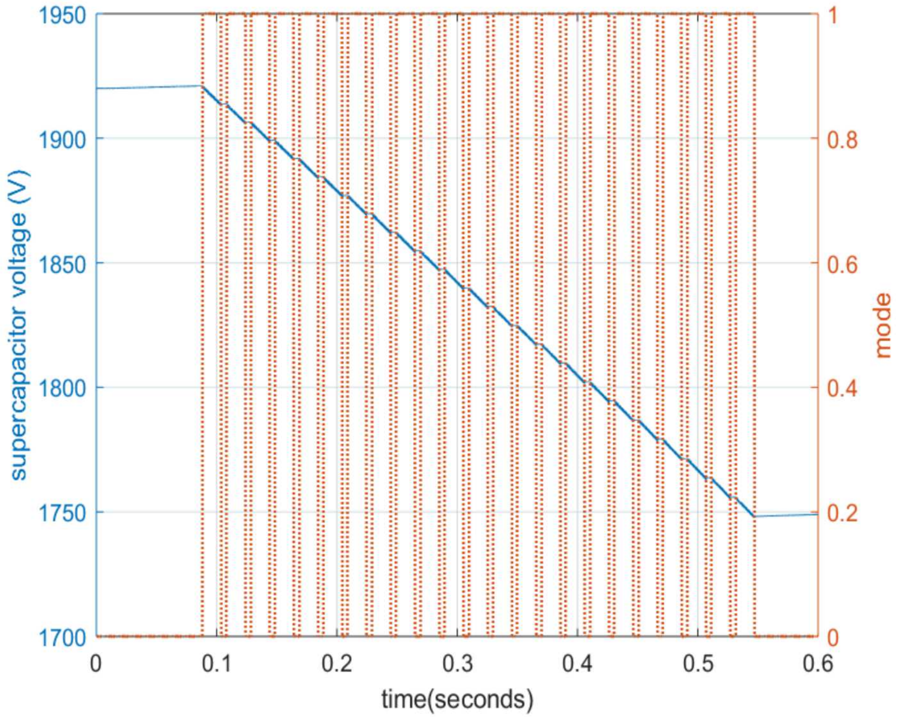
Mode controller needs improvement.

- Switches between active and standby mode several time during fault.
- Ideally the controller would only switch twice
  - To active upon fault
  - To standby upon fault clearance

Supercapacitor voltage

- Drops during active mode (rapid)
- Increases during standby mode (gradual)





Simulation Results (Synchronous Condenser)

Storage modes

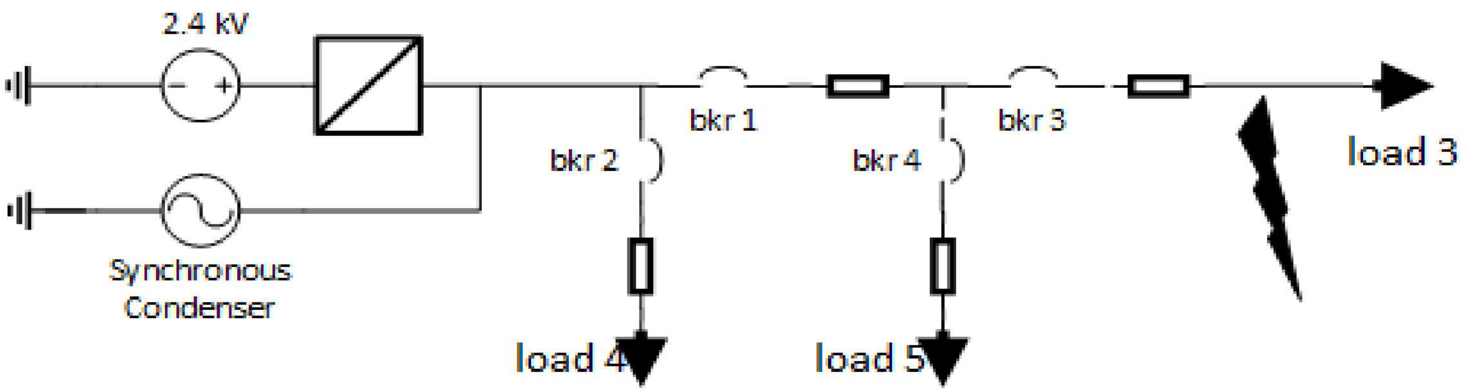
- 0 = standby (charging)
- 1 = active (discharge)

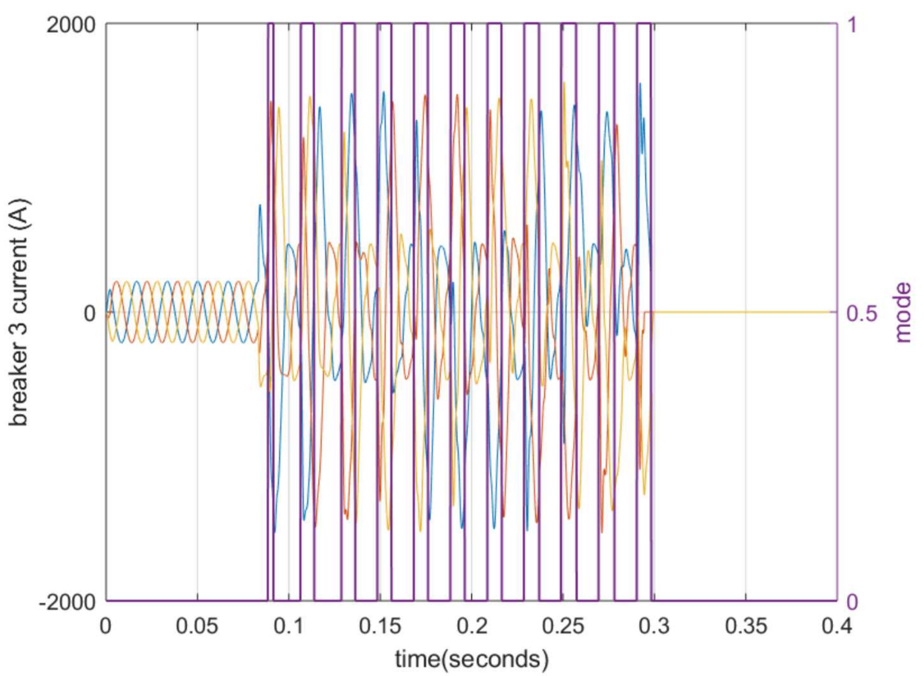
Pros

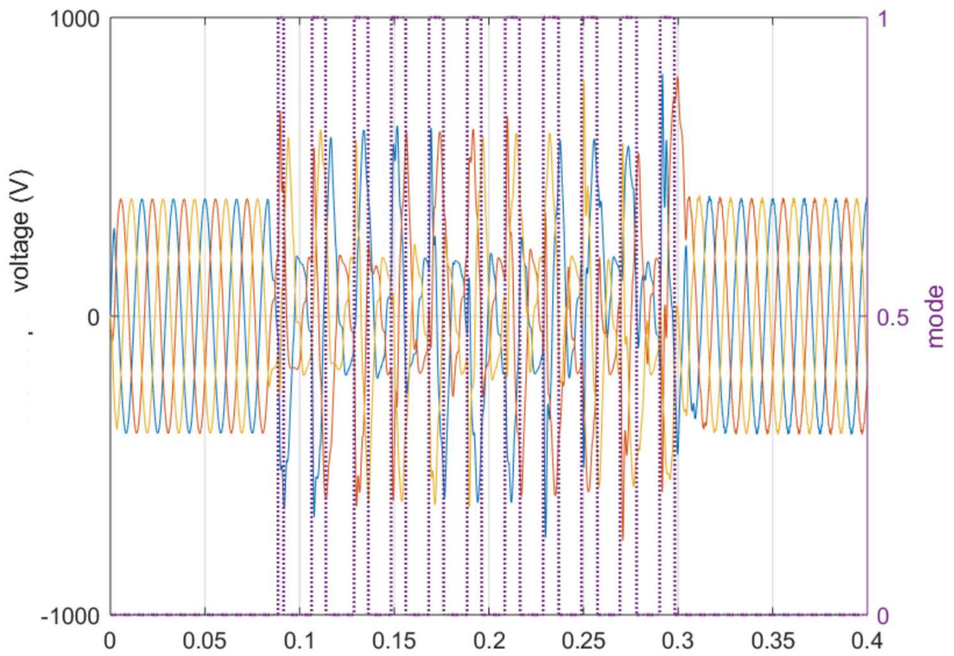
- Designated primary breaker clears fault successfully
- No additional power electronics interface required (cost)

Cons

- Voltage waveform highly distorted during fault
- Maintenance cost for synchronous condenser.
  - Still magnitudes lower than the cost for the supercapacitor's fixed cost over the lifetime of operation







Simulation Results (Synchronous Condenser)

Breaker 3 clears fault in about 0.2s

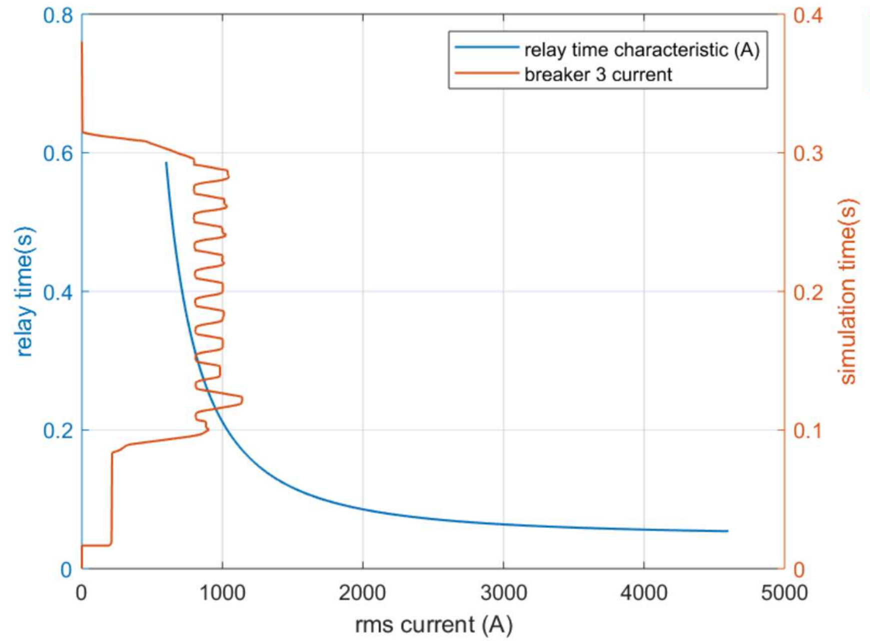
- Oscillating fault current as backup storage switching between active and standby mode

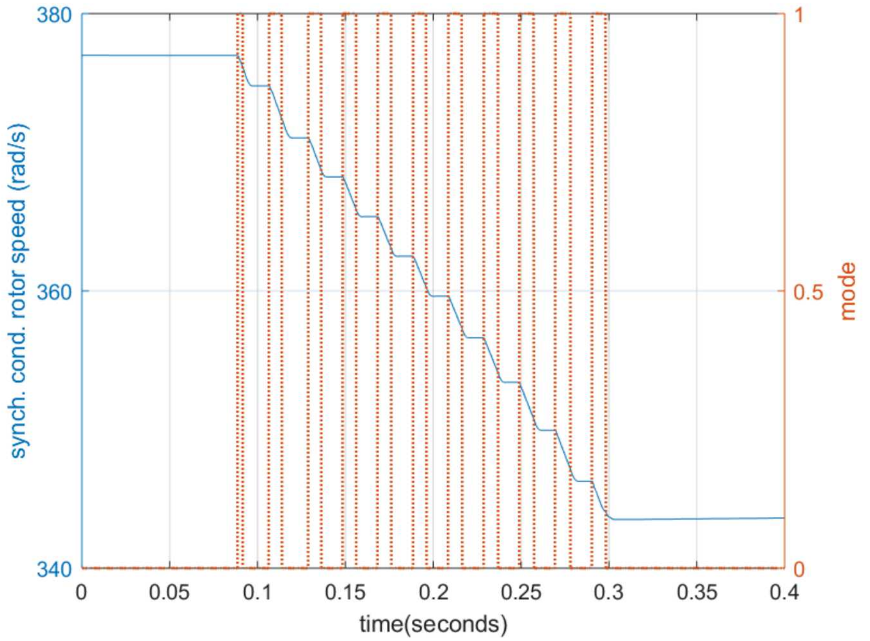
Mode controller needs improvement.

- For synchronous condenser active power is not controllable
  - Improvement is more problematic than for supercapacitor case

Rotor speed

- Drops during active mode (rapid)
- Increases during standby mode (gradual)





Conclusions/Future Work

Conclusions

- Both flywheel and supercapacitor storage provide sufficient energy to the clear fault
- Clearance times were relatively close.
  - The flywheel case was twice as fast, but a generalization cannot currently be made about this phenomena
- The synchronous condenser flywheel is lower cost
- The supercapacitor/inverter provides better voltage quality+

Future Work

- Logic for switching between active and standby modes need drastic improvement for both cases
- LG, LL, and LLG faults need to be further investigated
  - Most faults are asymmetric
  - Control schemes may need to be altered for these cases

Questions?

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