MONTHLY PROGRESS REPORT

Contractor Name:
University of Notre Dame (Michael Lemmon)

Contractor Address:
Office of Research, 940 Grace Hall, Notre Dame, IN 46556

Contract/Purchase Order No. W9132T-10-C-0008 (prime contract no.)	Task Order No.

Project Title:
Design and Simulation of Intelligent Control Architecture for Military Microgrids

Period Covered:
January 1 2011 – February 1, 2011

POC/COR (Reference Paragraph 5 of the SOW):

Achievements (Describe by task. Add additional tasks, if needed.):
task numbers refer to tasks in Odyssian's original contract

Task II: Model and Simulate Intelligent Microgrid

Developed frequency estimator and load-shedding component.
Developed simulink model of e-board prototype with priority based load shedding logic.
Developed simulink model of microsource couple that synchronizes reconnection of new generator to the microgrid.

Task III: Distributed Control Algorithm Development

No activity

Task VI: Develop Wireless Communication

No activity

Task VII: Develop Wireless Distributed Control

Designed digital frequency estimator to support load-shedding component.
Development of simple priority based load shedding algorithm.

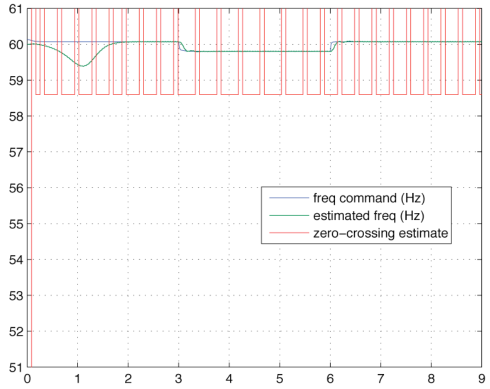
Problems Encountered (Describe by task. Add additional tasks, if needed):

Task II: None
Task III: None
Task VI: None
Task VII: None

Open Items (List items that require action by the Contractor or the Government):s
No open items

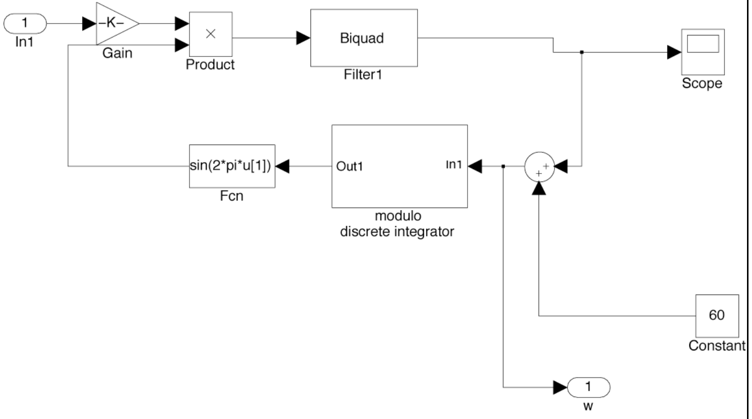
Summary Assessment and Forecast (Provide an overall assessment of the work and a forecast of contract completion):

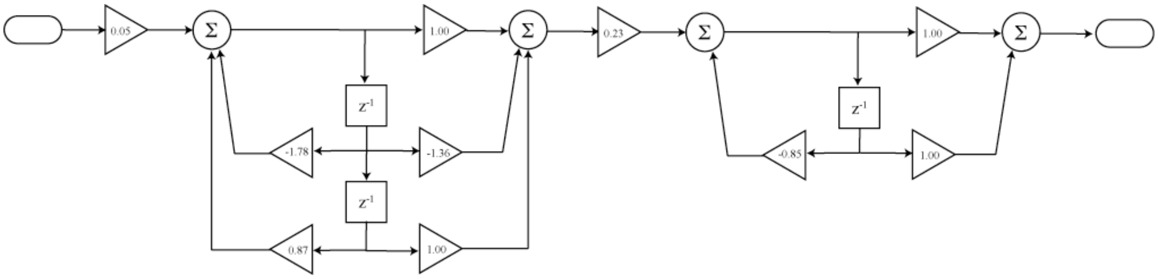
The main accomplishment from this reporting period was the development of a frequency estimator to support frequency-based load shedding. The original frequency estimator was based on counting zero-crossings over a specified interval of time. This approach generated estimates that had an precision of 1.0 Hz every 0.3 seconds. An example of the estimated frequency is shown in the following figure. This simulation was generated for the microgrid simulation model used in testing the CERTS controller on a microsource. To generate frequency estimates with greater precision would require a greater interval between estimates. This level of estimation performance is inadequate for load shedding.



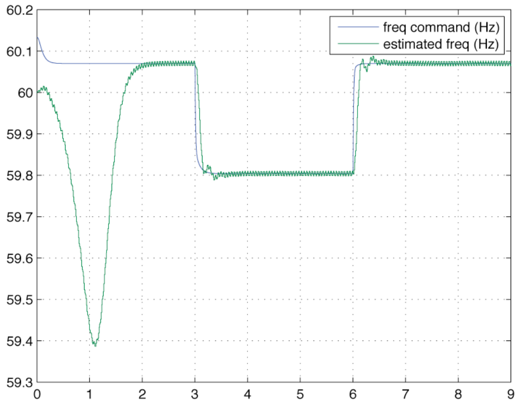
An alternative frequency estimator was designed using a phase-locked loop (PLL). In this estimator, the input waveform is mixed with a 60 Hz sinusoid and then run through a low pass filter. The output of this filter is used to change the frequency of a voltage controlled oscillator (VCO) generating the mixing sinusoid. The output of the filter represents the change in frequency from the 60 Hz reference sinusoid. This method provides an extremely fast and accurate estimate of the input signal's frequency. A simulink block diagram for the PLL frequency estimator is shown in the following figure.

The simulink model was constructed as a digital model assuming a sampling time of 10 msec. The key components in the filter are the biquad filter and the modulo digital integrator. The "modulo" nature of the integrator prevents integrator overflows that can reduce accuracy. The Biquad filter is an elliptical lowpass digital filter with a 100 Hz sampling frequency, a 5 Hz cutoff frequency, and a 20 Hz stopband frequency with 40 dB attenuation. The filter was implemented as a two stage biquad structure in direct form II. A block diagram for this filter is shown below in the following figure.

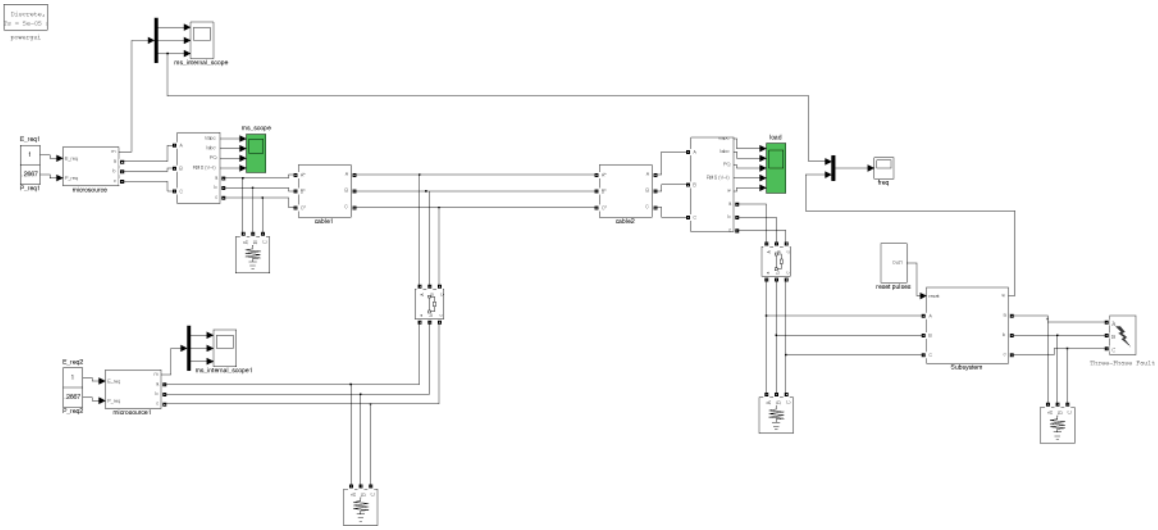




The performance of this estimator is shown in the following figure. There is an initial transient as the estimated frequency converges to the true value. At 3 seconds into the simulation an additional load is reconnected to the grid thereby causing a frequency droop. This droop is seen in the commanded frequency generated by the generator's CERTS microsource controller. As can be seen the frequency estimator tracks this commanded frequency with a higher degree of precision and more quickly than the zero-counting frequency estimator.

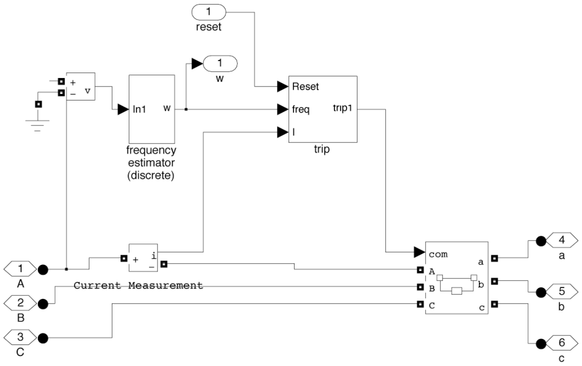


This frequency detector was integrated into a prototype load-shedding module. The load shedding component was designed to disconnect a load if the line frequency drops below 59.7 Hz or the RMS line current exceeds 100 A. Once the load has been disconnected, the load remains disconnected until a reset pulse is sent to the load-shedding component.

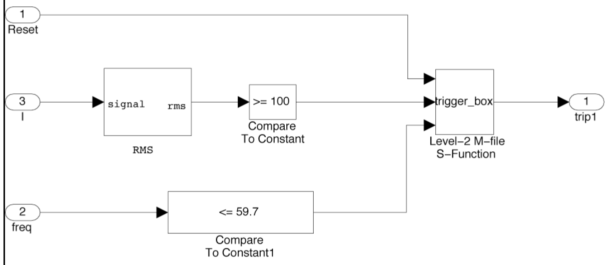


The above figure is a simulink model for the microgrid used to test the load shedding component. This grid has two CERTS controlled 15 kW microsource generators connected to a total of 20 kW loads. 8 kW's of these loads can be shed on the basis of either a current or frequency limit. At 3 second a ground fault occurs, which clears it self in 4/60 seconds. At 5 seconds the second microsource generator is disconnected. Reset pulses are sent to the load shedding module 1 and 4 seconds. These reset pulses clear the disconnection due to the fault, thereby allowing the system to shed to extra load when the second microsource is lost at 5 seconds.

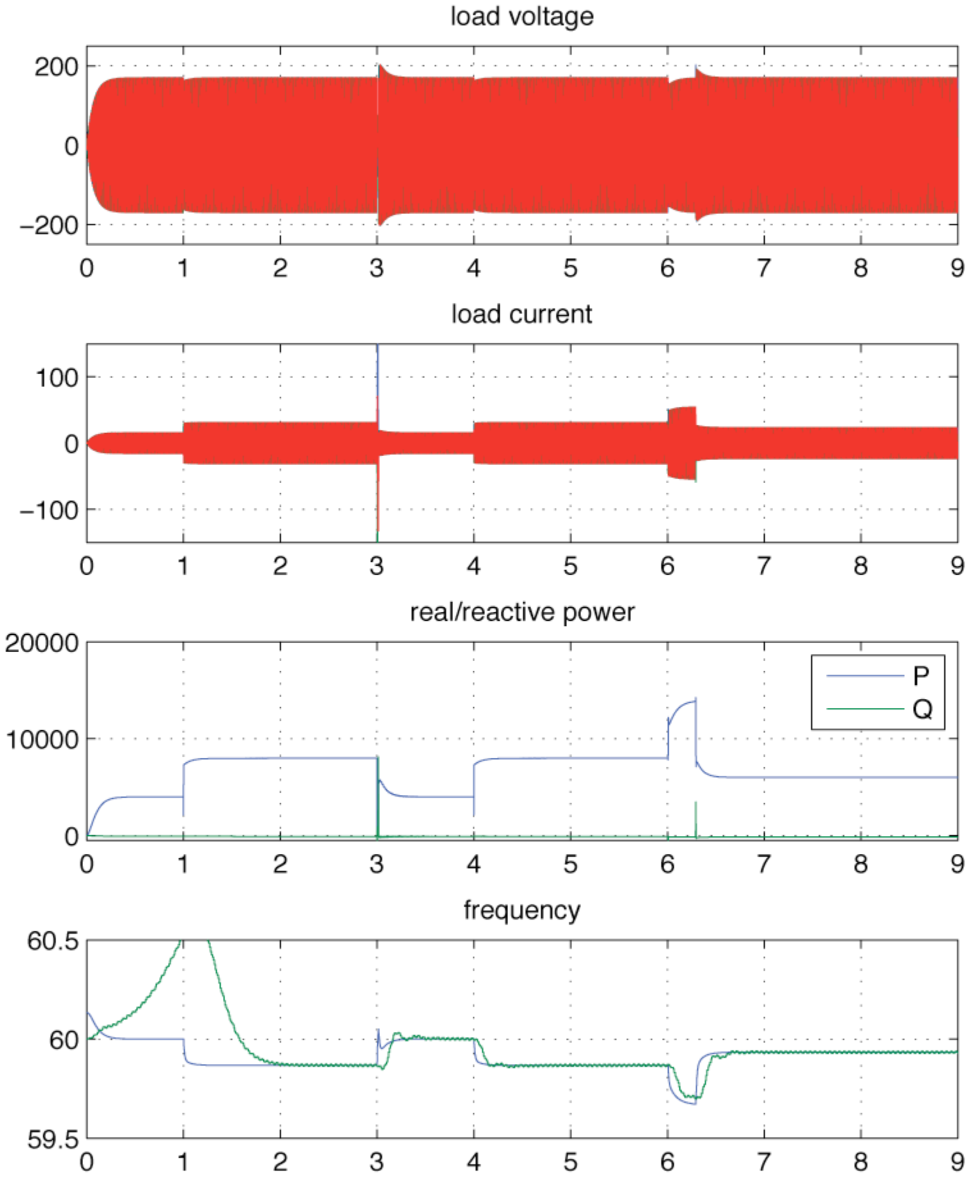
The following simulink block shows the load-shedding module. The inputs to this module are the 3 phase lines. The voltage on phase A is fed into the frequency estimator (described above), whose output is fed into the trigger component. The current on phase A is also measured and fed into the triggering component. The other input to the load-shedding module is the reset pulse. The triggering component uses the reset signal, the line frequency, and the RMS line current to open or close the breaker.



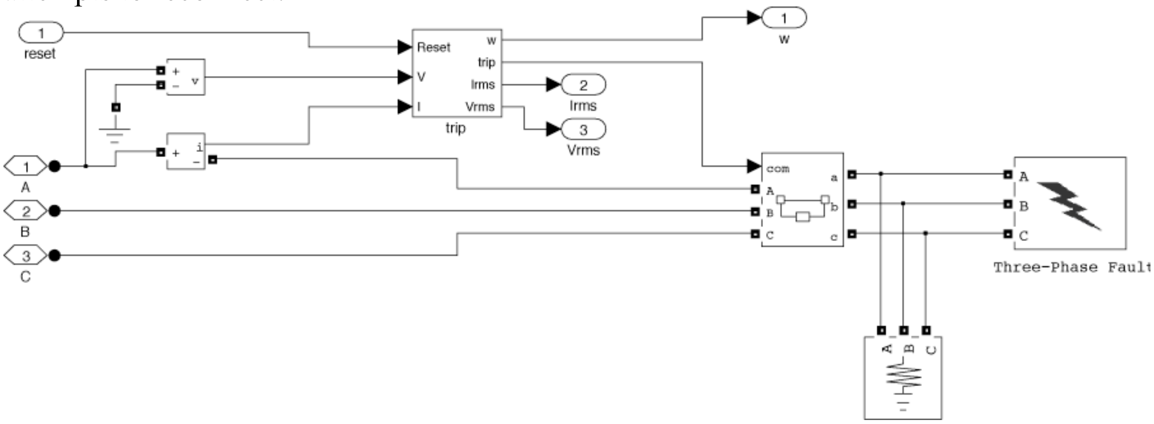
The triggering component's simulink model is shown in the following figure. This component generates a frequency event, if the frequency falls below 59.7 Hz and a current event if the RMS current exceeds 100 A. The triggering logic is coded into a level 2 M-file S-function (trigger_box). The logic opens the breaker if the frequency or current events are triggered. Once opened, the breaker stays open until a reset pulse is received. Receipt of the reset pulse closes the breaker and resets the event logic, so the breaker can be opened again by either a frequency or current event.



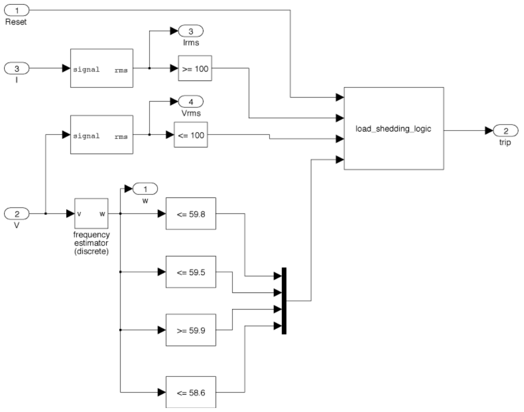
In the simulation used to test this component, we have 3 events. The controlled breaker is initially open. There is an event at 1 second when a reset signal is sent to the breaker, causing it to close. At 3 seconds, a fault occurs on the load connected to this breaker. This results in a current event that causes the breaker to open and thereby drop 8kW of load. At 4 seconds another reset pulse is sent to the load-shedding module, thereby reconnecting the load (since the fault has cleared). At 6 seconds, the second microsource is disconnected, causing the line frequency to drop below 59.7 Hz. The load shedding module successfully detects the frequency event and drops the 8 kW load again at 6.4 seconds into the simulation. The simulation plots are shown below. These plots clearly show the occurrence of the current and frequency events. The step changes in current and power clearly show that the extra load is dropped as expected.


load voltage
200
0
−200
0
1
2
3
4
5
6
7
8
9
load current
100
0
−100
0
1
2
3
4
5
6
7
8
9
real/reactive power
20000
10000
0
P
Q
0
1
2
3
4
5
6
7
8
9
frequency
60.5
60
59.5
0
1
2
3
4
5
6
7
8
9

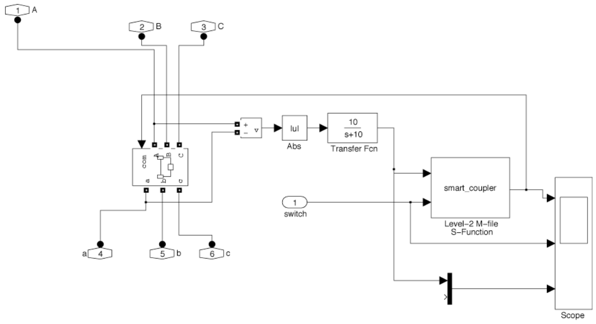
Began the development of a simulink model for a prototypical e-board load shedding device. This simulink model uses the frequency detection component to estimate frequency and includes a 4kW load with programmable fault. The model also measures RMS line voltage and current (phase A). The load shedding logic is implemented using a matlab S-function. This logic assumes that the load has one of two priority levels; critical (1) and non-critical (2). Non-critical loads are dropped when the line frequency drops below 59.8 Hz. Critical loads are dropped when the line frequency drops below 59.5 Hz. Both critical and non-critical loads are dropped in a voltage sag (phase A RMS voltage drops below 100V) or current surge (phase A RMS current rises above 100A). Once a load has been disconnected, it starts a timer. If the line frequency is above 59.9 Hz when the timer expires (nominal timer expiration is set to 0.25 seconds), then the load attempts to reconnect.



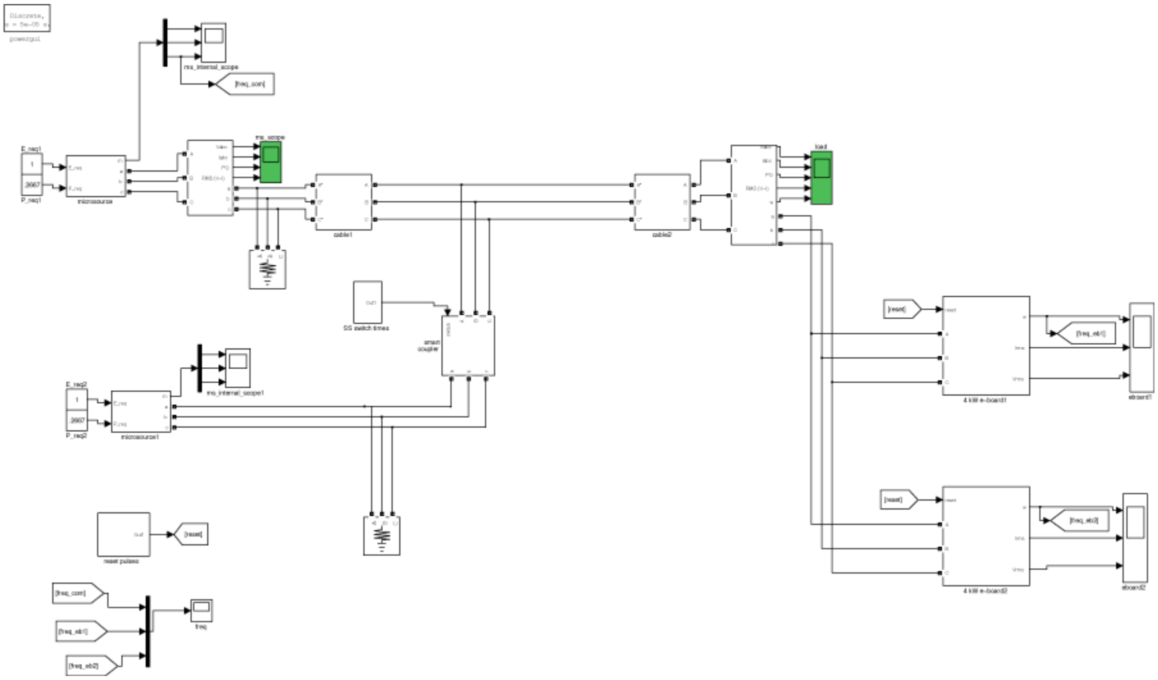
The block diagram for the eboard block is shown above. The block's funcitionality is buried with the "trip" block. The diagram for the trip block is shown below. This block has three inputs; the reset signal, the line current and the line voltage. The block generates the RMS current/voltage and checks whether they lie within the required bounds (voltage greater than 100V and current less than 100A). The frequency estimate is checked to see if it is less than 59.8, 59.5 or greater than 59.9. The Boolean inputs are used by the "load_shedding_logic" S-function to decide whether or not to disconnect.

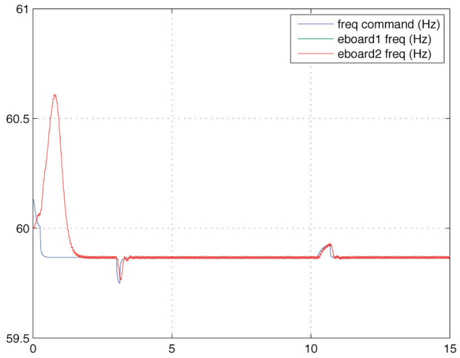


To test the e-board's reconnection logic, we had to implement a smart coupling device that would reconnect a disconnect generator when the voltage across the switch was small. The simulink block for this "smart-coupler" is shown below.

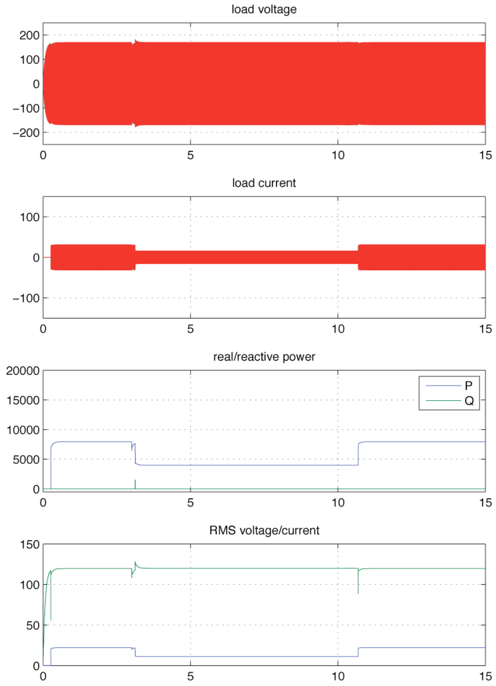


We tested the e-board prototype and smart-coupler on a simulink model that had two 15kW generators and 16kW of total load. 8 kW's of this load are attached as two 4kW e-board modules. One of these e-board loads is classified as "critical" and the other is classified as "non-critical". The simulation starts with the two generators connected to the microgrid and 8kW of attached load. The eboard loads connect at time 0.25 seconds. 3 seconds into the simulation, one of the microsource generators disconnects from the grid. This causes a drop in frequency below 59.8 Hz and the non-critical loads disconnects from the grid. The frequency recovers to just below 59.9 Hz. 10 seconds into the simulation, the disconnected generator reconnects to the microgrid. The reconnection transients are small due to the smart-coupler's ability to synchronize the reconnection. Once the microsource reconnects, the frequency recovers above 59.9Hz. At this point, the disconnected e-board starts a time and 0.25 seconds it reconnects to the microgrid in a safe manner. The simulink model for this scenario is shown below.





The frequency estimated at both eboards and the frequency of the generator that remains connected throughout the simulation is plotted below. Note the initial startup transient in the frequency estimator that stabilizes by 2 seconds into the simulation. The first drop in frequency at 3 seconds into the simulation is due to one of the source dropping off. As soon as the estimated frequency drops below 59.8 Hz, the non-critical load is dropped and we can see the frequency return to its original value. At 10 seconds into the simulation, the second generator reconnects. We see an increase in frequency as the system has excess generation capacity. Once the frequency exceeds 59.9 Hz, the load shedding logic starts a timer that reconnects the non-critical load to the microgrid. We then see the frequency drop back to its nominal level when the load is reconnected.



The next figure plots the line voltage/current, power, and RMS voltage/currents going through the cable connecting the two e-boards to the microgrid. What one should note here is that voltage quality is good during the disconnection and reconnection of the loads and generators. One can clearly see at 0.25 seconds when both eboard loads are first connected to the grid for a total of 8 kW. At 3 seconds, the non-critical load is shed thereby dropping the total power flow through the cable to 4 kW. Finally after 10 seconds, the non-critical load is reconnected and we see the total power flow return to 8 kW.