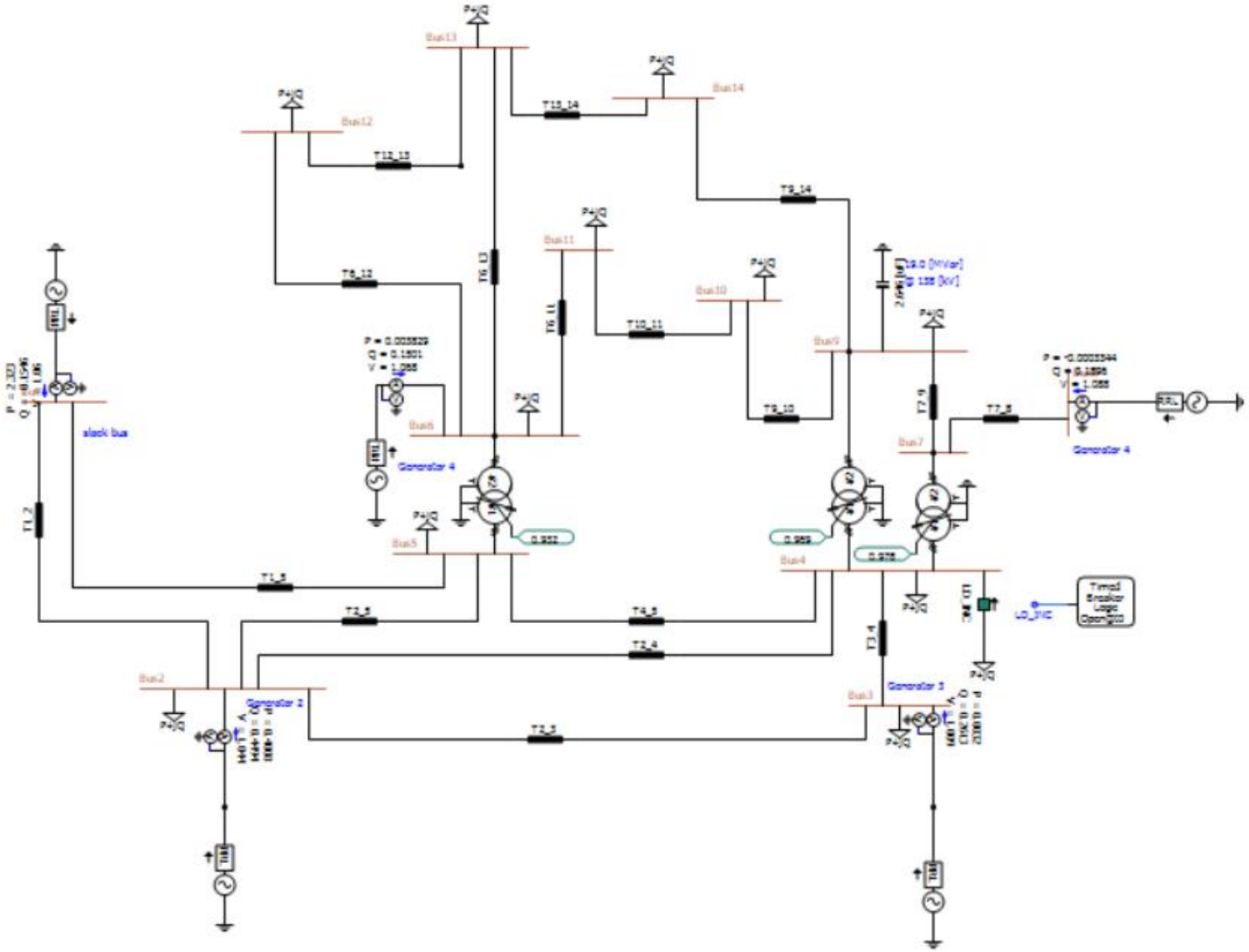
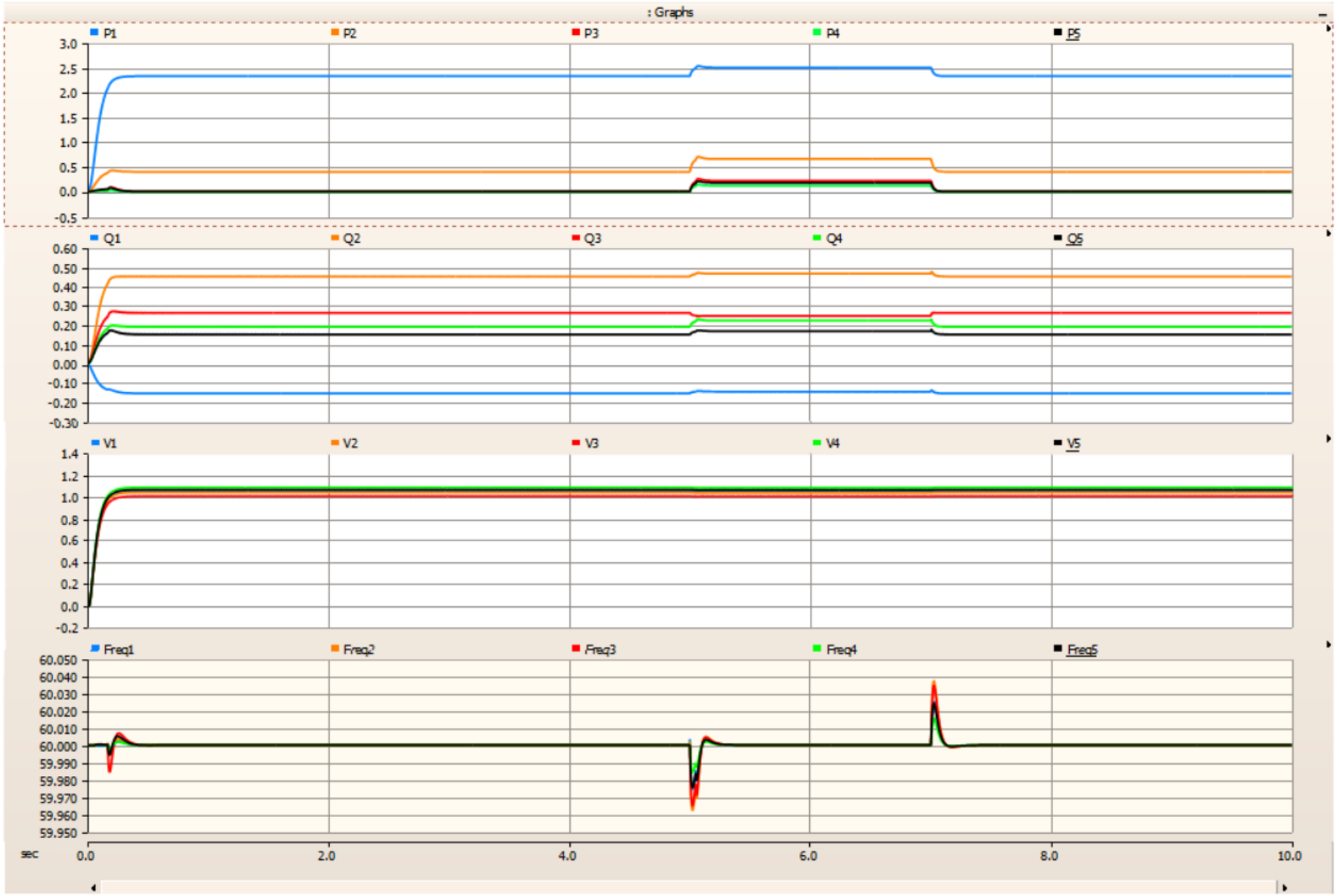
Simulations:

- Load Increase (14 Bus) at Bus 4 (+ 50 MW, - 1.30 MVAR)
  - Bus 4: Base case – bus with highest load
  - Zero Inertia (GFM Slack)
    - 5:0 (GFM:GFL)
    - 4:1
    - 3:2
    - 2:3
    - 1:4
  - High Penetration (Ideal Voltage Source Slack)
    - 4:0
    - 3:1
    - 2:2
    - 1:3
    - 0:4

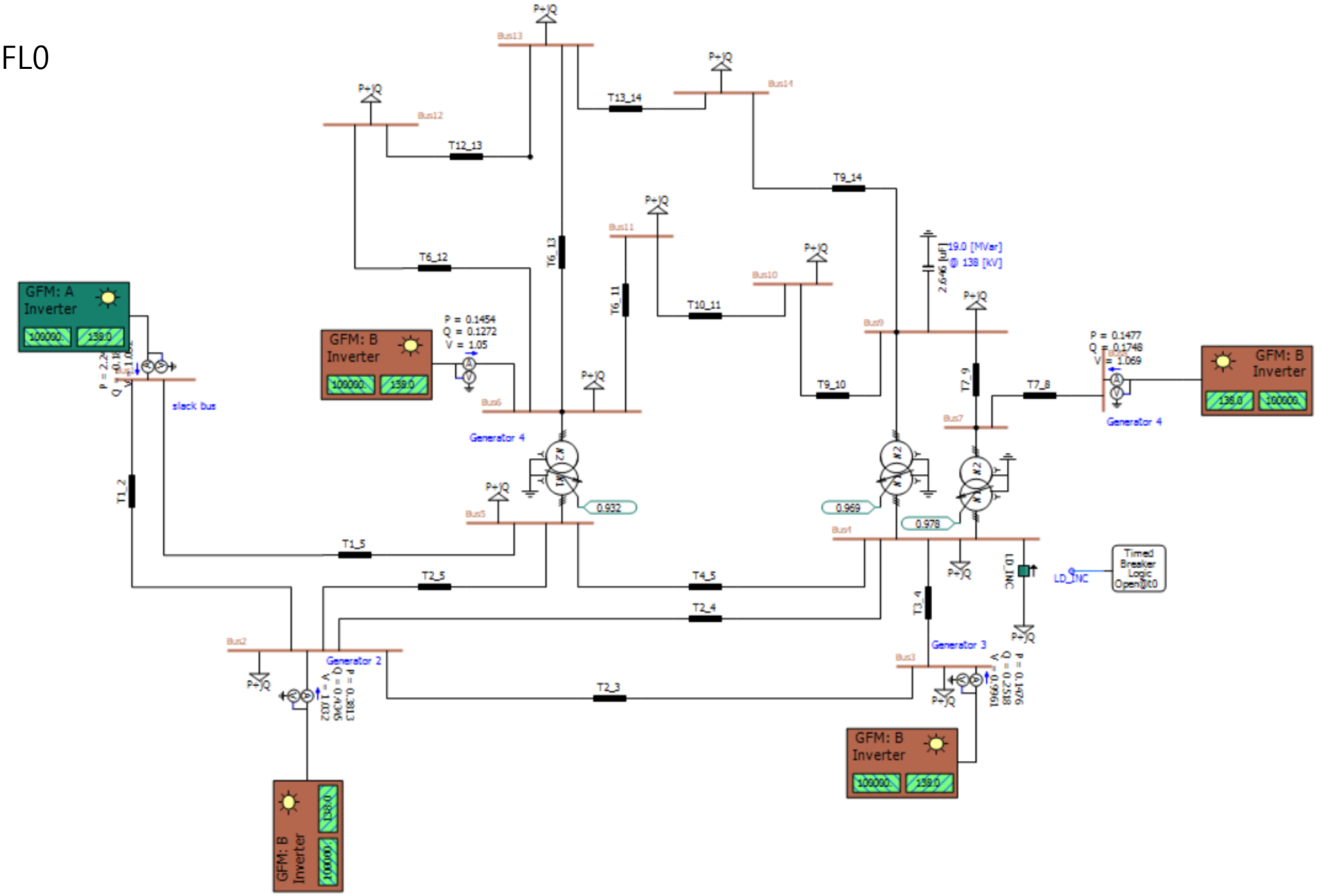
14 Bus Base Case



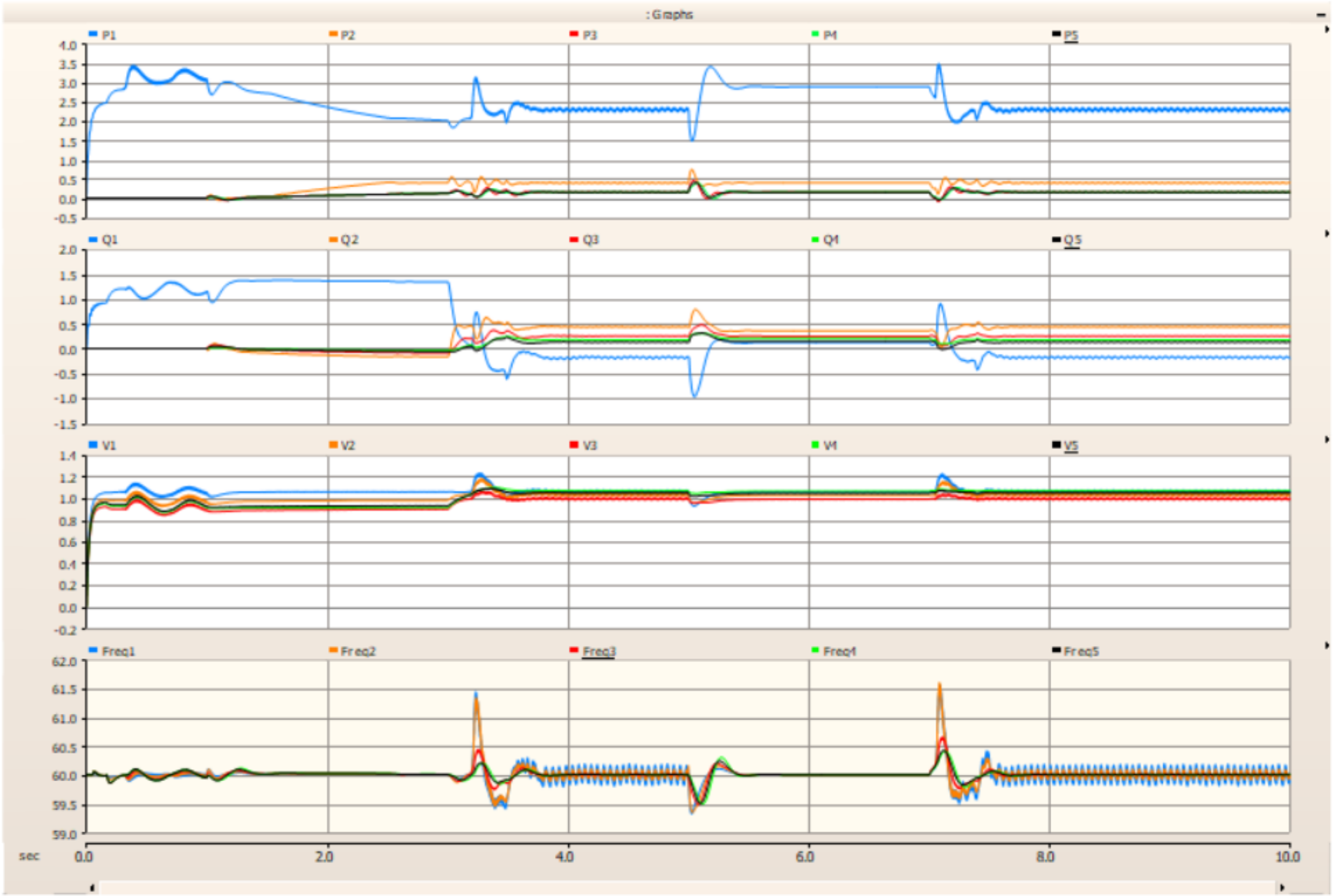
14 Bus Base Case



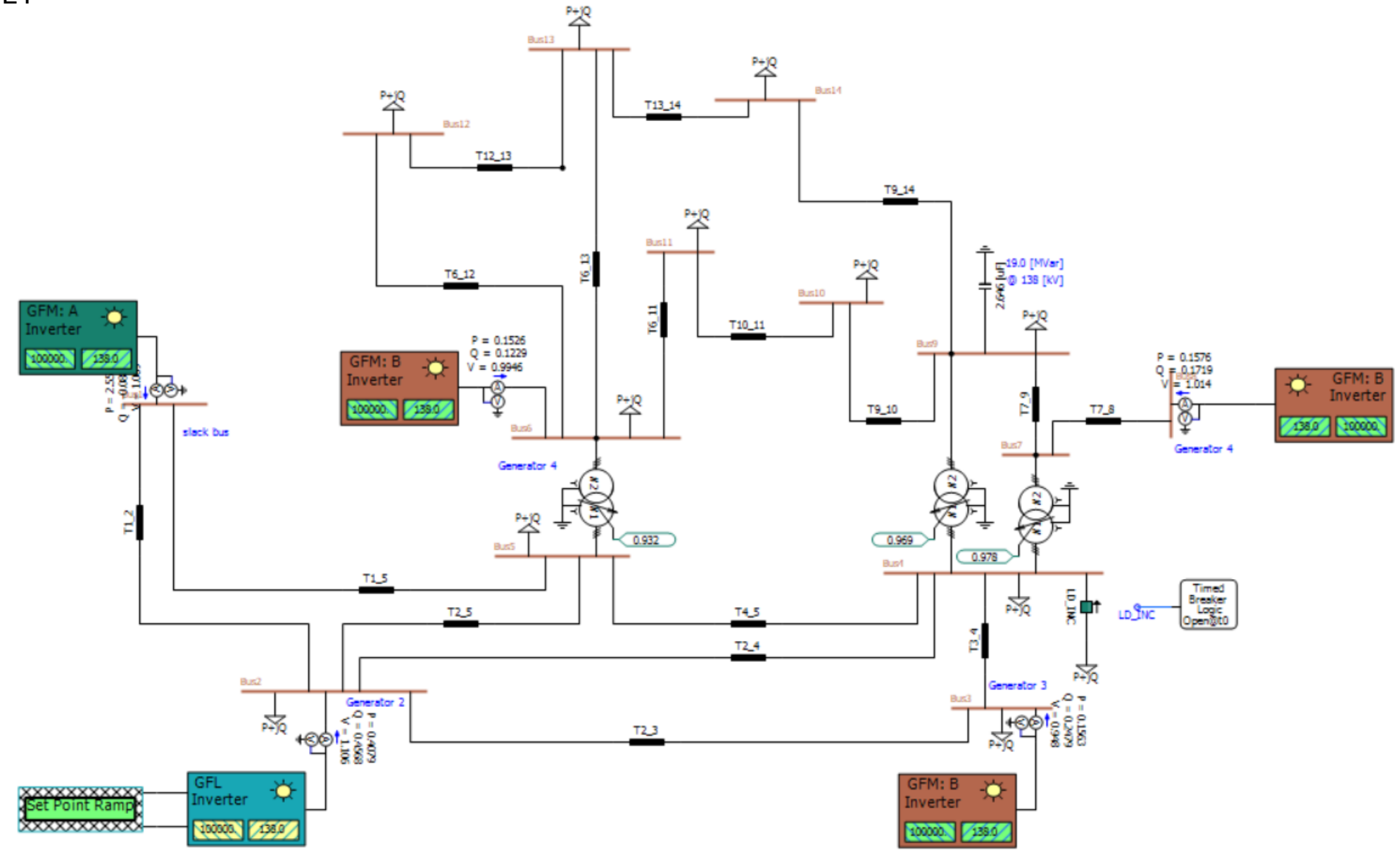
GFM5_GFL0


GFM: A Inverter
100000.
138.0
slack bus
GFM: B Inverter
P = 0.1454
Q = 0.1272
V = 1.05
Generator 4
0.932
0.969
0.978
19.0 [MVar] @ 138 [KV]
P = 0.1477
Q = 0.1748
V = 1.069
Generator 4
Timed Breaker Logic Open@10
LD_INC
Generator 3
Generator 2
GFM: B Inverter
GFM: B Inverter
GFM: B Inverter
Bus13
Bus14
Bus12
Bus11
Bus10
Bus9
Bus7
Bus6
Bus5
Bus4
Bus3
Bus2
T13_14
T12_13
T9_14
T6_12
T6_13
T6_11
T10_11
T9_10
T7_9
T7_8
T1_2
T1_5
T2_5
T4_5
T2_4
T3_4
T2_3

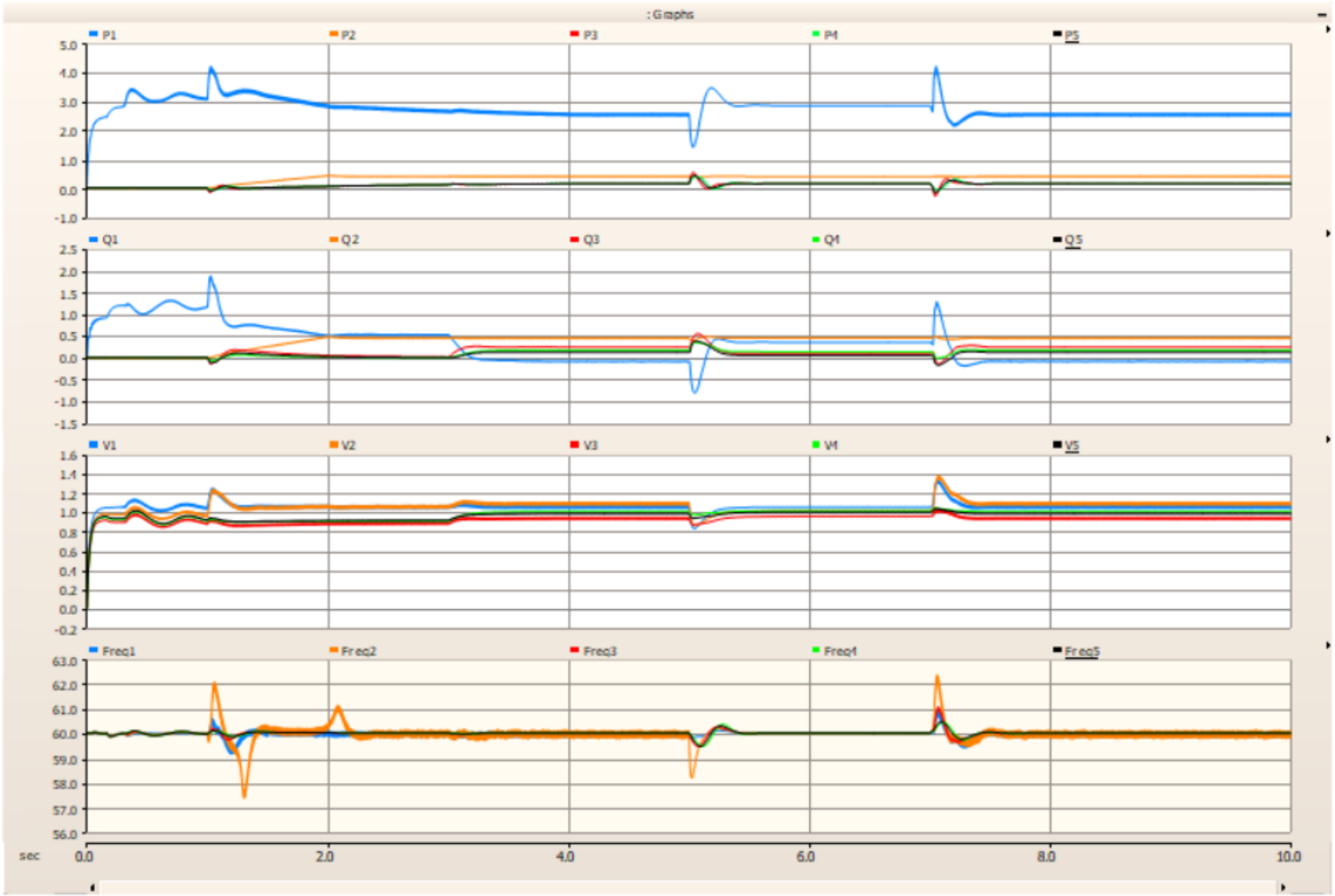
GFM5_GFL0


: Graphs
P1
P2
P3
P4
P5
Q1
Q2
Q3
Q4
Q5
V1
V2
V3
V4
V5
Freq1
Freq2
Freq3
Freq4
Freq5
sec
0.0
2.0
4.0
6.0
8.0
10.0

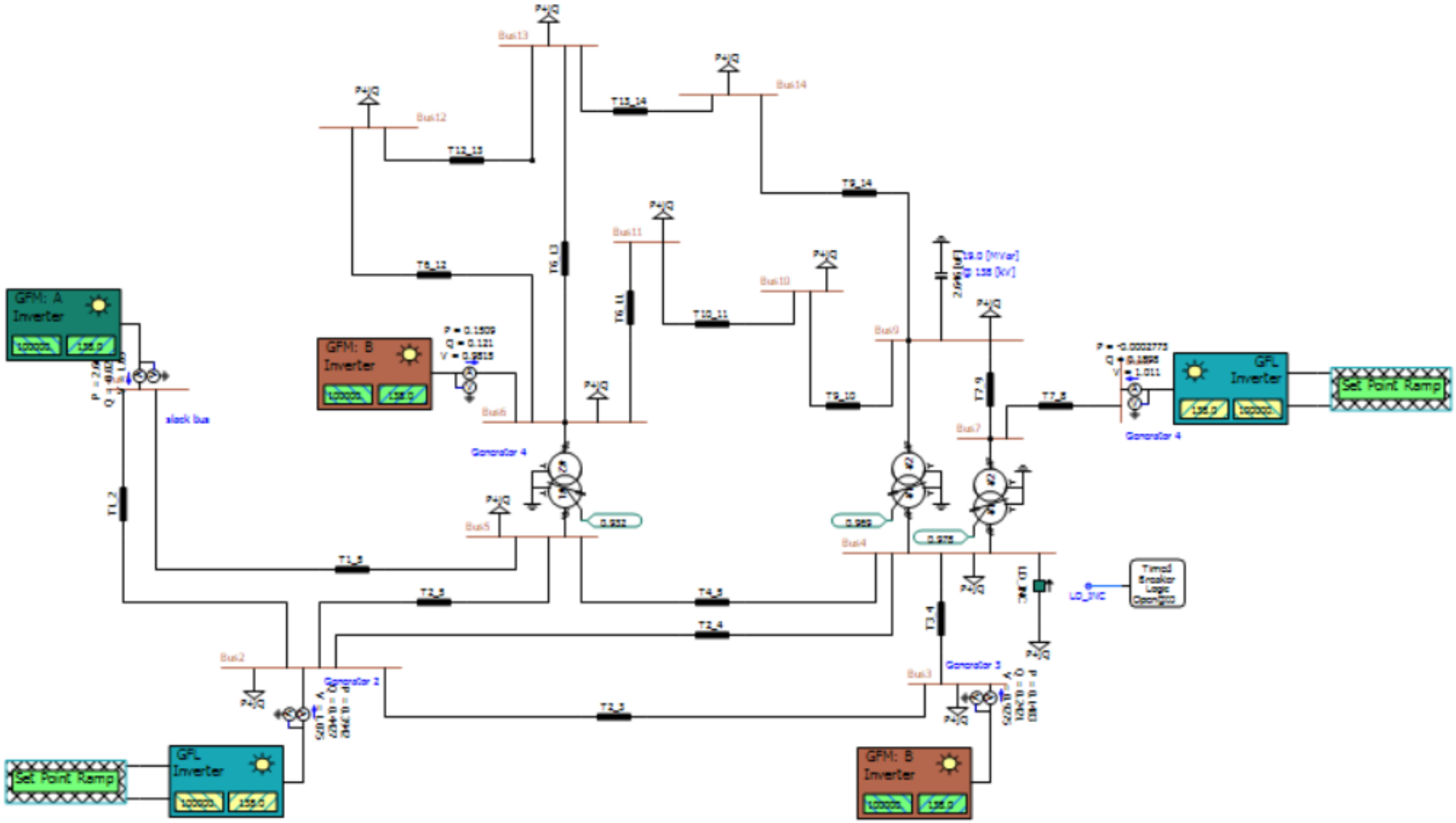
GFM4_GFL1


GFM: A Inverter
100000
138.0
slack bus
GFM: B Inverter
P = 0.1526
Q = 0.1229
V = 0.9946
Generator 4
0.932
0.969
0.978
19.0 [MVar] @ 138 [kV]
P = 0.1576
Q = 0.1719
V = 1.014
GFM: B Inverter
Generator 4
Timed Breaker Logic Open@t0
LD_INC
Generator 3
Generator 2
GFL Inverter
Set Point Ramp
GFM: B Inverter
T1_2
T1_5
T2_5
T4_5
T2_4
T2_3
T3_4
T6_12
T6_13
T6_11
T10_11
T9_10
T9_14
T13_14
T12_13
T7_8
T7_9
Bus1
Bus2
Bus3
Bus5
Bus6
Bus7
Bus9
Bus10
Bus11
Bus12
Bus13
Bus14

GFM4_GFL1


: Graphs
P1
P2
P3
P4
P5
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
Q1
Q2
Q3
Q4
Q5
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
V1
V2
V3
V4
V5
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Freq1
Freq2
Freq3
Freq4
Freq5
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
sec
0.0
2.0
4.0
6.0
8.0
10.0

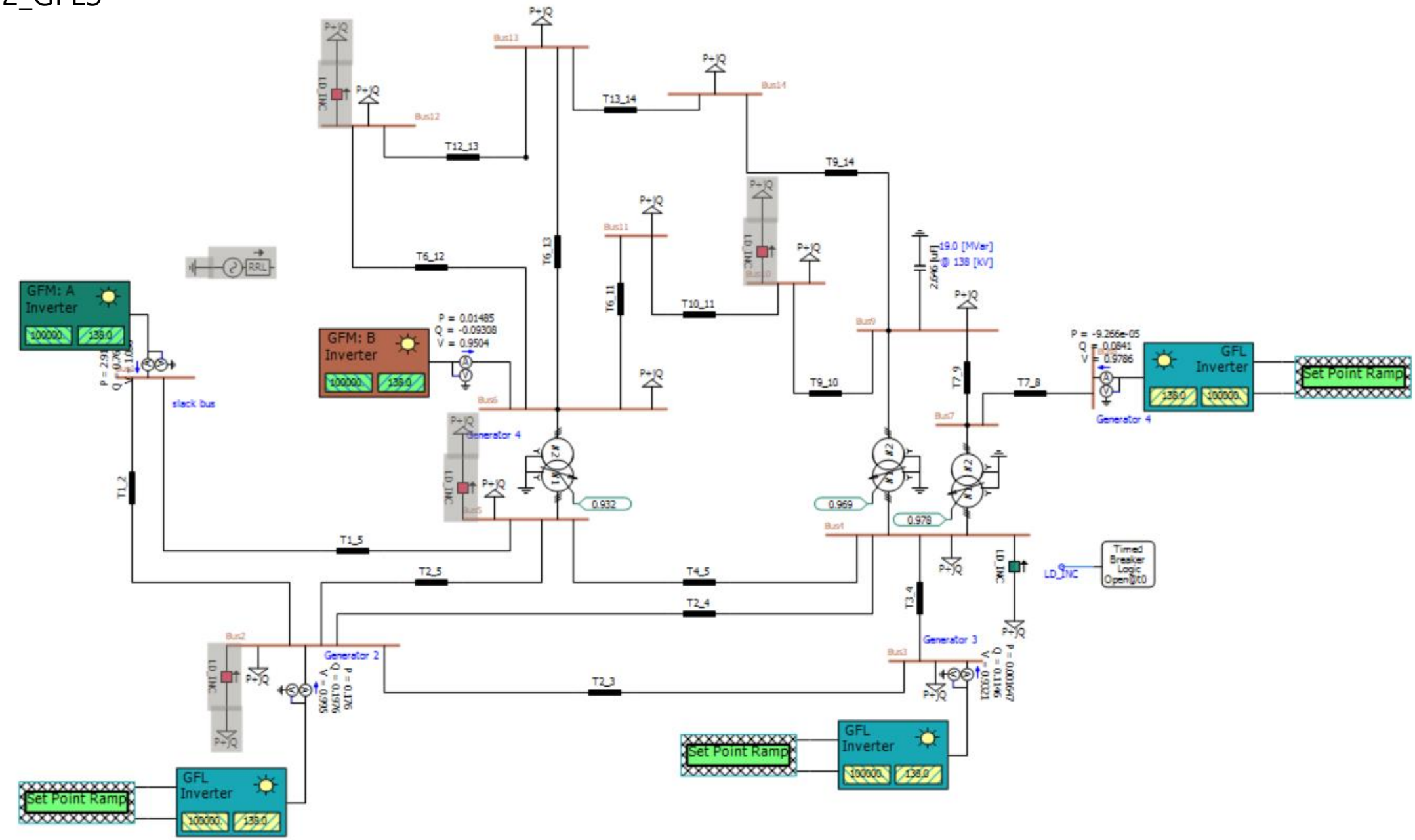
GFM3_GFL2


GFM: A Inverter
GFM: B Inverter
GFL Inverter
Set Point Ramp
slack bus
Generator 4
Generator 2
Generator 3
Bus13
Bus14
Bus12
Bus11
Bus10
Bus9
Bus7
Bus6
Bus5
Bus4
Bus2
Bus3
T13_14
T12_13
T9_14
T6_12
T6_13
T6_11
T10_11
T9_10
T7_9
T7_8
T1_2
T1_5
T2_5
T4_5
T2_4
T3_4
T2_3
Timed Breaker Logic
LO_INC

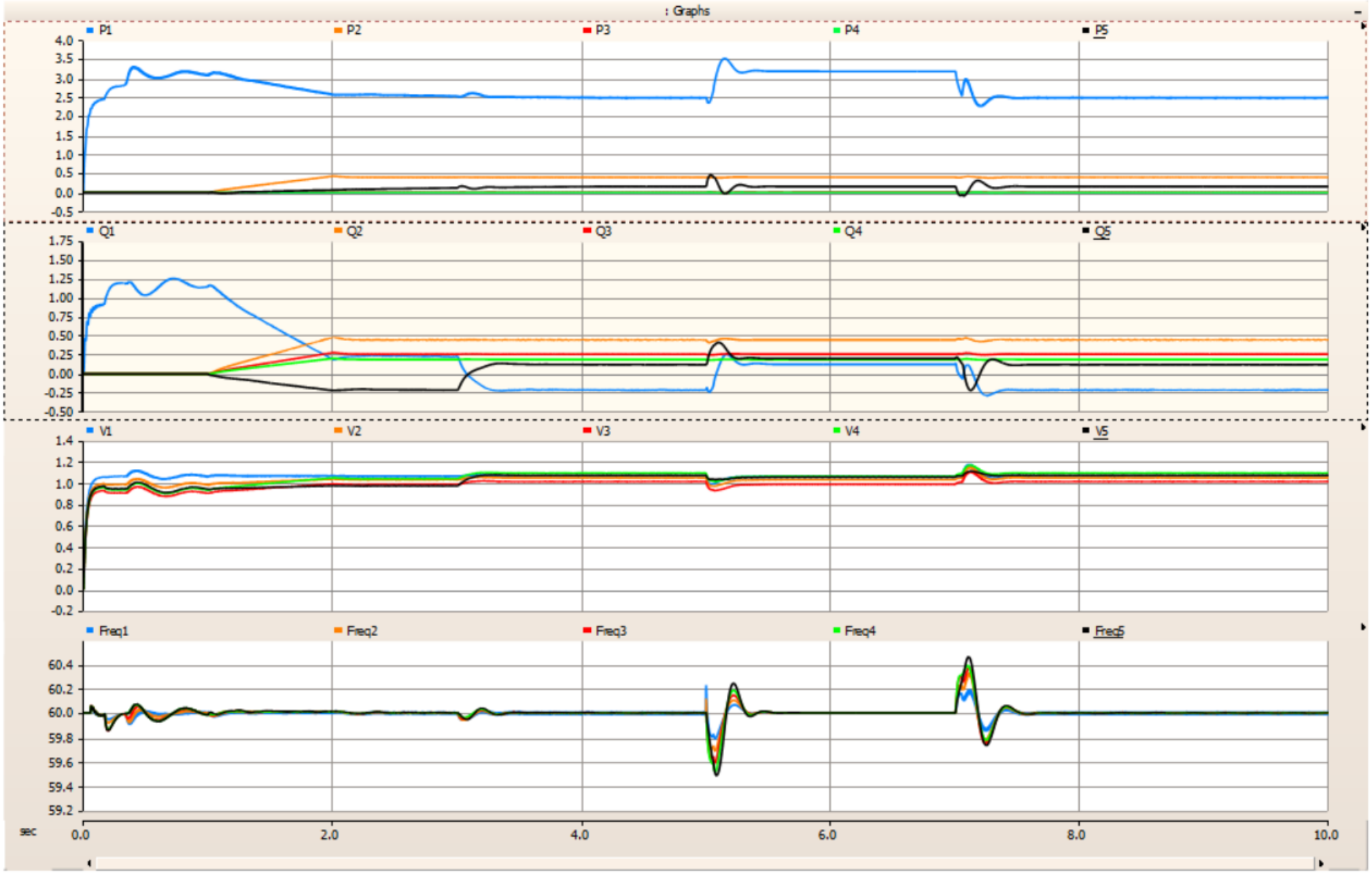
GFM3_GFL2


: Graphs
P1
P2
P3
P4
P5
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
Q1
Q2
Q3
Q4
Q5
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
V1
V2
V3
V4
V5
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Freq1
Freq2
Freq3
Freq4
Freq5
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
sec
0.0
2.0
4.0
6.0
8.0
10.0

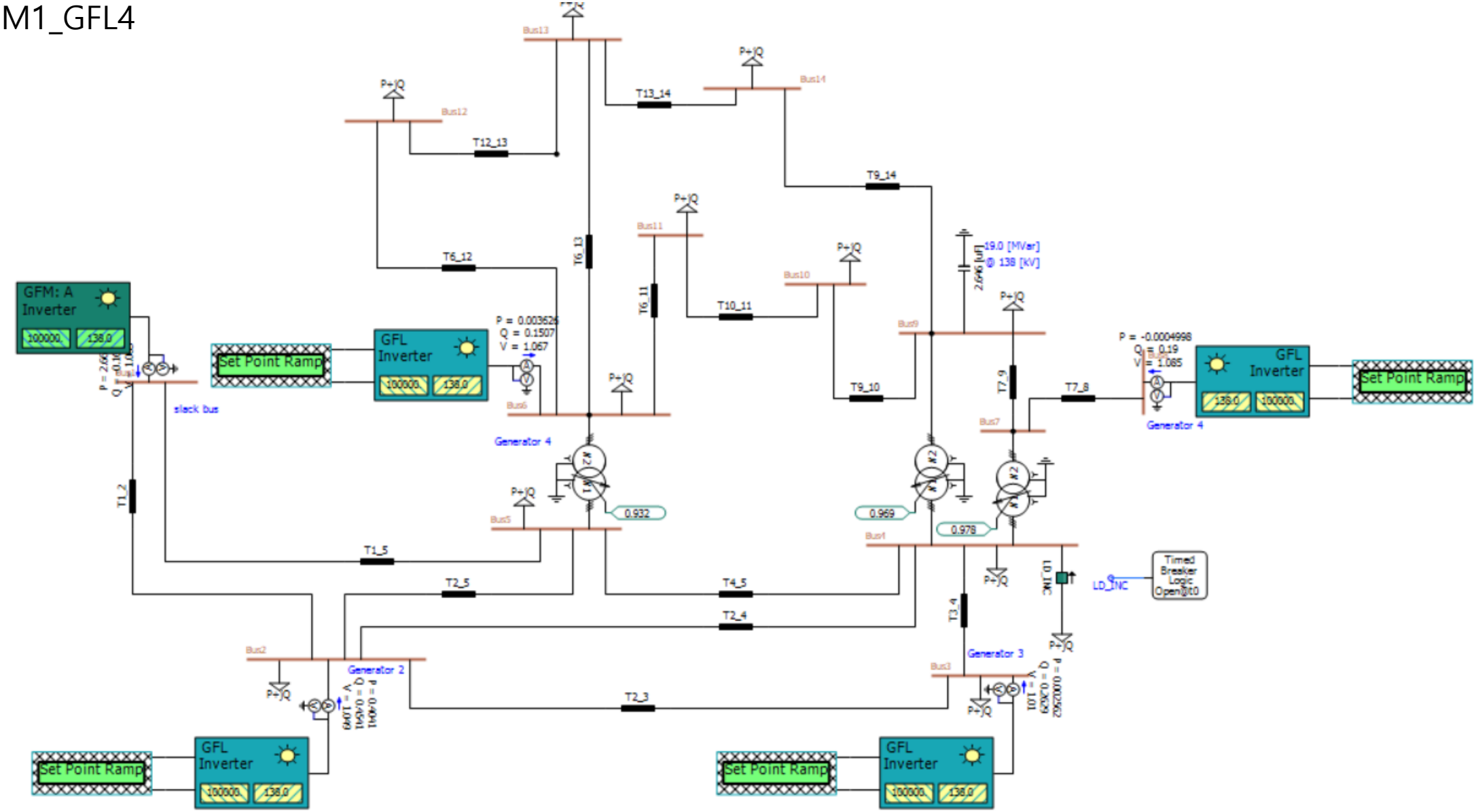
GFM2_GFL3


GFM: A Inverter
100000
138.0
GFM: B Inverter
100000
138.0
P = 0.01485
Q = -0.09308
V = 0.9504
slack bus
RRL
Bus13
Bus12
Bus14
Bus11
Bus6
Bus9
Bus7
Bus1
Bus2
Bus3
Bus5
T12_13
T13_14
T9_14
T6_12
T6_13
T6_11
T10_11
T9_10
T7_9
T7_8
T1_2
T1_5
T2_5
T4_5
T2_4
T2_3
T3_4
19.0 [MVar] @ 138 [kV]
2.696 [µH]
P = -9.266e-05
Q = 0.0841
V = 0.9786
GFL Inverter
Set Point Ramp
Generator 4
Generator 2
Generator 3
0.932
0.969
0.979
LD_INC
Timed Breaker Logic Open@t0
P = 0.3476
Q = 0.1936
V = 0.995
P = 0.000597
Q = 0.1146
V = 0.9321

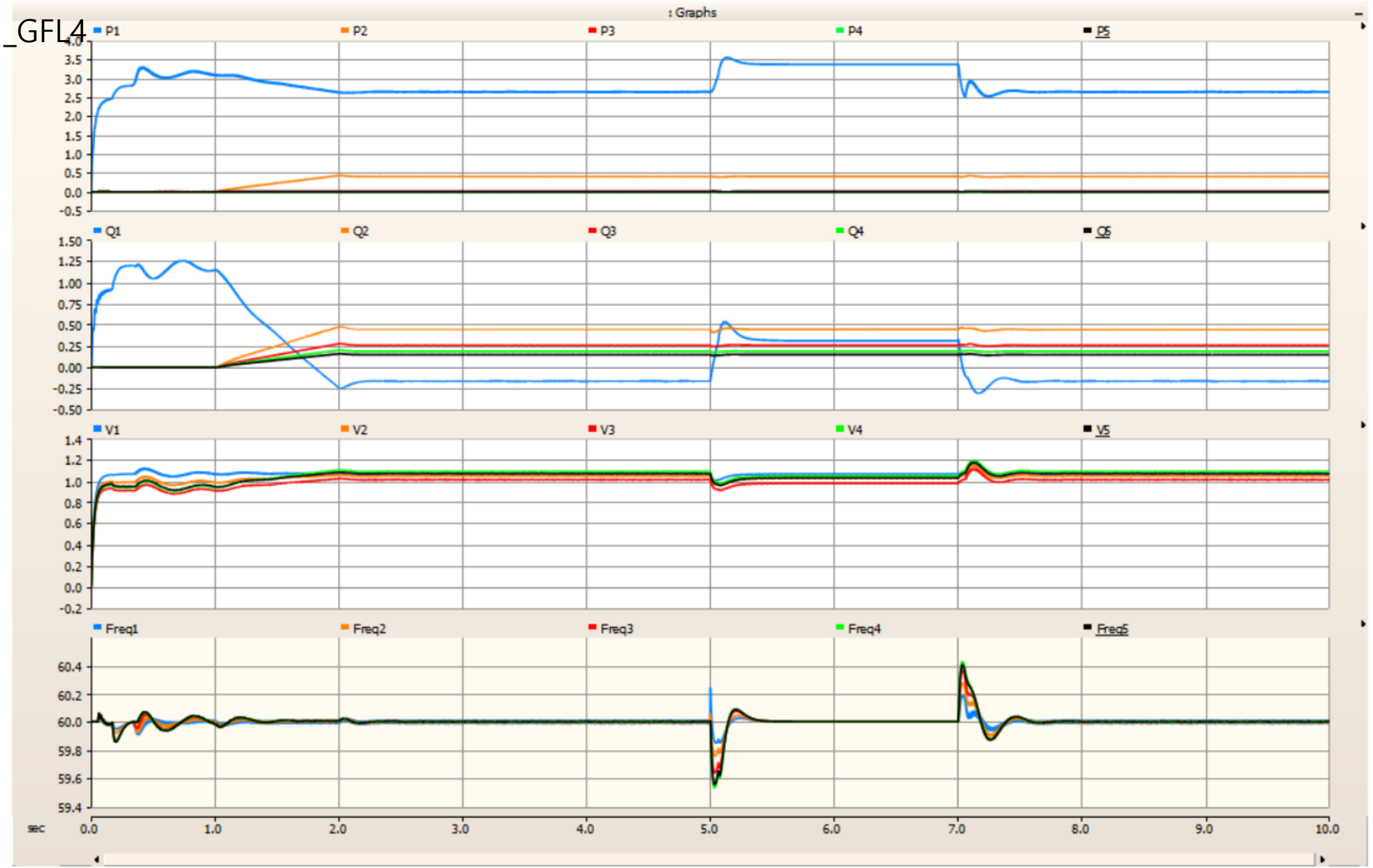
GFM2_GFL3


: Graphs
P1
P2
P3
P4
P5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
Q1
Q2
Q3
Q4
Q5
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
V1
V2
V3
V4
V5
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Freq1
Freq2
Freq3
Freq4
Freq5
60.4
60.2
60.0
59.8
59.6
59.4
59.2
sec
0.0
2.0
4.0
6.0
8.0
10.0

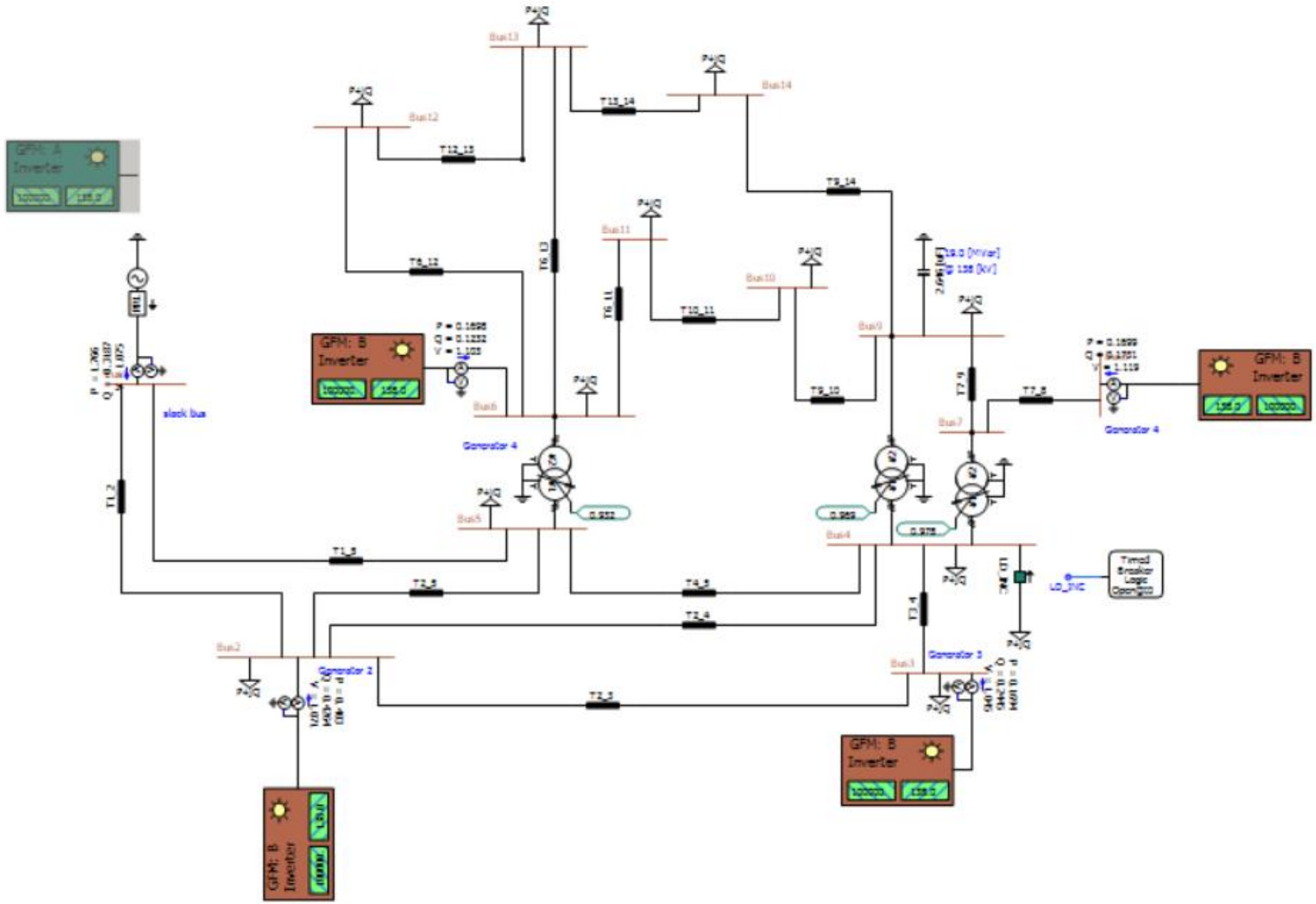
GFM1_GFL4


GFM: A Inverter
100000
138.0
Set Point Ramp
GFL Inverter
100000
138.0
slack bus
Generator 4
Generator 2
Generator 3
Bus1
Bus2
Bus3
Bus5
Bus6
Bus7
Bus9
Bus10
Bus11
Bus12
Bus13
Bus14
T1_2
T1_5
T2_3
T2_4
T2_5
T3_4
T4_5
T6_11
T6_12
T6_13
T7_8
T7_9
T9_10
T9_14
T10_11
T12_13
T13_14
0.932
0.969
0.978
19.0 [MVar]
@ 138 [kV]
LD_INC
Timed Breaker Logic Open@t0

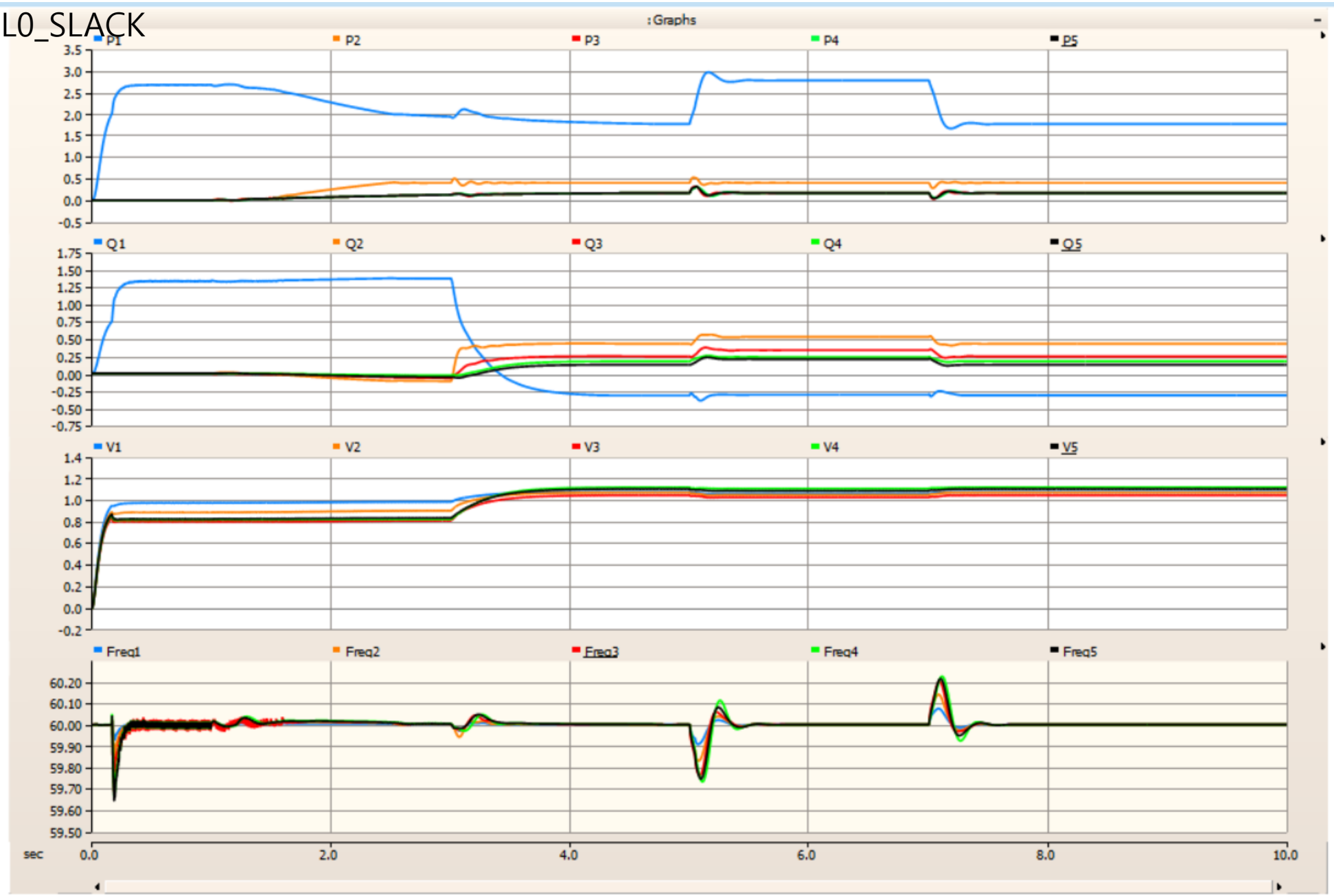
GFM1_GFL4


: Graphs
P1
P2
P3
P4
P5
Q1
Q2
Q3
Q4
Q5
V1
V2
V3
V4
V5
Freq1
Freq2
Freq3
Freq4
Freq5
sec
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

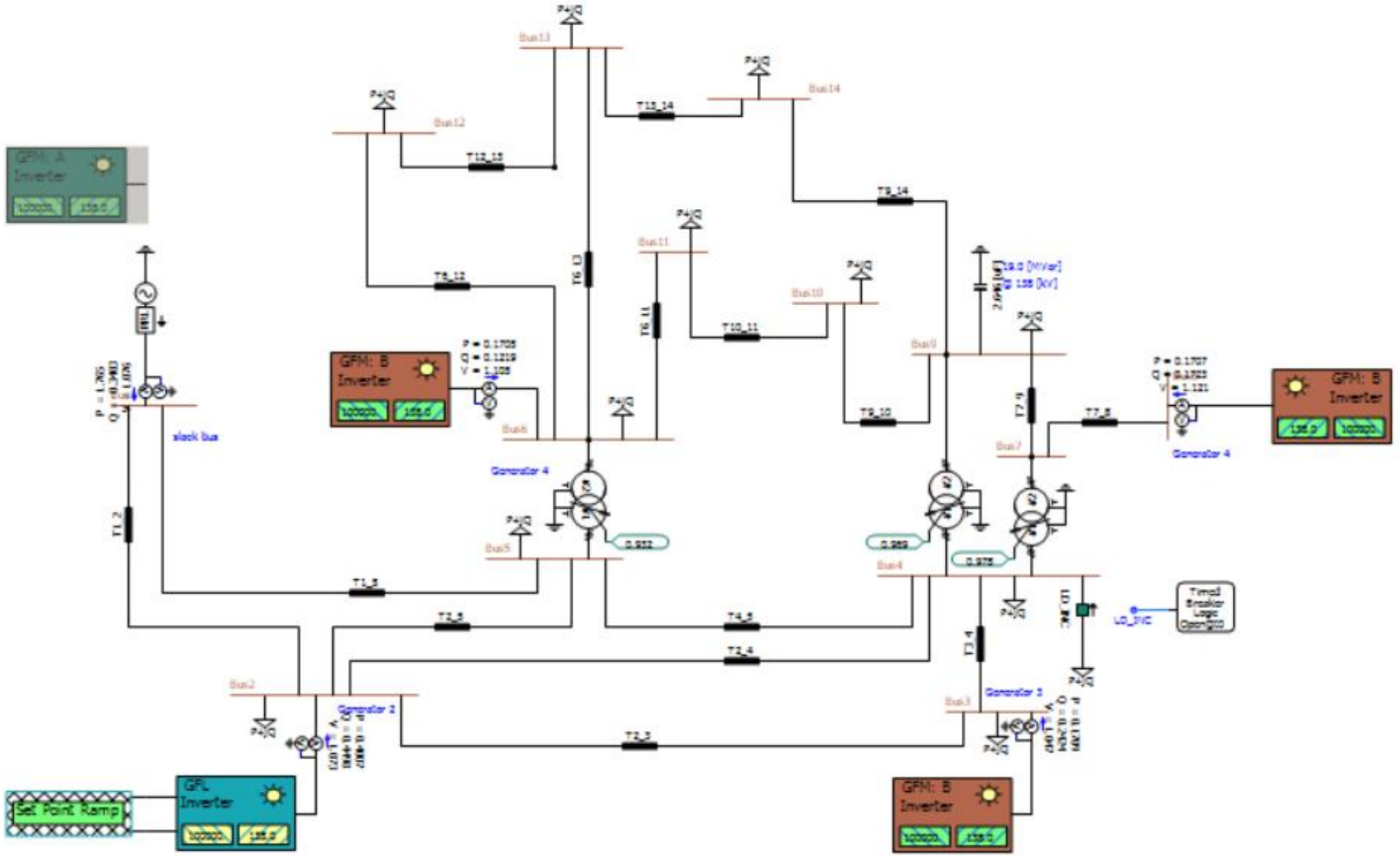
GFM4_GFL0_SLACK



GFM4_GFL0_SLACK

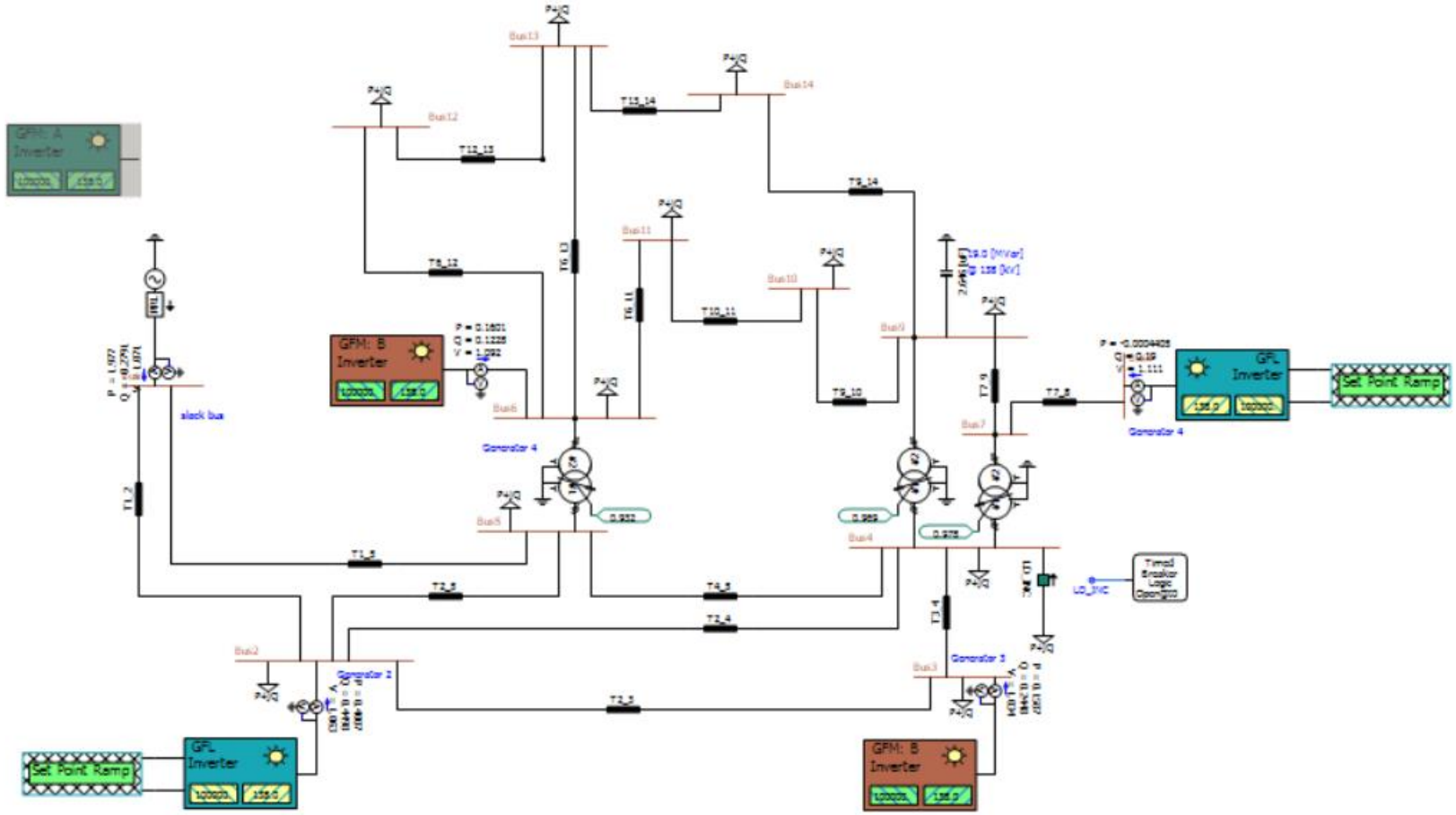


GFM3_GFL1_SLACK

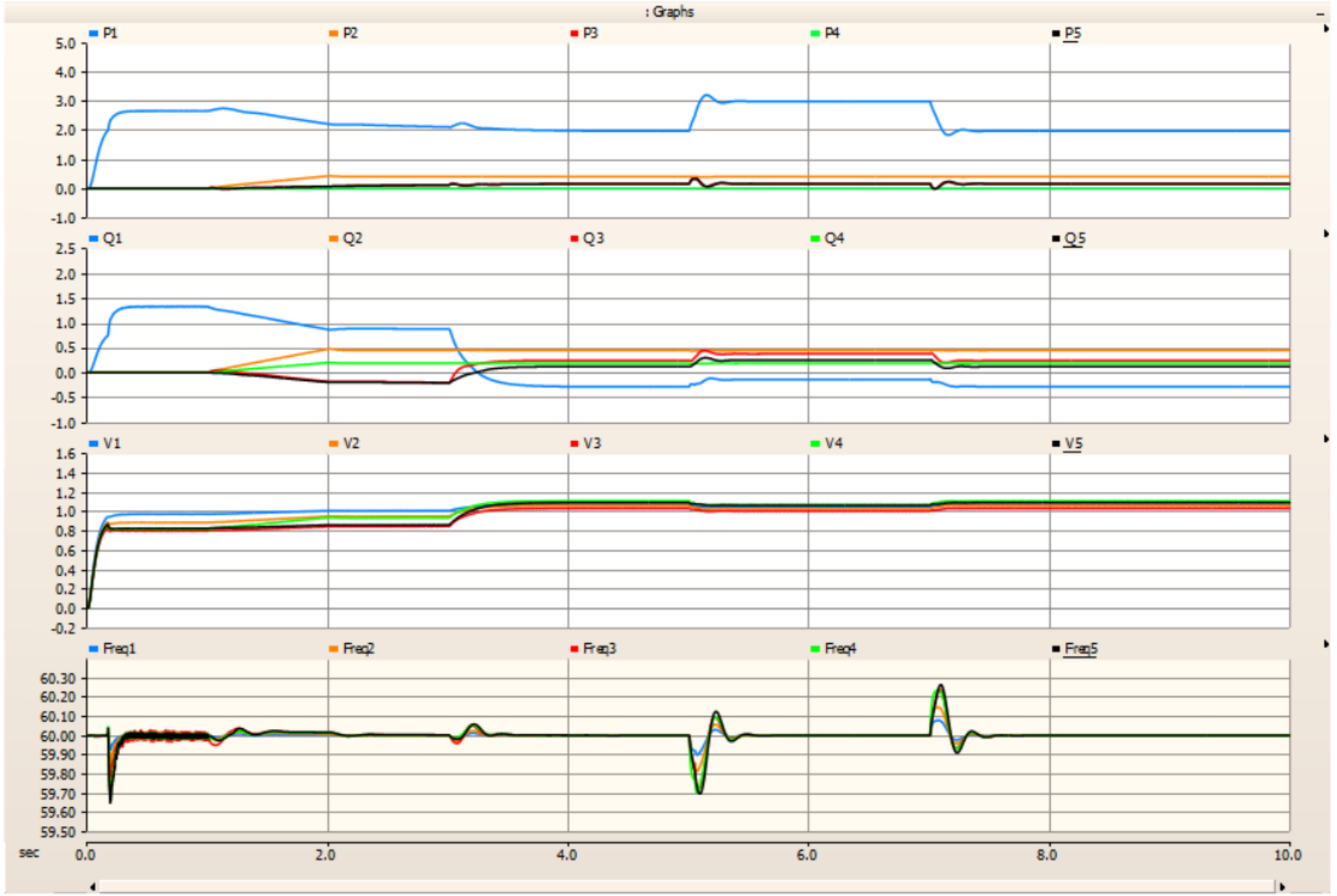


GFM3_GFL1_SLACK

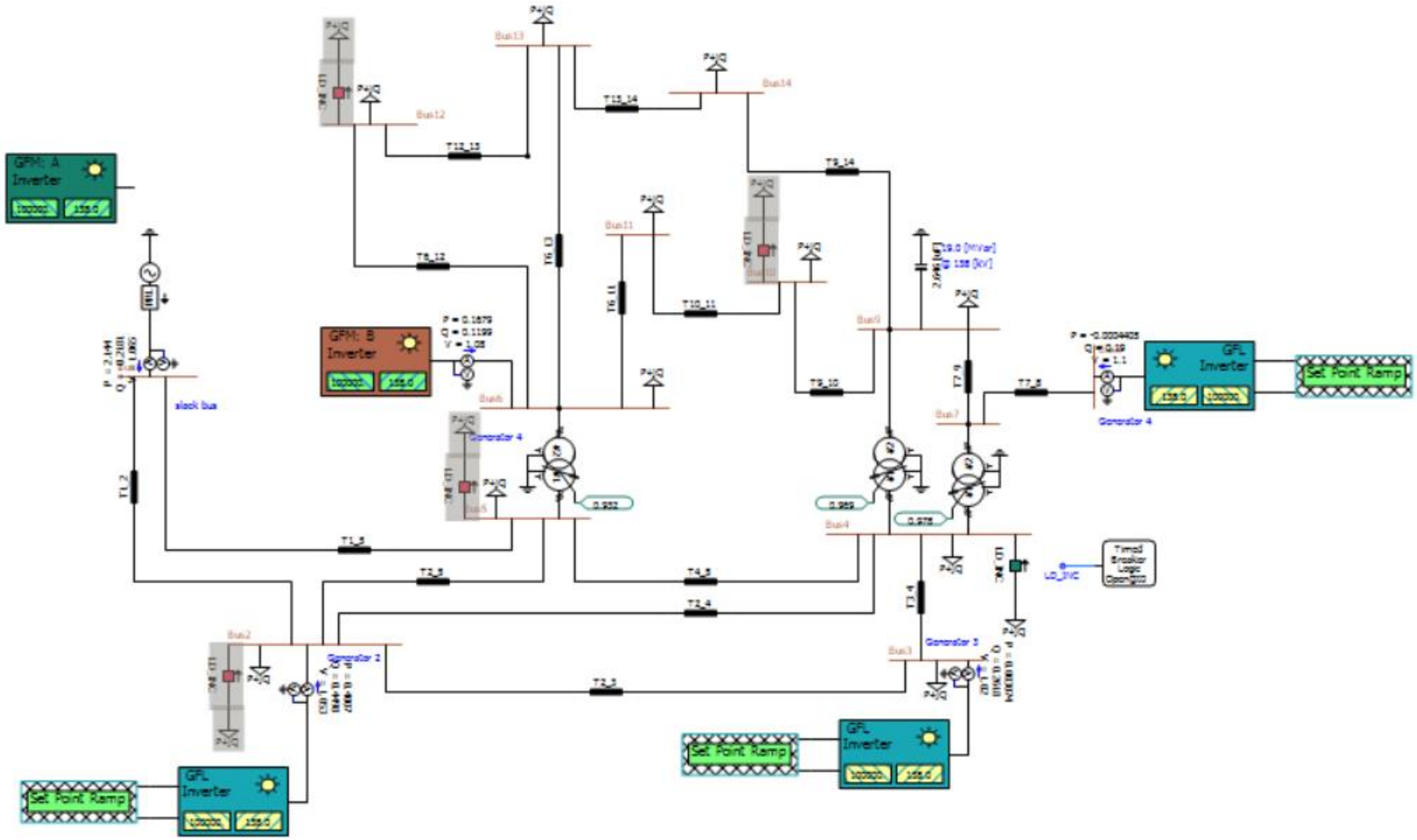
GFM2_GFL2_SLACK



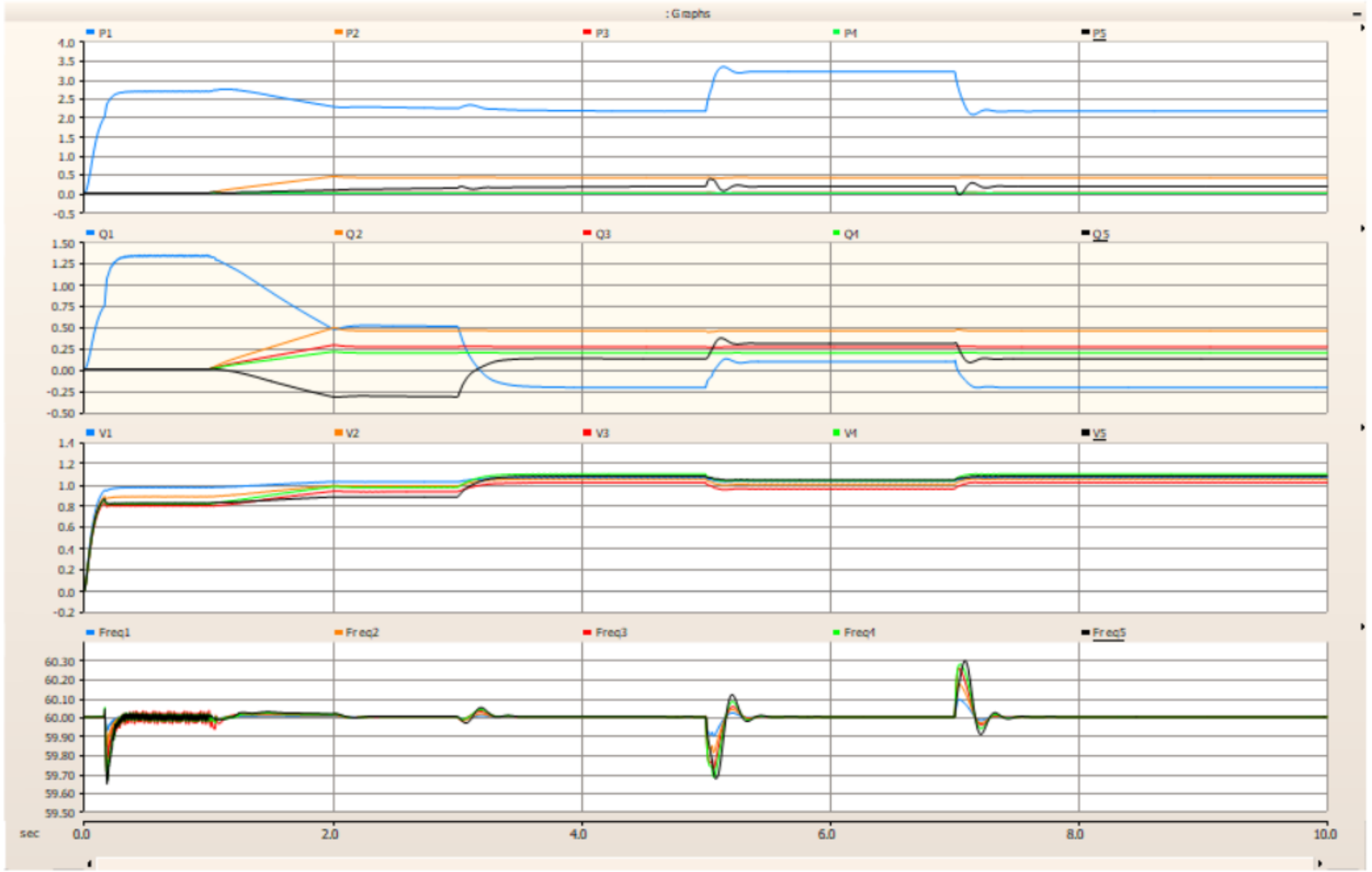
GFM2_GFL2_SLACK



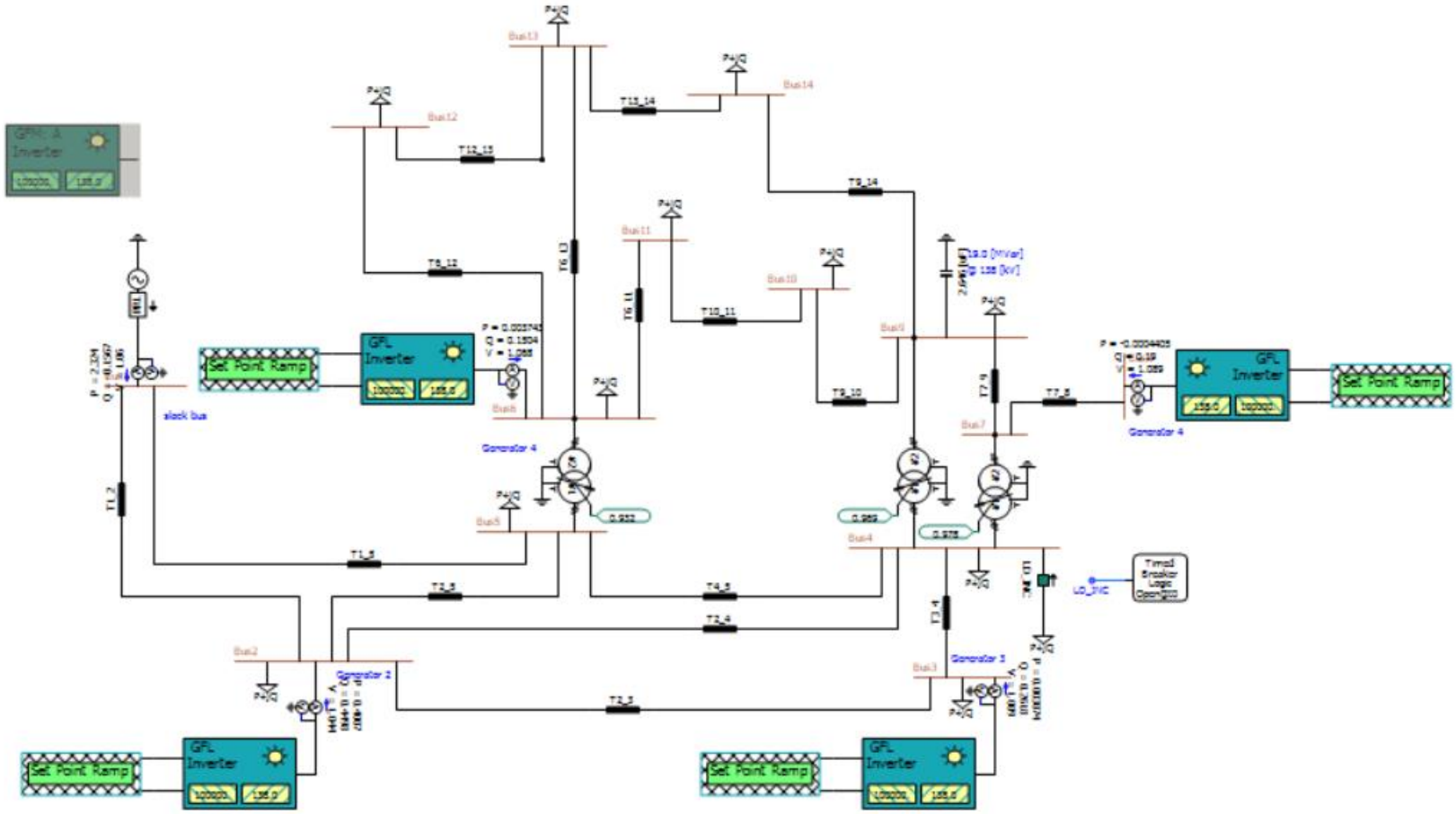
GFM1_GFL3_SLACK



GFM1_GFL3_SLACK



GFM0_GFL4_SLACK



GFM0_GFL4_SLACK

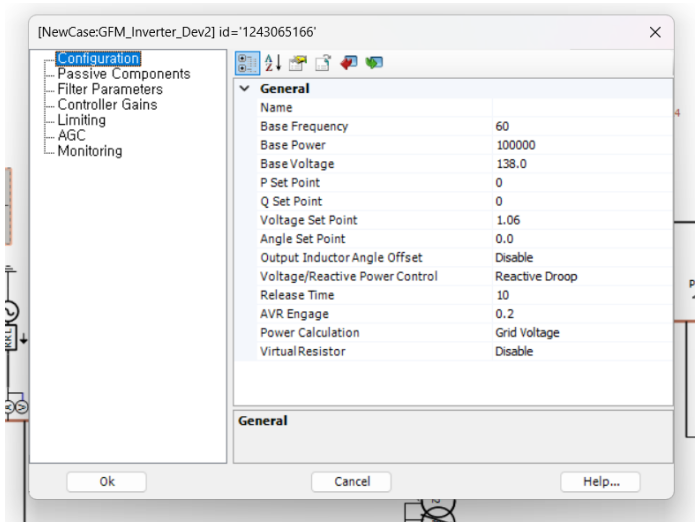
Zero Inertia

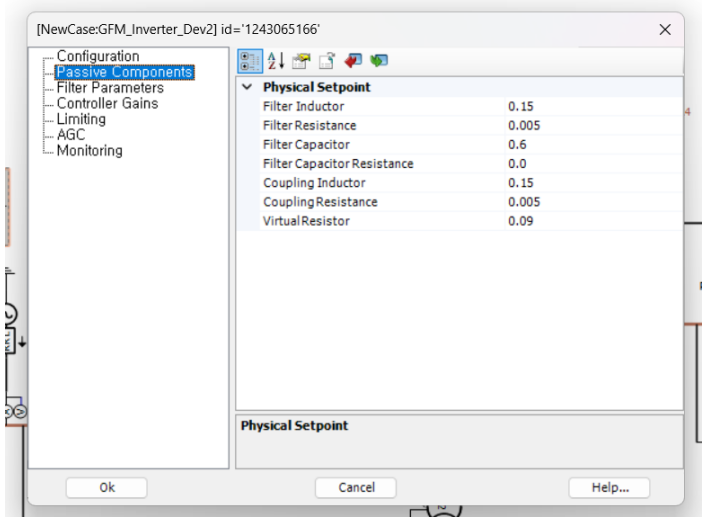
- (예상과 같이) GFM이 GFL보다 더 많을 때
  - GFM의 freq Nadir 더 좋지만 transient response 느린다.
  - 예상과 같이 동일
  - GFM이 frequency를 지원할 수 있는 기능이 있음으로 frequency stability 더 좋음
  - GFL이 이런 기능이 없음으로 frequency spike 더 심각함
- GFL이 GFM보다 더 많을 때
  - 전체 그리드의 transient response가 더 좋아졌다는 것을 확인했음
  - GFL-GFM switching 논문에 따라 GFL의 transient response가 GFM의 transient response보다 더 빠르다는 것을 관찰할 수 있었다.
  - 놀랍게도 전체 frequency stability 더 좋아진다는 것을 확인했음.
- Duality Paper의 결과를 따르면:
  - GFM은 Z가 낮은 grid에서 약하다 -> GFM5_GFL0 시뮬레이션에서 보여주었다.
  - GFL은 Y가 낮은 grid에서 약하다 -> simulation에 사용된 grid의 Z 값이 낮아서 그런지 GFL이 더 좋은 frequency stability를 보여줬다.
- GFM의 load sharing 기능을 잘 관찰했다.
- GFL이 constant PQ source 듯이 load 증가에 출력 PQ 변하지 않다.

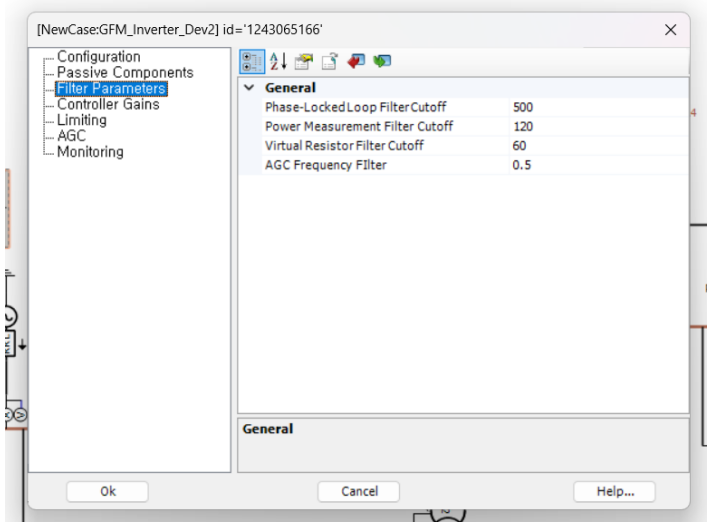
High Penetration

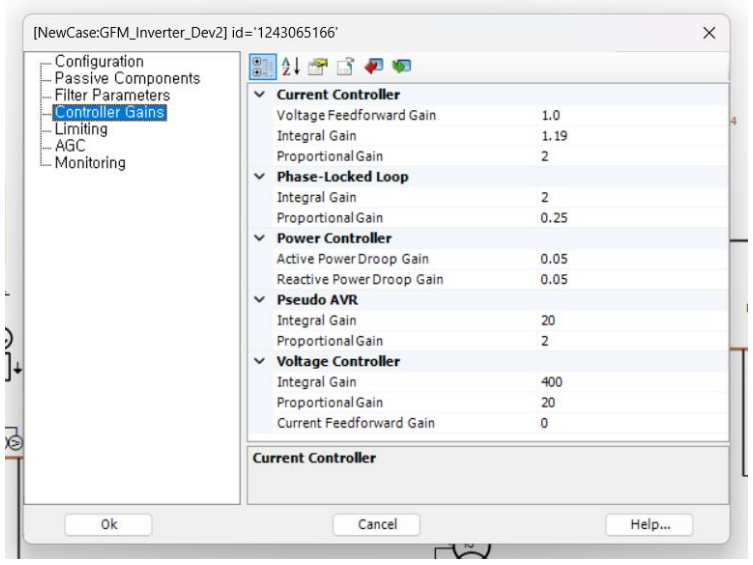
- GFM이 더 많으면 많을 수록 frequency stability가 더 좋아진다.
- 실은 GFL를 도임하면 frequency nadir 더 낮은 값으로 나타난다.
- Ideal voltage source 있는 그리드에서 GFM만 있으면 더 좋아 보인다.
- 예상한 결과를 얻었다:
  - GFM이 frequency와 voltage를 지원해서 GFL보다 더 좋은 frequency stability를 보여줬다.
  - GFM이 voltage source으로 생각할 수 있기 때문에 ideal voltage source인 slack과 grid stability를 잘 지원할 수 있다.
  - GFM의 load sharing 기능을 잘 관찰 했다.
  - GFL은 constant PQ source 듯이 load 증가 때 출력 PQ 값을 변하지 않다.

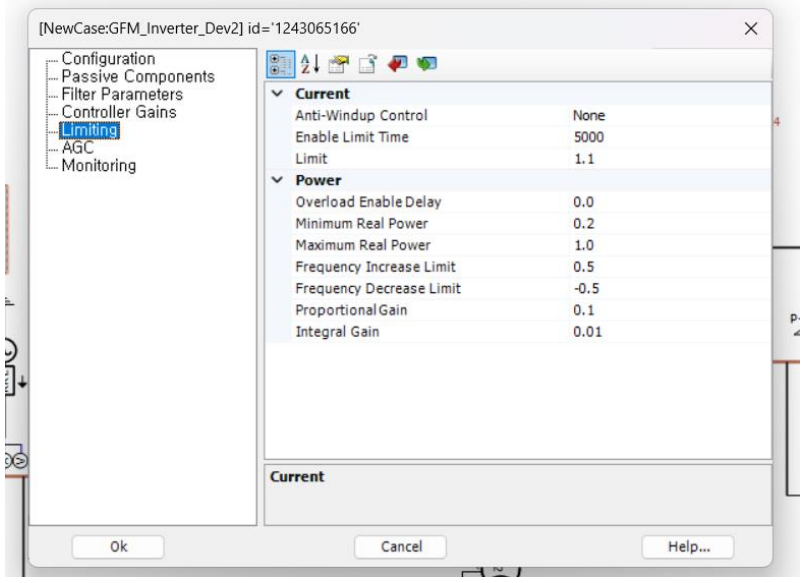
GFM A (Slack)

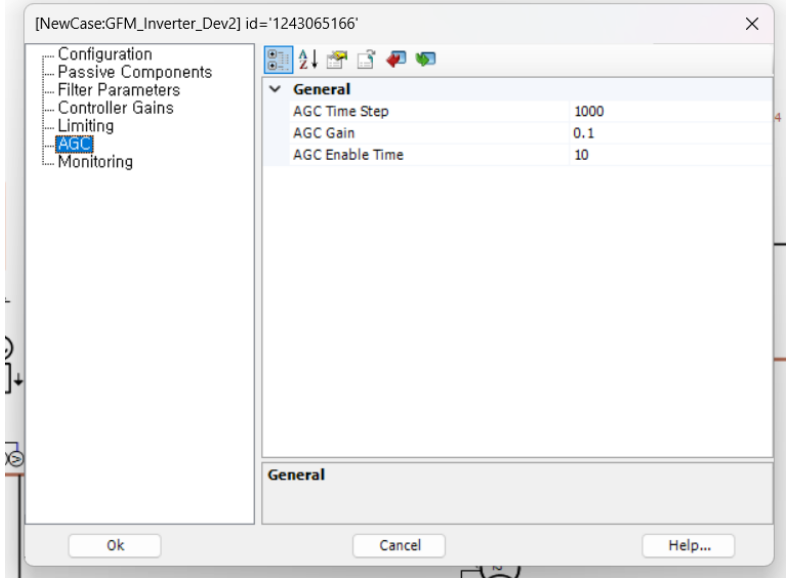

[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
General
Name
Base Frequency 60
Base Power 100000
Base Voltage 138.0
P Set Point 0
Q Set Point 0
Voltage Set Point 1.06
Angle Set Point 0.0
Output Inductor Angle Offset Disable
Voltage/Reactive Power Control Reactive Droop
Release Time 10
AVR Engage 0.2
Power Calculation Grid Voltage
Virtual Resistor Disable
General
Ok
Cancel
Help...


[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
Physical Setpoint
Filter Inductor 0.15
Filter Resistance 0.005
Filter Capacitor 0.6
Filter Capacitor Resistance 0.0
Coupling Inductor 0.15
Coupling Resistance 0.005
Virtual Resistor 0.09
Physical Setpoint
Ok
Cancel
Help...

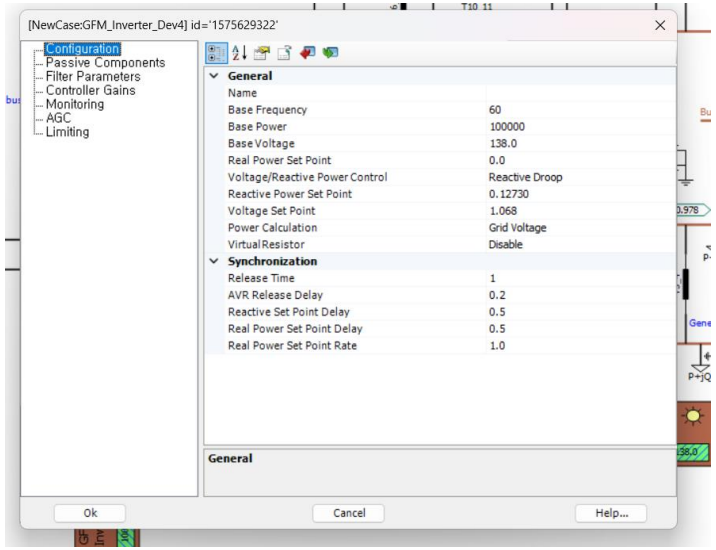

[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
General
Phase-Locked Loop Filter Cutoff 500
Power Measurement Filter Cutoff 120
Virtual Resistor Filter Cutoff 60
AGC Frequency FIlter 0.5
General
Ok
Cancel
Help...

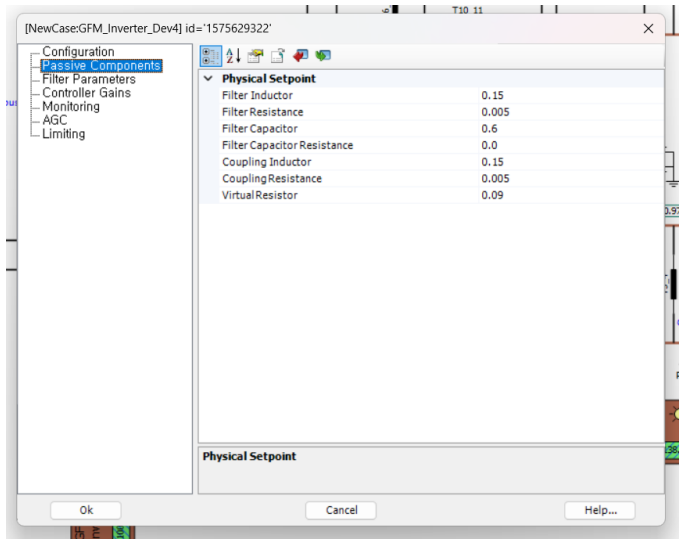

[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
Current Controller
Voltage Feedforward Gain 1.0
Integral Gain 1.19
Proportional Gain 2
Phase-Locked Loop
Integral Gain 2
Proportional Gain 0.25
Power Controller
Active Power Droop Gain 0.05
Reactive Power Droop Gain 0.05
Pseudo AVR
Integral Gain 20
Proportional Gain 2
Voltage Controller
Integral Gain 400
Proportional Gain 20
Current Feedforward Gain 0
Current Controller
Ok
Cancel
Help...

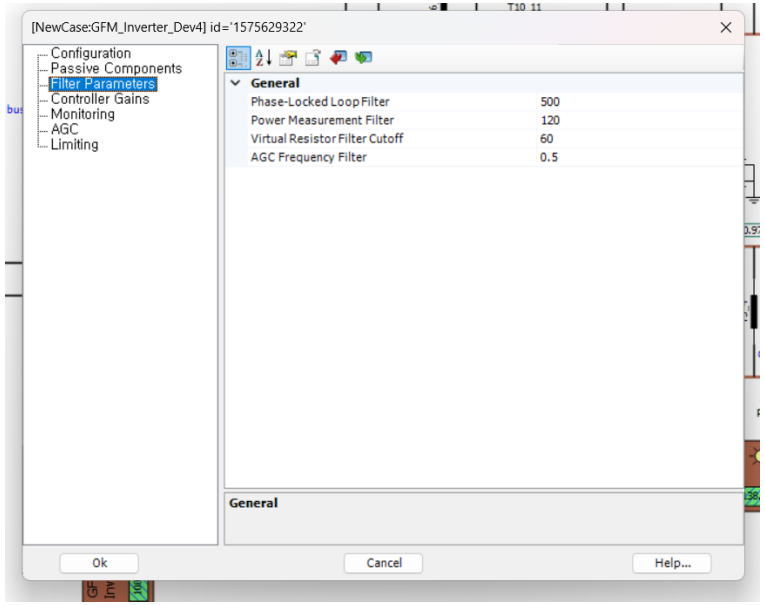

[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
Current
Anti-Windup Control None
Enable Limit Time 5000
Limit 1.1
Power
Overload Enable Delay 0.0
Minimum Real Power 0.2
Maximum Real Power 1.0
Frequency Increase Limit 0.5
Frequency Decrease Limit -0.5
Proportional Gain 0.1
Integral Gain 0.01
Current
Ok
Cancel
Help...

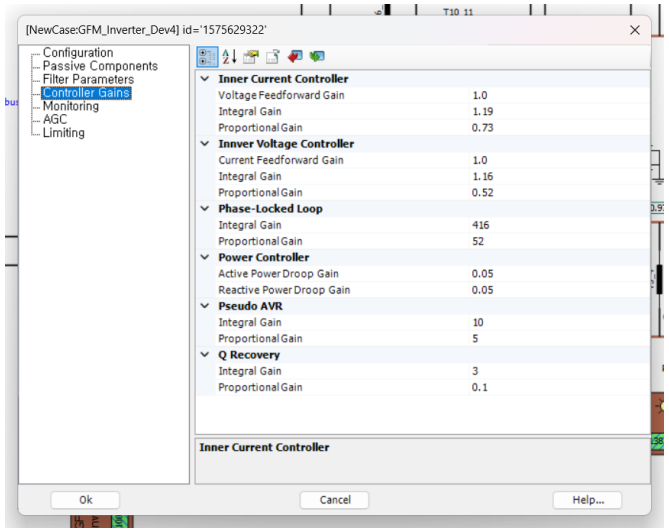

[NewCase:GFM_Inverter_Dev2] id='1243065166'
Configuration
Passive Components
Filter Parameters
Controller Gains
Limiting
AGC
Monitoring
General
AGC Time Step 1000
AGC Gain 0.1
AGC Enable Time 10
General
Ok
Cancel
Help...

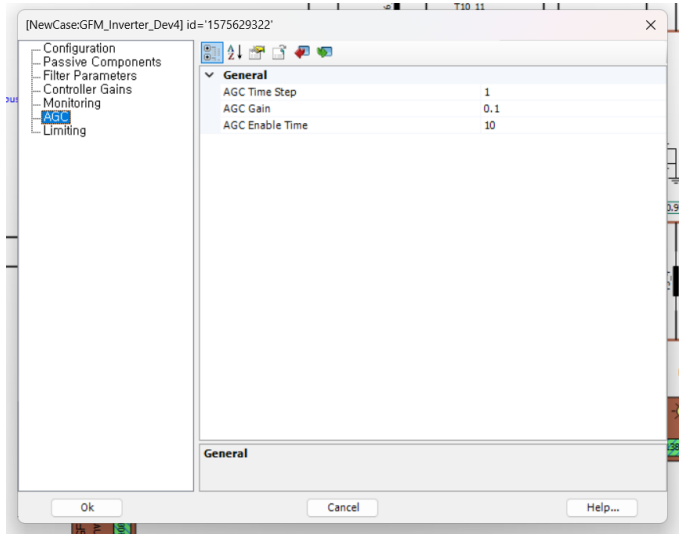
GFM B (PV Generator)

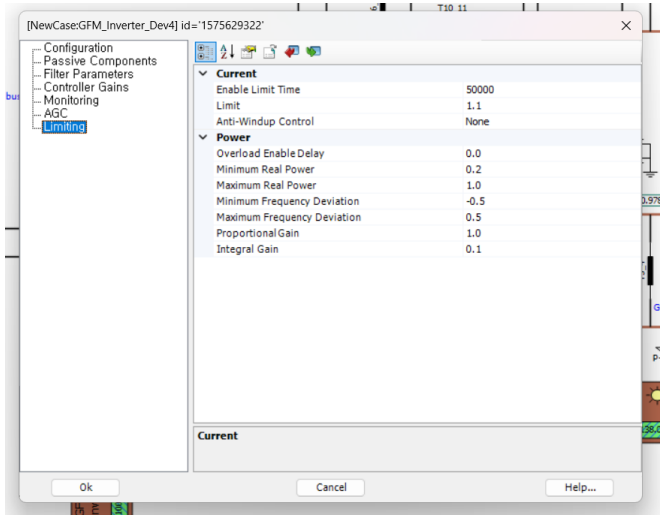




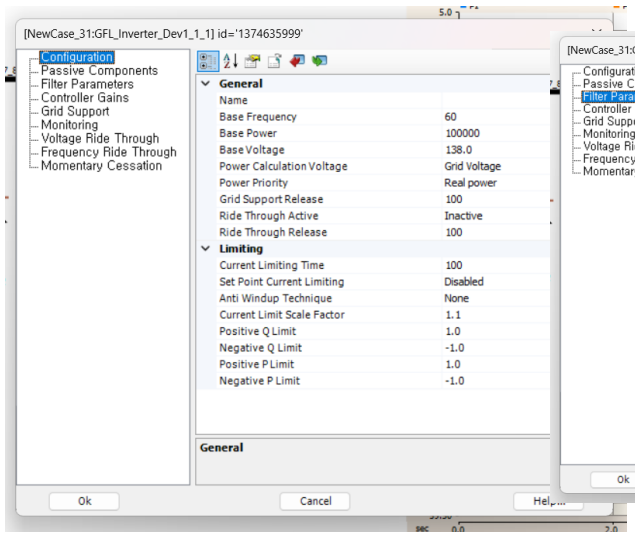








GFL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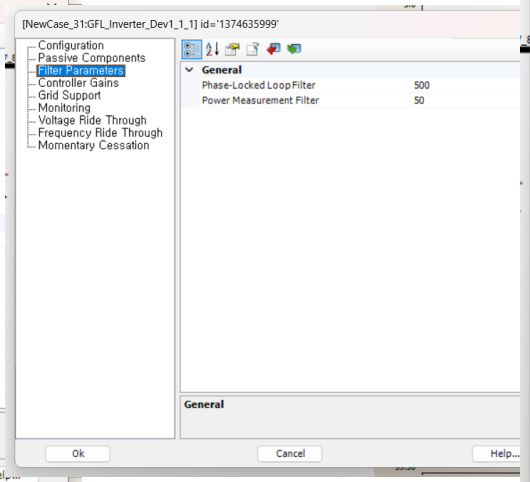
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
General
Name
Base Frequency 60
Base Power 100000
Base Voltage 138.0
Power Calculation Voltage Grid Voltage
Power Priority Real power
Grid Support Release 100
Ride Through Active Inactive
Ride Through Release 100
Limiting
Current Limiting Time 100
Set Point Current Limiting Disabled
Anti Windup Technique None
Current Limit Scale Factor 1.1
Positive Q Limit 1.0
Negative Q Limit -1.0
Positive P Limit 1.0
Negative P Limit -1.0
General
Ok
Cancel
Help...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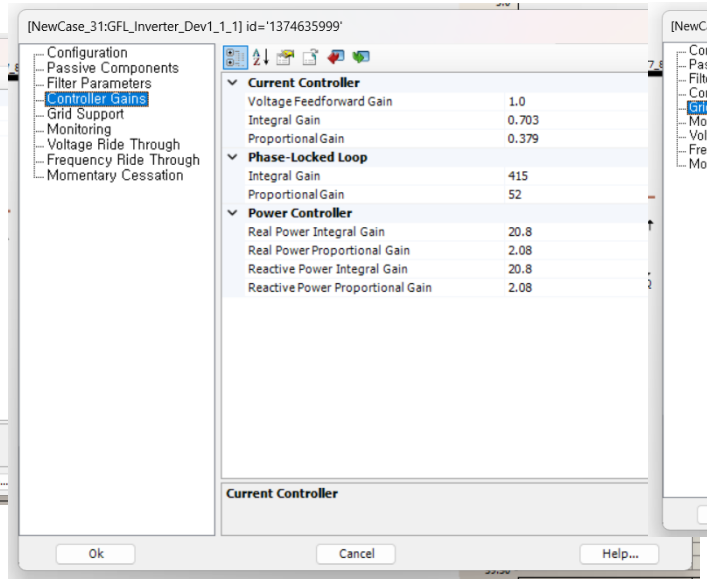
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
General
Phase-Locked Loop Filter 500
Power Measurement Filter 50
General
Ok
Cancel
Help...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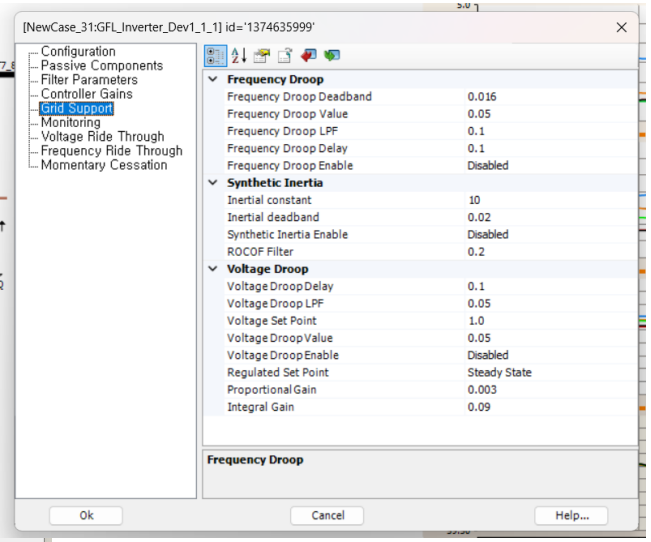
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
Current Controller
Voltage Feedforward Gain 1.0
Integral Gain 0.703
Proportional Gain 0.379
Phase-Locked Loop
Integral Gain 415
Proportional Gain 52
Power Controller
Real Power Integral Gain 20.8
Real Power Proportional Gain 2.08
Reactive Power Integral Gain 20.8
Reactive Power Proportional Gain 2.08
Current Controller
Ok
Cancel
Help...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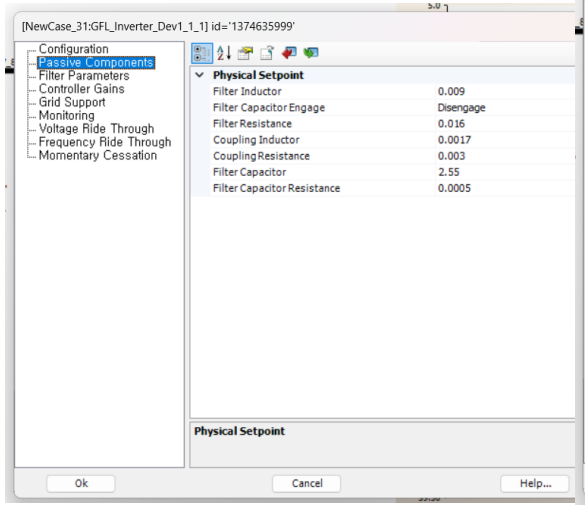
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
Frequency Droop
Frequency Droop Deadband 0.016
Frequency Droop Value 0.05
Frequency Droop LPF 0.1
Frequency Droop Delay 0.1
Frequency Droop Enable Disabled
Synthetic Inertia
Inertial constant 10
Inertial deadband 0.02
Synthetic Inertia Enable Disabled
ROCOF Filter 0.2
Voltage Droop
Voltage Droop Delay 0.1
Voltage Droop LPF 0.05
Voltage Set Point 1.0
Voltage Droop Value 0.05
Voltage Droop Enable Disabled
Regulated Set Point Steady State
Proportional Gain 0.003
Integral Gain 0.09
Frequency Droop
Ok
Cancel
Help...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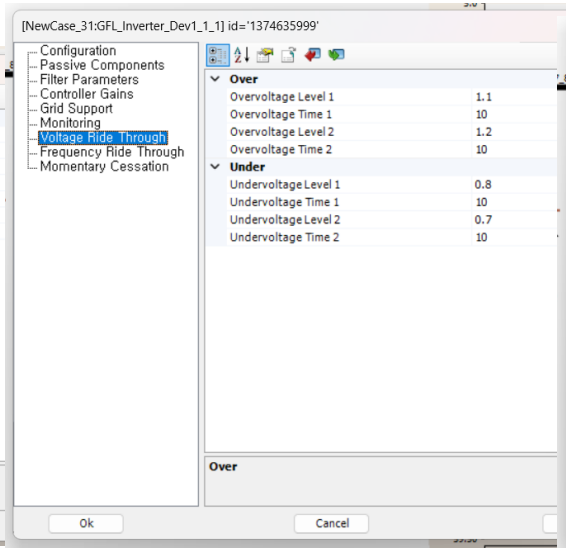
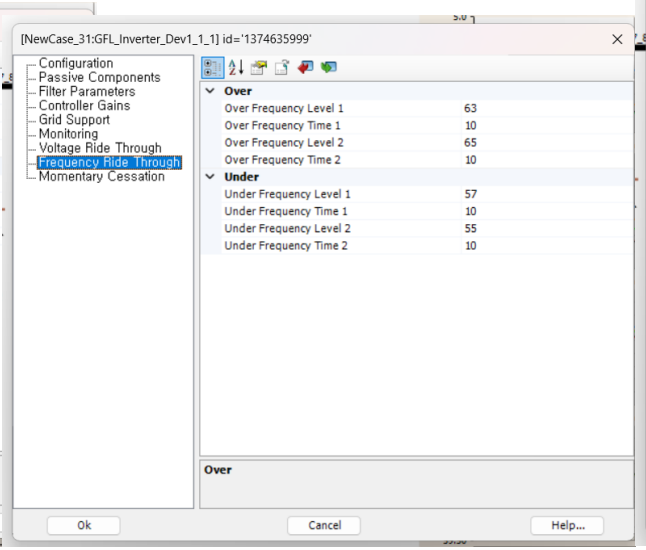
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
Physical Setpoint
Filter Inductor 0.009
Filter Capacitor Engage Disengage
Filter Resistance 0.016
Coupling Inductor 0.0017
Coupling Resistance 0.003
Filter Capacitor 2.55
Filter Capacitor Resistance 0.0005
Physical Setpoint
Ok
Cancel
Help...


[NewCase_31:GFL_Inverter_Dev1_1_1] id='1374635999'
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
Over
Overvoltage Level 1 1.1
Overvoltage Time 1 10
Overvoltage Level 2 1.2
Overvoltage Time 2 10
Under
Undervoltage Level 1 0.8
Undervoltage Time 1 10
Undervoltage Level 2 0.7
Undervoltage Time 2 10
Over
Ok
Cancel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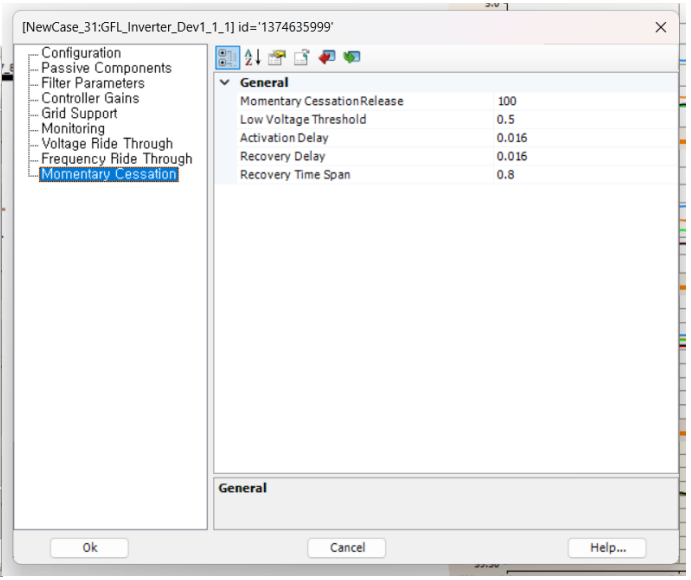
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
Over
Over Frequency Level 1 63
Over Frequency Time 1 10
Over Frequency Level 2 65
Over Frequency Time 2 10
Under
Under Frequency Level 1 57
Under Frequency Time 1 10
Under Frequency Level 2 55
Under Frequency Time 2 10
Over
Ok
Cancel
Help...


[NewCase_31:GFL_Inverter_Dev1_1_1] id='1374635999'
Configuration
Passive Components
Filter Parameters
Controller Gains
Grid Support
Monitoring
Voltage Ride Through
Frequency Ride Through
Momentary Cessation
General
Momentary Cessation Release 100
Low Voltage Threshold 0.5
Activation Delay 0.016
Recovery Delay 0.016
Recovery Time Span 0.8
General
Ok
Cancel
Help...

Source Controls

Slack / Generator 1 (Bus 1):
100 MVA
138.0 kV
Fixed Control
Voltage Magnitude: 146.28 kV (1.06)
Phase: 0 deg
Initial Real Power: 2.32392 pu
Initial Reactive Power: -0.16549 pu

Generator 2 (Bus 2):
100 MVA
138.0 kV
Fixed Control
Voltage Magnitude: 144.21 kV (1.045)
Phase: -4.9826 deg
Initial Real Power: 0.4 pu
Initial Reactive Power: 0.43556 pu

Generator 3 (Bus 3, Synchronous Condenser)
100 MVA
138.0 kV
Fixed Control
Voltage Magnitude: 139.38 kV (1.009)
Phase: -12.7250 deg
Initial Real Power: 0.0 pu
Initial Reactive Power 0.25075 pu

Generator 4 (Bus 8, Synchronous Condenser)
100 MVA
138.0 kV
Fixed Control
Voltage Magnitude 150.42 kV (1.088)
Phase: -13.3596 deg
Initial Real Power: 0.0 pu
Initial Reactive Power: 0.17623 pu

Generator 5 (Bus 6, Synchronous Condenser):
100 MVA
138.0 kV
Fixed Control
Voltage Magnitude: 147.66 kV (1.068)
Phase: -14.2209 deg
Initial Real Power: 0.0 pu
Initial Reactive Power: 0.12730 pu

Generator Output - Base Case

Slack
P = 2.323
Q = 0.1545
V = 1.06

Generator 2 (Bus 2)
P = 0.4007
Q = 0.4498
V = 1.044

Generator 3 (Bus 3)
P = 0.003074
Q = 0.2618
V = 1.009

Generator 4 (Bus 8)
P = -0.0004405
Q = 0.19
V = 1.008

Generator 5 (Bus 6)
P = 0.003743
Q = 0.1504
V = 1.068

Transmission Line Details (17 TLs)

- T1_2
  - P = 1.526
  - Q = -0.2732
  - V = 1.044
- T1_5
  - P = 0.7546
  - Q = 0.04592
  - V = 1.06
- T2_5
  - P = 0.04058
  - Q = 0.0861
  - V = 0.4058
- T2_4
  - P = 0.5611
  - Q = -0.00609
  - V = 1.044
- T2_3
  - P = 0.733
  - Q = 0.3534
  - V = 1.044
- T3_4
  - P = -0.2315
  - Q = 0.05427
  - V = 1.009
- T4_5
  - P = 0.6107
  - Q = -0.1506
  - V = 1.015
- T6_12
  - P = -0.07765
  - Q = -0.02404
  - V = 1.053
- T6_13
  - P = -0.1766
  - Q = -0.0701
  - V = 1.048
- T6_11
  - P = 0.07519
  - Q = -0.0397
  - V = 1.064
- T7_8
  - P = -0.0004405
  - Q = 0.19
  - V =1.088
- T7_9
  - P = -0.2799
  - Q = 0.05438
  - V = 1.052
- T9_10
  - P = 0.05088
  - Q = 0.03788
  - V = 1.047
- T9_14
  - P = -0.09227
  - Q = -0.03115
  - V = 1.032
- T10_11
  - P = 0.03935
  - Q = 0.02027
  - V = 1.047
- T12_13
  - P = 0.01649
  - Q = 0.007996
  - V = 1.053
- T13_14
  - P = 0.05712
  - Q = 0.01894
  - V = 1.032