Transient Stability Analysis of an all Converter Interfaced Generation (CIG) WECC system

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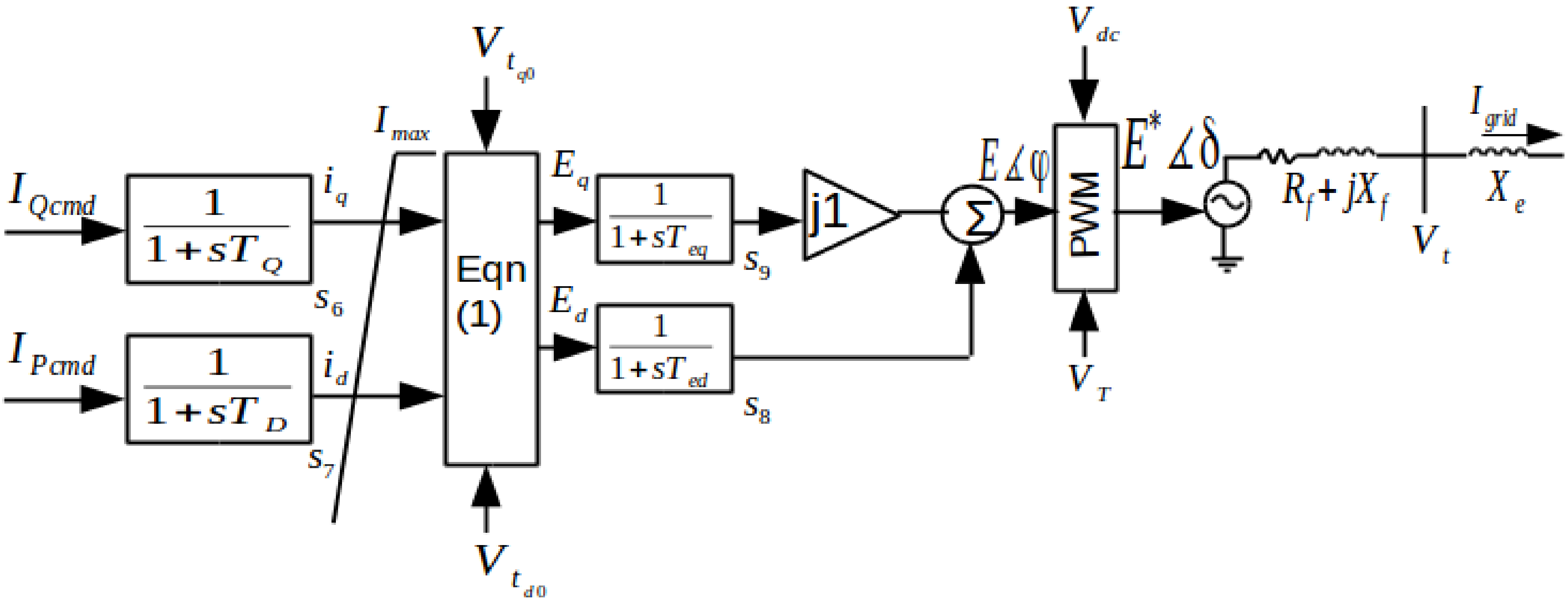
Converter model

- Controlled voltage source model has been used.
- In contrast, literature suggests a boundary current injection model.
- Why controlled voltage source?
  - Converters are practically voltage sources.
  - ac side voltage produced by manipulation of solid state switches.
  - ac voltage proportional to dc voltage.
  - Allows for explicit representation of coupling inductor.

- Network interface :

Controlled voltage source	Model suggested in literature
Thévenin voltage source	Boundary current injection
Function of model state variables	Nonlinear algebraic relationship
Constant between two iterations of network solution	Varies from one iteration to next
Good numerical convergence	Numerical convergence issues can arise
All CIG system can be simulated	Requires presence of at least one synchronous machine

Controlled voltage source representation of the converter

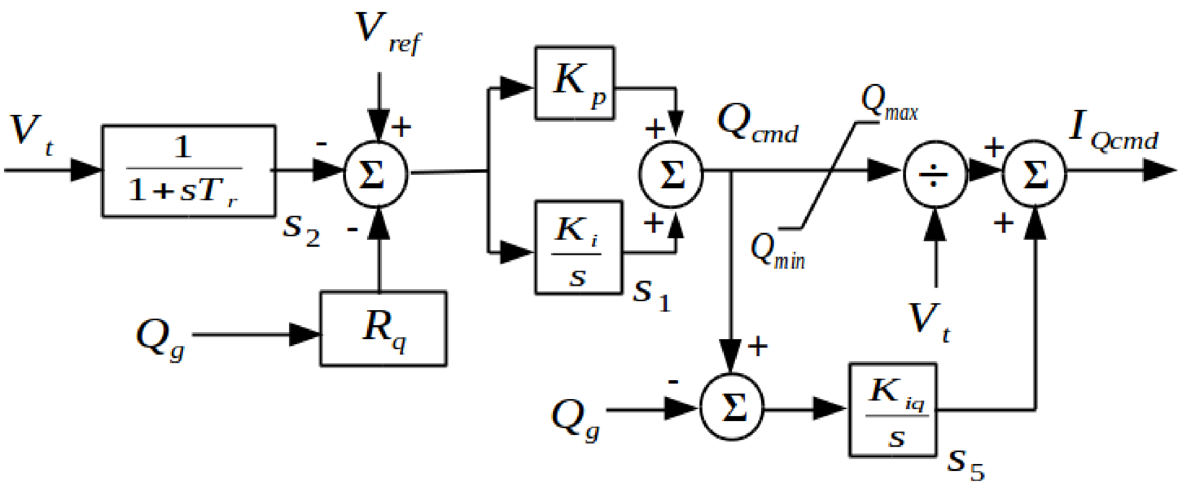


$$E_d = V_{td0} + i_d R_f - i_q X_f \quad (1)$$
$$E_q = V_{tq0} + i_q R_f + i_d X_f$$

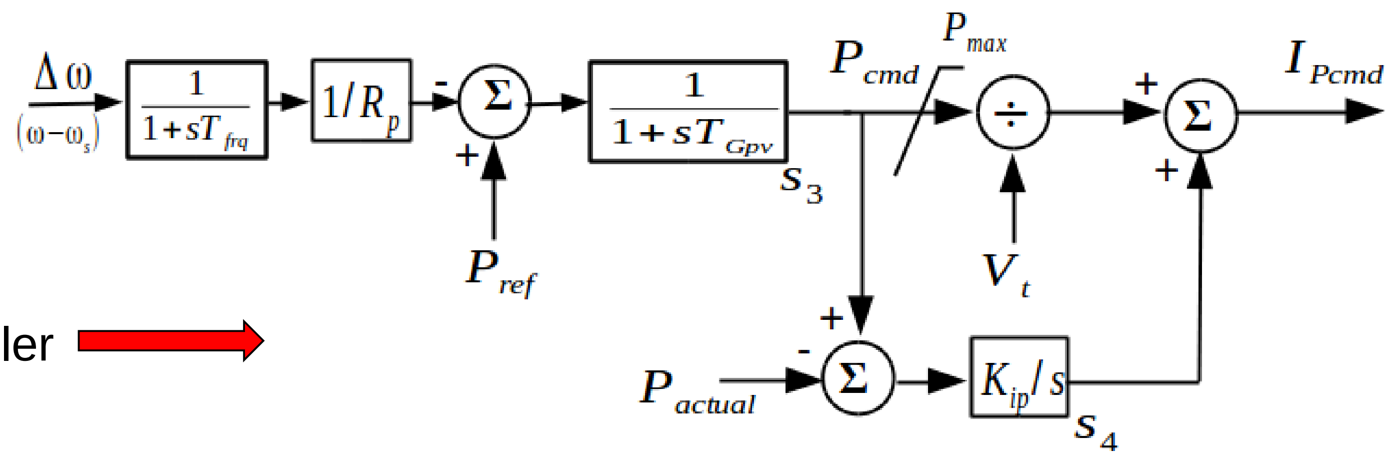
Controlled voltage source representation of the converter

- R_f and X_f represent the resistance and reactance of the converter coupling filter and/or generation step up transformer between the converter and point of connection to the grid.
- They have a value of 0.004pu and 0.05pu on a converter MVA base.
- A steady state PWM amplitude modulation ratio (*m*) of 0.6 has been assumed. V_T is the amplitude of the triangular carrier wave for generating the switching pulses.

Control model



Reactive power controller

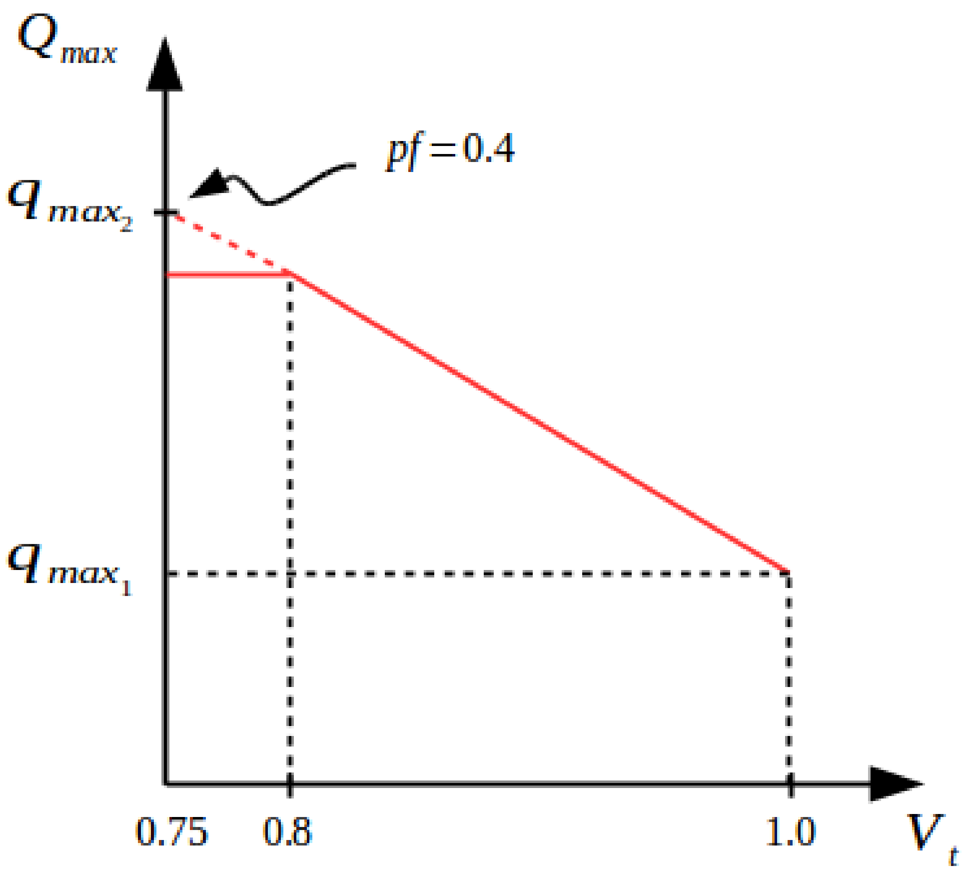


Active power controller

Features of control model

- Change in electrical frequency ($\Delta\omega$) calculated by numerical differentiation of bus voltage angle.
- Value of Q_{max} adjusted according to change in terminal voltage while value of P_{max} adjusted accordingly to maintain MVA of the converter.
- Hard current trip at I_{max} = 1.7pu.
- Overvoltage trip if terminal voltage rises 0.15pu above the steady state voltage for more than 0.1s.
- All time constants have a value of 0.01s except T_{frq} which has a default software established value of 0.05s.

Setting of P and Q limits



Assumptions

- Maximum ***instantaneous*** MVA is 1.7MVA
- At terminal voltage of 0.75pu, minimum operable power factor is 0.4.
- Constant reactive power for voltages below 0.8pu.
- Value of q_{max1} from the powerflow is assumed to be at terminal voltage 1.0pu

$$q_{\max 2} = \sqrt{\frac{(1.7MVA)^2}{1 + \left(\frac{1}{\tan \cos^{-1} 0.4}\right)^2}}$$

- At any terminal voltage (V_t) level above 0.8pu,

$$Q_{\max} = q_{\max 1} + \frac{q_{\max 2} - q_{\max 1}}{0.75 - 1.0}\left(V_t - 1.0\right)$$

- Value of Qmin is maintained constant as powerflow value.
- To maintain the maximum instantaneous MVA,

$$P_{\max} = \sqrt{\left(1.7MVA\right)^2 - Q_{\max}{}^2}$$

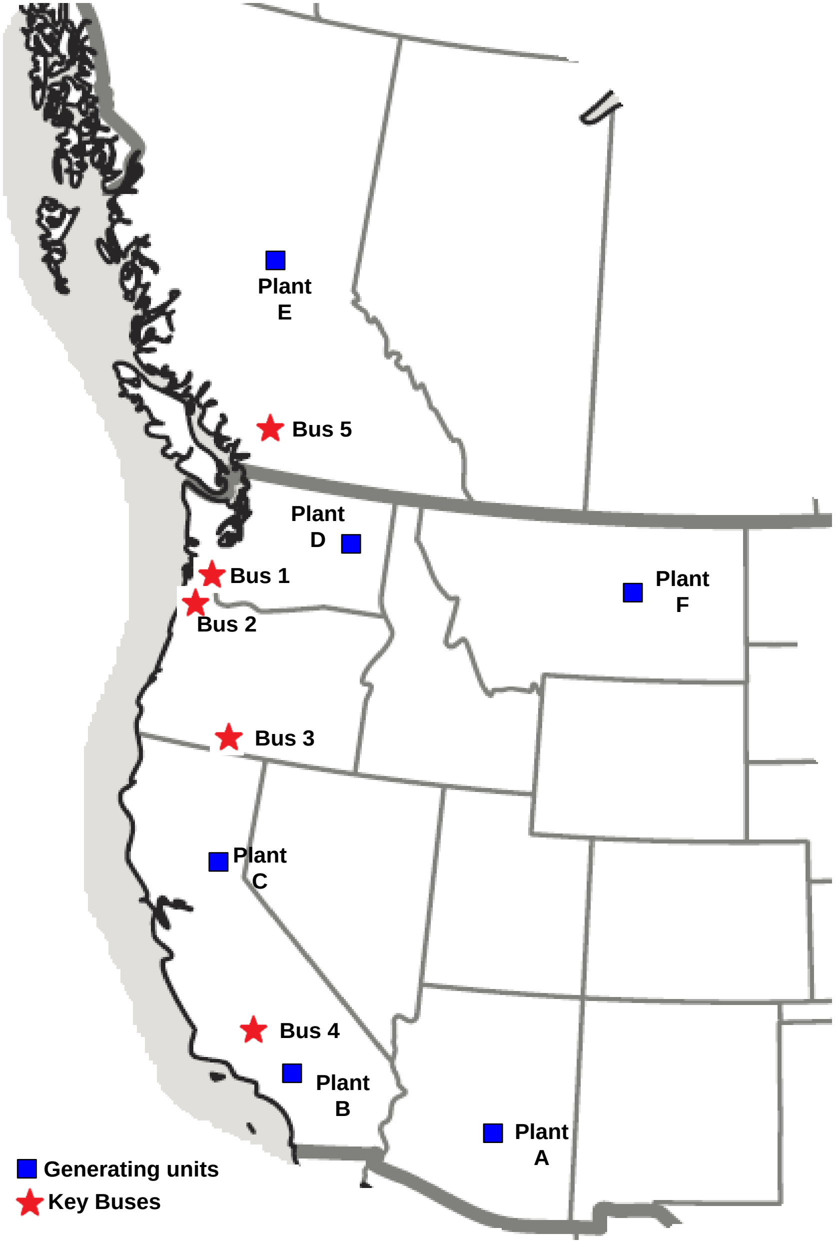
System studied

- Simulation run on the WECC 2012 system:
  - Number of buses: 18205
  - Number of conventional generating units: 2592
  - Number of induction motor loads: 5380
  - Around 90% of static load is voltage dependent.

Premise and assumptions

- All conventional generating units (2592 units) replaced by converter model of appropriate MVA rating.
- Active power droop enabled on CIG when present on replaced conventional generating unit. Same value of droop coefficient used.
- P_{max} of converter assumed to be P_{max} of turbine of replaced conventional generating unit.
- 5% reactive power droop enabled on all CIG.
- Terminal voltage control enabled on all CIG.

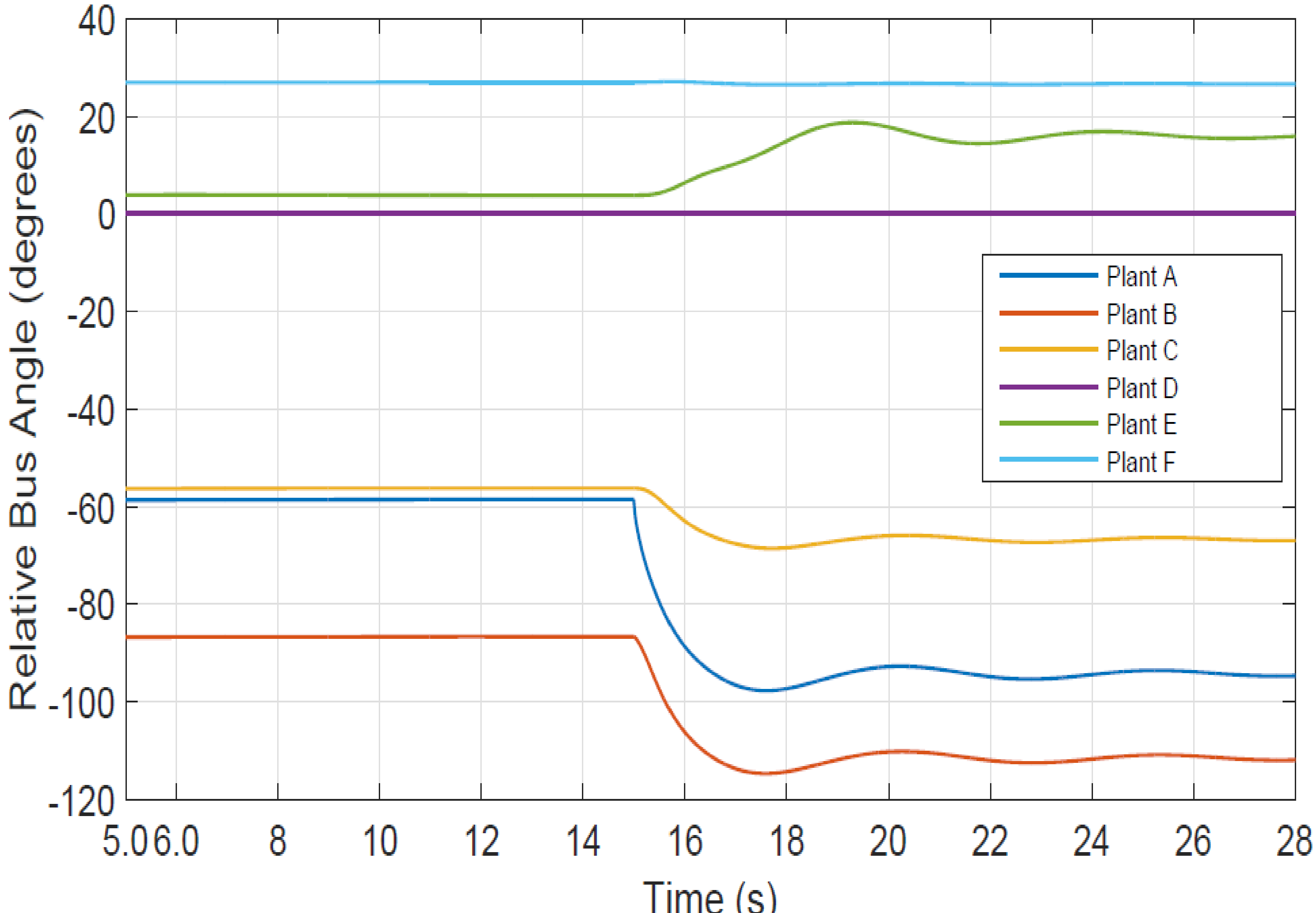
Simulation results

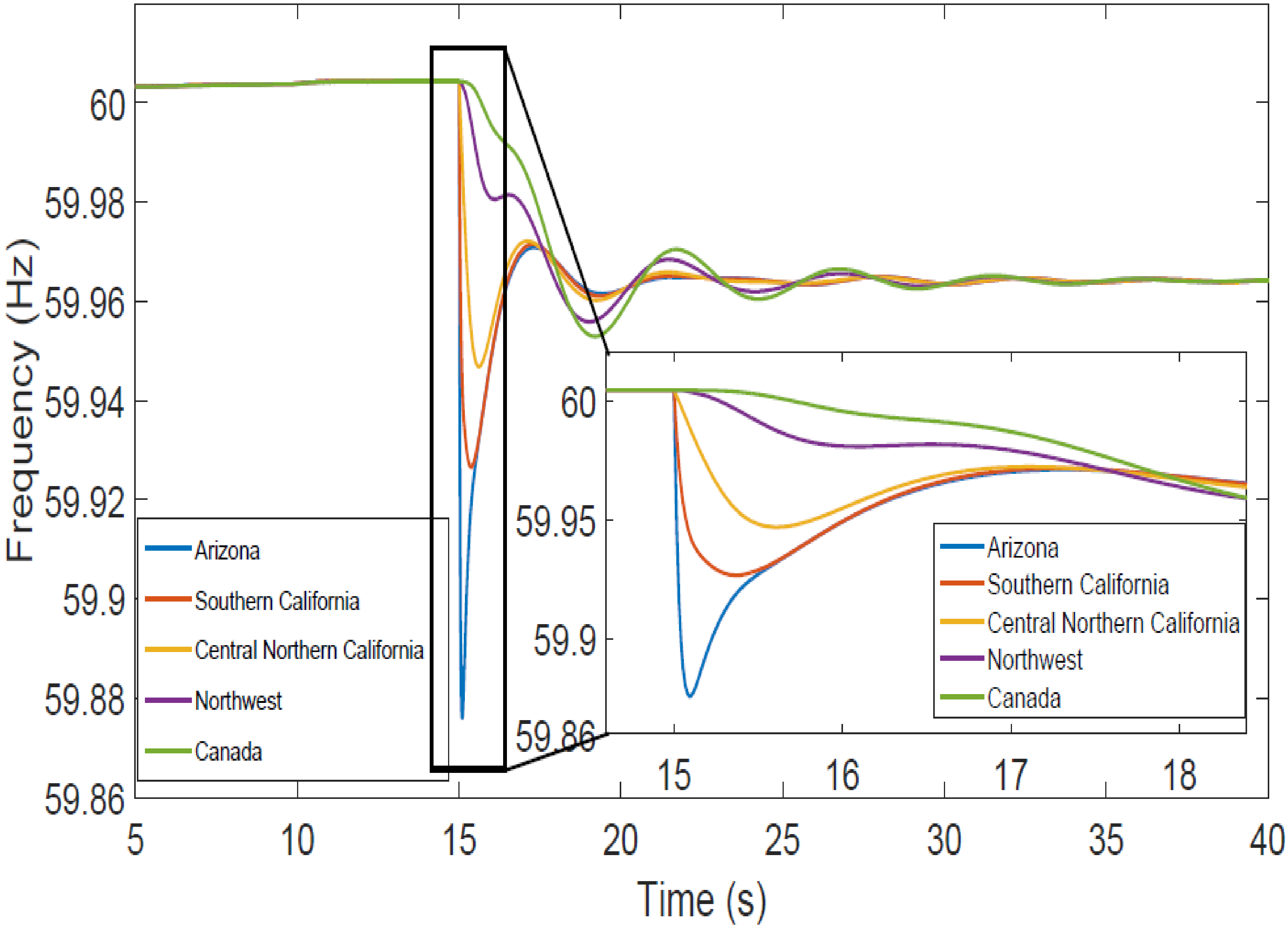


- Five generating units across the system observed.
- Five key buses identified across to system to observe the voltage.
- The interaction between the northern and southern regions of the system studied.
- Controller gains used:
  - K_p = 1.0, K_i = 5.0
  - K_{ip} = 10.0, K_{iq} = 10.0
  - K_{ip} = 10.0, K_{iq} = 120 (only for Plant A units)
- Simulations carried out in GE-PSLF.

Generation outage

- Two of the three units at Plant A in Arizona tripped at t=15s. Loss of 2755 MW of generation

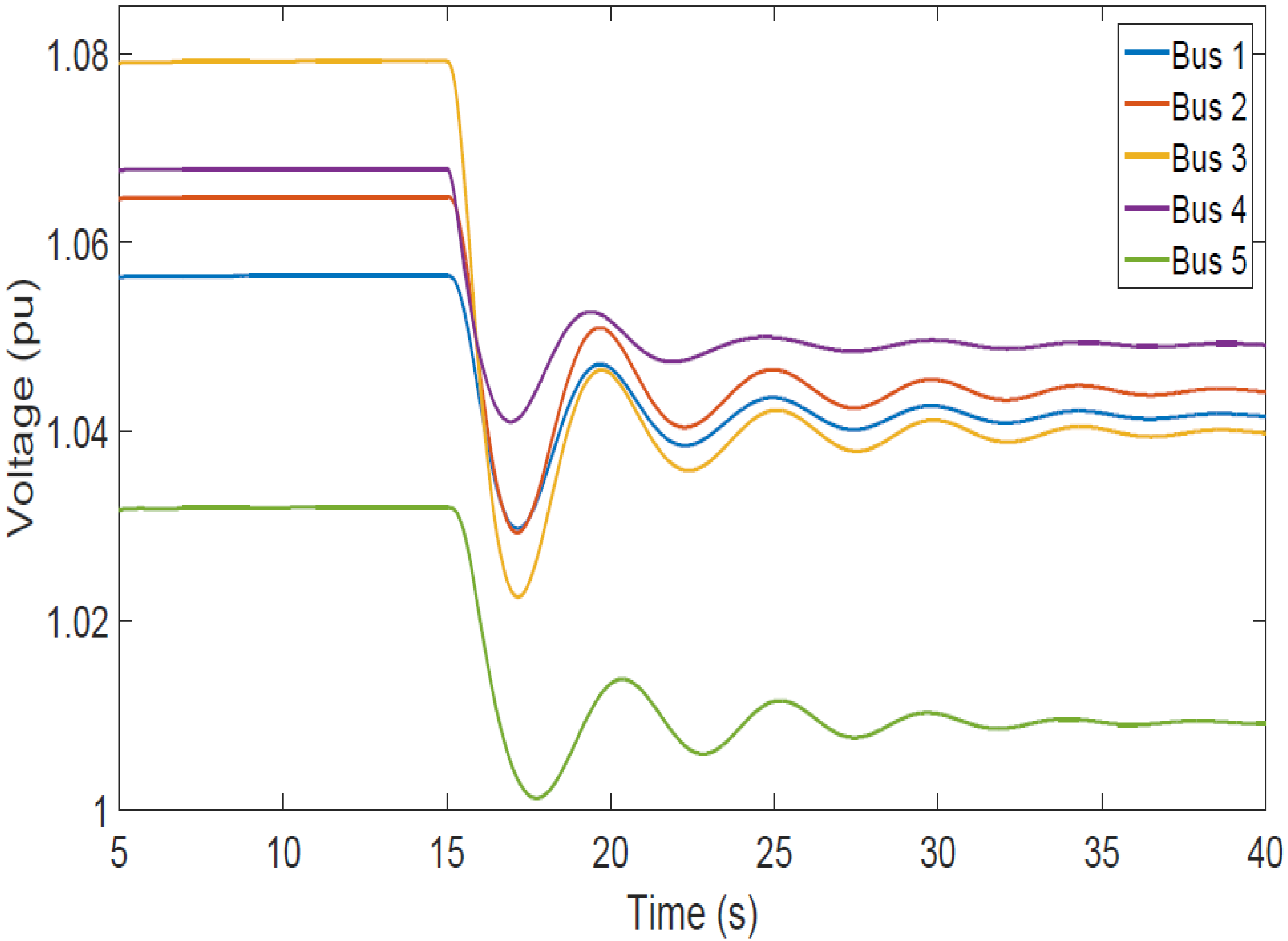




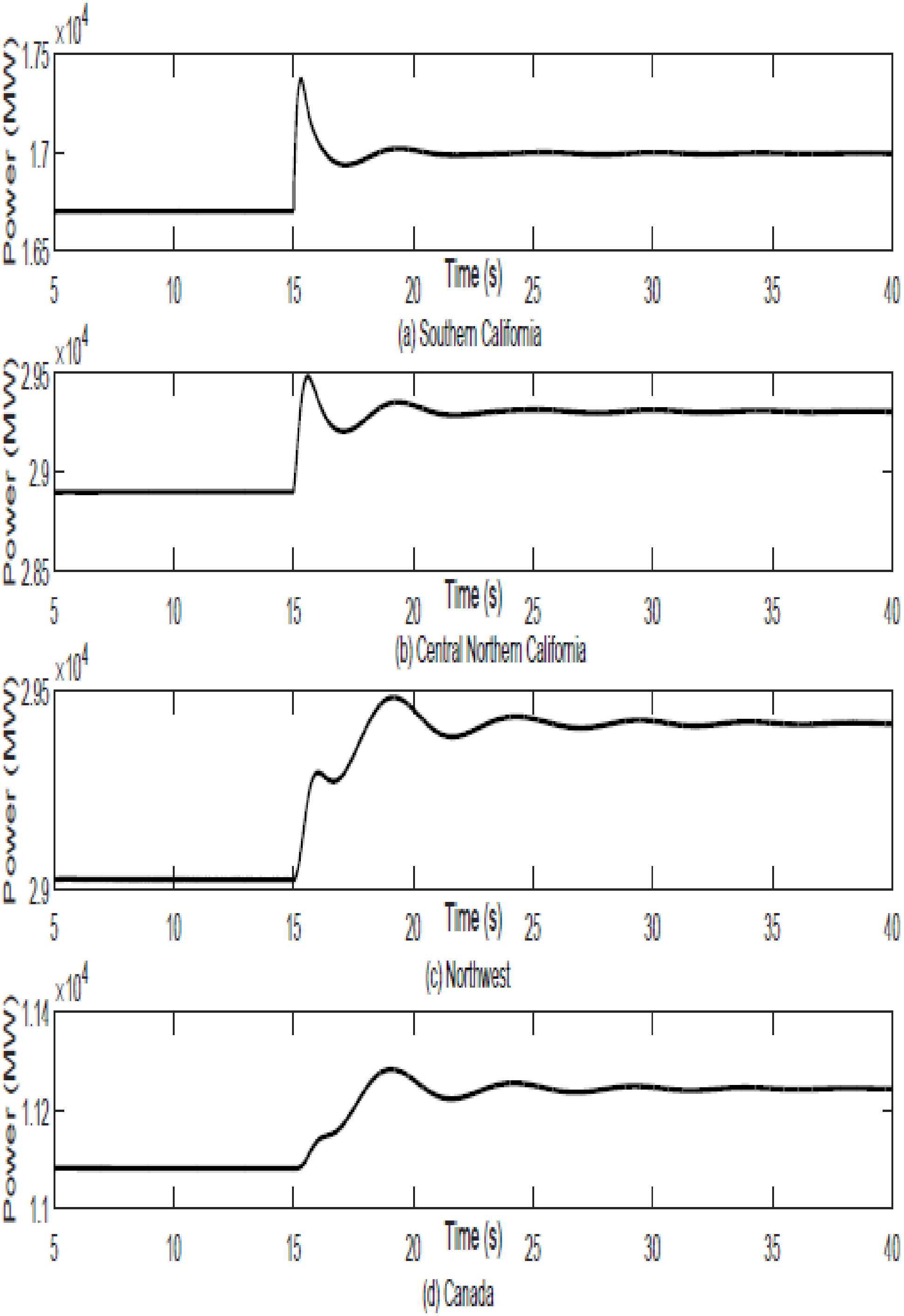
The frequency is calculated as rate of change of voltage phase angle.

Analysis of results

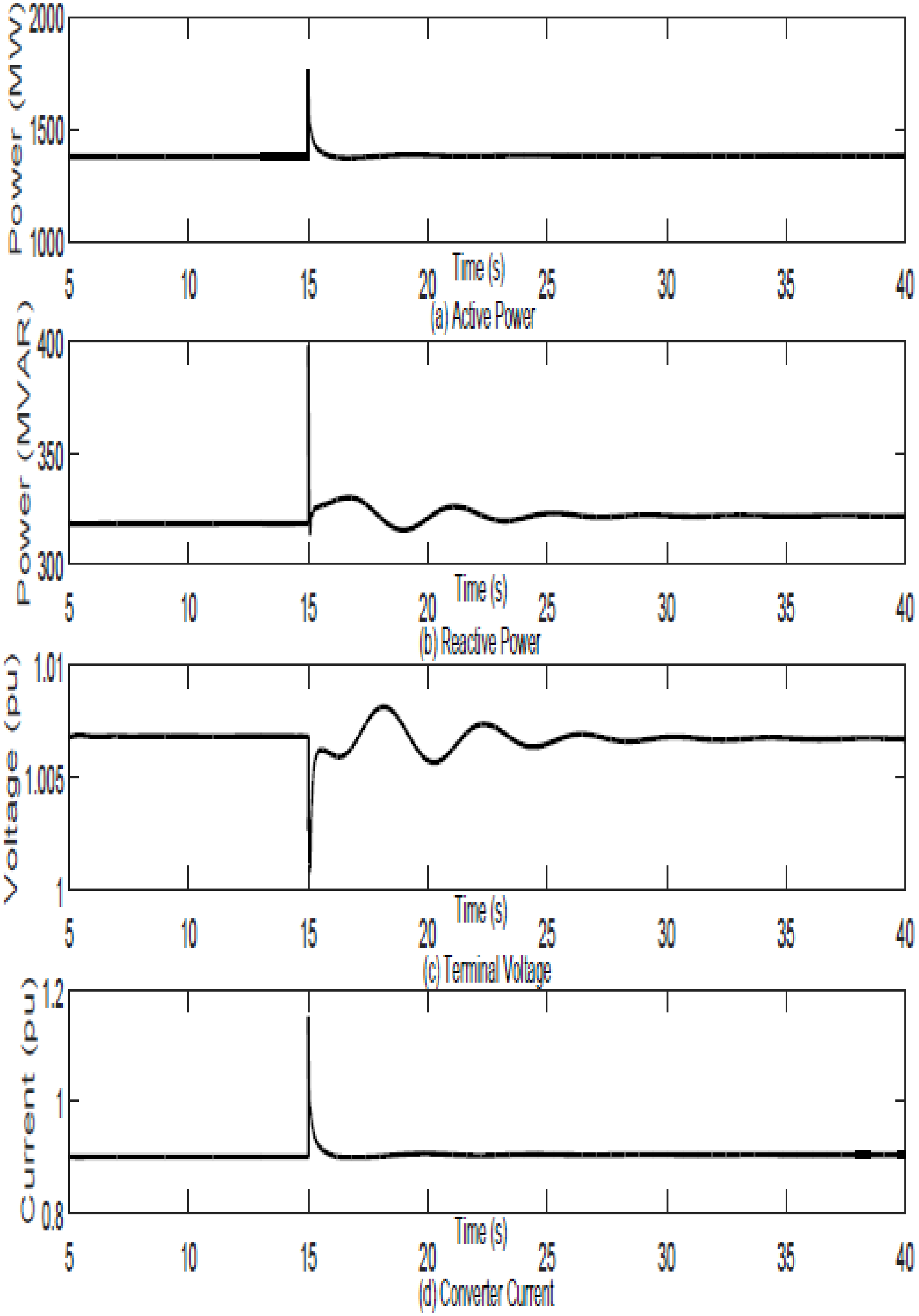
- Arizona exports close to 4000 MW of power to California.
- Large electrical separation between northern and southern regions of WECC.
- 2755 MW generation outage causes phase angles to move away from each other in the first 0.5s after disturbance.
- System separation prevented by increased inflow of power, due to droop control, from Northwest area to central northern California.



Voltage at the key buses shows that as phase separation increases, the voltage at around the center of the north-south interface (Bus 3), decreases.



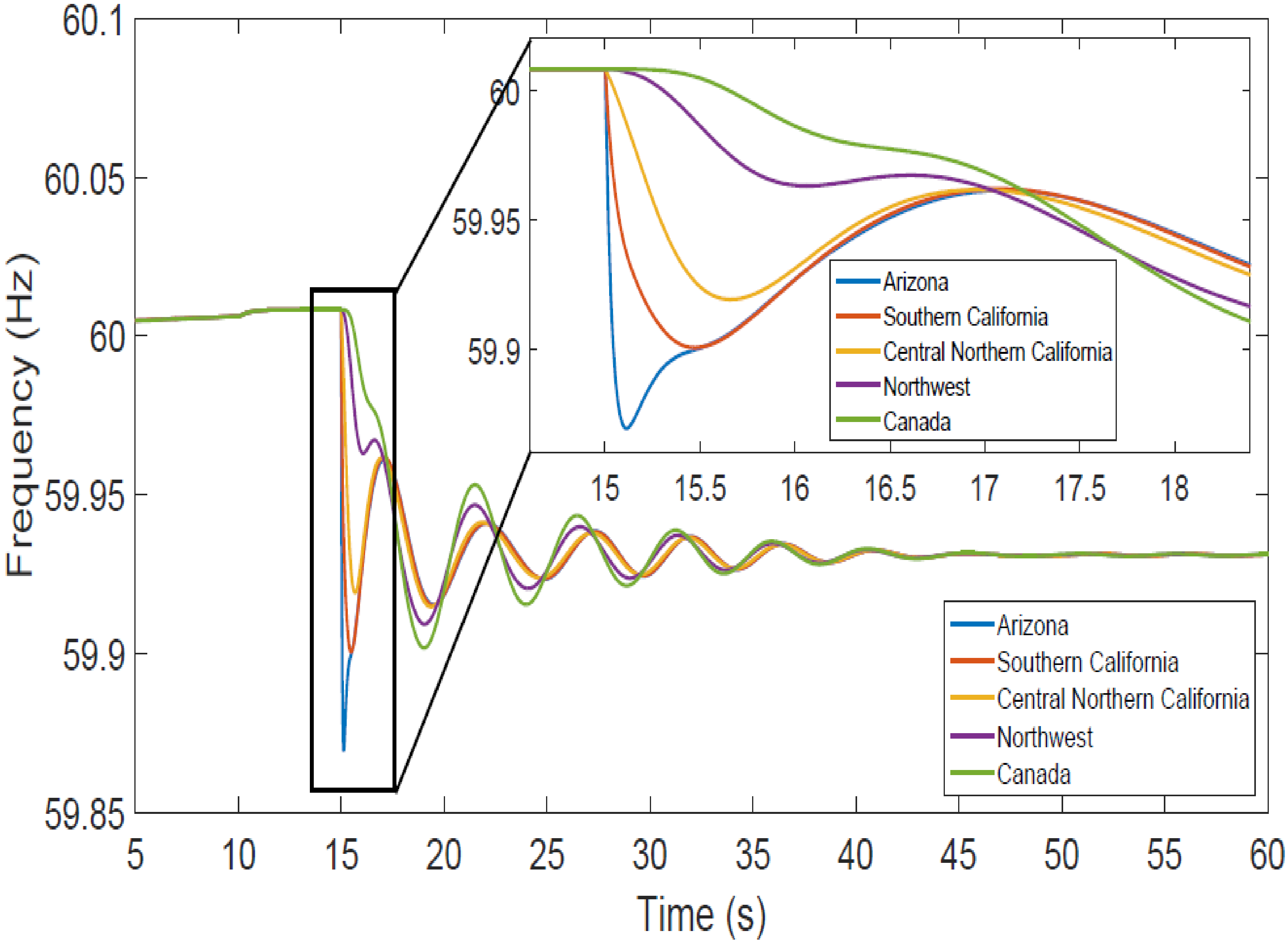
- Total pre-disturbance active power generation is 172670 MW.
- Total post-disturbance active power generation is 172300 MW.
- 86.5% of the lost generation (due to trip of two Plant A units) is recovered through droop control.
- Remaining 13.5% of the lost generation is recovered through voltage dependent loads



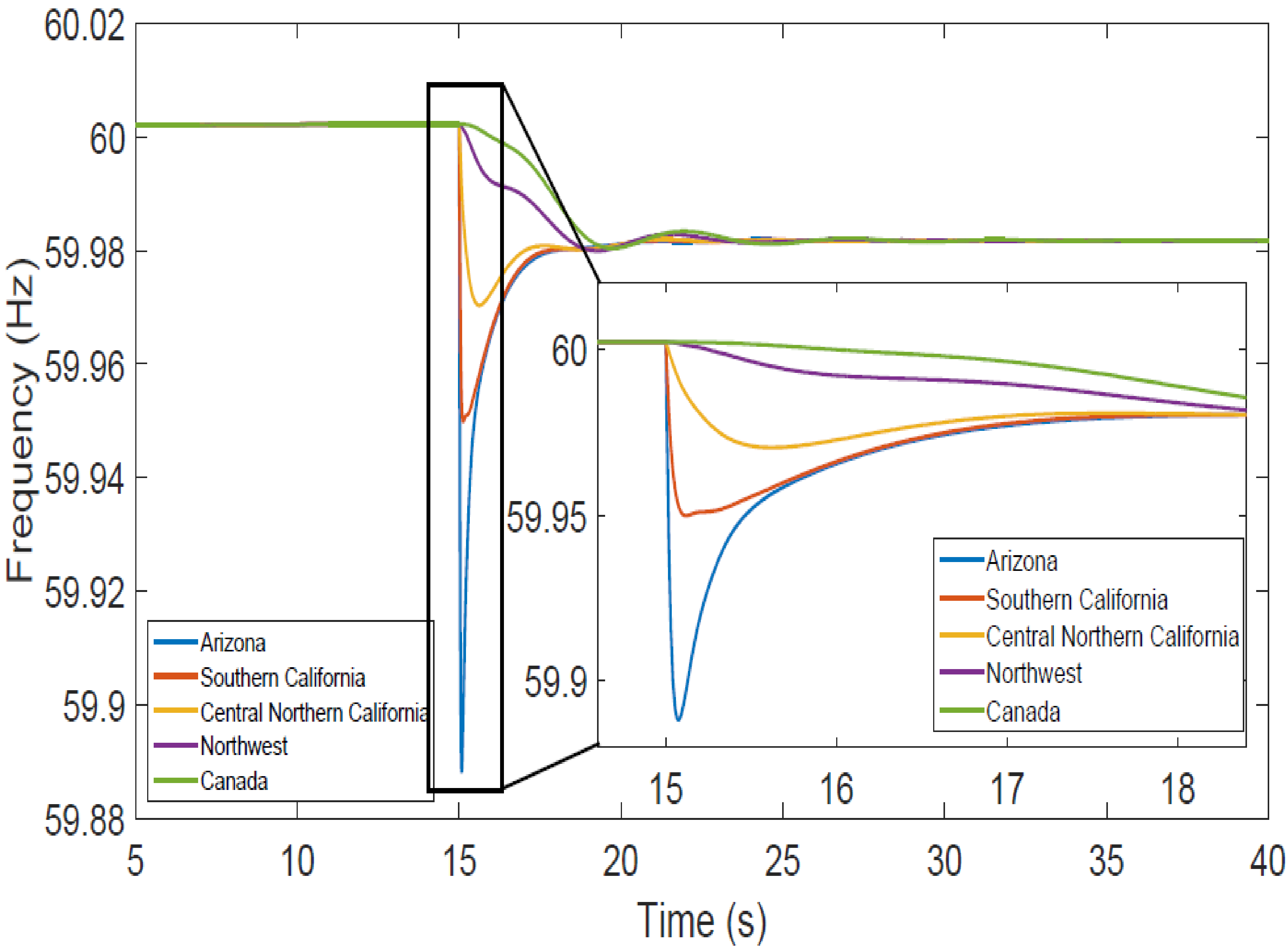
- Third unit at Plant A is electrically closest to the outage.
- Converter response to the outage is quick.
- Converter current is within limits.
- Voltage control loop brings the voltage back to the pre-disturbance value.
- Very little reserve margin available as Plant A units operate close to their maximum active power limit.

Effect of R_p on generation outage

- With the trip of the two Plant A units, the system behavior with active power droop coefficient as $2R_p$ and $R_p/2$ has been observed.
- Individual CIG units would still have different values of droop.
- The droop coefficient in the previous study was considered to be R_p



Active power droop coefficient was $2R_p$ in this scenario – Less responsive to disturbances.



Active power droop coefficient was $R_p/2$ in this scenario – More responsive to disturbances.

- Change in active power droop coefficient changes the settling time and final steady state value.
- Large value of droop coefficient corresponds to smaller proportional gain in the active loop and thus results in a longer settling time with greater oscillatory behavior.

Simulation Metrics:

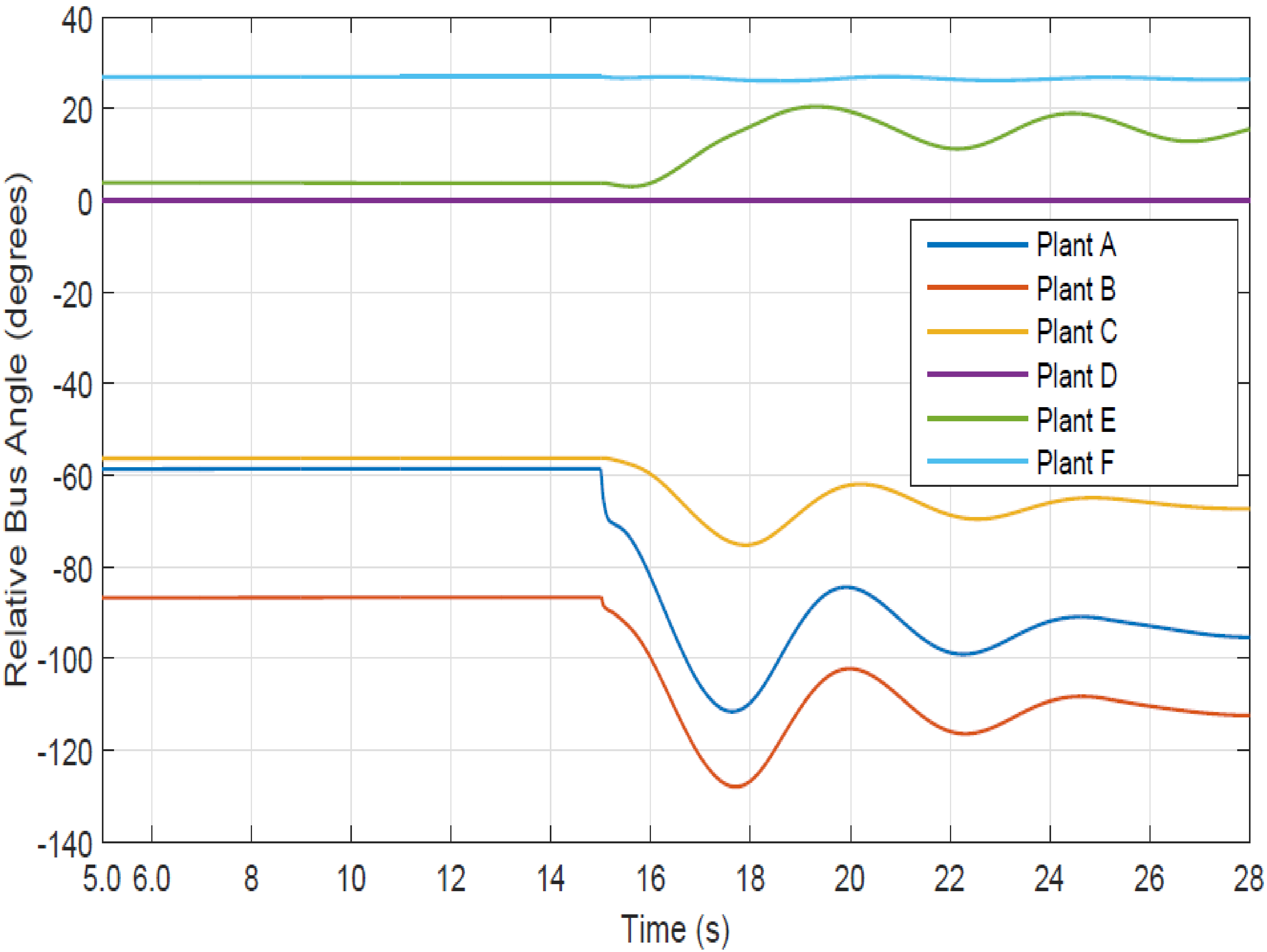
With droop coefficient R_p, a 40 second simulation run took 8.10 minutes with the first 20 seconds of simulation taking 3.52 minutes.

Simulation time step: 0.0041s

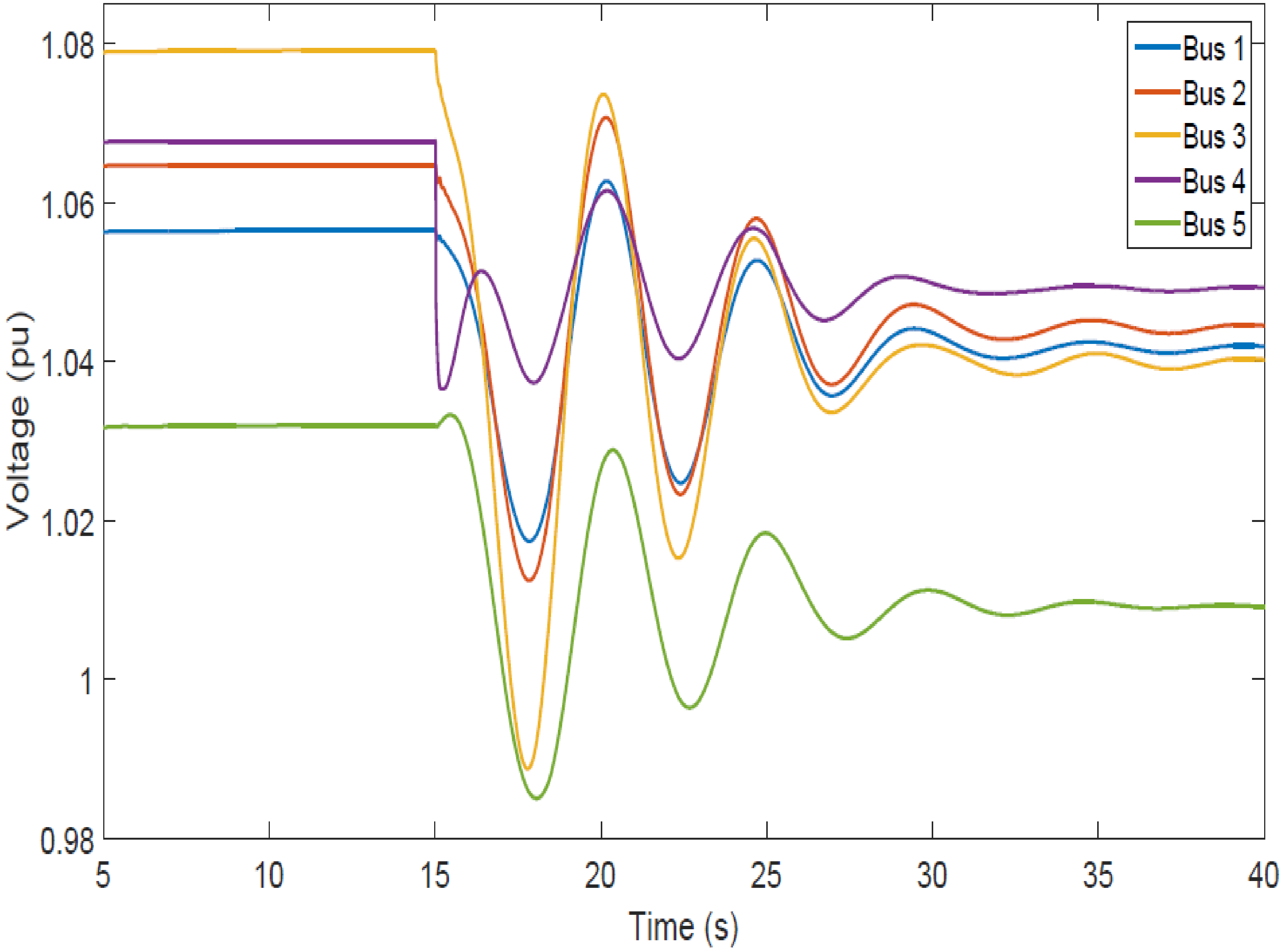
Computer specifications: i7 processor, 16.0 gb of RAM.

DC voltage dip and subsequent recovery

- Assumption of a battery as a constant source of power for all units is not realistic.
- Disturbance in the network would cause dc capacitor voltage to vary.
- Magnitude of ac voltage produced by converter generally falls in proportion to its dc voltage.
- Two units of Plant A tripped followed by a 10% reduction in dc voltage 0.02s later.
- dc voltage gradually restored over the next 10s
- dc voltage reduced only in Arizona and Southern California.



Drop in dc voltage does not increase the phase separation between the two areas.



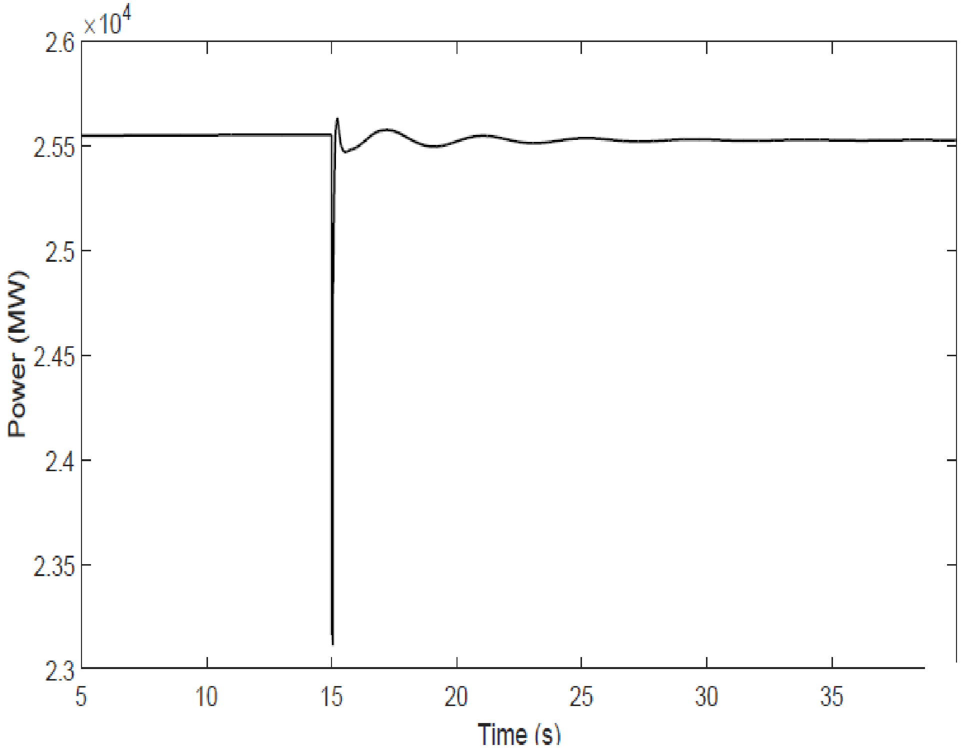
The transient decrease in bus voltage is however greater when compared to the transient decrease with constant dc voltage.

Analysis of results

- The dc voltage was reduced only in the southern region of the system.
- Reduction in terminal voltage along with loss of generation, increases power flow along north-south interfaced.
- Increased power flow causes the voltage at the center to decrease.
- With predominant voltage dependent load, continuous change in dc voltage (over a period of 10s after disturbance) causes load to continuously change and thus more pronounced oscillatory behavior.

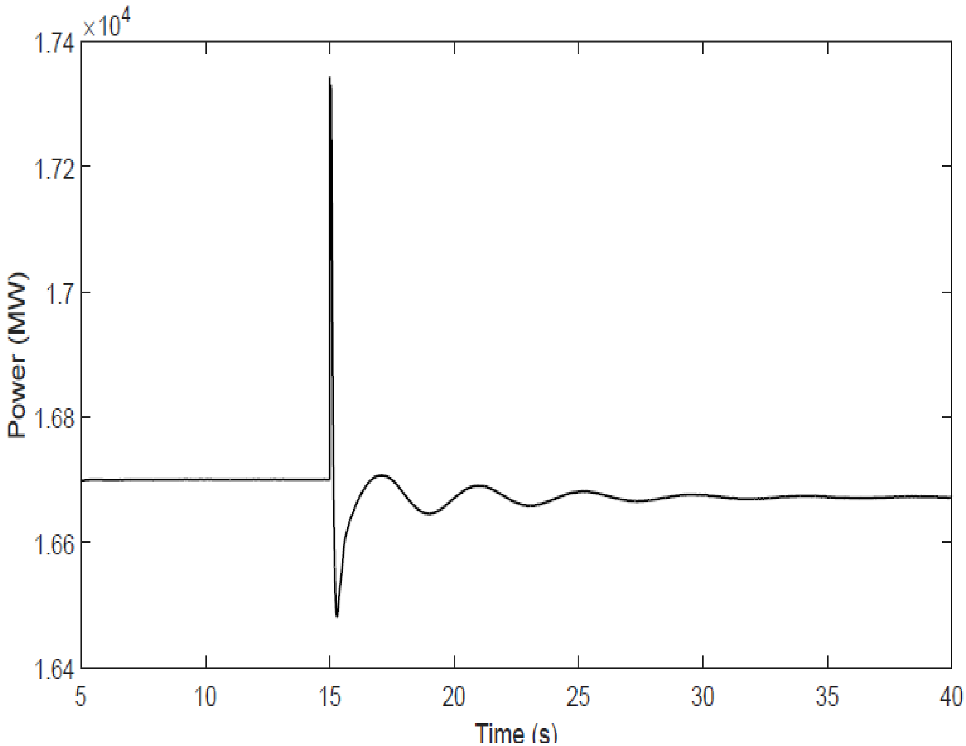
Line fault followed by outage

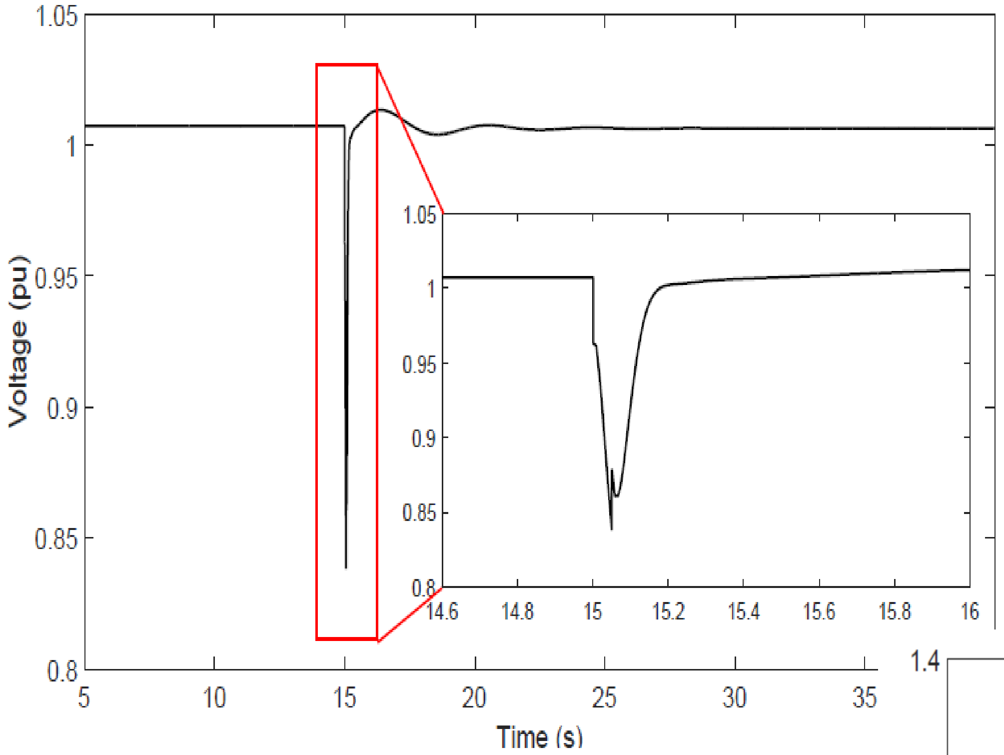
- Three phase fault applied at midpoint of a line between Arizona and Southern California areas.
- Fault cleared and line tripped in 0.05s
- Initial flow of power on the line: 1408.6 MW and 134.4 MVAR from the Arizona side.
- Active power generation in both areas and behavior of one unit of Plant A observed.



Arizona active power generation

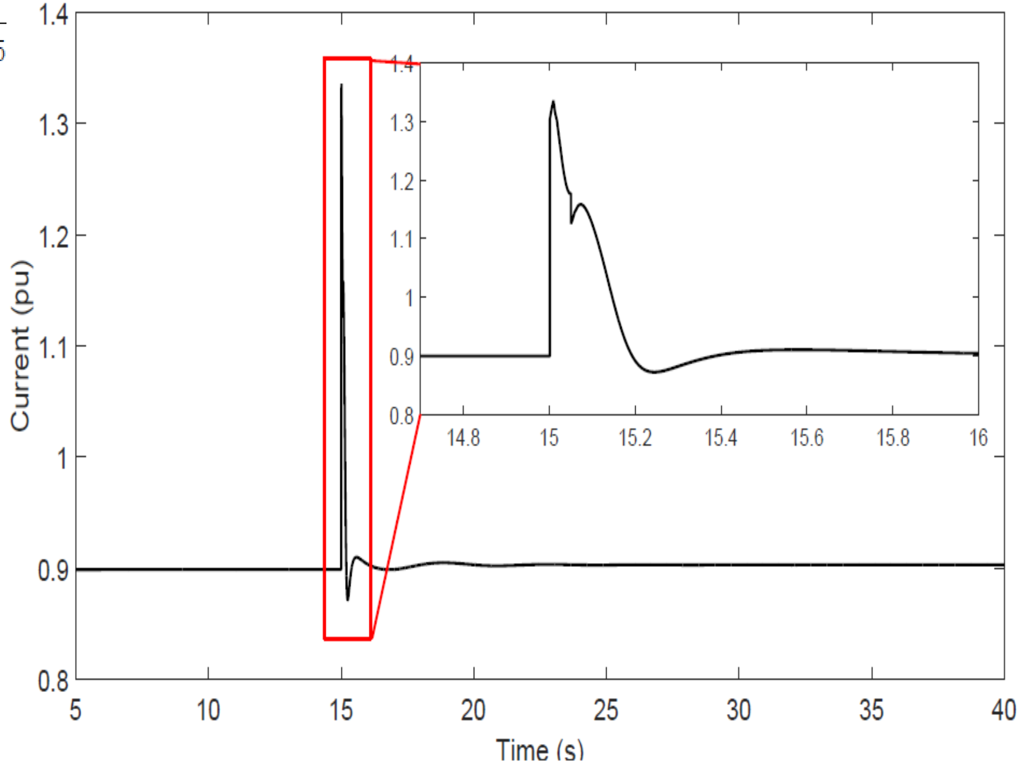
Southern California active power generation





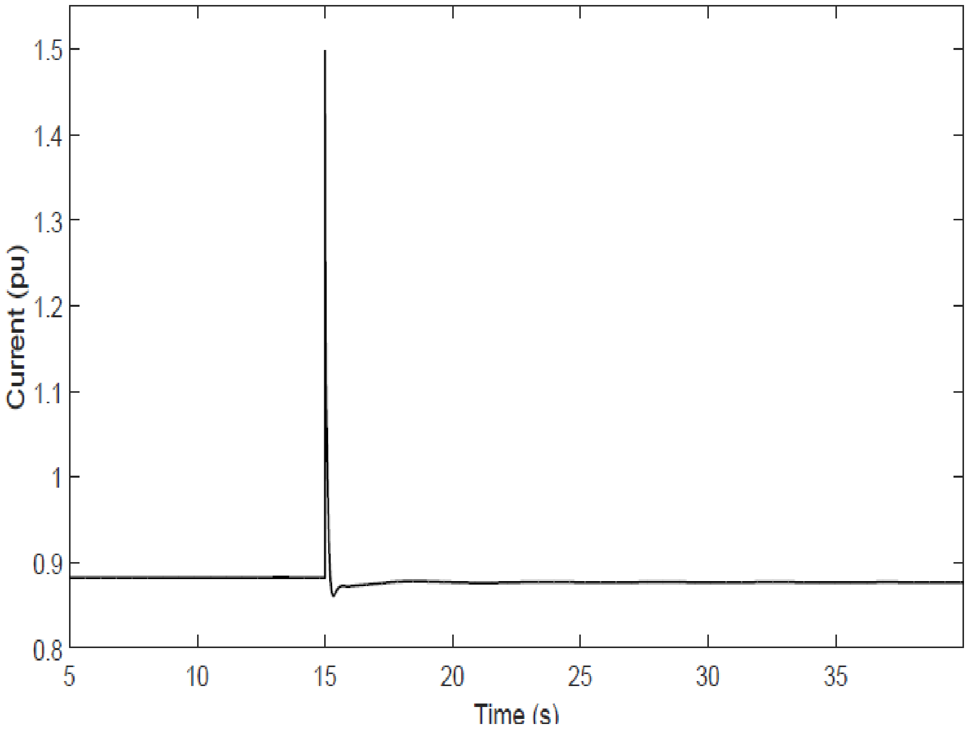
Terminal voltage of one unit of Plant A

Current of one unit of Plant A



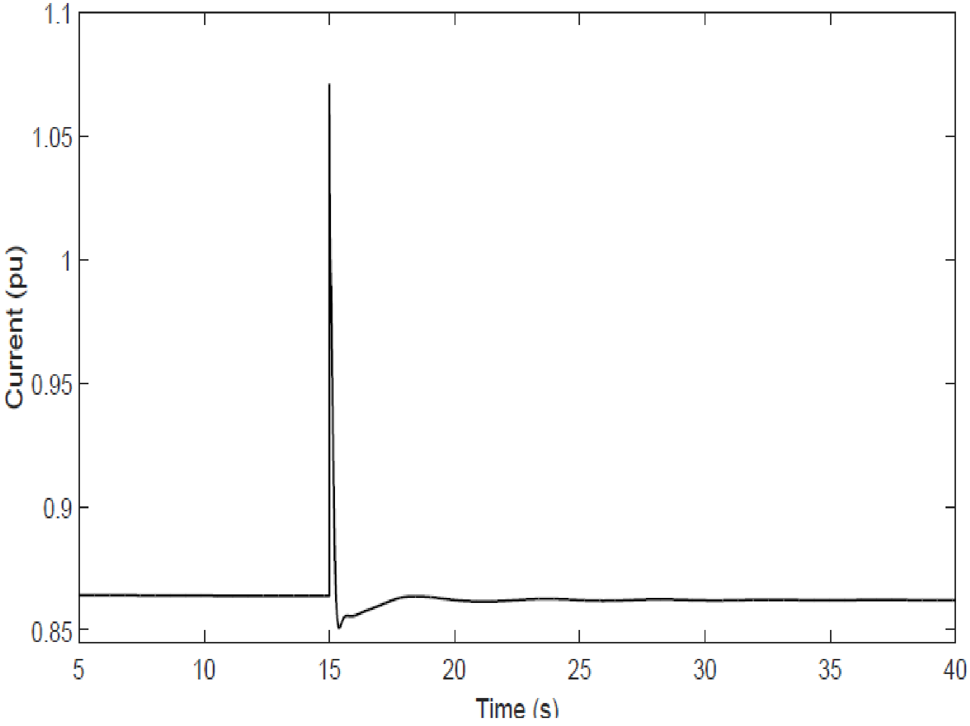
Line closure

- Closure of a transmission line should not cause excessive current and voltage transients.
- Power flow solved with major line open resulting in angle difference of 40.23° between the buses to which the line was connected.
- The line was closed during simulation.



Current of a CIG unit located near the line

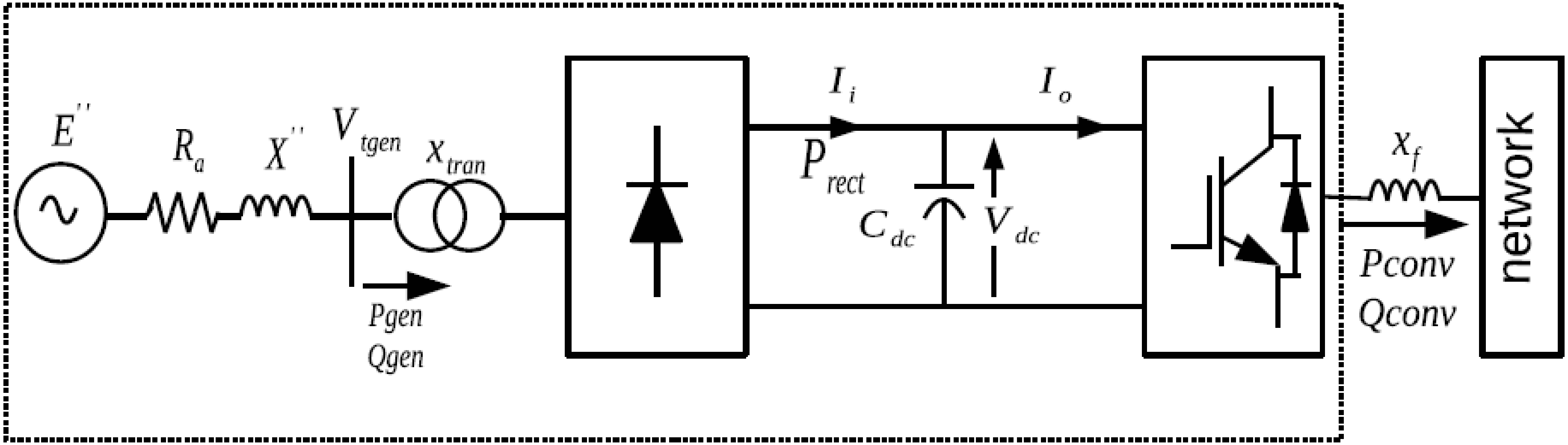
Current of a CIG unit located one bus away



Synchronous machine behind converter

- Gas turbines and hydro turbines can be interfaced through converters for higher efficiency at part-load operation.
- Due to reasons of safety and economy, the dc capacitor has to be as small as viable.
- Role played by dynamics of source in grid behavior has to be analysed.

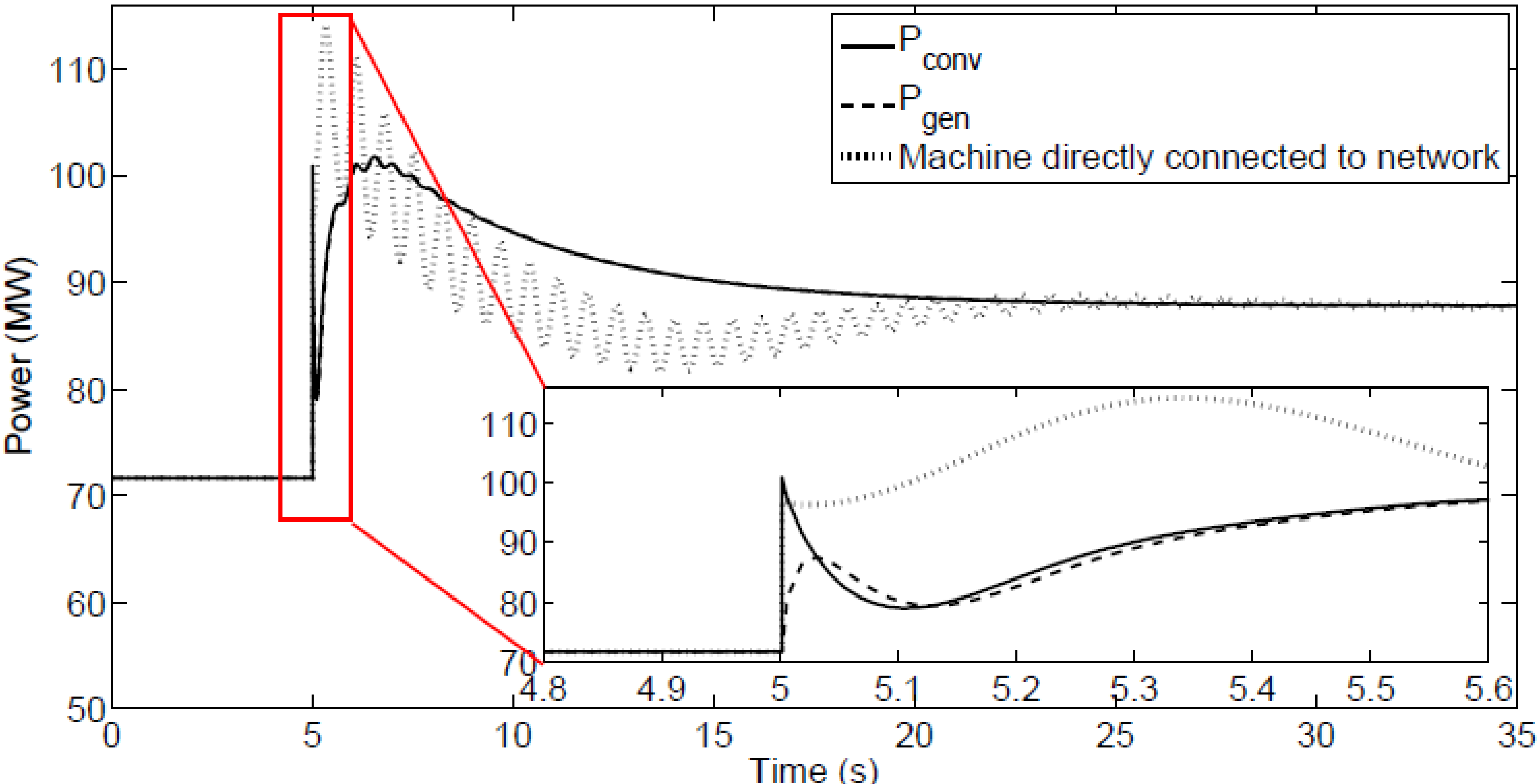
Positive sequence model



- Controlled voltage representation for inverter.
- dc capacitor dynamics considered.
- Non ideal operation of rectifier assumed.
- Synchronous machine has governor and static exciter.

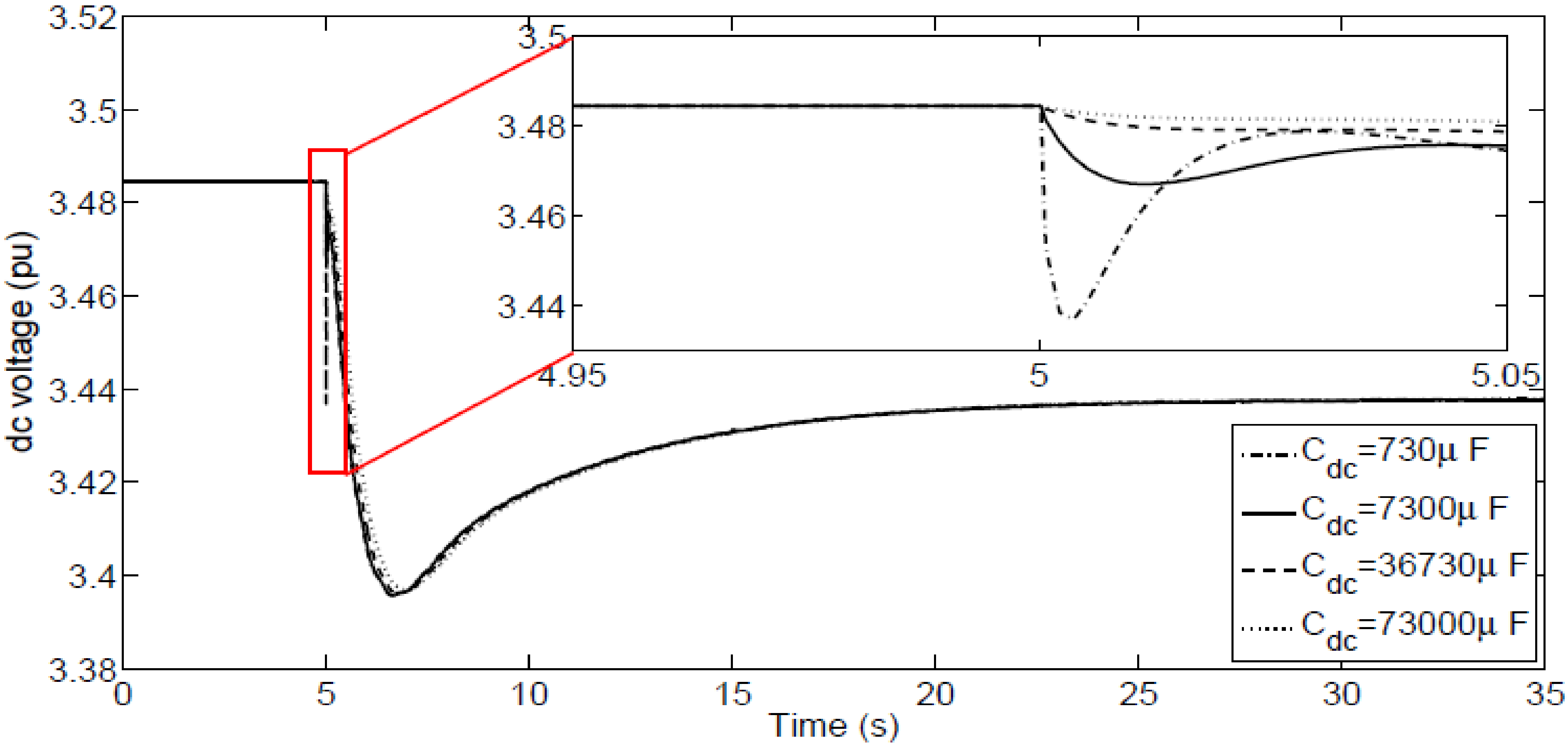
Results

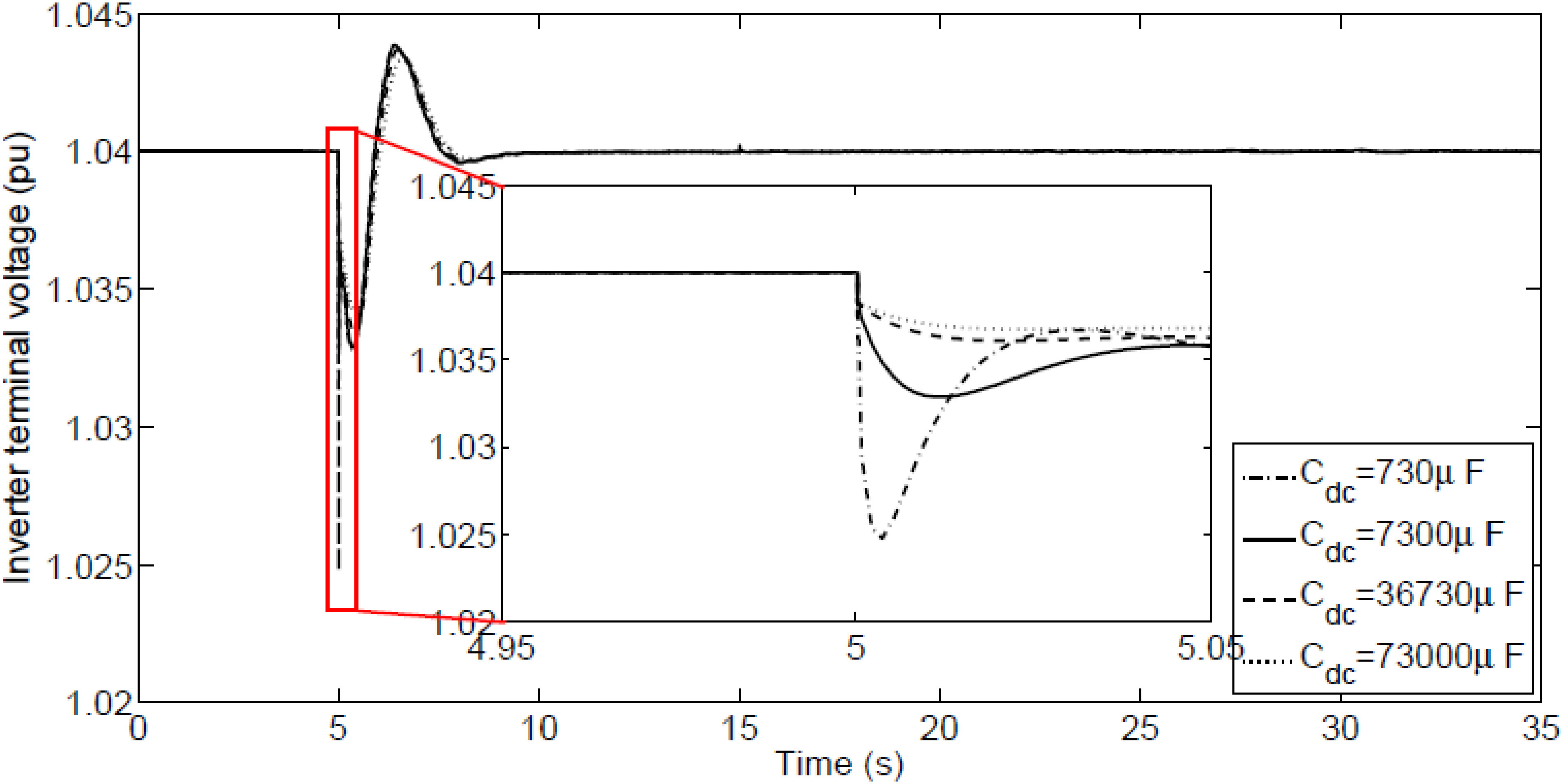
- Using a three machine nine bus WSCC equivalent system, with 1 source replaced by synchronous machine behind converter, for a load increase of 50 MW



- Sensitivity to C_{dc}

C_{dc} (μF)	Time constant (s)	Energy (MWs)
730	0.002	1.21
7340	0.02	12.1
36730	0.1	60.55
73000	0.2	120.35





- Variation of inverter terminal voltage with change in C_{dc}.

Conclusion

- A controlled voltage source representation of a CIG is more accurate compared to a boundary current representation.
- An all CIG WECC system, if required, is viable.
- The system operates in a stable manner for various contingencies.
- Long proven principle of droop relationships works.
- Important to consider the source behind the dc bus and incorporate its model into positive sequence simulations.
- Sensitivity of behavior to values of C_{dc} and its affect on grid behavior has to be studied.
- A coordinated well designed wide area control structure may also be required.

Publications

- Ramasubramanian, D., Z. Yu, R. Ayyanar, V. Vittal, and J. Undrill, "Converter Model for Representing Converter Interfaced Generation in Large Scale Grid Simulations," *IEEE Transactions on Power Systems*, Vol. 32, No. 1, pp. 765-773, January 2017.
- Ramasubramanian, D., and V. Vittal, "Positive Sequence Induction Motor Speed Control Drive Model for Time Domain Simulations," *IET Generation, Transmission and Distribution*, Vol. 11, Iss. 7, pp. 1809-1819, 2017.
- Ramasubramanian, D., and V. Vittal, "Positive Sequence Model for Converter Interfaced Synchronous Generation with Finite dc Capacitance," To appear in the *IEEE Transactions on Power Systems*.
- Ramasubramanian, D., V. Vittal, J. Undrill, "Transient Stability Analysis of an all Converter Interfaced Generation WECC System," Paper #44 PSCC 2016, Genoa, Italy, June 20-24, 2016.