Comparison of Hardware Tests with SIMULINK Models of UW Microgrid

Introduction

This report includes a detailed discussion of the microsources available on the University-of-Wisconsin microgrid. This includes details of the SIMULINK models and their comparison with actual dynamic tests. Critical model parameters are also provided. The microsources include inverter based sources, AC storage and a field wound synchronous generator. The appendix includes SIMULINK models and the network parameters for the network studies in Phase VIII. Note there is a significant differences in the system presented at the start of this project. The loads are different representing the actual loads available in at Wisconsin.

Current UW Microgrid Parameters

This section documents the current actual microgrid circuit used a University of Wisconsin. This includes line impedances and transformer data. This is the system for providing the hardware test data of the system's dynamics.

Figure 1 shows the UW Microgrid diagram.

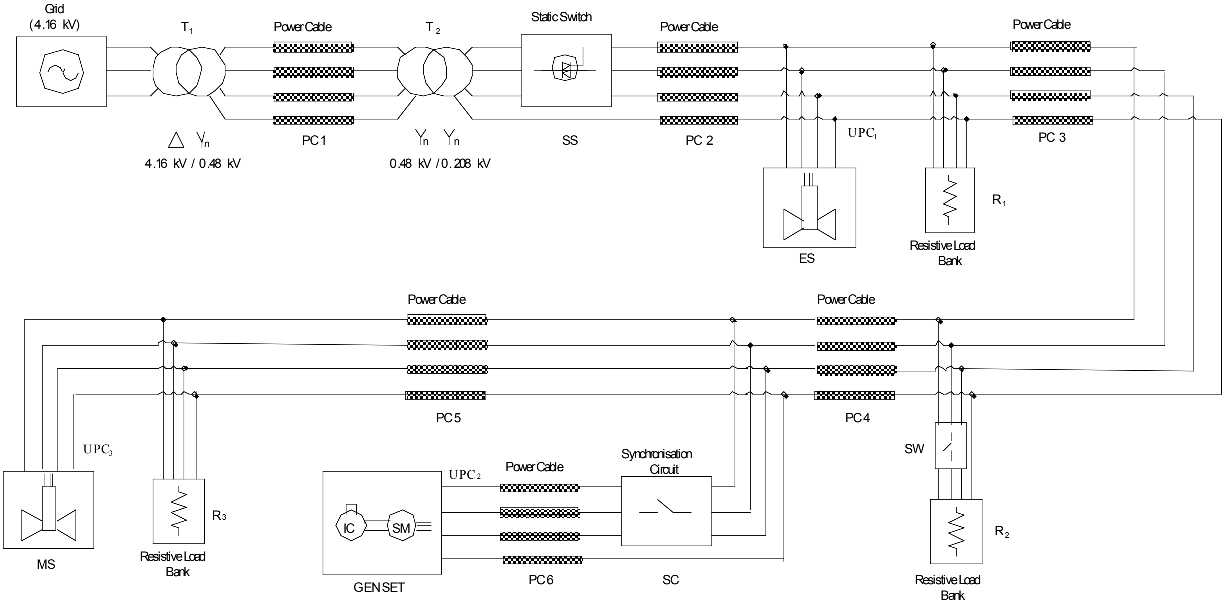


Figure 1. Three Phase Diagram of UW Microgrid

Impedances of microgrid lines and transformers are listed in Table 1 and 2 respectively.

Table 1. Line impedances of UW microgrid

Line Impedance	**Length [ft]**	**R [Ω]**	**X_L [Ω]**	**X_C [Ω]**
PC1	366	0.093400	0.025500	
PC2	18	0.002810	0.000679	
PC3	175	0.027352	0.006600	288.6
PC4	108	0.016880	0.004070	336.7
PC5	17	0.002657	0.000641	2020.2
PC6	105	0.065600	0.002100	345.6

Table 2. Transformer impedances of UW microgrid

Tag	**Volt-Amp Rating**	**Impedance**	**HV Side Resistance[Ω]**	**HV Side Reactance[Ω]**	**LV Side Resistance[Ω]**	**LV Side Reactance[Ω]**
T_1	2500 kVA	5.50%	0.04707123	0.1882849	0.000627	0.0025068
T_2	75 kVA	4.40%	0.01689600	0.0675840	0.003173	0.0126908
T_3	45 kVA	4.20%	0.02688000	0.1075200	0.005047	0.0201899
T_4	45 kVA	4.20%	0.00671900	0.0268800	0.005047	0.0201899
T_5	45 kVA	4.20%	0.02688000	0.1075200	0.005047	0.0201899

Inverter Microsource Details

Microsource (MS) is illustrated in Figure 2.

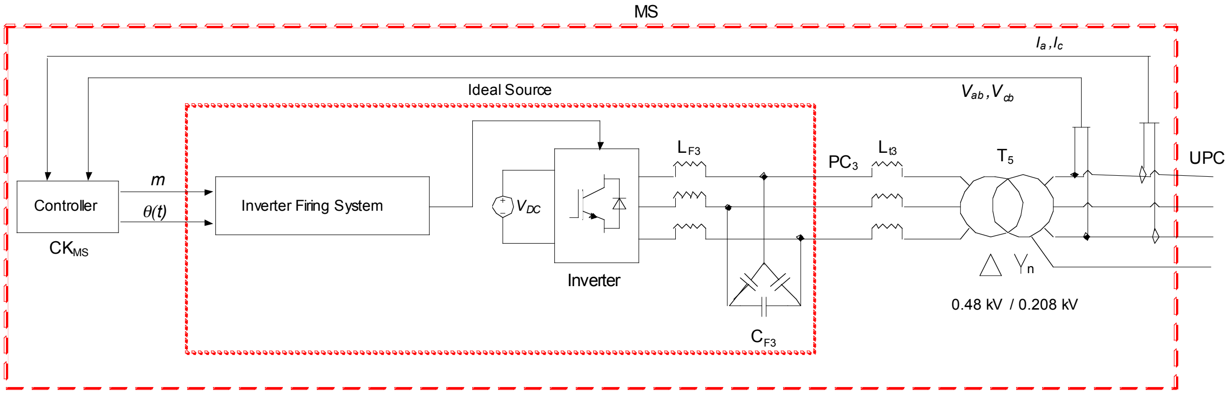


Figure 2. MS components

Inverter voltage and currents have a fundamental component and higher harmonics due to the turn-on/off effects of the switches. Harmonics are significantly eliminated by means of LC filter and the 10kHz switching frequency. The inverter is represented from the microgrid point of view as an ideal, balanced voltage source with only fundamental components. The output of the inverter is modeled as a controlled voltage source as shown in Figure 3.

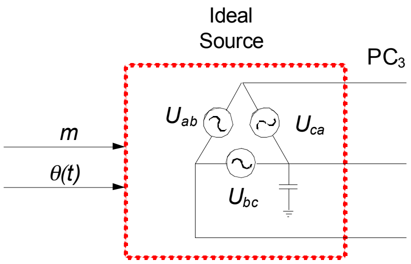


Figure 3. Ideal source model

Instantaneous voltages of the controlled voltage sources can be written as following;

$$U_{ab} = m.V_{DC}.\cos(\theta(t))$$

$$U_{bc} = m.V_{DC}.\cos\left(\theta(t) - \frac{2\pi}{3}\right)$$

$$U_{ca} = m.V_{DC}.\cos\left(\theta(t) + \frac{2\pi}{3}\right)$$

The quantities m and *θ(t)* are the outputs of the control block. The quantity *m* is a modulating index, a scalar coefficient that when is multiplied by the DC voltage yields the magnitude of the desired voltage at the inverter terminals. The quantity *θ(t)* is the desired instantaneous value of angle for the voltage at the inverter terminals.

Control quantities used in this model are voltage (V_{meas}), real power (P_{meas}) and reactive power (Q_{meas}). Detail of the controller is shown in Figure 4.

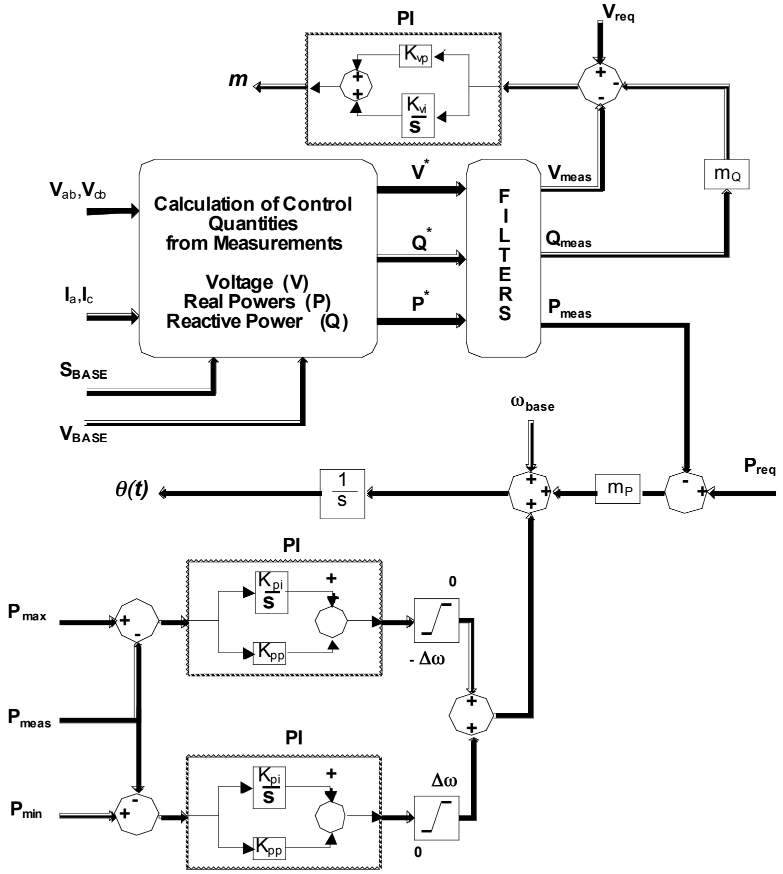


Figure 4. Detailed MS controller scheme, CK_{MS}

Real and reactive power (in pu) injected from MS and terminal voltage (in pu) are calculated by signal processing block illustrated in Figure 5.

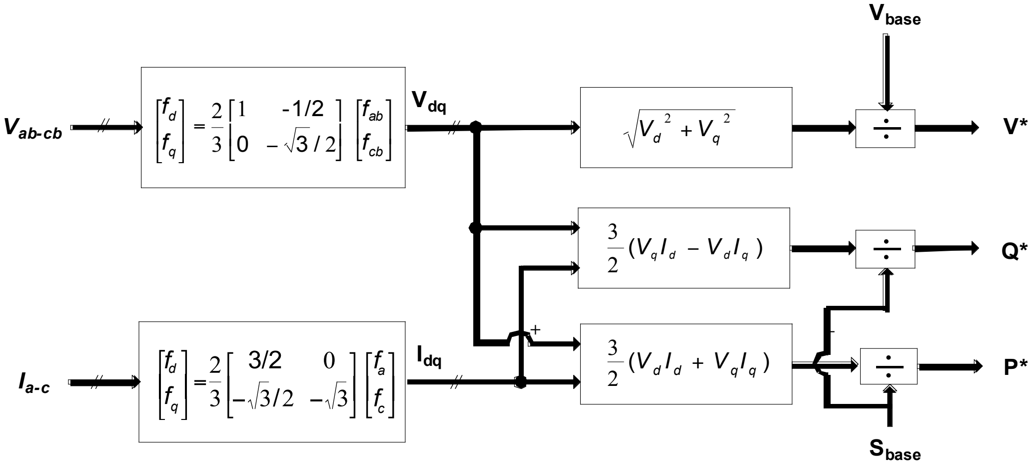


Figure 5. Control quantities calculation block

Instantaneous P, Q and V are calculated using the rotating d-q reference frame. Instantaneous voltage (current) magnitude is calculated by obtaining the in-phase (direct) and out of phase (quadrature) voltages (current) with respect to phase-a.

The calculated V, P and Q quantities are passed through the low pass filters to attenuate the high frequency components which occur at step load or power changes. Filter diagram is shown in Figure 6.

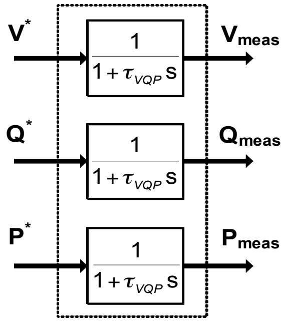


Figure 6. Filter diagram

Experimental vs. Simulation Results for MS

Experimental setup in which MS is island mode and grid-connected mode is shown in Figure 7.

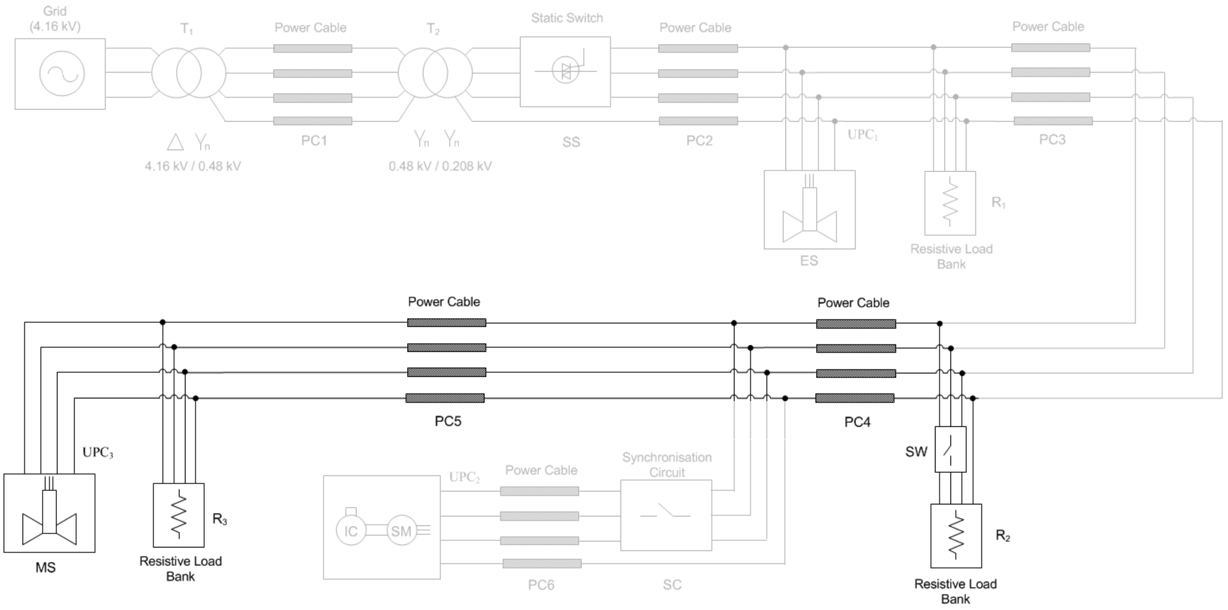


Figure 7. Experimental setup diagram for MS

MS parameters are listed in Table 3.

Table 3. MS parameters

V_{DC}	750 V
S_{BASE}	15 kVA
V_{BASE}	208 V
ω_{base}	376.9911 ($2\pi60$)
$\Delta\omega$	3.1416 ($2\pi0.5$)
P_{max}	15 kW (1 pu)
P_{min}	0 kW
P_{req}	4 kW (0.2667 pu)
V_{req}	208 V (1 pu)
K_{pp}	3
K_{pi}	30
K_{vp}	0.01
K_{vi}	5
m_Q	0.05
m_P	3.1416
τ_{VQP}	0.01

In this islanded case study the inverter has two resistive loads .

R2=10.8Ω R3=22.2Ω

Initially the load R3 is supplied by the inverter. R2 is switched in at t_1≅1.7 sec and out at t_2≅ 6.8.

Results of simulation and experiment are shown in Figure 8 through 11.

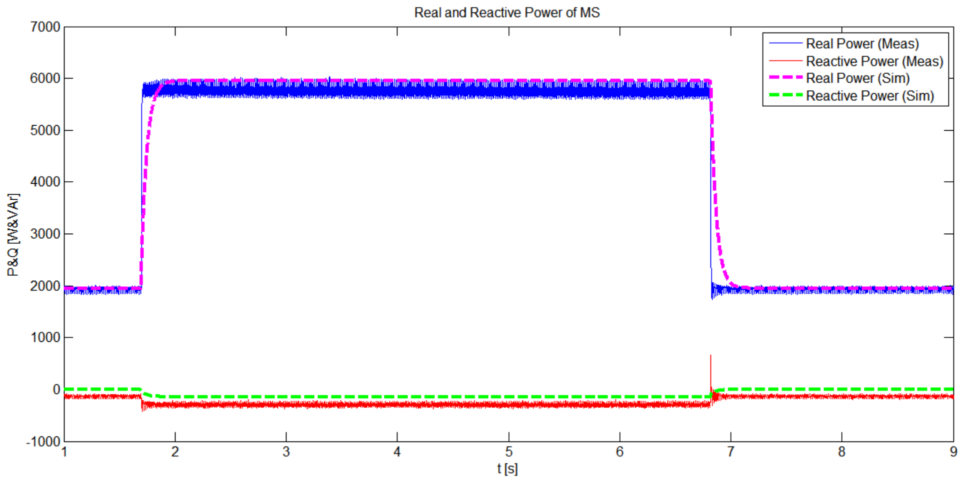


Figure 8. Real and reactive power variation of MS

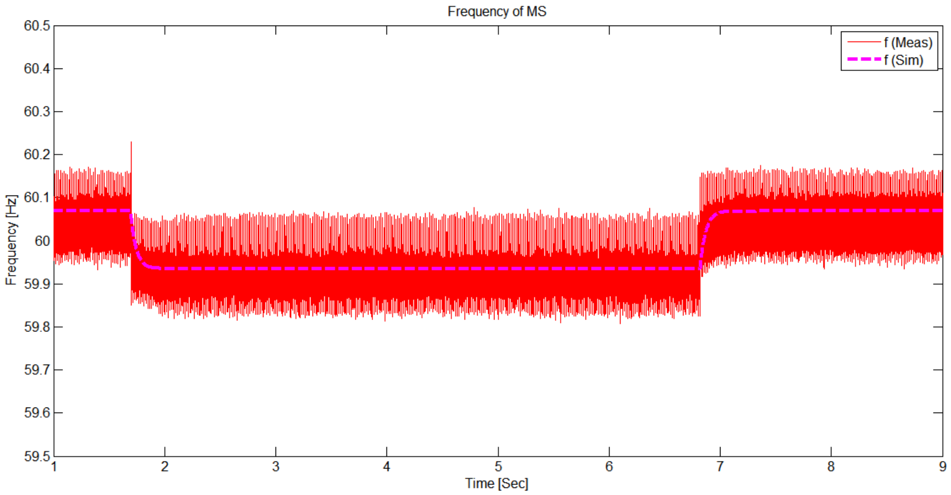


Figure 9. Frequency variation of MS

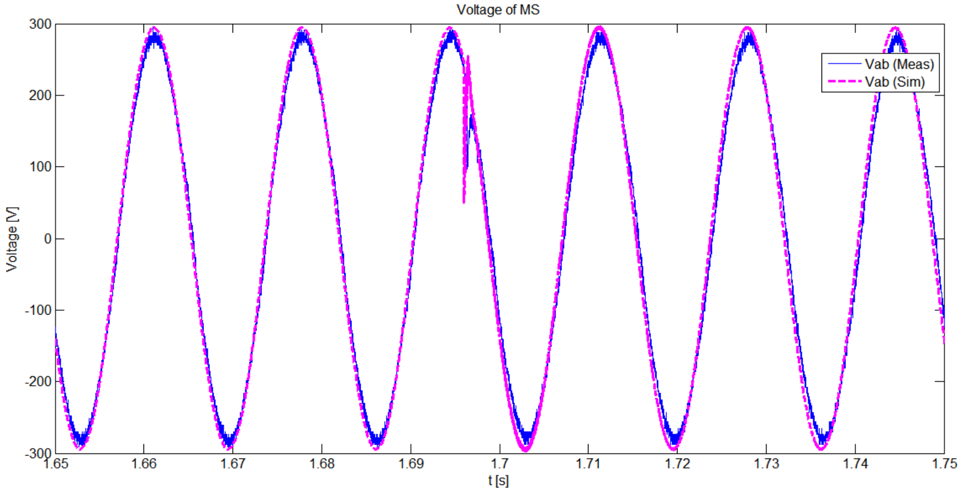


Figure 10. Voltage variation of MS during load step up

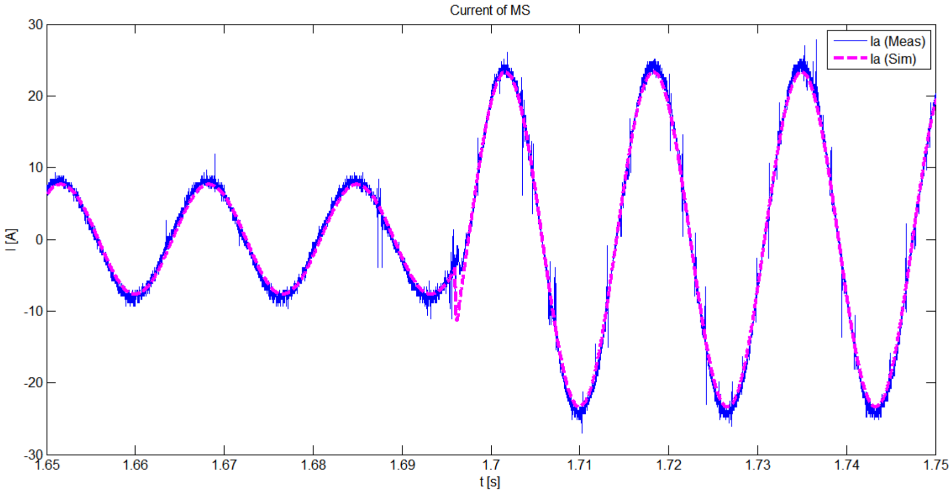


Figure 11. Current variation of MS during load step up

Energy Storage, ES, Details

Energy storage (ES) modeling details are illustrated in Figure 12. ES is also modeled as a controlled voltage source.

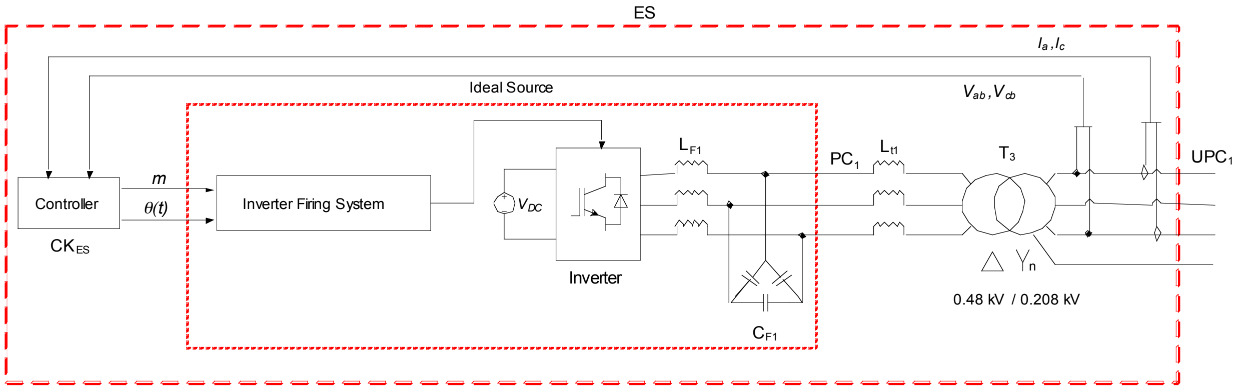


Figure 12. ES components

Detailed controller of ES is shown in Figure 13. As shown, the controller is same as that of MS. However, P_{min} can have negative value which correspond that of battery charging.

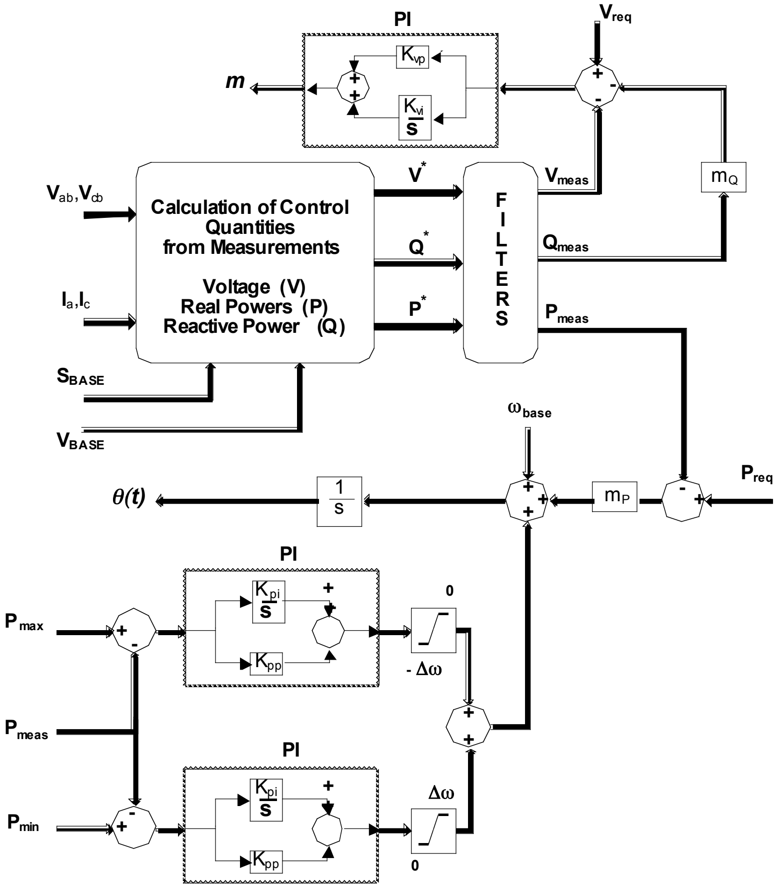


Figure 13. Detailed ES controller scheme, CK_{ES}

2.1. Experimental vs. Simulation Results for ES

Experimental setup for ES is illustrated in Figure 14.

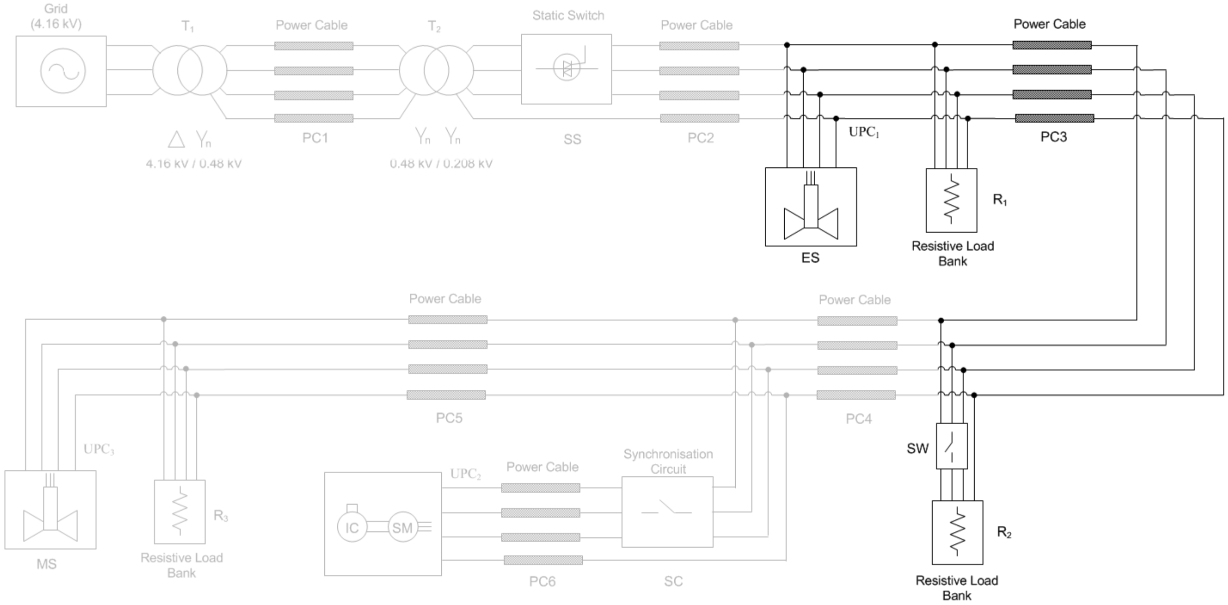


Figure 14. Experimental setup diagram for ES

ES parameters are listed in Table 4.

Table 4. ES parameters

V_{DC}	750 V
S_{BASE}	15 kVA
V_{BASE}	208 V
ω_{base}	376.9911 ($2\pi 60$)
$\Delta\omega$	3.1416 ($2\pi 0.5$)
P_{max}	15 kW (1 pu)
P_{min}	-2.5 kW (-0.1667 pu)
P_{req}	4 kW (0.2667 pu)
V_{req}	208 V (1 pu)
K_{pp}	3
K_{pi}	30
K_{vp}	0.01
K_{vi}	5
m_Q	0.05
m_P	3.1415
τ_{VQP}	0.01

In this case study, the ES inverter supplies the two resistive loads in islanding mode. The load values are fallowing:

R1=20.5Ω R2=10.8Ω

Initially the load R1 is supplied by the ES inverter. R2 switched in at t_1≅4.12 sec and out at t_2≅ 7.72, respectively.

Results of simulation and experiment are shown in Figure 15 through 18.

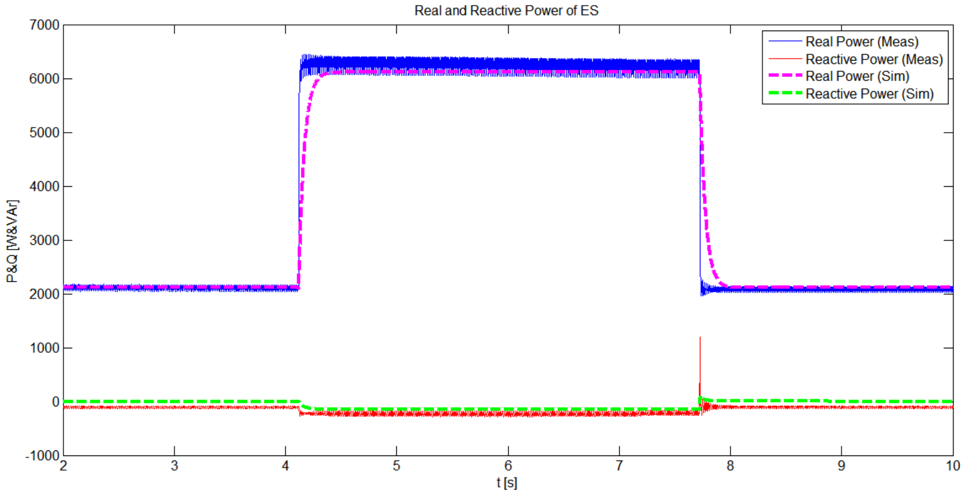


Figure 15. Real and reactive power variation of ES

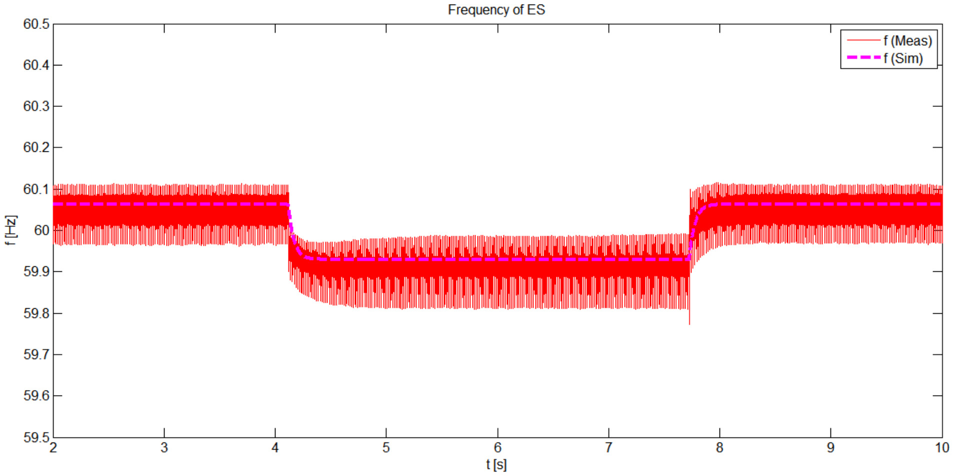


Figure 16. Frequency variation of ES

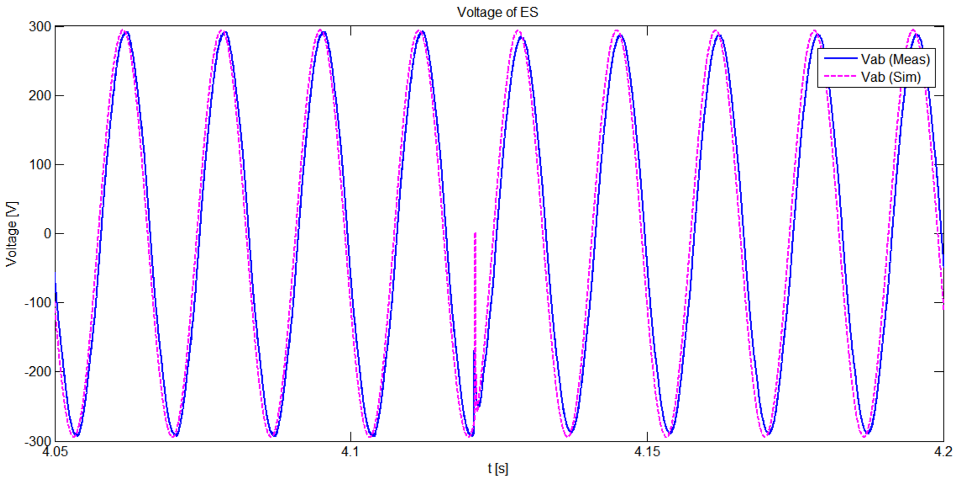


Figure 17. Voltage variation of ES during load step up

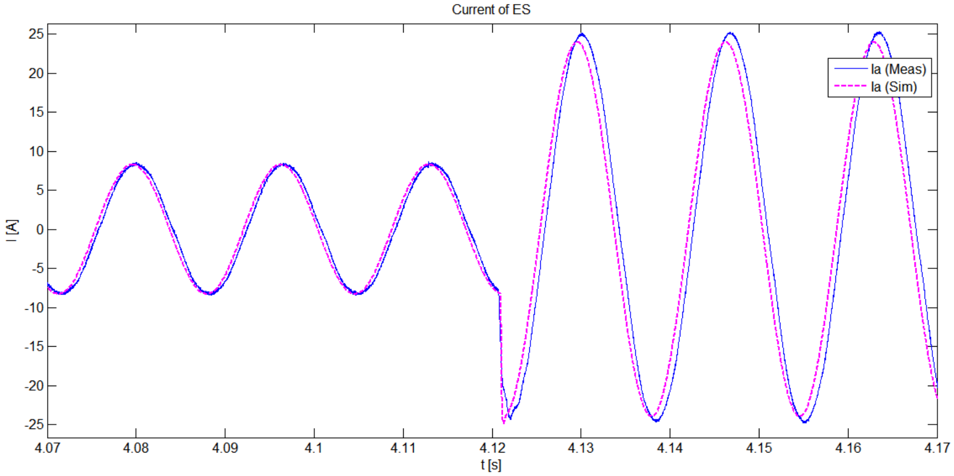


Figure 18. Current variation of ES during load step up

GENSET Details

The GENSET block is shown in Figure 19. It comprises of an internal combustion (IC) engine driven and a 12.5 KW Kohler field wound synchronous generator.

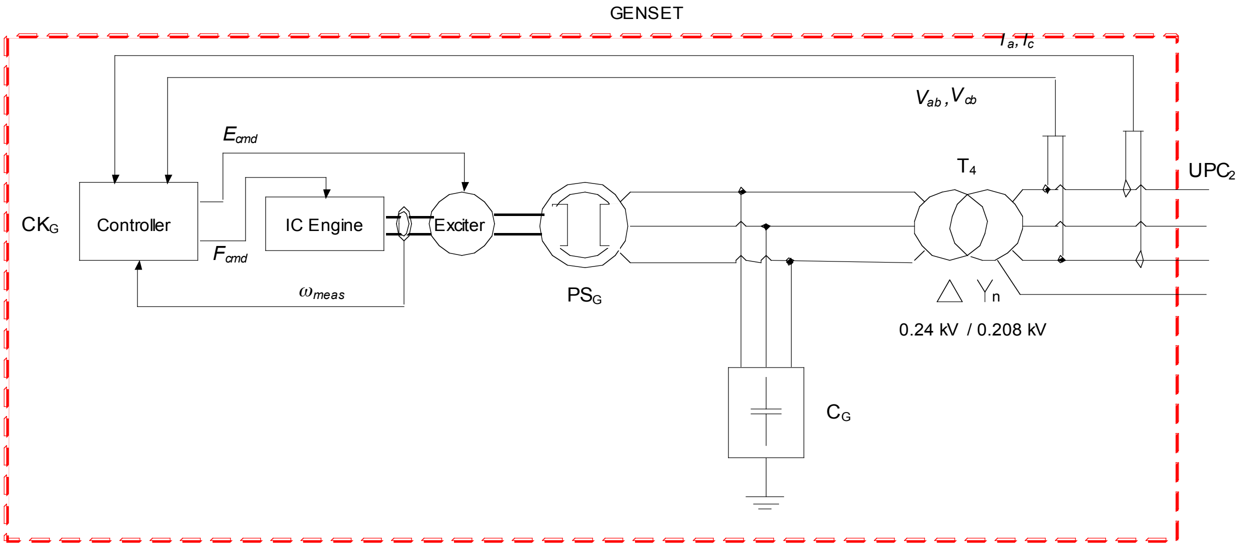


Figure 19. GENSET components

Internal combustion (IC) engine is illustrated in Figure 20. The exciter model is shown in Figure 21.

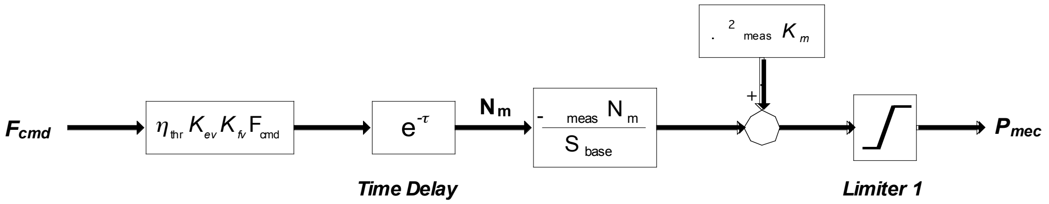


Figure 20. IC Engine model

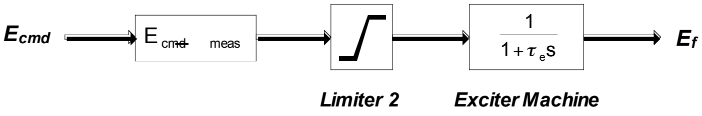


Figure 21. Exciter model

Control quantities used in this model are voltage (V_{meas}), real power (P_{meas}), reactive power (Q_{meas}) and speed of generator (ω_{meas}). Detail of the controller is shown in Figure 22.

The speed of generator is directly measured from synchronous machine measurement terminal. Therefore a speed observer model is not needed in this study.

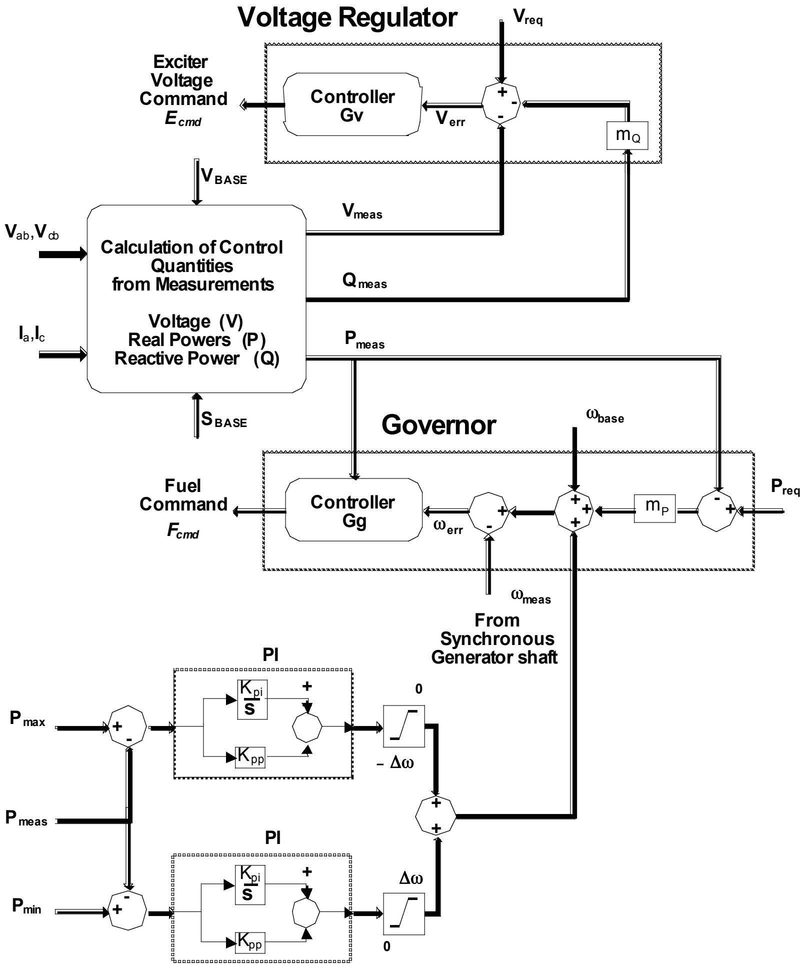


Figure 22. Detailed GENSET controller scheme, CK_G

The controller Gv in the voltage regulator block is shown in detail in figure 23.

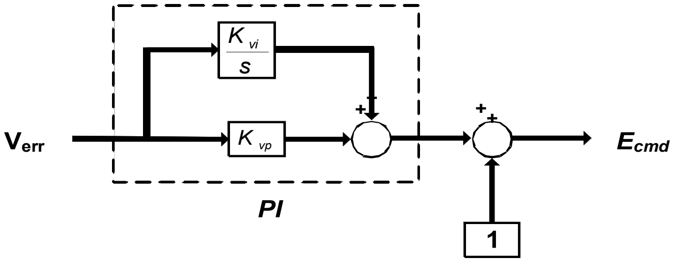


Figure 23. Detailed diagram of controller Gv

The Gv controller is the sum of the PI controller and the feed-forward value. This is the expected value required for nominal voltage at the terminals. This feed-forward constant allows for quicker initial convergence without the integrator having to wind up.

The controller Gg in governor block is shown in figure 24.

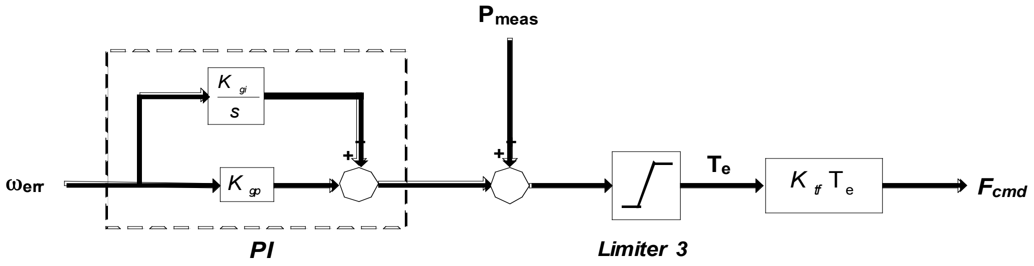


Figure 24. Detailed diagram of controller Gg

The governor controller regulates the rotational speed of the genset primarily by a combination of fuel commands calculated from the speed error and the output power that is used to decouple the loading of the machine.

The speed error is fed into a PI controller to modify the torque command. The output of the PI controller is the output power at the terminals of the machine. The limiter before the torque command output (T_e) is used to avoid unrealistic commands during large load transients. The torque command is translated into fuel unit command F_{cmd}.

Results for GENSET

Simulation setup for the GENSET in island mode is illustrated in Figure 25.

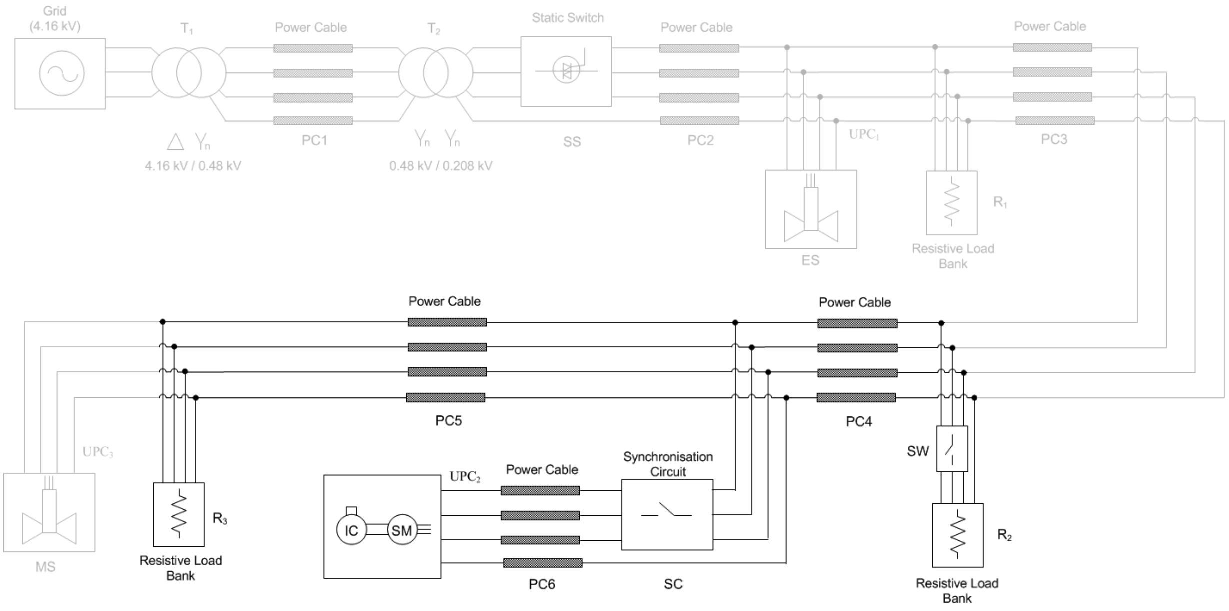


Figure 25. Simulation setup diagram for GENSET

ICE parameters and Synchronous generator parameters are listed in Table 5 and 6, respectively.

Table 5. GENSET parameters

S_{BASE}	12.5 kVA
V_{BASE}	208 V
ω_{base}	376.9911 ($2\pi 60$)
$\Delta\omega$	3.1416 ($2\pi 0.5$)
P_{max}	12.5 kW (1 pu)
P_{min}	0 kW
V_{req}	208V (1 pu)
K_{pp}	3
K_{pi}	30
m_P	3.1416

η_{thr}	0.47
K_{ev}	11.8238
K_{fv}	3600
τ	0.022
K_m	0.36
τ_e	0.001
K_{vp}	100
K_{vi}	30
K_{gp}	10
K_{gi}	20
K_{tf}	0.625

Table 6. Synchronous generator parameters

x_d	1.204
x_d'	0.125
x_d''	0.056
x_q	0.533
x_q'	0.051
x_q''	0.037

T_{d0}'	0.35523
T_{d0}''	0.00015
T_{q0}''	0.0067
Rs	0.0217
H	0.19
p	2

In this case study, the GENSET has two resistive loads.

R2=10.8Ω R3=22.2Ω

Initially the load R3 is supplied by the GENSET. R2 is switched in at t_1=3 sec and out at t_2= 7, respectively.

Results are shown in Figure 26 through 29.

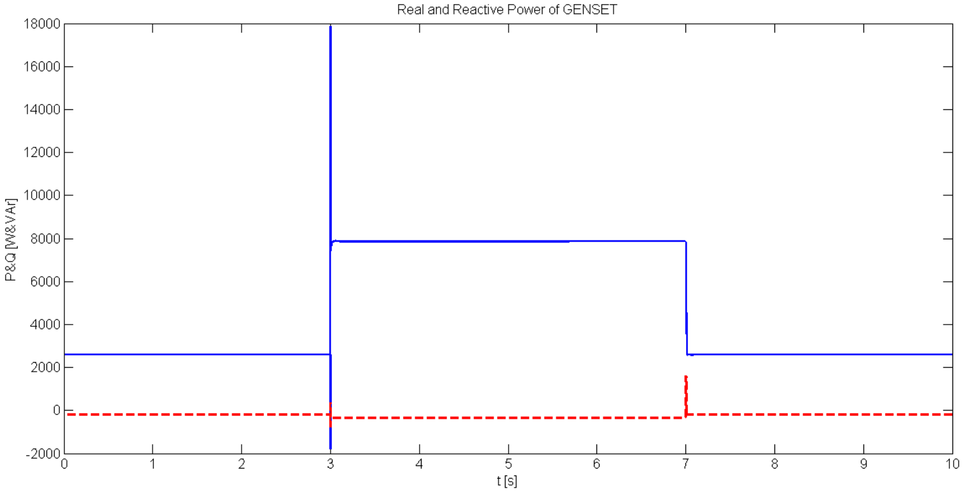


Figure 26. Real and reactive power variation of GENSET

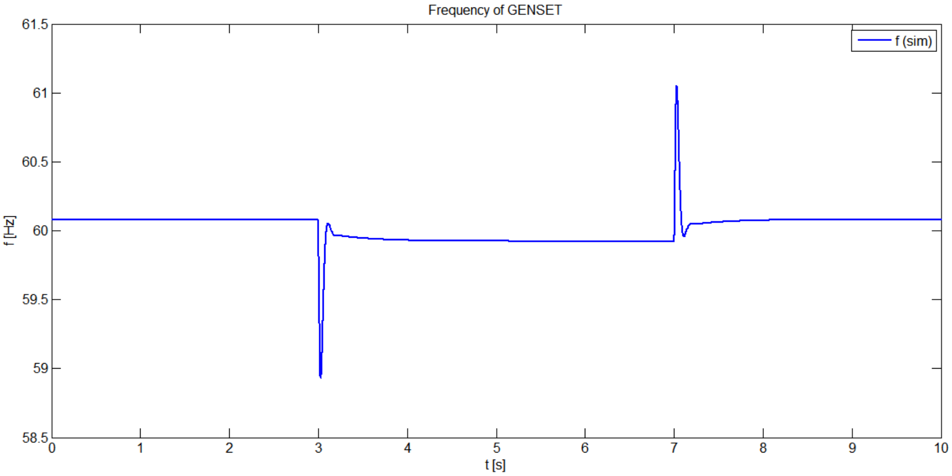


Figure 27. Frequency variation of GENSET

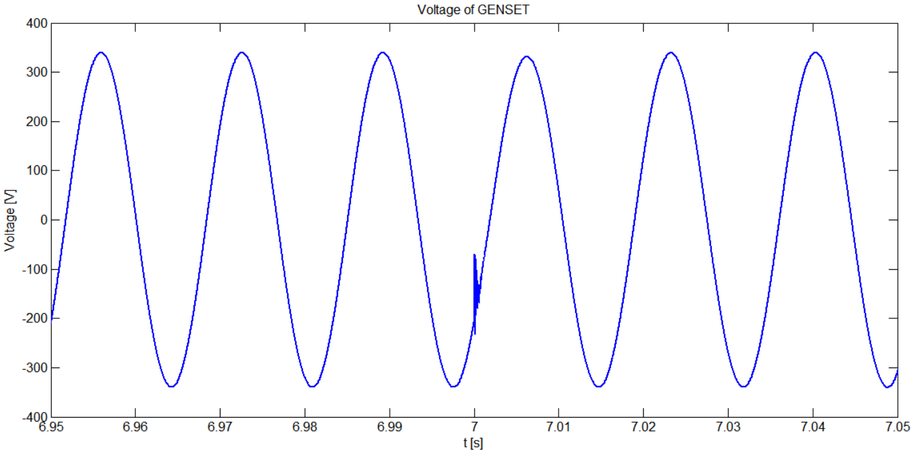


Figure 28. Voltage variation of GENSET during load step up

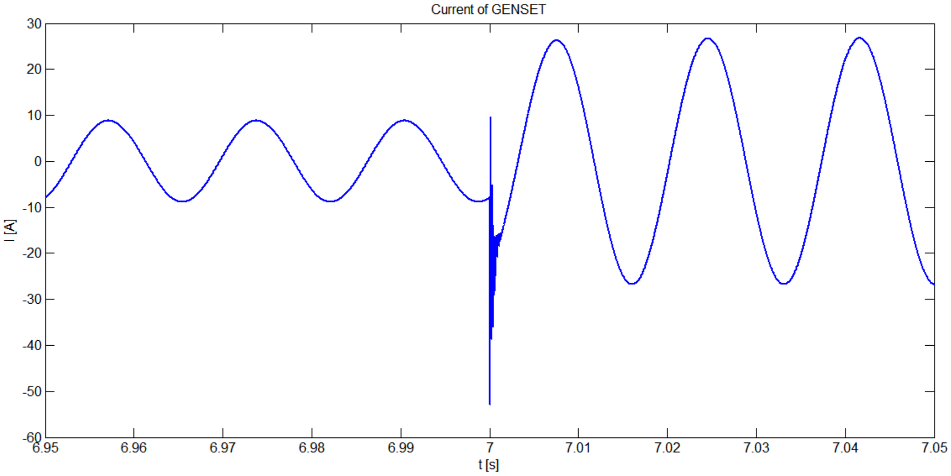


Figure 29. Current variation of GENSET during load step up

Appendix A: SIMULINK data

A. Microsource MS & Energy Storage ES

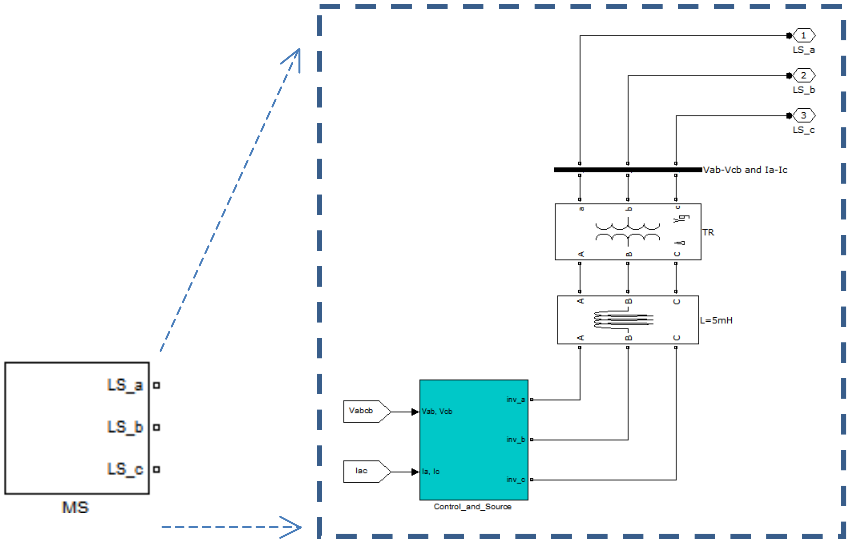
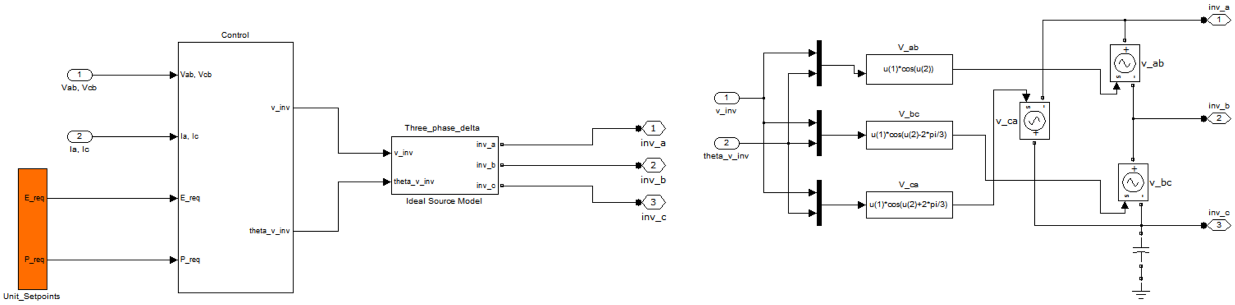


Figure A1. MS (ES) components



a) MS (ES) controls and source models

b) Ideal voltage source model

Figure A2. MS (ES) Controls and Source

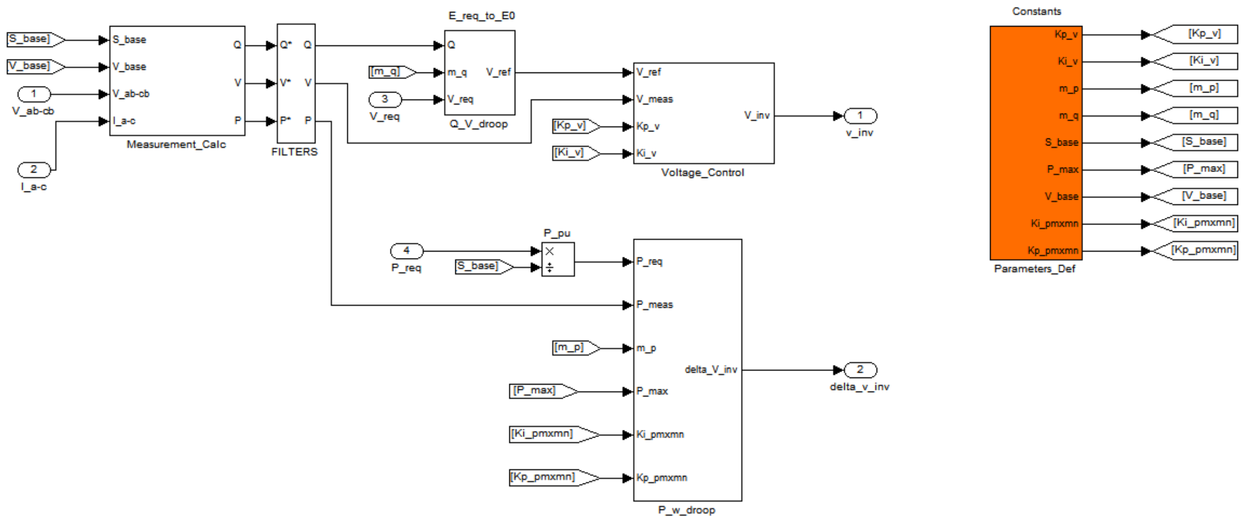


Figure A3. SIMULINK diagram of MS (ES) controller

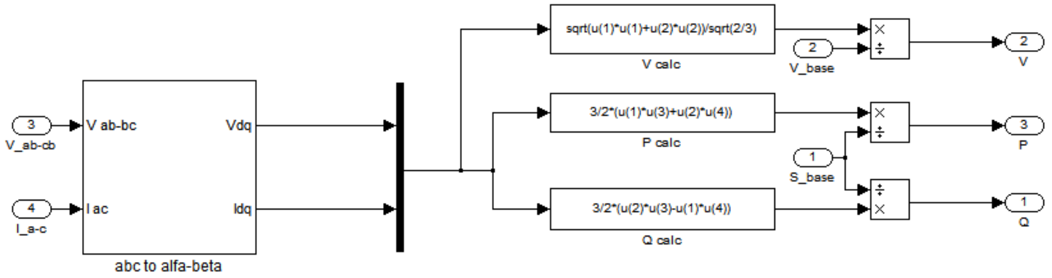


Figure A4. SIMULINK diagram of measurement calculation

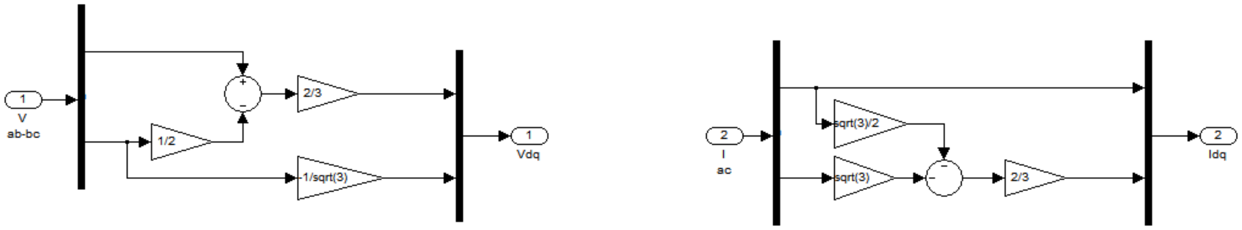


Figure A5. SIMULINK diagram of abc to αβ transformation

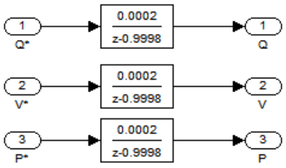


Figure A6. SIMULINK diagram of filters

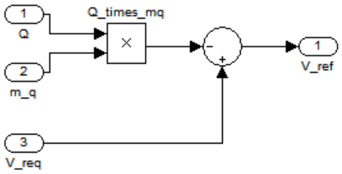


Figure A7. SIMULINK diagram of Q-V droop controller

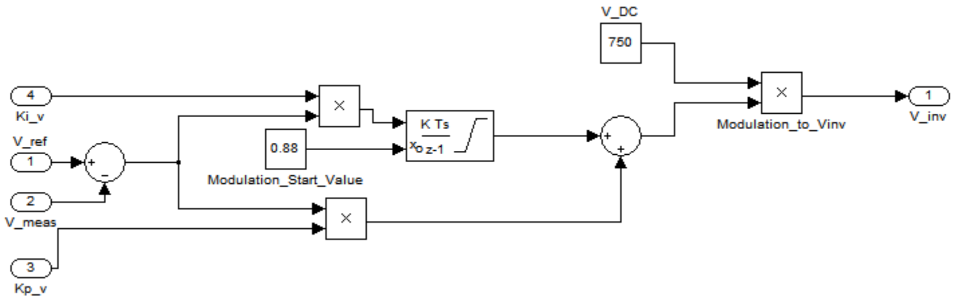


Figure A8. SIMULINK diagram of voltage control

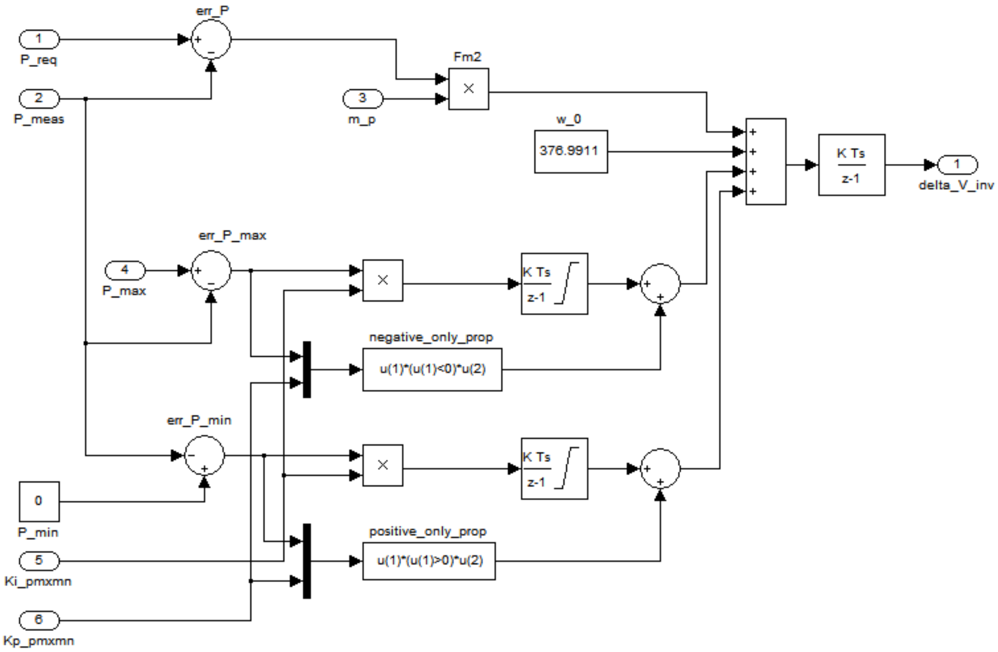


Figure A9. SIMULINK diagram of P-ω droop controller

B. Genset KG

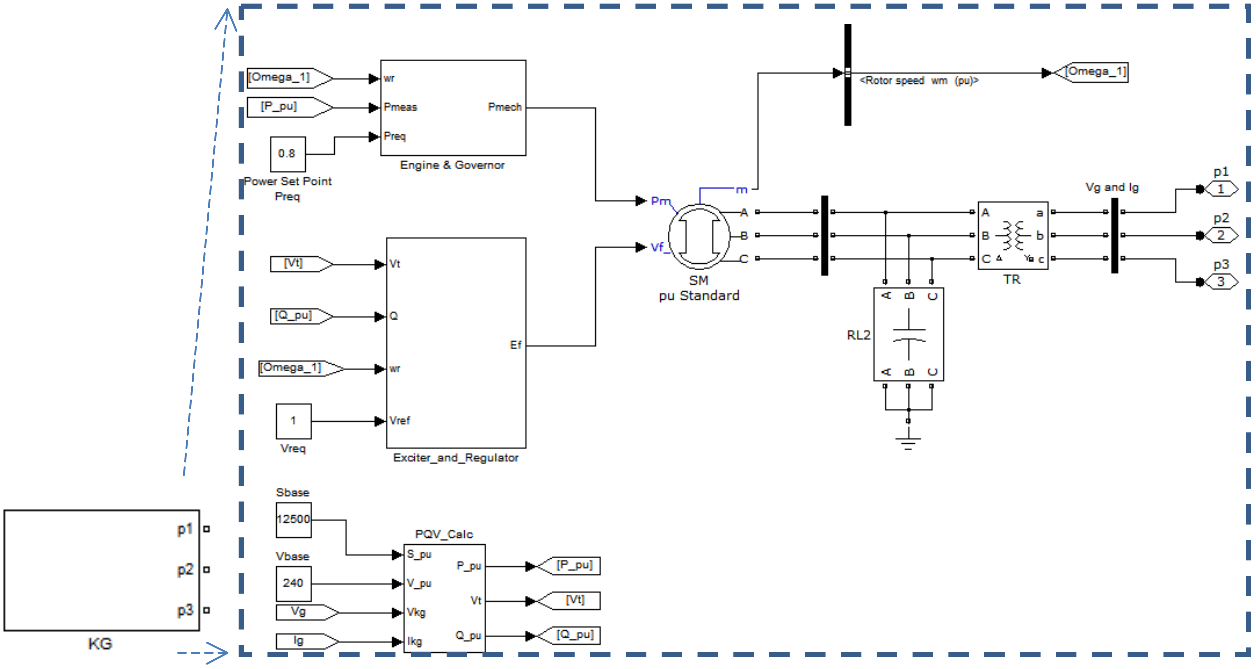


Figure B1. KG components

Note: *See Figure A4-A5 for PQV_Calc block detail*

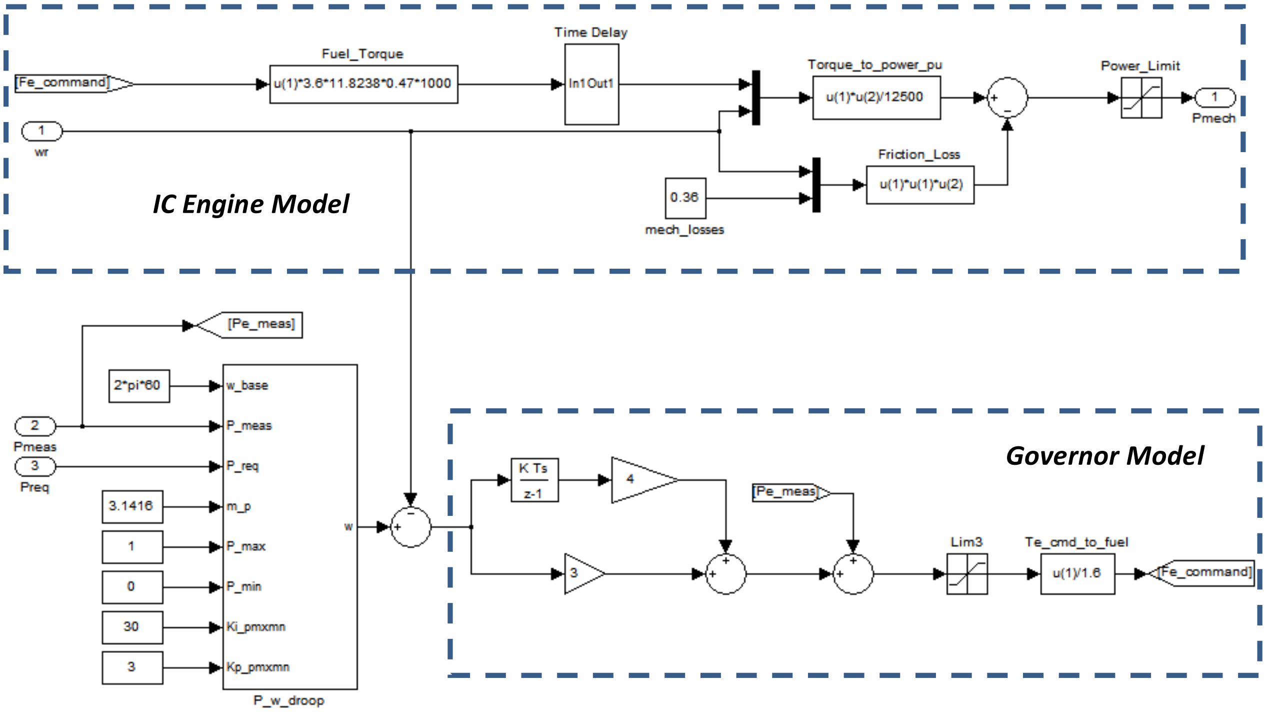


Figure B2. SIMULINK diagram of Engine & Governor

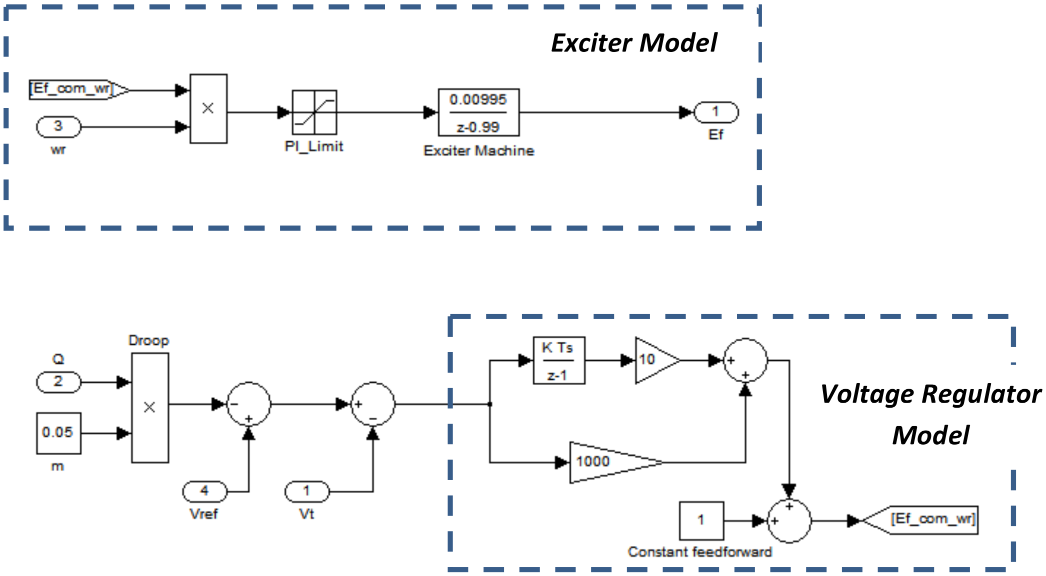


Figure B3. SIMULINK diagram of Exciter & Regulator

Appendix B Meshed Microgrid

Figure 1 shows the UW Meshed Microgrid diagram for Task VIII test.

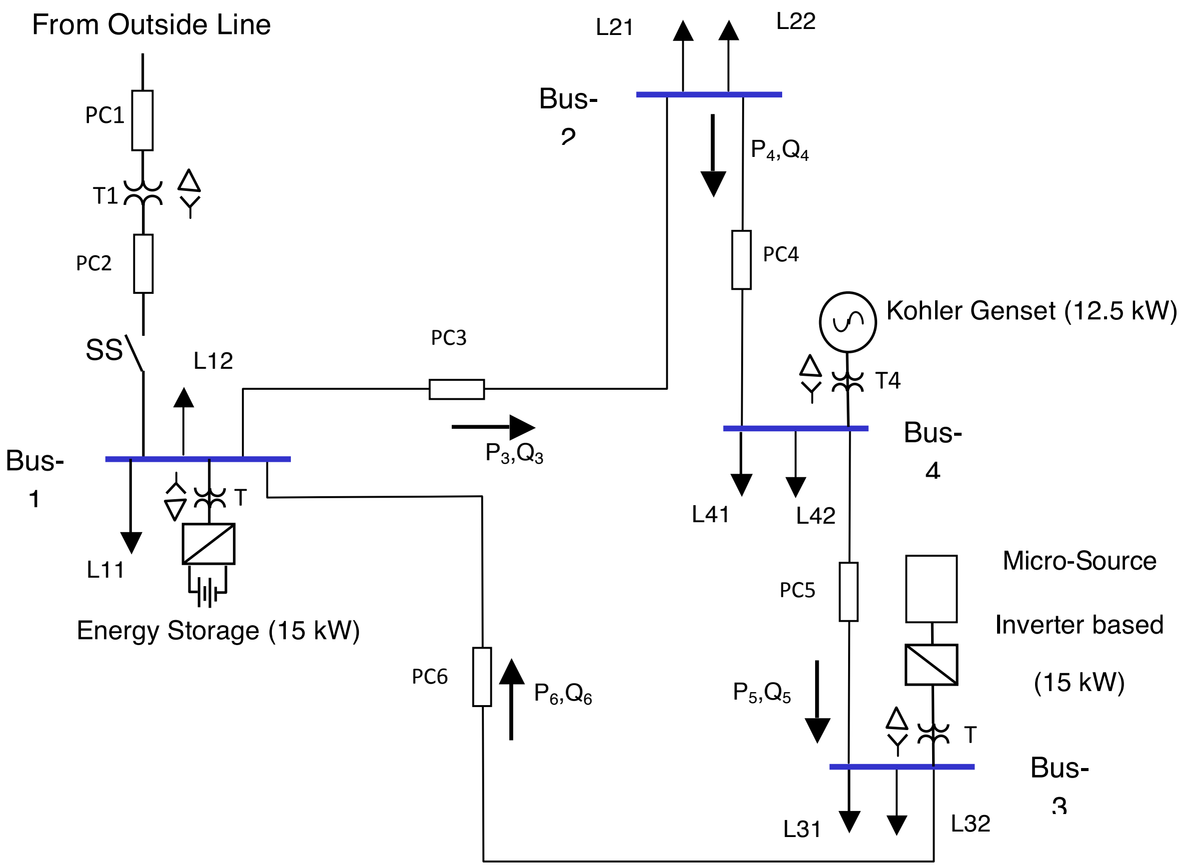


Figure 1. Single Phase Diagram of UW Meshed Microgrid

Impedances of microgrid lines and transformers are listed in Table 1 and 2 respectively.

Table 1. Line impedances of UW meshed microgrid

Line Impedance	**Length [ft]**	**R [Ω]**	**X_L [Ω]**	**X_C [Ω]**
PC1	366	0.093400	0.025500	82.7
PC2	18	0.002810	0.000679	2894.3
PC3	175	0.027352	0.006600	288.6
PC4	108	0.016880	0.004070	336.7
PC5	17	0.002600	0.000640	2020.2
PC6	75	0.013700	0.003300	577.2

Table 2. Transformer impedances of UW meshed microgrid

Tag	**Volt-Amp Rating**	**Impedance**	**HV Side Resistance[Ω]**	**HV Side Reactance[Ω]**	**LV Side Resistance[Ω]**	**LV Side Reactance[Ω]**
T_1	2500 kVA	5.50%	0.04707123	0.1882849	0.000627	0.0025068
T_2	75 kVA	4.40%	0.01689600	0.0675840	0.003173	0.0126908
T_3	45 kVA	4.20%	0.02688000	0.1075200	0.005047	0.0201899
T_4	45 kVA	4.20%	0.00671900	0.0268800	0.005047	0.0201899
T_5	45 kVA	4.20%	0.02688000	0.1075200	0.005047	0.0201899

Table 3. Loads of UW meshed microgrid

Tag	**Power Rating**
L11-L12	4 kW
L21-L22	4 kW
L31-L32	4 kW
L41-L42	4 kW