Microgrid Testbeds & Controller Procurement

Testing and Comparing Microgrid Controllers Performance Aspects Using Hardware-in-the-Loop Simulations

Agenda

- ESIF-NREL intro
- Microgrid Controller Procurement 2017
- Microgrid testbed
- Model validation
- Test sequences
- Controllers evaluation criteria
- Example results

NREL – ESIF

Clean, reliable, and affordable energy at a pace and scale that matters

https://www.nrel.gov/esif/

Energy Systems Integration Facility (ESIF)

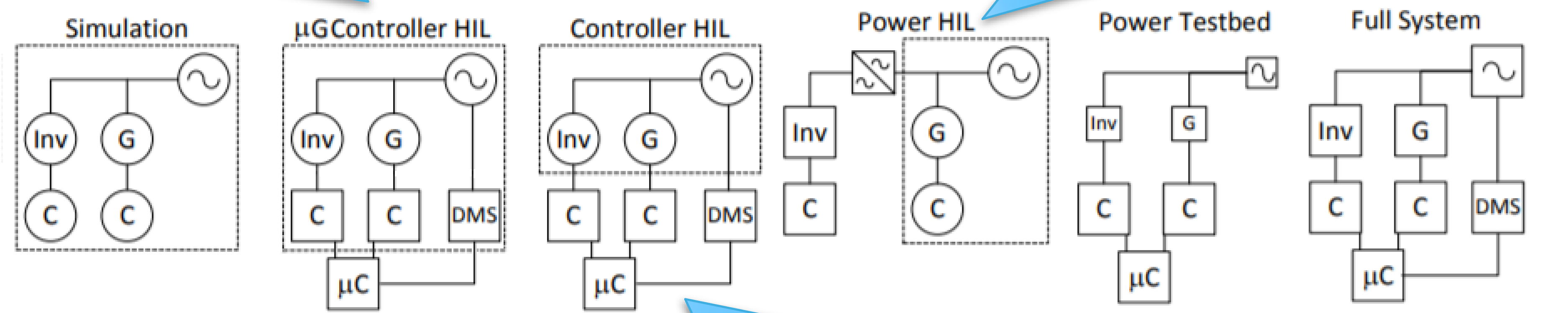
µGC Procurement

- NREL is seeking a microgrid control technology for installation in a permanent microgrid research testbed at the Energy Systems Integration Facility located in Golden, Colorado.
- The top-performing control technology will be installed at ESIF in 2018

Testing microgrid controls

NREL Stage 1 - CHIL

NREL Stage 2 - PHIL



MIT Microgrid Symposium 2017
github.com/PowerSystemsHIL

OPAL-RT TECHNOLOGIES

* Pictures from "Development of a Real-Time Hardwarein-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers", R.O. Salcedo J.K. Nowocin C.L. Smith R.P. Rekha E.G. Corbett E.R. Limpaecher J.M. LaPenta

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Simulated Microgrid

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- Single phase nodes: 291x
- 3x Synchronous Generators with controls
- 2x ESS (VSI, Battery with controls)
- 2x PV (VSI with controls)
- 49x CB with Protective Relays
- 1x DMS interface
- OP6500 – 12 cores utilized to run 100µs

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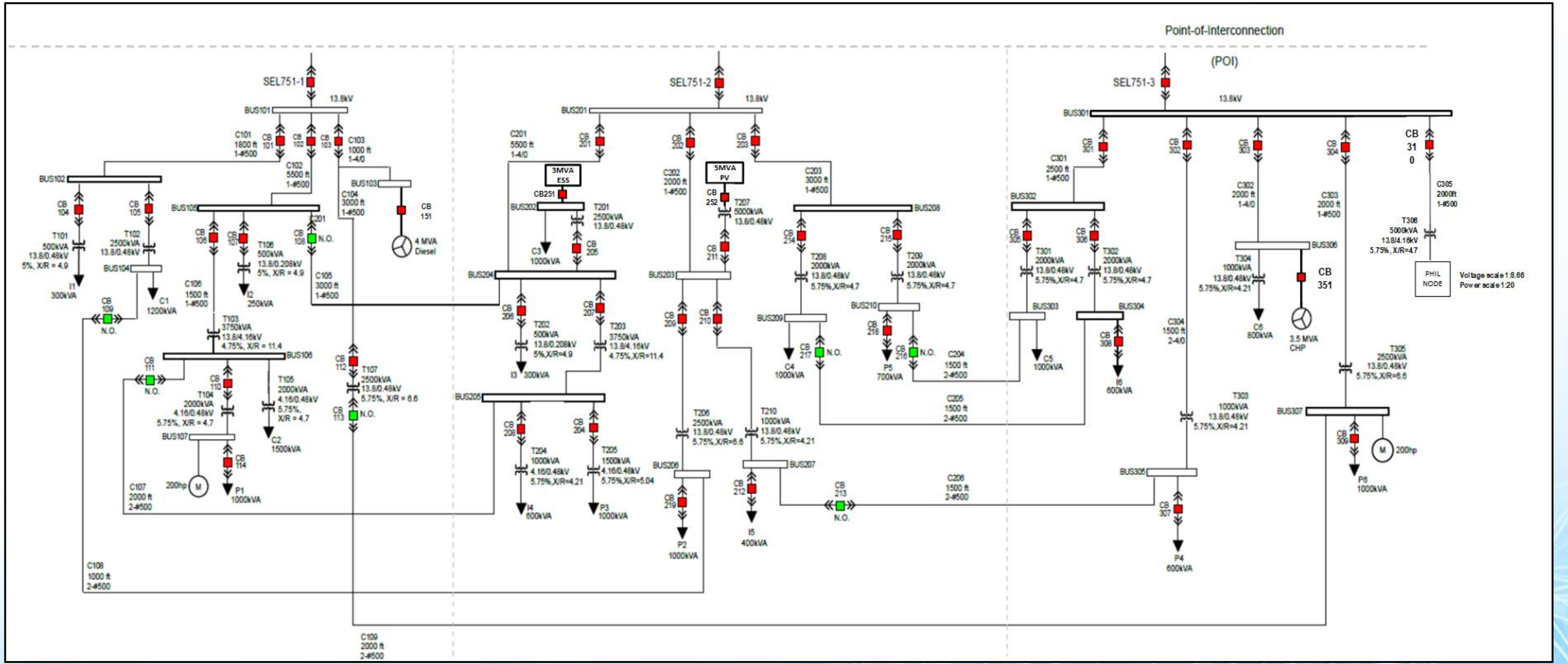
Single line diagram



Single line diagram – PHIL

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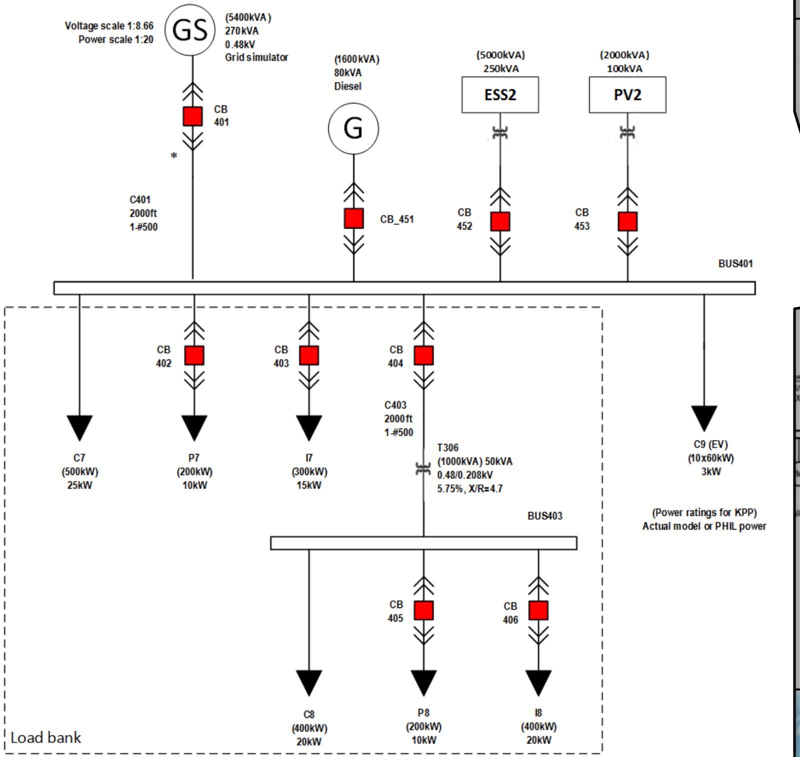
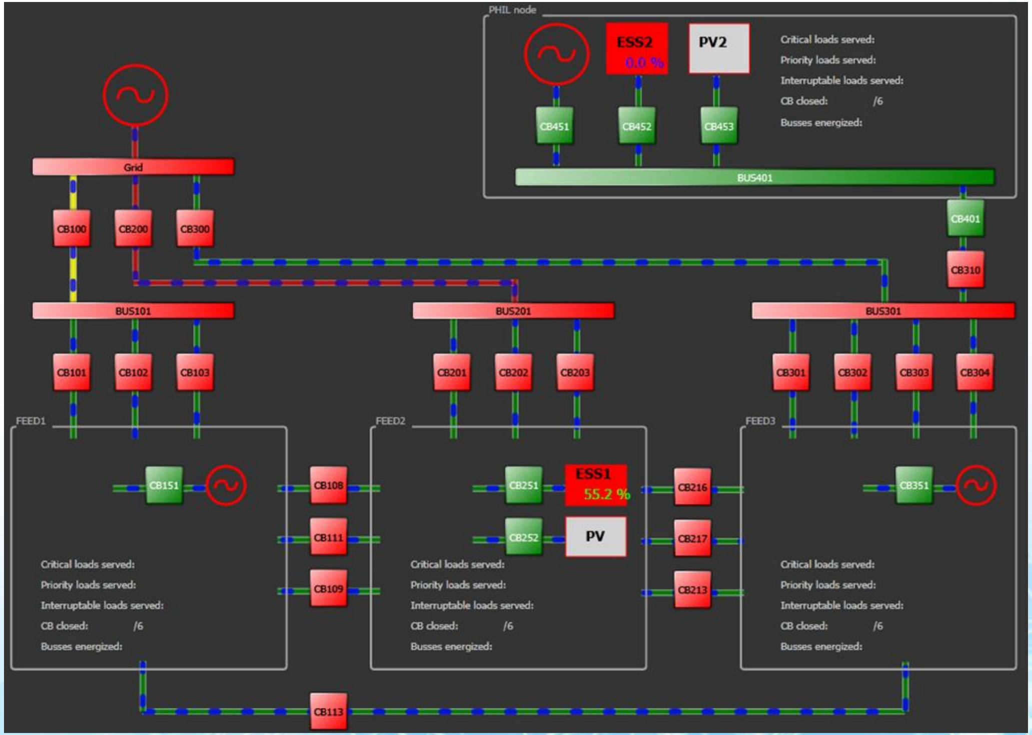
Real power hardware:
- 270kVA Amatek grid simulator
- AE100 100kVA PV inv
- Magna power DC - PV simulator
- Caterpillar BDP250 – 250kVA ESS inverter
- AV900 bi-directional DC supply – battery emulator
- 250kW LoadTec loadbank
- ABB CB
- Onan Cummins 80kW diesel generator



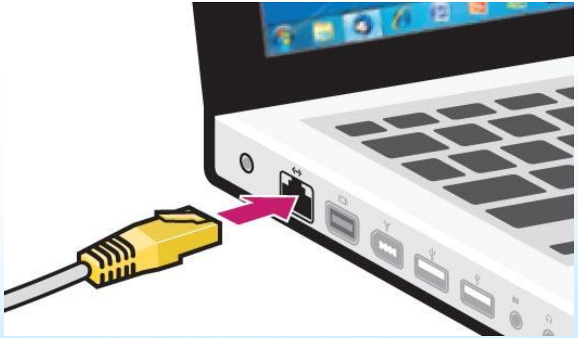
HMI & DAQ

- Real time visualization of microgrid status using off-the-shelf RTAC
- Matlab used as test sequence generator and DAQ system
- Matlab⇔Opal-RT communication using UDP



Controller interface

- Based on Ethernet only
- 50x IEC61850 GOOSE messages (Opal-RT)
- 56x Modbus TCP interfaces (Opal-RT)
- Direct Modbus&IEC61850 communication to devices in PHIL

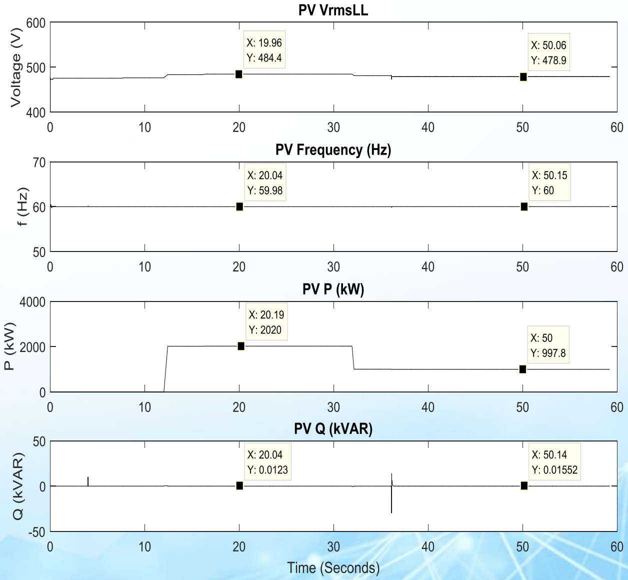


Device	IP Address	TCP Port	Feeder Location ID
GEN3 – Real Diesel Genset Controller	10.79.112.37	502	F4
ESS2 Inverter – BDP250	10.79.112.38	502	F4
PV2 Inverter – AE 100	10.79.112.39	502	F4
“DMS” Dispatch Interface	10.79.112.80	502	n/a
GEN1 – Simulated Diesel Genset Controller	10.79.112.81	502	F1
GEN2 – Simulated Natural Gas Engine Controller	10.79.112.82	502	F3
GEN2 – Simulated CHP Thermal Controller	10.79.112.83	502	F3
GEN3 – Simulated Diesel Genset Controller	10.79.112.84	502	F1
ESS1 Simulated Controller	10.79.112.85	502	F2
ESS2 Simulated Controller	10.79.112.86	502	F2
PV1 Simulated Controller	10.79.112.87	502	F2
PV2 Simulated Controller	10.79.112.88	502	F2
Generic Relay CB101	10.79.112.101	502	F1
Generic Relay CB102	10.79.112.102	502	F1
Generic Relay CB103	10.79.112.103	502	F1
…	…	…	…

Load flow validation

SimPowerSystems Load flow → Opal-RT Real-Time execution → Steady state comparison

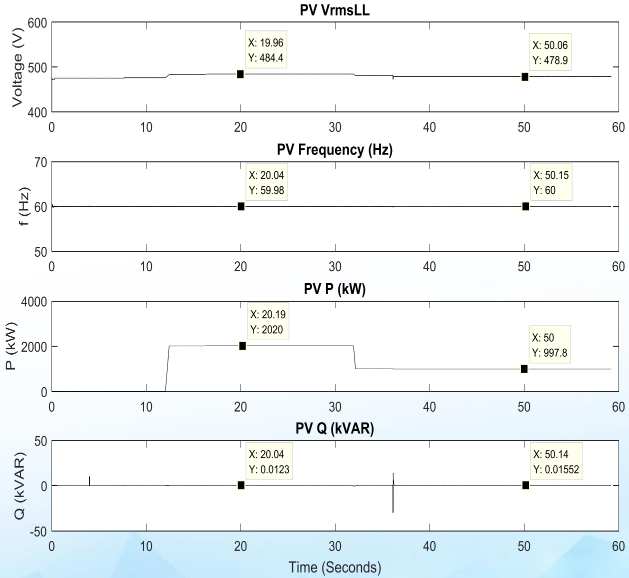
```
  Total generation  : P=     1.81 MW Q=     0.88 Mvar
  Total PQ load     : P=     0.00 MW Q=     0.01 Mvar
  Total Zshunt load : P=     1.79 MW Q=     0.87 Mvar
  Total ASM load    : P=     0.00 MW Q=     0.00 Mvar
  Total losses      : P=     0.01 MW Q=     0.00 Mvar

1 : BESS  V= 1.000 pu/0.48kV 0.00 deg  ; Swing bus
        Generation : P=   0.81 MW Q=   0.88 Mvar
        PQ_load    : P=   0.00 MW Q=   0.00 Mvar
        Z_shunt    : P=   0.00 MW Q=   0.00 Mvar
   -->  *23*       : P=  -0.10 MW Q=   0.43 Mvar
   -->  C3         : P=   0.90 MW Q=   0.44 Mvar

2 : C3  V= 0.999 pu/0.48kV 0.01 deg
        Generation : P=   0.00 MW Q=   0.00 Mvar
        PQ_load    : P=   0.00 MW Q=   0.01 Mvar
        Z_shunt    : P=   0.90 MW Q=   0.43 Mvar
   -->  BESS       : P=  -0.90 MW Q=  -0.44 Mvar

3 : C4  V= 0.994 pu/0.48kV 0.27 deg
        Generation : P=   0.00 MW Q=   0.00 Mvar
        PQ_load    : P=   0.00 MW Q=  -0.00 Mvar
        Z_shunt    : P=   0.89 MW Q=   0.43 Mvar
   -->  *11*       : P=  -0.89 MW Q=  -0.43 Mvar

4 : PV  V= 1.002 pu/0.48kV 0.18 deg
        Generation : P=   1.00 MW Q=   0.00 Mvar
        PQ_load    : P=  -0.00 MW Q=   0.00 Mvar
        Z_shunt    : P=  -0.00 MW Q=   0.00 Mvar
   -->  *28*       : P=   1.00 MW Q=  -0.00 Mvar
```



Islanded	Load flow	Real time	Error [%]
C3– V (pu)	1.00	0.99	0.88
C4– V (pu)	0.99	0.98	0.95
ESS– V (pu)	1.00	1.00	0.31
ESS– P (MW)	0.81	0.84	3.43
ESS– Q (MVAR)	0.88	0.85	3.08
PV– V (pu)	1.00	1.00	0.43
PV– P (MW)	1.00	1.00	0.22
PV– Q (MVAR)	0.00	0.00	0.00
…	…	…	…

Inverse load flow validation

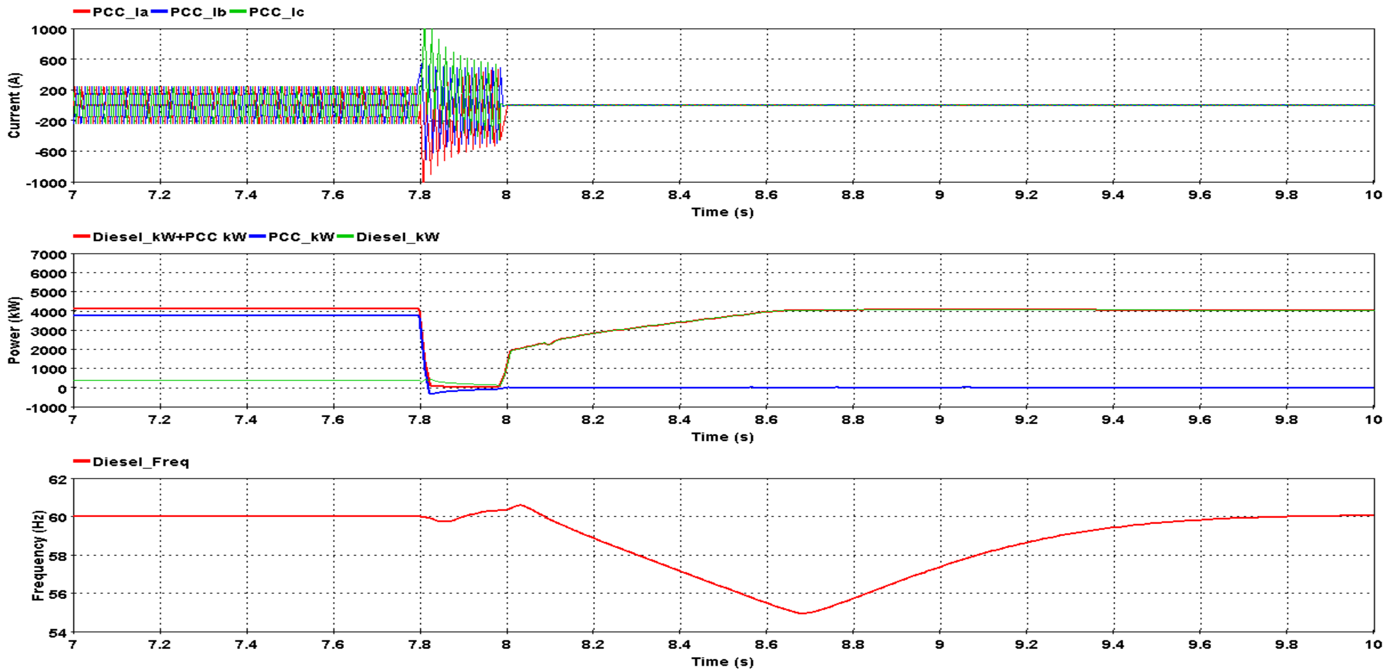
Opal-RT Real-Time execution → SimPowerSystems Load flow → Steady state comparison




```
Total generation  : P=     1.81 MW Q=     0.88 Mvar
Total PQ load     : P=     0.00 MW Q=     0.01 Mvar
Total Zshunt load : P=     1.79 MW Q=     0.87 Mvar
Total ASM load    : P=     0.00 MW Q=     0.00 Mvar
Total losses      : P=     0.01 MW Q=     0.00 Mvar

1 : BESS   V= 1.000 pu/0.48kV 0.00 deg   ; Swing bus
        Generation : P=     0.81 MW Q=     0.88 Mvar
        PQ_load    : P=     0.00 MW Q=     0.00 Mvar
        Z_shunt    : P=     0.00 MW Q=     0.00 Mvar
   -->  *23*       : P=    -0.10 MW Q=     0.43 Mvar
   -->  C3         : P=     0.90 MW Q=     0.44 Mvar

2 : C3     V= 0.999 pu/0.48kV 0.01 deg
        Generation : P=     0.00 MW Q=     0.00 Mvar
        PQ_load    : P=     0.00 MW Q=     0.01 Mvar
        Z_shunt    : P=     0.90 MW Q=     0.43 Mvar
   -->  BESS       : P=    -0.90 MW Q=    -0.44 Mvar

3 : C4     V= 0.994 pu/0.48kV 0.27 deg
        Generation : P=     0.00 MW Q=     0.00 Mvar
        PQ_load    : P=     0.00 MW Q=    -0.00 Mvar
        Z_shunt    : P=     0.89 MW Q=     0.43 Mvar
   -->  *11*       : P=    -0.89 MW Q=    -0.43 Mvar

4 : PV     V= 1.002 pu/0.48kV 0.18 deg
        Generation : P=     1.00 MW Q=     0.00 Mvar
        PQ_load    : P=    -0.00 MW Q=     0.00 Mvar
        Z_shunt    : P=    -0.00 MW Q=     0.00 Mvar
   -->  *28*       : P=     1.00 MW Q=    -0.00 Mvar
```

Point	Load flow	Real time	Error [%]
C1 – V (pu)	0.994	0.993	0.13
C2 – V (pu)	0.985	0.984	0.13
I1 – V (pu)	0.993	0.992	0.08
I2-V (pu)	0.990	0.989	0.06
P1-V (pu)	0.975	0.974	0.15
GEN1 – V (pu)	1.001	1.000	0.10
GEN1 – P (MW)	3.600	3.600	0.00
GEN1 – Q (MVAR)	1.720	1.720	0.00
Motor1-V (pu)	0.986	0.960	2.64
C3 – V (pu)	0.996	0.993	0.30
C4 – V (pu)	0.993	0.990	0.30

Transient behavior validation



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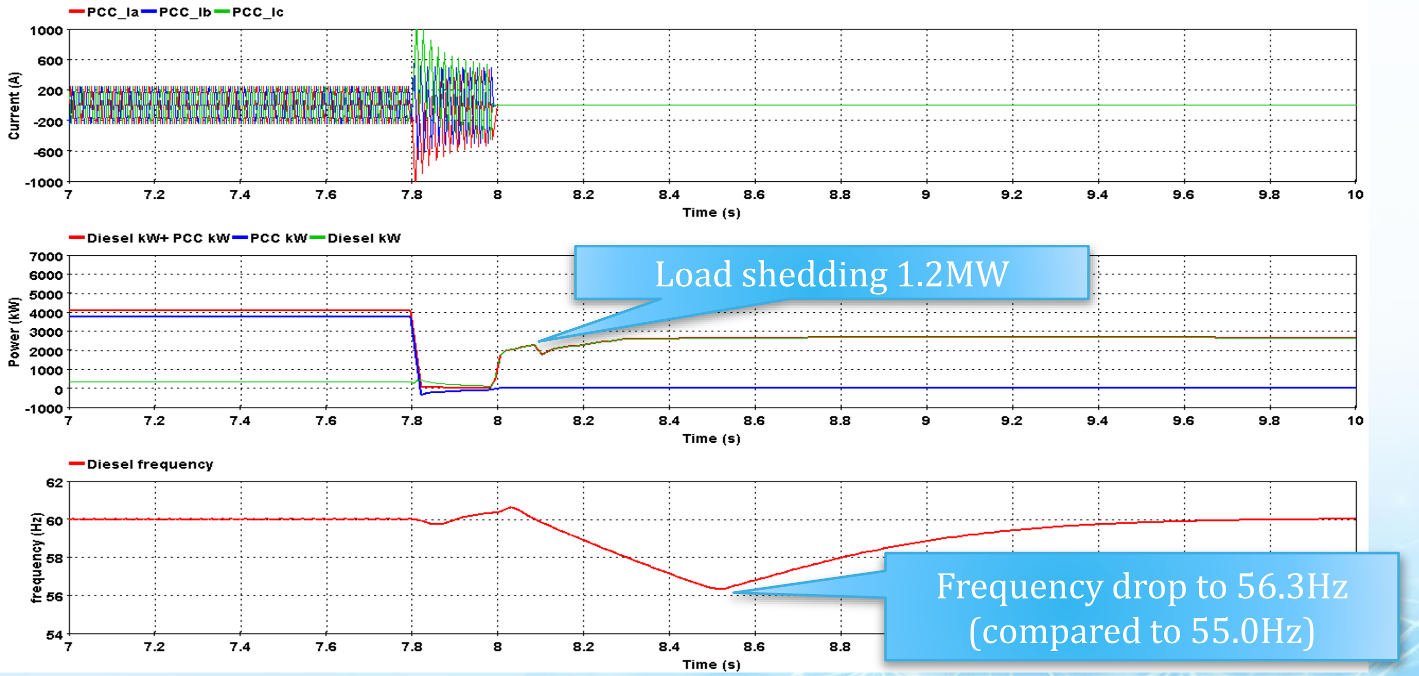
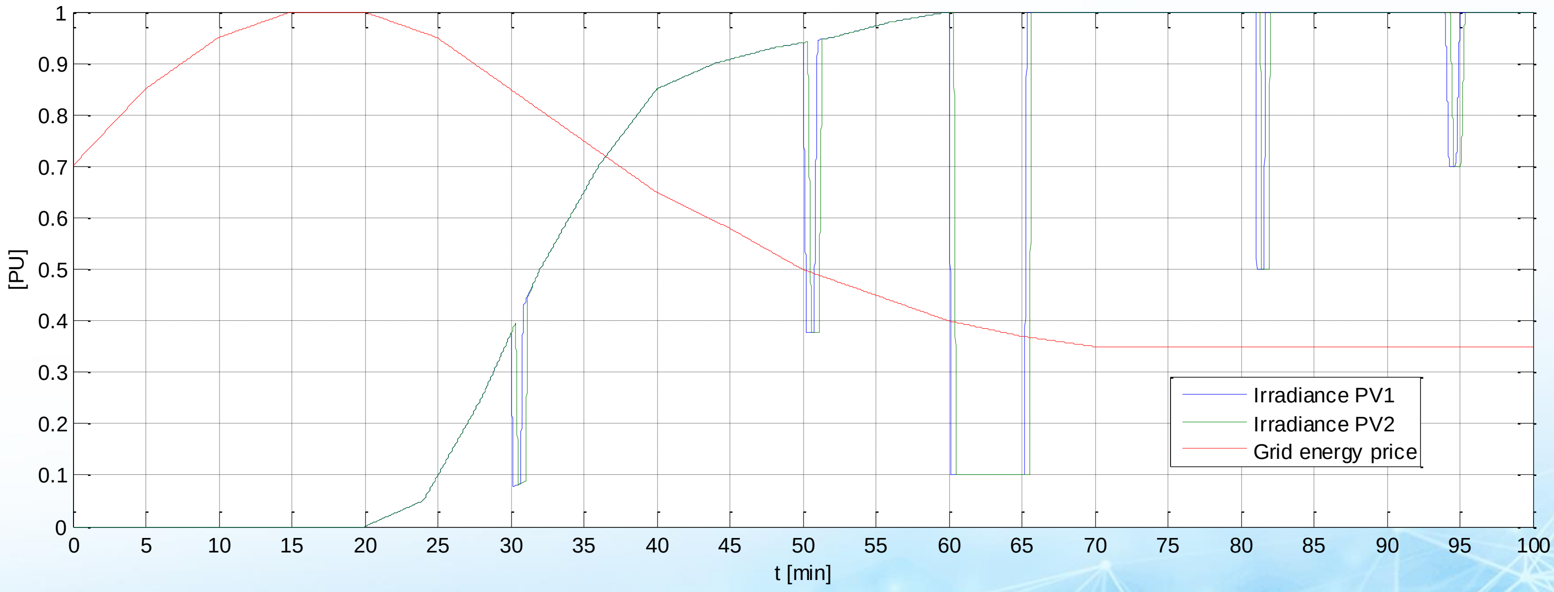
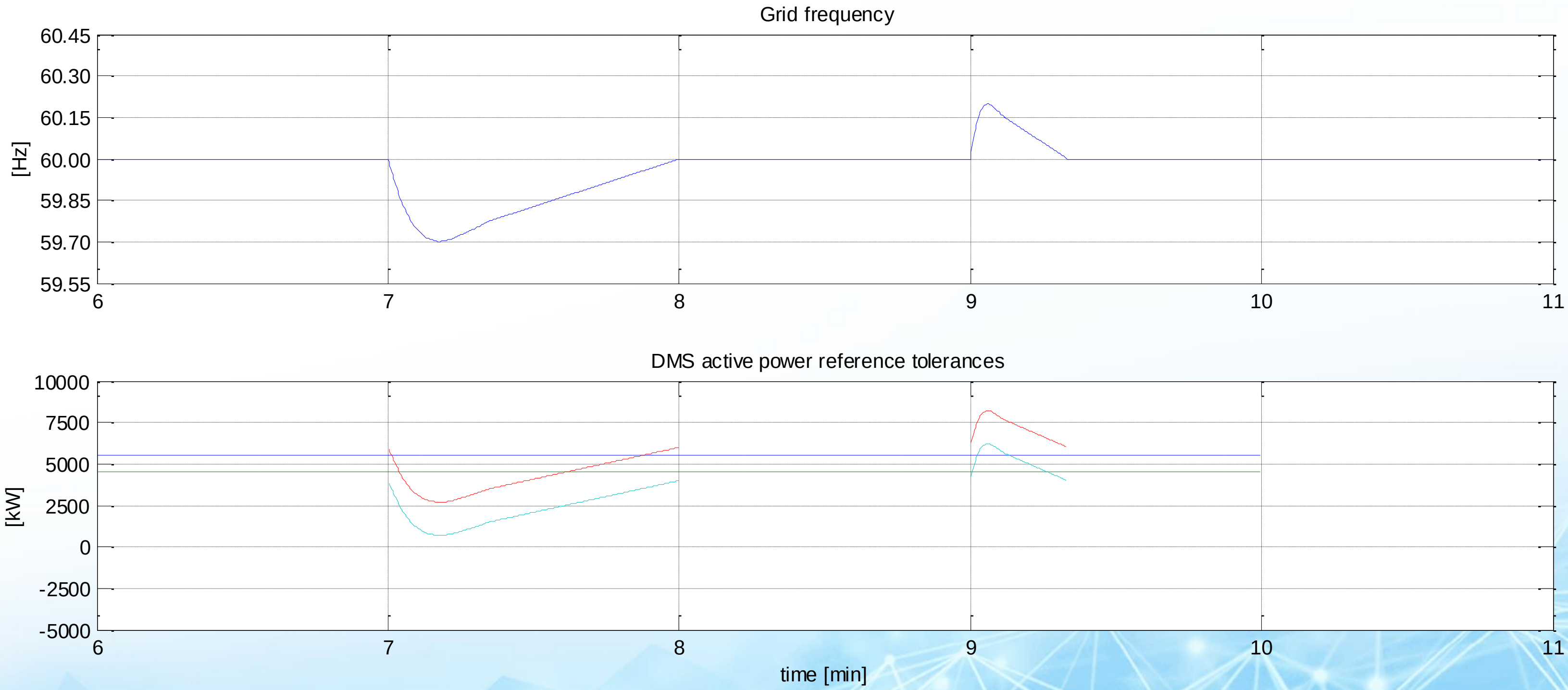
Transient behavior validation



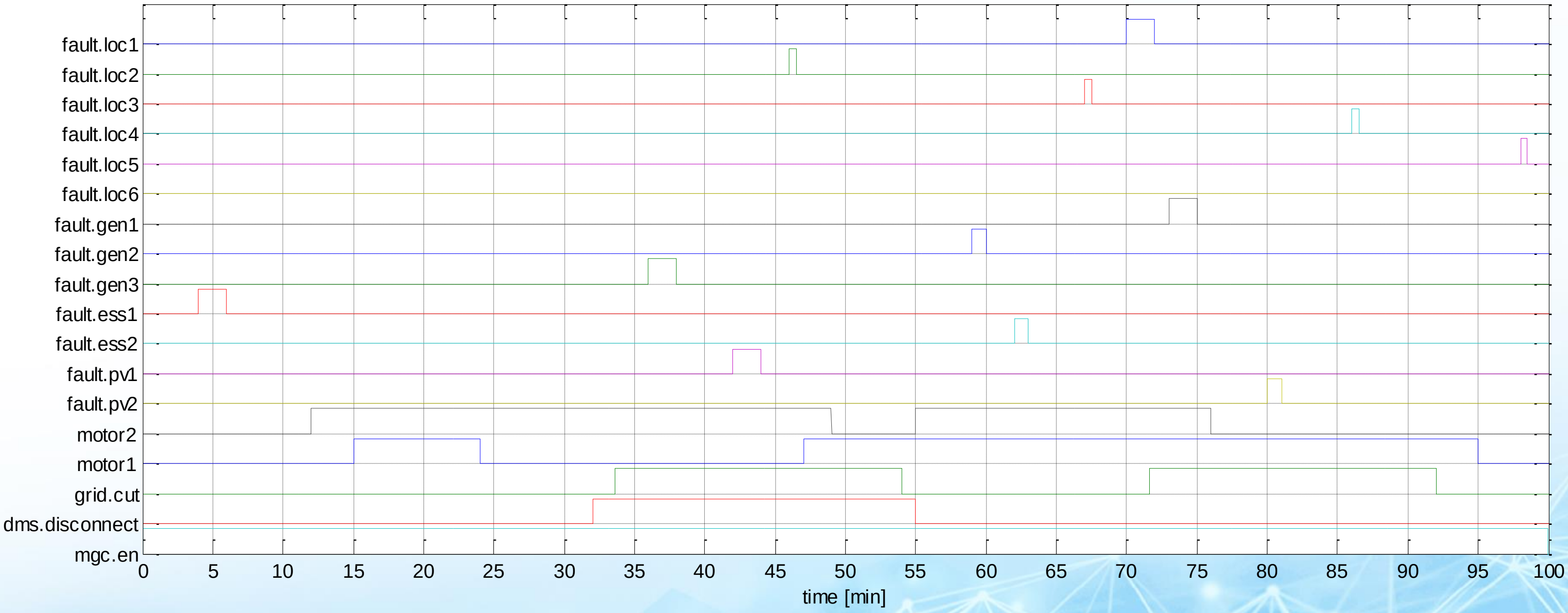
Test sequence - stimuli



Test sequence – grid stimuli



Test sequence – stimuli



Key Performance Parameters (KPP)

KPP1 - Resiliency and Reliability

Measured by calculating the energy delivered to predetermined categories of load. A penalty will be added for any outage on critical loads.

KPP2 - Operation and Maintenance

The cost of fuels to run DER's and values device degradation from use (e.g. causing faster failure, circuit breakers use).

KPP3 - Interconnection Contract

The price of energy during the test sequence will vary to allow the controller to benefit from various choices (e.g. dispatching energy from battery).

KPP4 - Distribution Service Operator (DSO) Commands

The microgrid controller can allow additional revenue by providing services to DSO on request. Failing to provide required services will result in a penalty.

KPP5 - Power Quality

Voltage and frequency violating IEEE 1547a-2014 clearing times (Tables 1 and 2 of the standard) will be counted. of the standard will be counted.

KPP6 - Microgrid Survivability

Keeping battery State of Charge (SoC) below the predetermined level during grid connected conditions will result in a penalty.

KPP7- Fuel- Free Asset Utilization

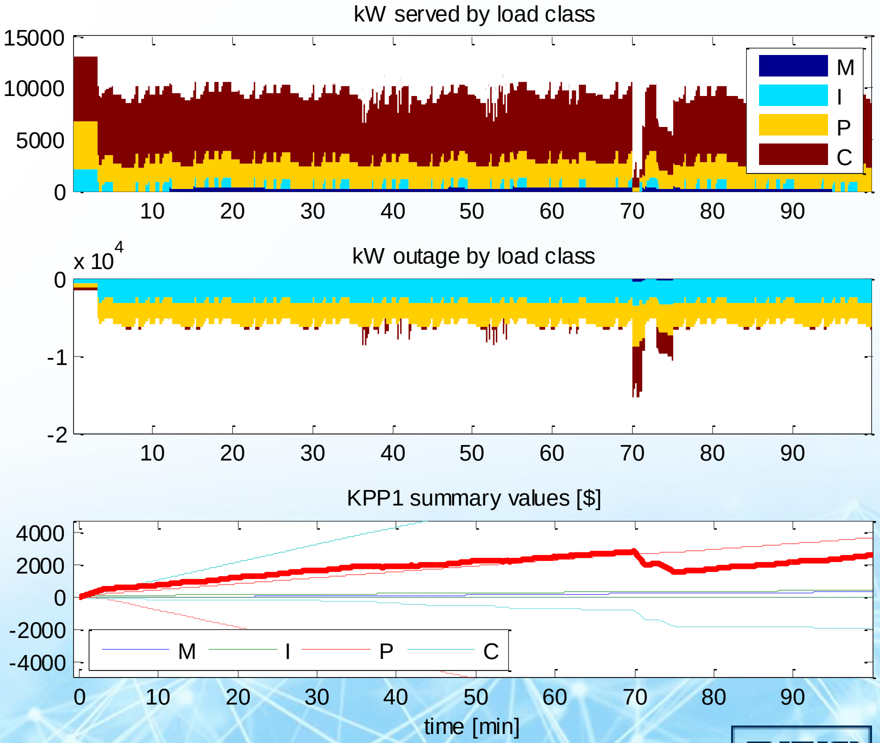
The amount of energy generated from PV to supply 1MWh of loads in the microgrid and PV energy generation will be measured.

KPP8 – Economic operation

Dollar sum of KPP1 to KPP7 allowing for overall comparison of various controllers under test

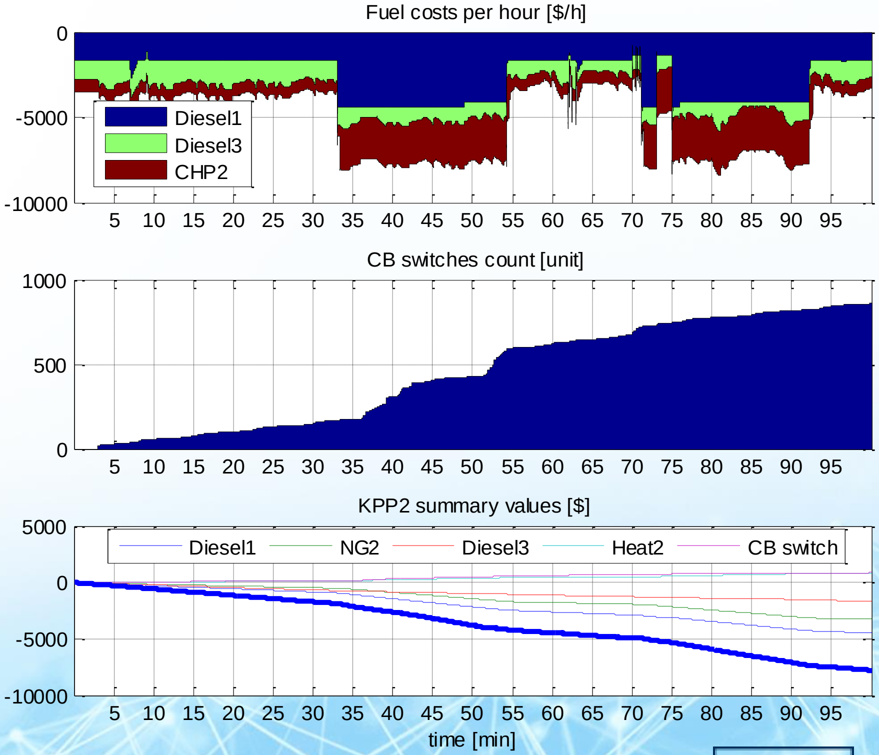
KPP1 – Resiliency

Energy delivered to Critical loads (E_C)	E_C [kWh]	P_{11} = 1.00[$/kWh]
Energy delivered to Priority loads (E_P)	E_P [kWh]	P_{12} = 0.90[$/kWh]]
Energy delivered to Interruptible loads (E_I)	E_I [kWh]	P_{13} = 0.85[$/kWh]
Energy Critical loads Outage (ECO)	E_{CO} [kWh]	P_{15} = 4.50 [$/kWh]
Energy Priority loads Outage (ECO)	E_{PO} [kWh]	P_{16} = 2.25 [$/kWh]
Energy left in ESS at the end of the sequence compared to initial state of charge	E_{ESS} [kWh]	P_{17} = 1.00 [$/kWh]



KPP2 – Operational costs

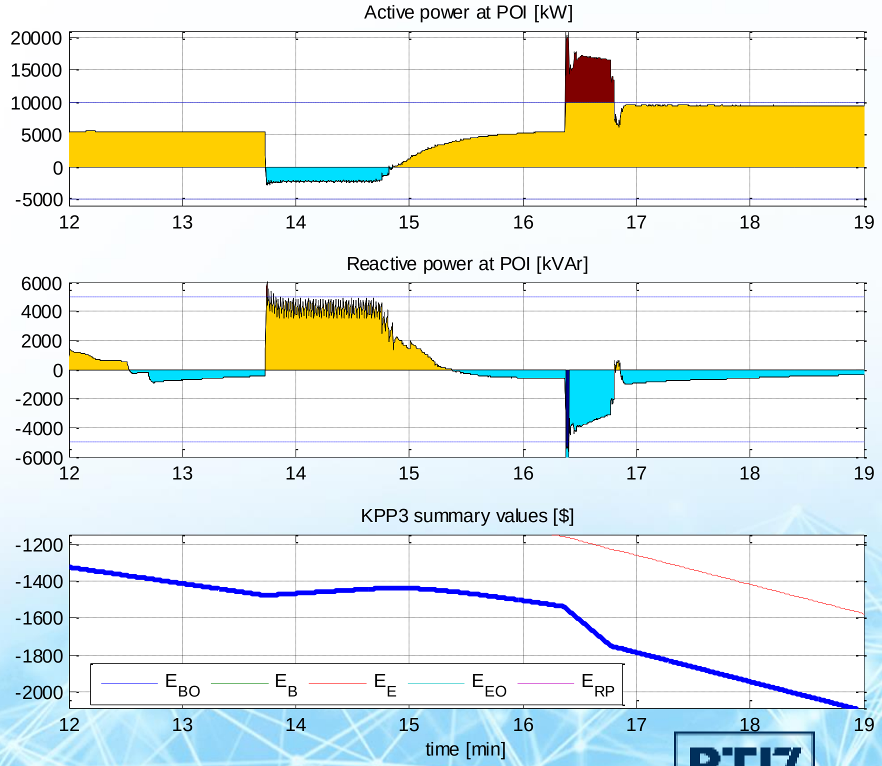
Used Fuel - Diesel (F_D)	F_D [gal]	P_{21} = 74.55 [$/gal]
Used Fuel- Natural Gas (F_{NG})	F_{NG} [m^3]	P_{22} = 4.18 [$/$m^3$]
Number of Diesel starts (N_D)	N_D	P_{23} = 10 00[$]
Number Combined Heat & Power re-starts (N_{CHP})	N_{CHP}	P_{24} = 10.00 [$]
Number of Battery cycles (N_B)	N_B	P_{25} = 10.00 [$]
Number of Circuit Breaker cycles (N_{CB})	N_{CB}	P_{26} = 1.00 [$]
Energy delivered as Heat (E_H)	E_H [MBtu]	P_{28} = 147.00[$/MBtu]



KPP3 – Interconnection contract

Active Power Import Limit = 12 MW
Active Power Export Limit = 6 MW
Reactive Power Limit = 5 MVAr

Exported Energy (E_E)	E_E [kWh]	P_E [$/kWh] ($p_{31}$)
Exported Energy Over limit (E_{E0})	E_{E0} [kWh]	P_{EO} [$/kWh] ($p_{32}=p_{31}*k_{EO}$)
Energy imported (bought from grid. E_B)	E_B [kWh]	P_B [$/kWh] ($p_{31}$)
Energy imported over limit (bought from grid, E_{BO})	E_{BO} [kWh]	P_{BO} [$/kWh] ($p_{33}=p_{31}*k_{BO}$)
Reactive power over limit penalty	E_{RP} [kVArh]	P_{33} = 0.50 [$/kVArh]



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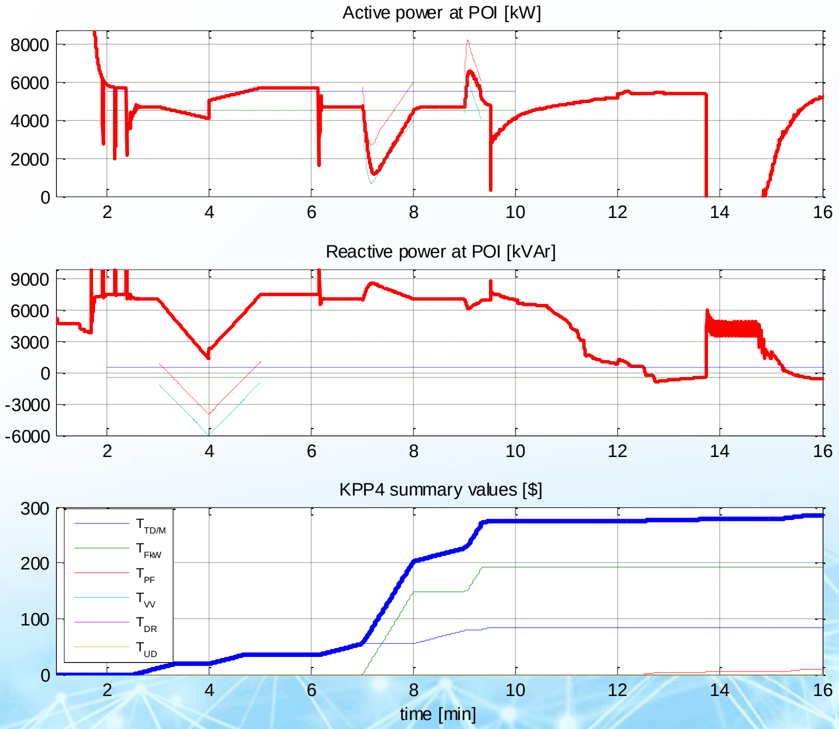
KPP4 – Grid services

Meeting dispatch command premium (DP). Power imported from Grid to µG	T_{DP} min	P_{41} = 23.60 [$/min]
Meeting demand command premium (DM). Power exported from µG to Grid	T_{DM} min	P_{41} = 23.60 [$/min]
Following Volt/Var support premium (VV)	T_{VV} min	P_{43} = 290.00 [$/min]
Following Demand response curve (Freq/kW, FkW)	T_{FkW} min	P_{44} = 149.50 [$/min]
Meeting power factor request (PF)	T_{PF} min	P_{46} = 11.21 [$/min]
Violating planned disconnect request (DR)	T_{DR} min	P_{45} = 19.50 [$/min]
Unplanned disconnect – failure to disconnect (UD)	T_{UD} min	P_{47} = 26.40 [$/min]



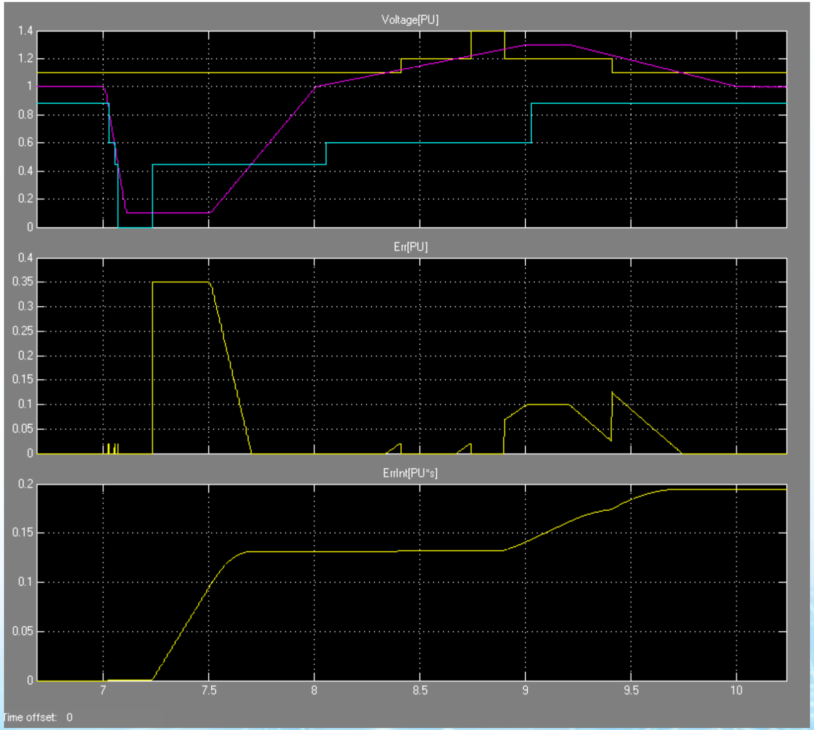
KPP5 – Power quality

- Voltage monitored on every bus
- According to IEEE 1547a-2014
- Fault integrators implemented in real time

Default settings[a]		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45 ≤ V < 60	1	11
60 ≤ V < 88	2	21
110 < V < 120	1	13
V ≥ 120	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted
[b] Base voltages are the nominal system voltages stated in ANSI C84.1-2011, Table 1.

* Table 1 from IEEE1547a-2014 standard

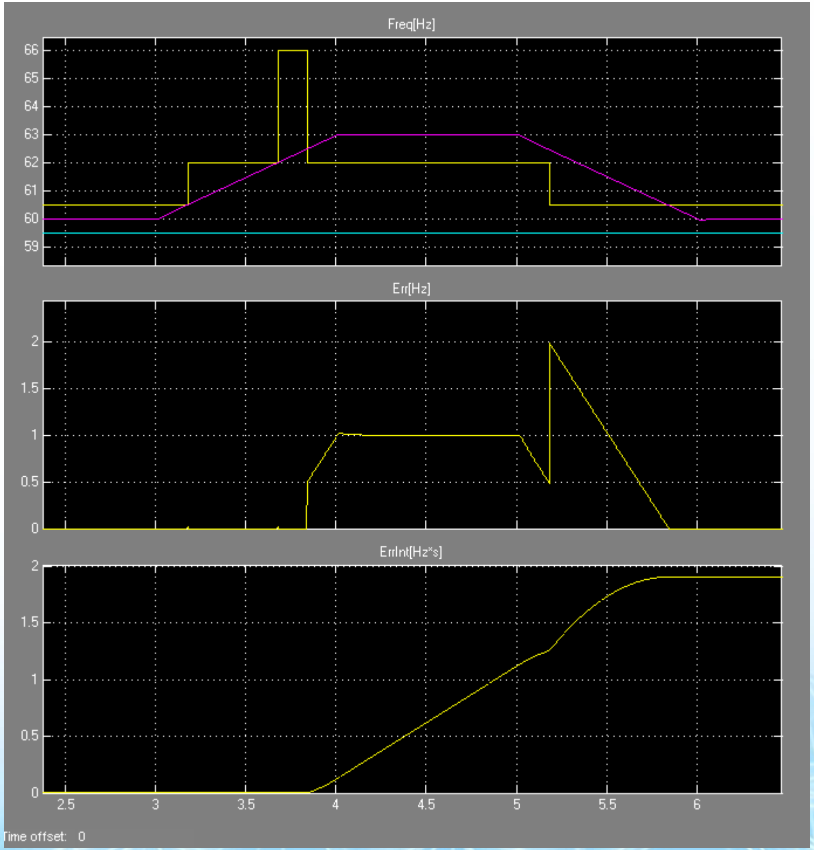


KPP5 – Power quality

- Frequency monitored on every bus
- According to IEEE 1547a-2014
- Fault integrators implemented in real time

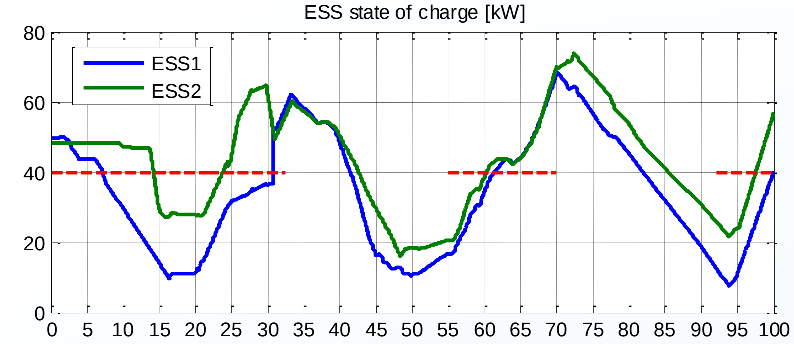
	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
UF1	< 57	0.16	56 – 60	10
UF2	< 59.5	2	56 – 60	300
OF1	> 60.5	2	60 – 64	300
OF2	> 62	0.16	60 – 64	10

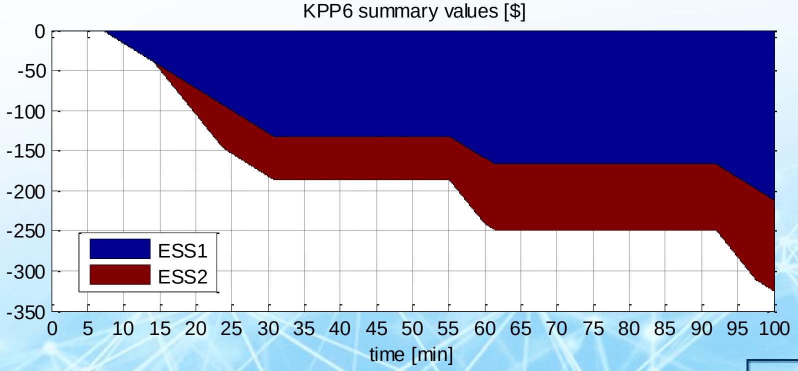
* Table 2 from IEEE1547a-2014 standard



KPP6 – Microgrid survivability

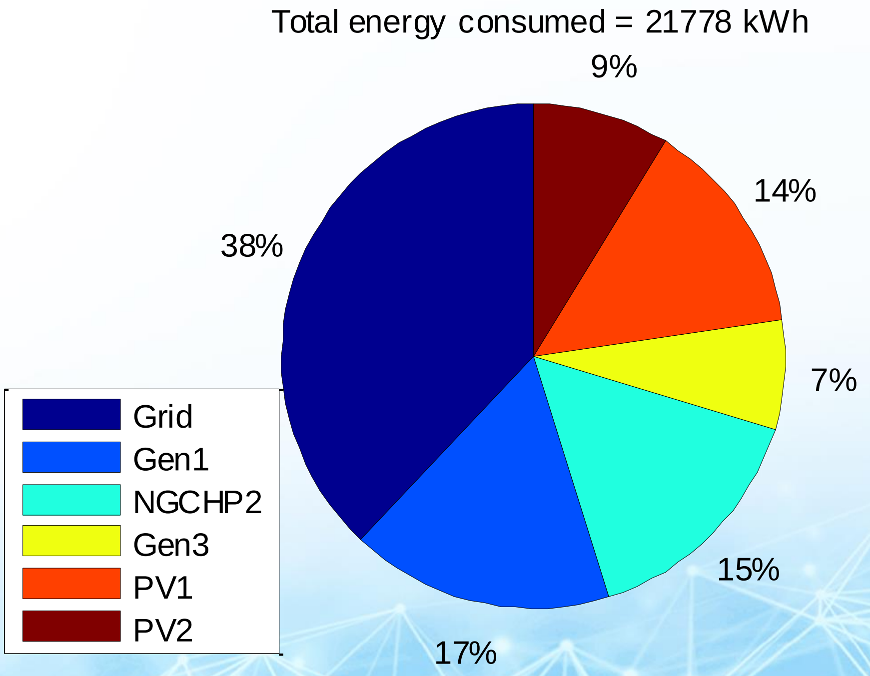
- Penalty is issued when SoC is below 40% during grid connected operation





KPP7 – Free assets utilization

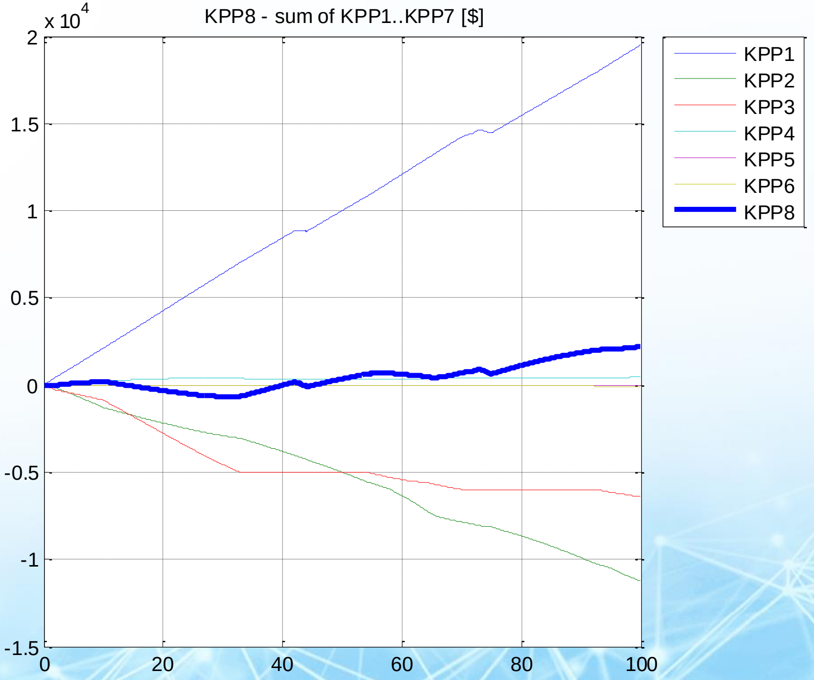
- >25% energy can come from solar in this test pattern
- >43% power can come from solar at peak irradiation
- Solar doesn't have a cost associated thus it is very favorable to use it



KPP8 – Summary result

Test case 1

Test case 2



Next steps

- Currently in are at Stage 1 (CHIL) and validating Team #4
- We will publish details about competition winner's strategies and analyze various teams' approaches
- Models will be published after procurement:
  github.com/mgcp2017/

Acknowledgements

This work was supported by the U.S. Department of Energy. NREL would like to thank MIT Lincoln Laboratories for their collaboration on this project.

THANK YOU