Research Title

DYNAMIC MODELING OF A WIND-DIESEL-HYDROGEN HYBRID POWER SYSTEM

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Outlines

- Prospects of RE sources in Canada.
- Status of electrical generation and consumption at Ramea (HOMER based analysis).
- Modeling and simulations of WTs, hydrogen systems and diesel gensets.
- Transient analysis of Ramea hybrid power system.
- Conclusions.
- Future works.

Location of Ramea

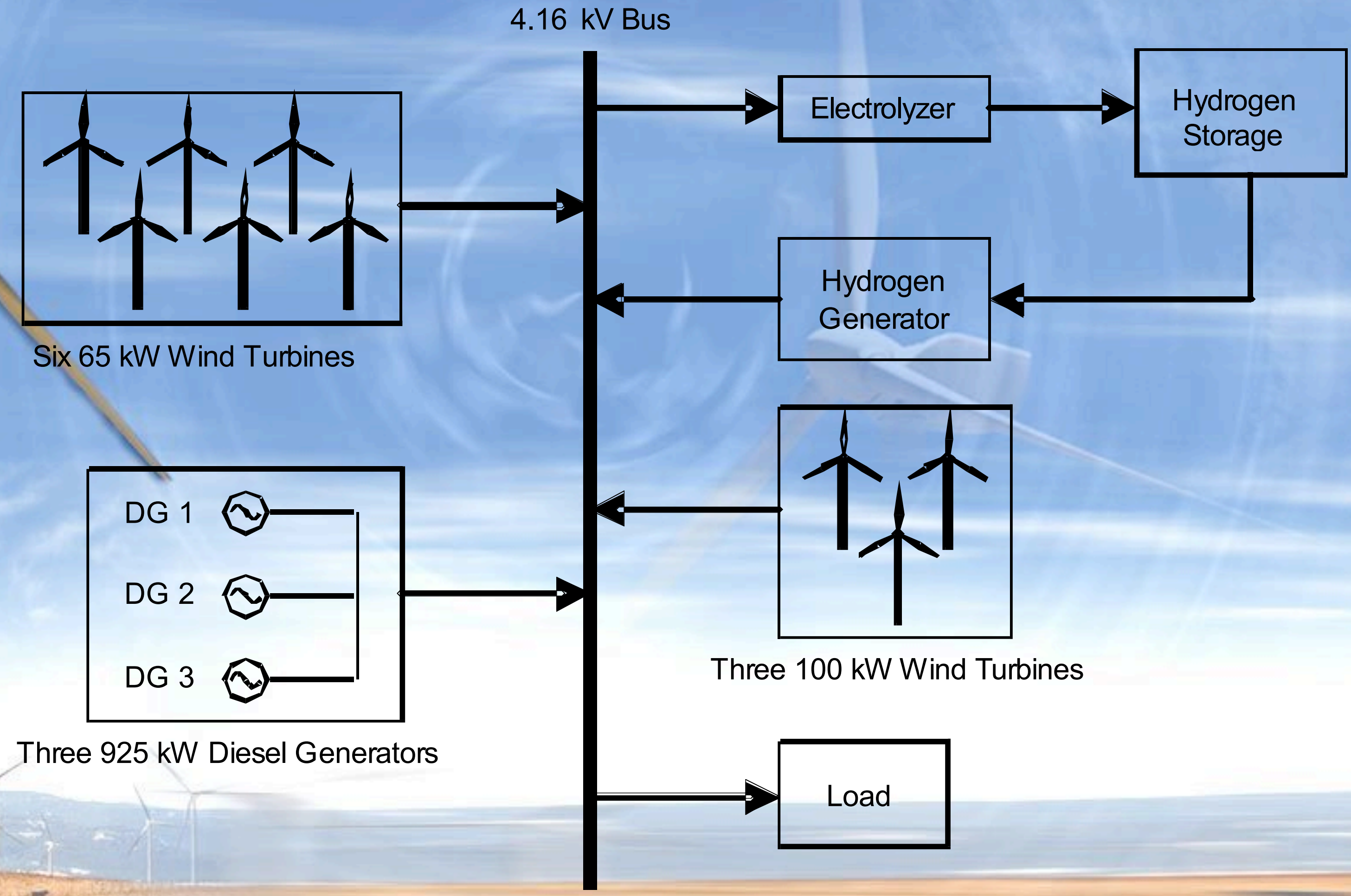
- It is a small island 10 km from the South coast of Newfoundland.
- Population is about 700.
- Traditional fishery community

Wind Quality of Canada

Countries	Annual Mean Wind Speed (m/s)	Wind Power Density (W/m^2)
Germany	5.5-7.0	200-400
Spain	5.5-8.0	200-600
USA	6.5-9.0	300-800
India	5.5-8.0	200-600
China	5.5-9.0	200-800
Canada	6.5-9.0	300-800

- Canada is blessed with adequate wind resources.
- She has the longest coast-line and the second largest land mass.
- They are in a better position to deploy more number of WECS.

Ramea Electrical System (cont.)



Ramea Electrical System

Load Characteristics

- Peak Load – 1,211 kW
- Average Load – 528 kW
- Minimum Load – 202 kW
- Annual Energy – 4,556 MWh

Distribution System

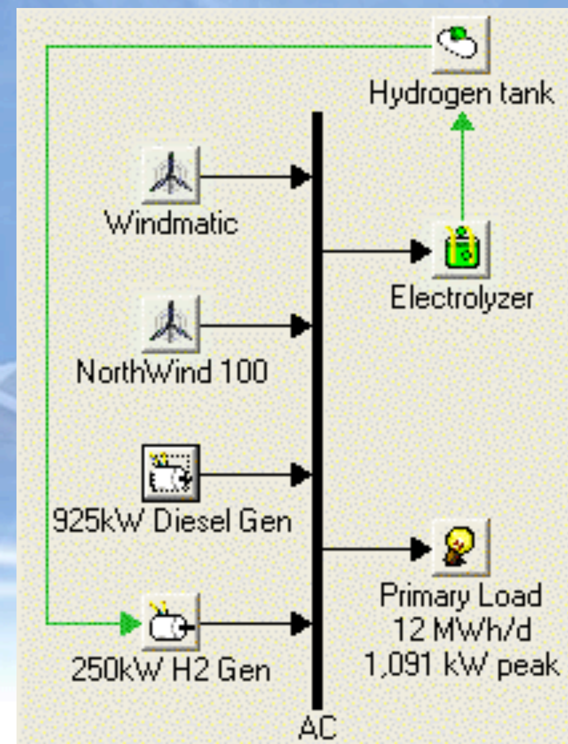
- 4.16 kV, 2 Feeders

Energy Production

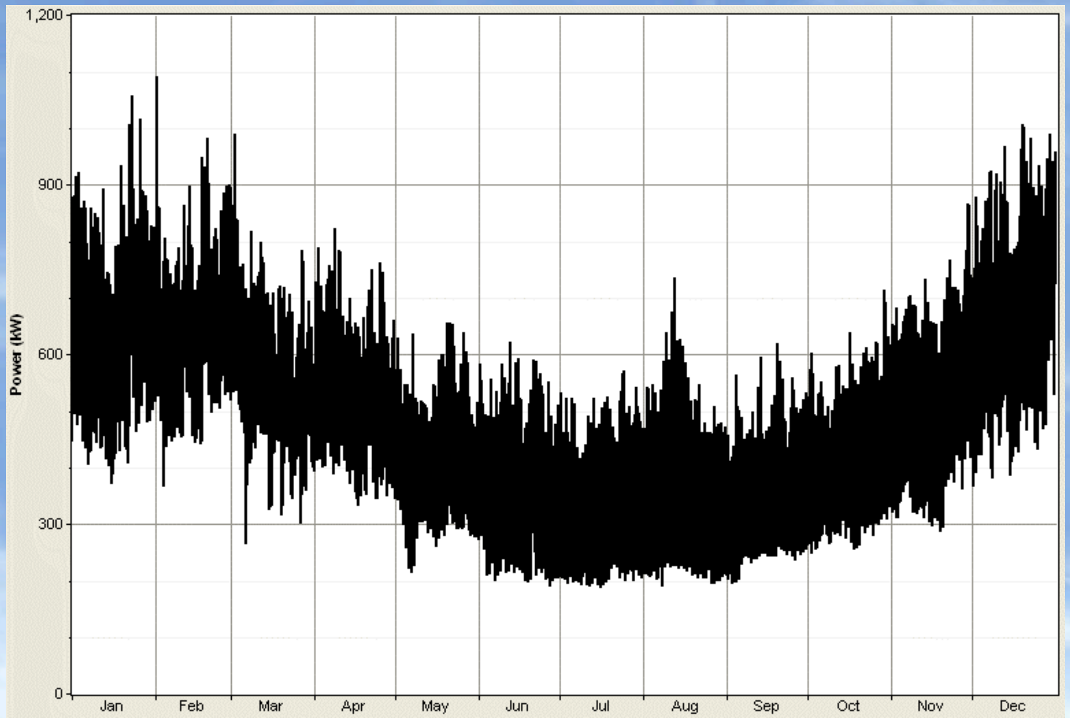
- Nine wind turbines (6X65 kW and 3X100 kW).
- Three diesel generators (3X925 kW).
- Four hydrogen generators (4X62.5 kW)

Ramea Power System simulation in HOMER

Hybrid System Components	Capital Costs ($)	Replace-ment Costs ($)	O&M Costs
WM15S Wind Turbines	90,000	70,000	$1,200 per yr
NW100 Wind Turbines	550,000	480,000	$3,600 per yr
Diesel Generators	100,000	80,000	$5 per hr
Hydrogen Generators	50,000	37,500	$5 per hr
Electrolyzers	150,000	120,000	$600 per yr
Hydrogen Tanks	100,000	70,000	n/a

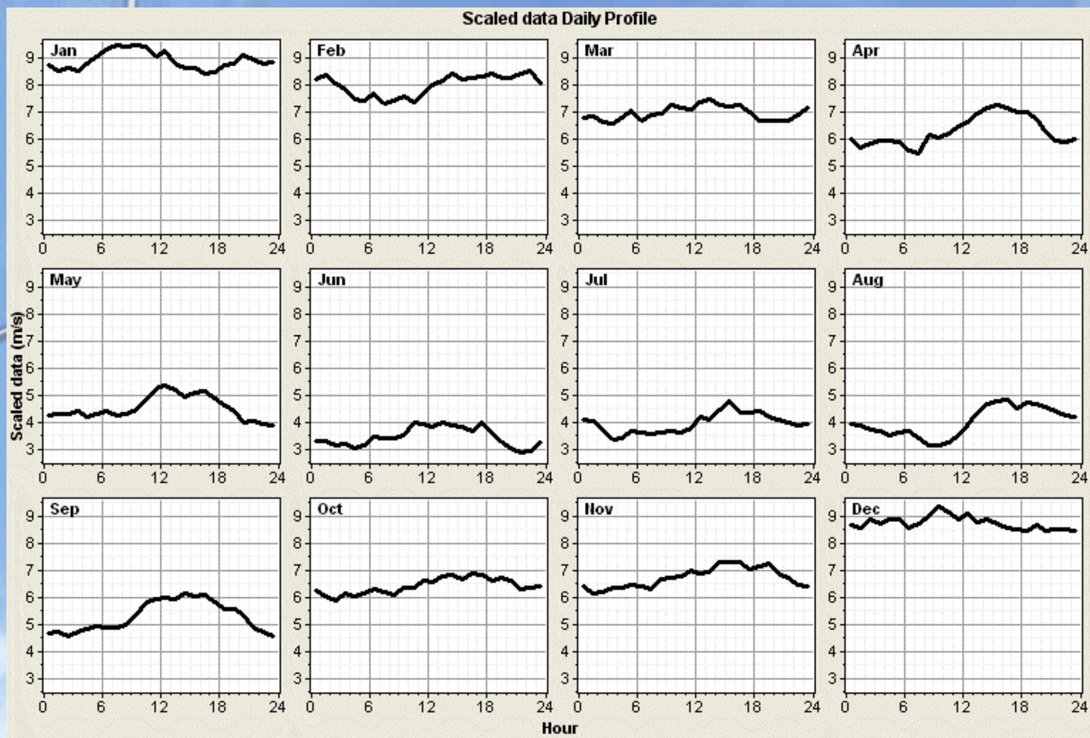


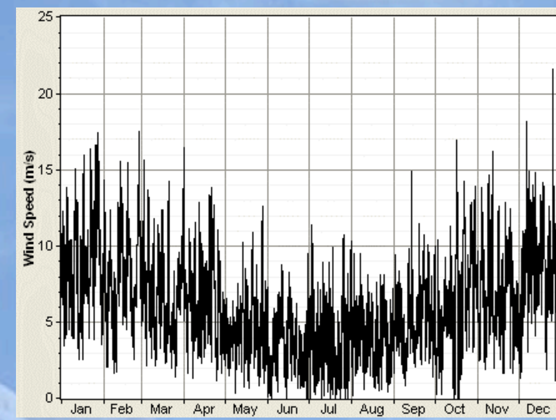
Load Profile at Ramea

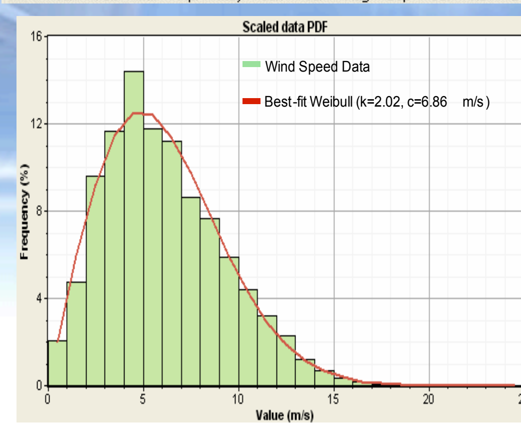


- Day-to-day variability – 8.14%.
- Time step-to-time step variability – 7.86%.
- Load factor – 0.448.

Wind Resource at Ramea

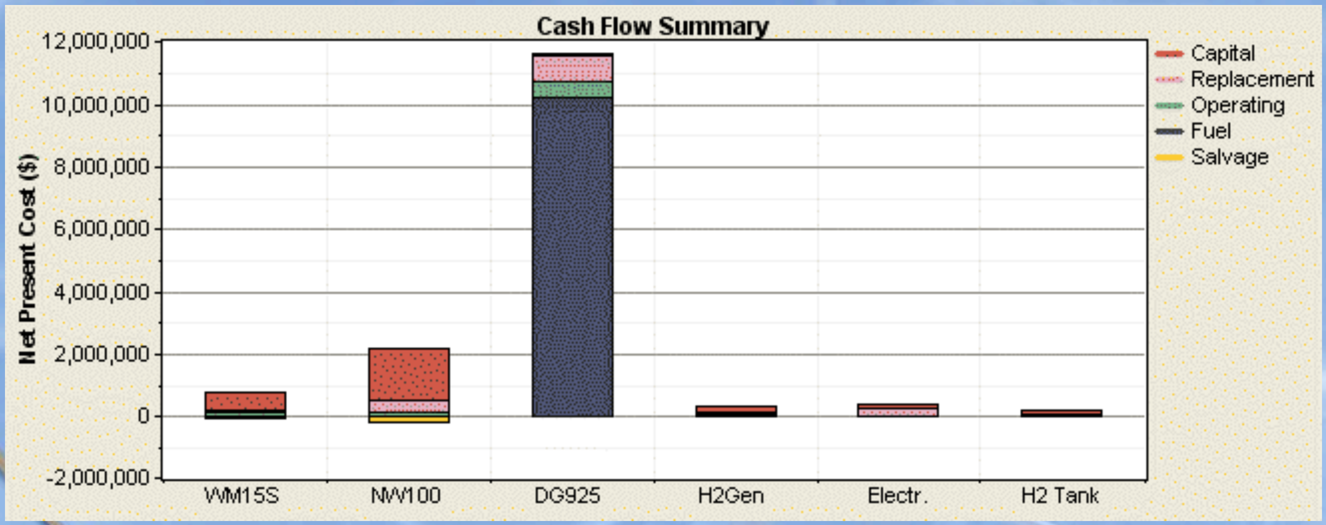






- ➢ Weibull shape factor – 2.02.
- ➢ Correlation factor – 0.947.
- ➢ Diurnal pattern strength – 0.0584.

Cost Summary of Ramea System



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Windmatic	540,000	108,536	83,906	0	-58,038	674,403
NorthWind 100	1,650,000	372,123	125,859	0	-198,989	1,948,993
925kW Diesel Gen	100,000	799,520	510,427	10,232,138	-1,474	11,640,613
250kW H2 Gen	200,000	57,216	40,904	0	-6,771	291,349
Electrolyzer	150,000	221,064	6,992	0	0	378,056
Hydrogen Tank	100,000	53,674	0	0	-6,449	147,225
System	2,740,000	1,612,133	768,087	10,232,138	-271,721	15,080,637

Electrical Performance of System Components (cont.)

Quantity	Value	Units
Total rated capacity	396	kW
Mean output	117	kW
Capacity factor	29.5	%
Total production	1,022,662	kWh/yr

Quantity	Value	Units
Minimum output	0	kW
Maximum output	396	kW
Wind penetration	23.9	%
Hours of operation	6,832	hr/yr
Levelized cost	0.0566	$/kWh

Table: Electrical Characteristics of WM15S Wind Turbines

Quantity	Value	Units
Total rated capacity	309	kW
Mean output	92	kW
Capacity factor	29.8	%
Total production	805,500	kWh/yr

Quantity	Value	Units
Minimum output	0	kW
Maximum output	308	kW
Wind penetration	18.8	%
Hours of operation	7,003	hr/yr
Levelized cost	0.208	$/kWh

Table: Electrical Characteristics of NW100 Wind Turbines

Electrical Performance of System Components (cont.)

Quantity	Value	Units
Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	1.14	yr
Capacity factor	38.8	%
Fixed generation cost	31.0	$/hr
Marginal generation cost	0.229	$/kWh

Quantity	Value	Units
Electrical production	3,141,887	kWh/yr
Mean electrical output	359	kW
Min. electrical output	278	kW
Max. electrical output	925	kW

Quantity	Value	Units
Fuel consumption	878,026	L/yr
Specific fuel consumption	0.279	L/kWh
Fuel energy input	8,639,772	kWh/yr
Mean electrical efficiency	36.4	%

Table: Electrical Characteristics of 925 kW Diesel Generators

Quantity	Value	Units
Hours of operation	702	hr/yr
Number of starts	702	starts/yr
Operational life	14.2	yr
Capacity factor	2.41	%
Fixed generation cost	20.0	$/hr
Marginal generation cost	0.00	$/kWh

Quantity	Value	Units
Electrical production	52,752	kWh/yr
Mean electrical output	75.1	kW
Min. electrical output	75.0	kW
Max. electrical output	93.6	kW

Quantity	Value	Units
Hydrogen consumption	9,162	kg/yr
Specific fuel consumption	0.174	kg/kWh
Fuel energy input	305,384	kWh/yr
Mean electrical efficiency	17.3	%

Table: Electrical Characteristics of 250 kW Hydrogen Generators

Electrical Performance of System Components (cont.)

Production	kWh/yr	%
Wind turbines	1,828,162	36
925kW Diesel Gen	3,141,887	63
250kW H2 Gen	52,752	1
Total	5,022,801	100

Consumption	kWh/yr	%
AC primary load	4,280,795	90
Electrolyzer load	482,333	10
Total	4,763,128	100

Quantity	kWh/yr	%
Excess electricity	259,549	5.17
Unmet electric load	302	0.01
Capacity shortage	704	0.02

Quantity	Value
Renewable fraction	0.374

Table: Electrical Characteristics of the Whole System

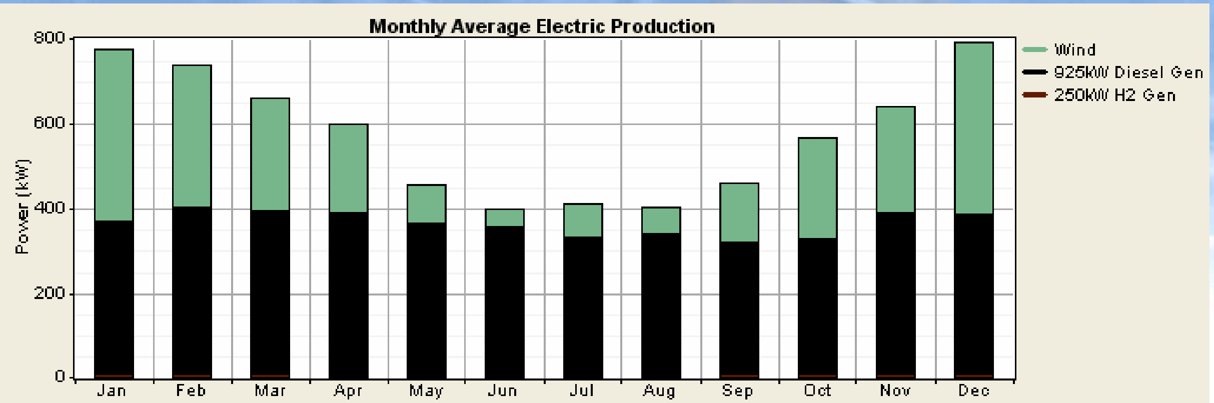


Figure: Monthly Energy Production by Wind, Diesel and Hydrogen

Electrical Performance of System Components

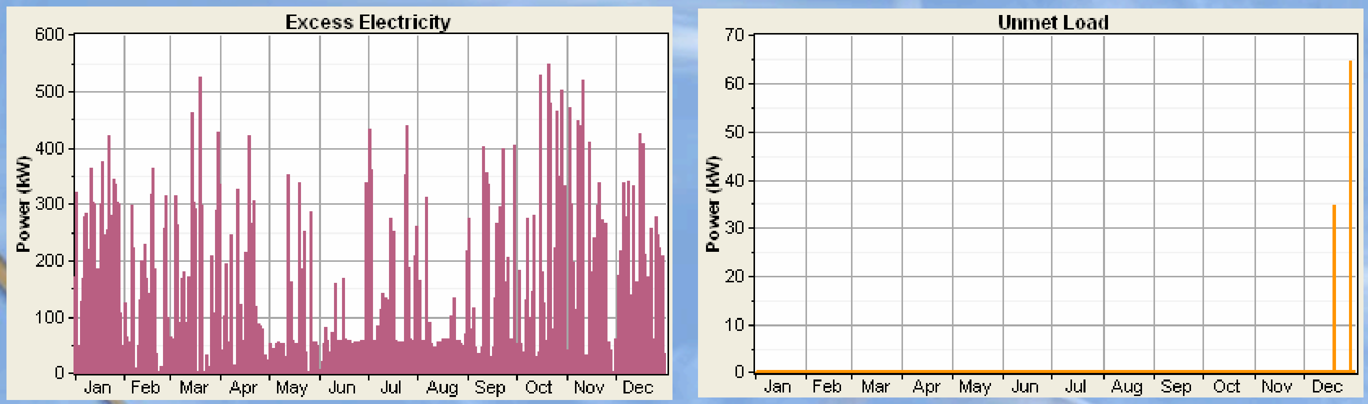
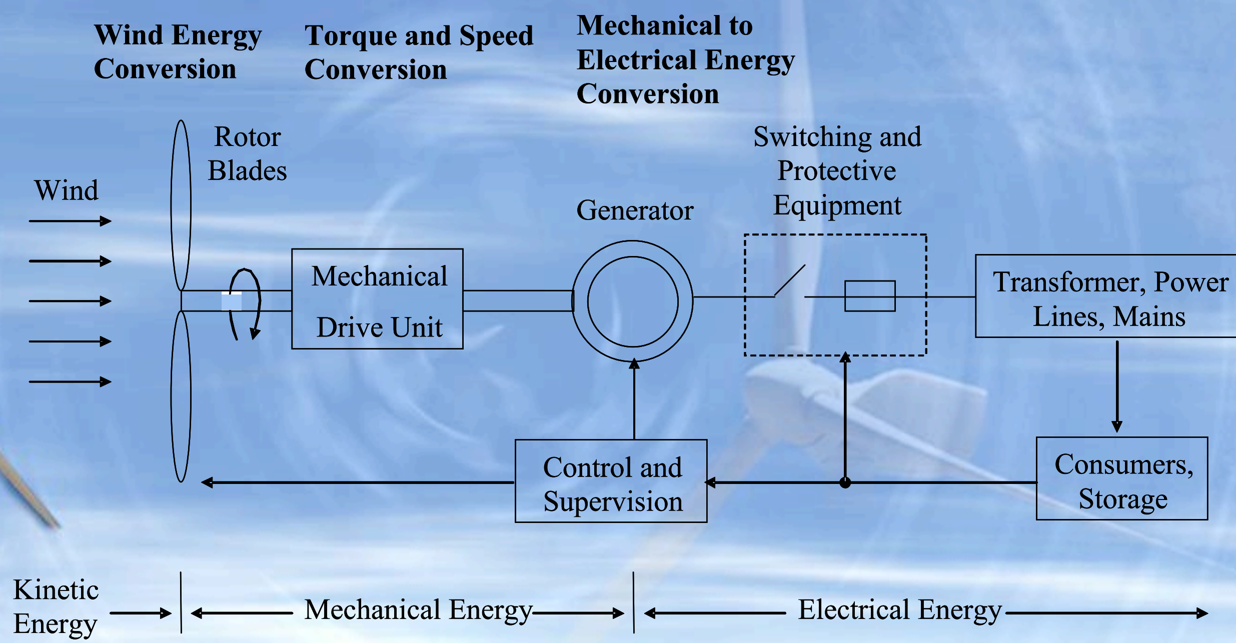


Figure: Excess Electricity and Unmet Load of Ramea Hybrid Power System

- Excess energy – 259,549 kWh per year.
- Unmet load – 302 kWh per year.
- Capacity shortage – 704 kWh

WECS Components



- Rotor Blades
- Shaft and Bearings
- Brakes
- Electrical Generator
- Transformer
- Capacitor Bank

Power Extraction from the Wind

$$P_t = \frac{1}{2}\rho A C_p(\lambda, \beta) v_w^3$$

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_1} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_1}} + c_6\lambda$$

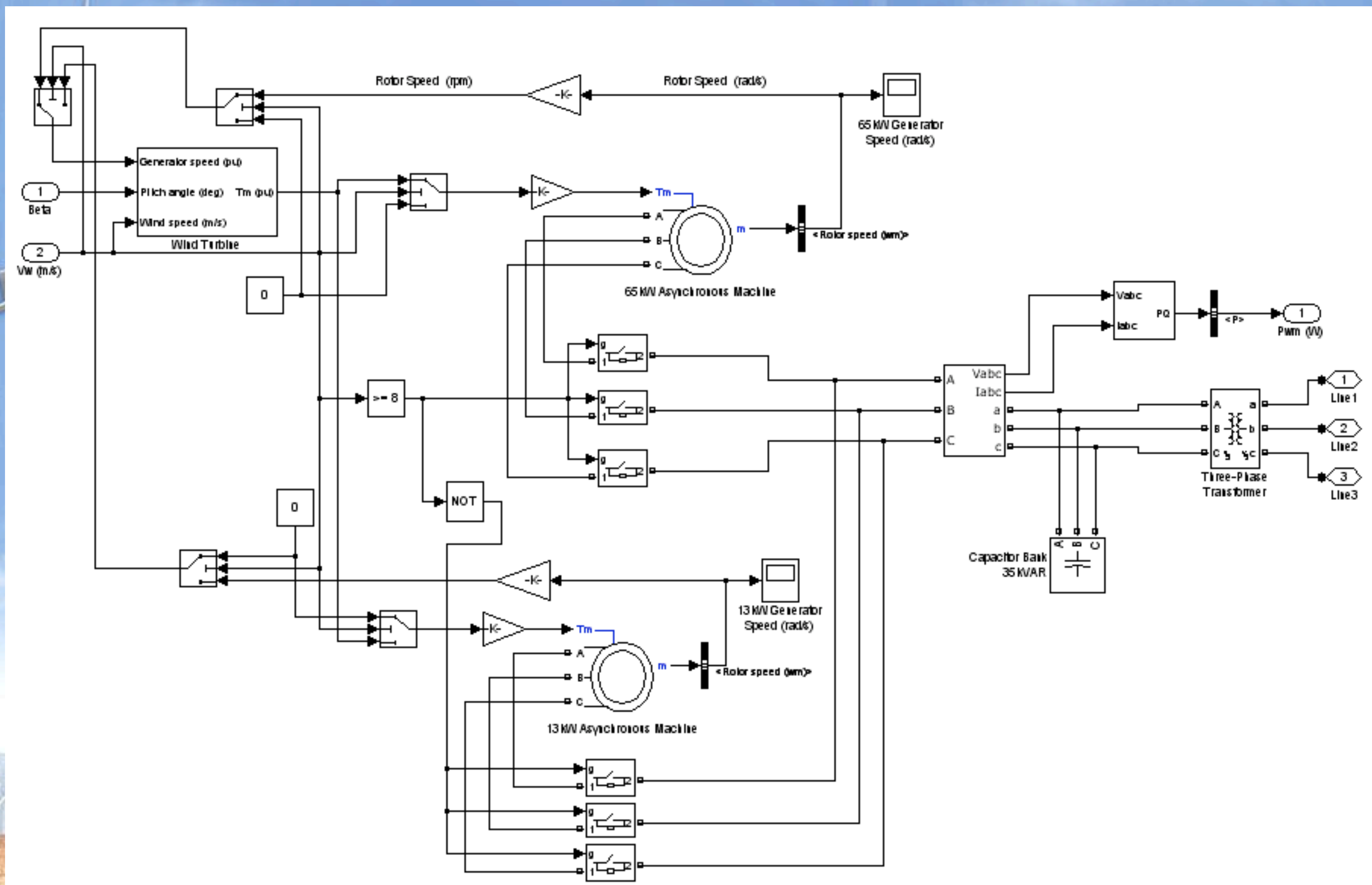
$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

$$\lambda = \frac{\omega R}{v_w}$$

$$T_t = \frac{1}{2}\rho A R \frac{C_p(\lambda, \beta)}{\lambda} v_w^2 = \frac{1}{2}\rho A R C_q(\lambda, \beta) v_w^2$$

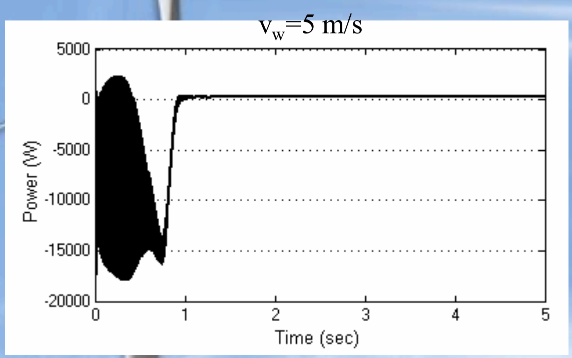
$$C_q(\lambda, \beta) = \frac{C_p(\lambda, \beta)}{\lambda}$$

Modeling and Simulation of WM15S WT (cont.)

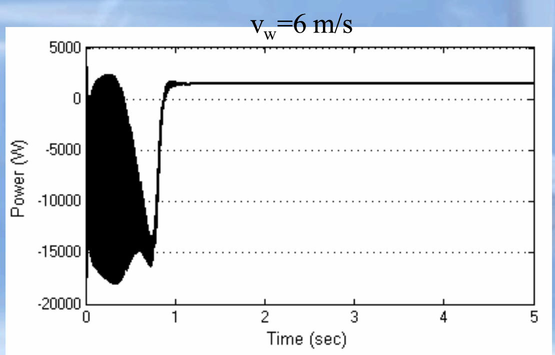


Modeling and Simulation of WM15S WT (cont.)

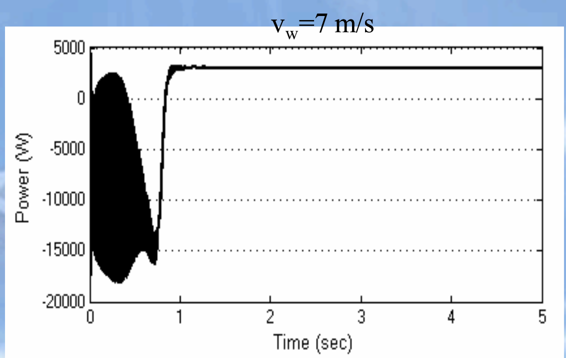
13 kW Generator in Operation



0.25 kW Output



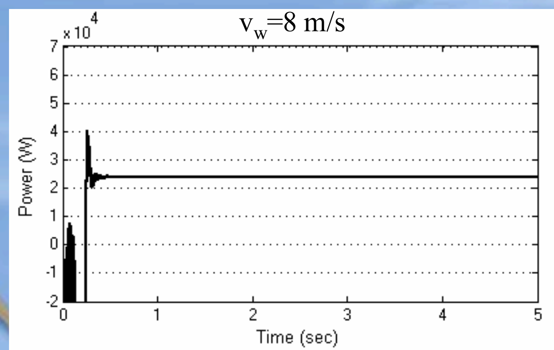
1.48 kW Output



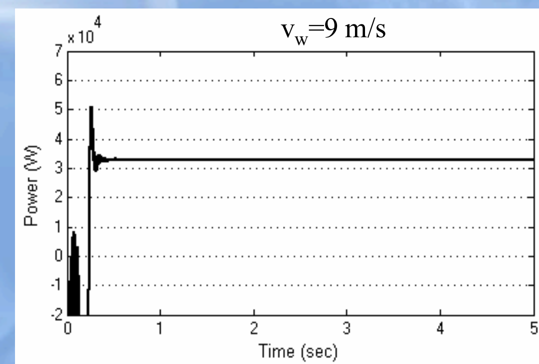
3.05 kW Output

Modeling and Simulation of WM15S WT (cont.)

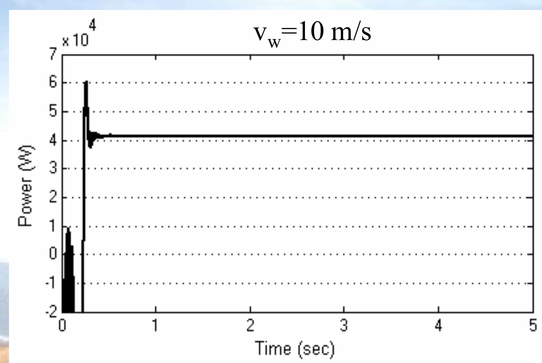
65 kW Generator in Operation



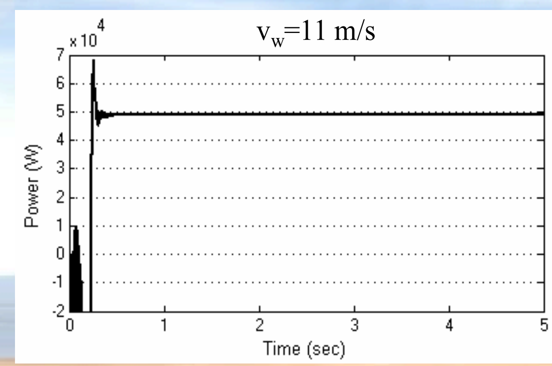
24 kW Output



32.9 kW Output



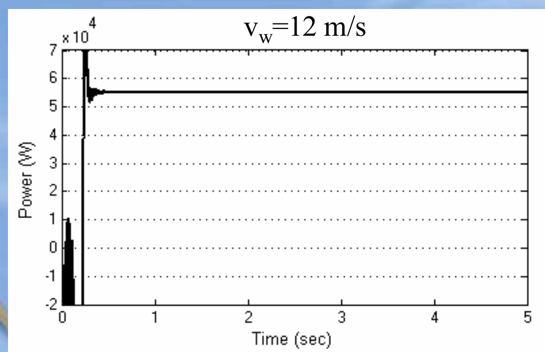
41.4 kW Output



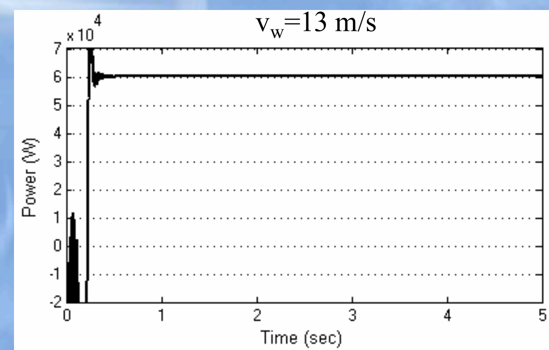
48.9 kW Output

Modeling and Simulation of WM15S WT (cont.)

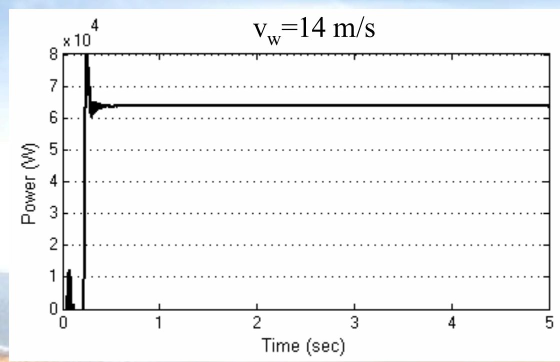
65 kW Generator in Operation



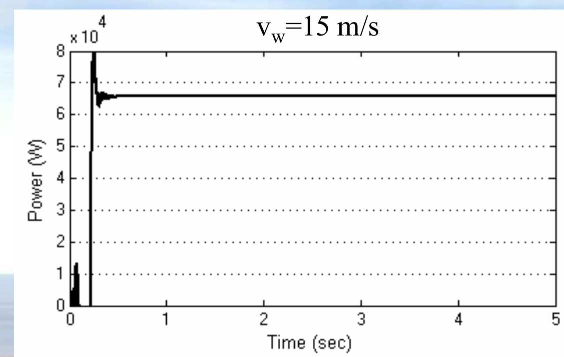
55.3 kW Output



60.2 kW Output



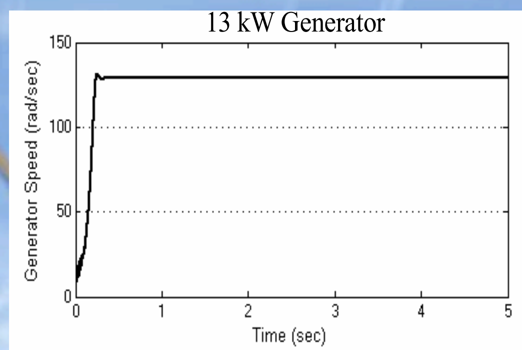
63.7 kW Output



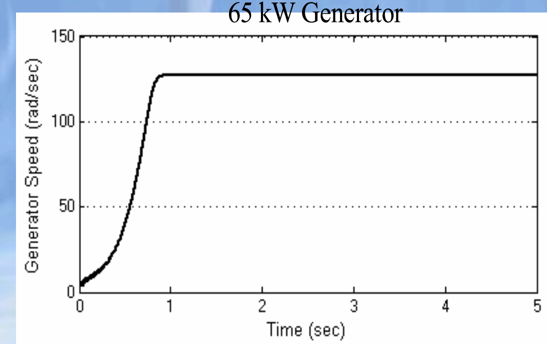
65.8 kW Output

Modeling and Simulation of WM15S WT

Generator Rotational Speeds

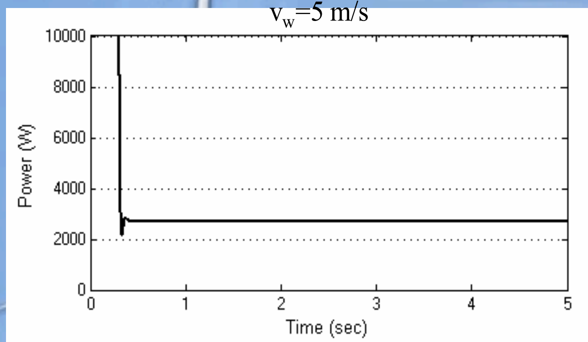


ω_1=128 rad/s

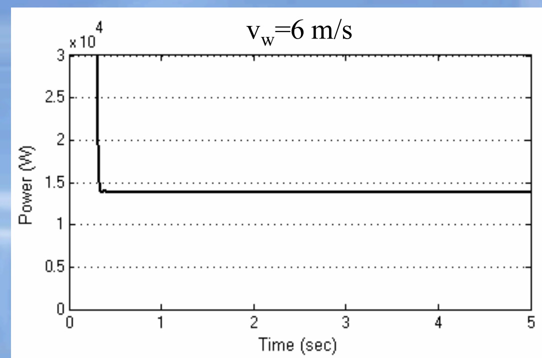


ω_2=125 rad/s

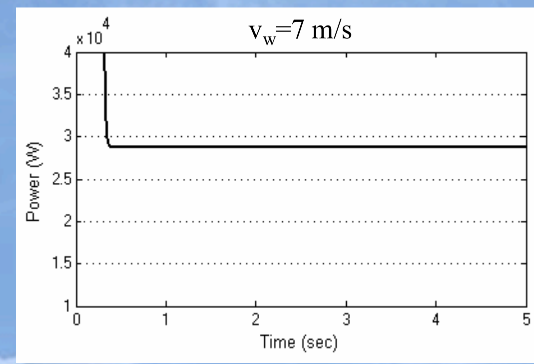
Modeling and Simulation of NW100 WT (cont.)



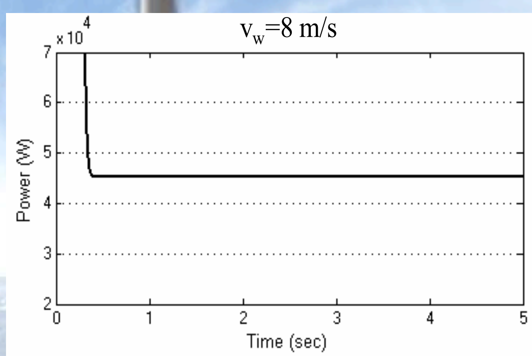
2.8 kW Output



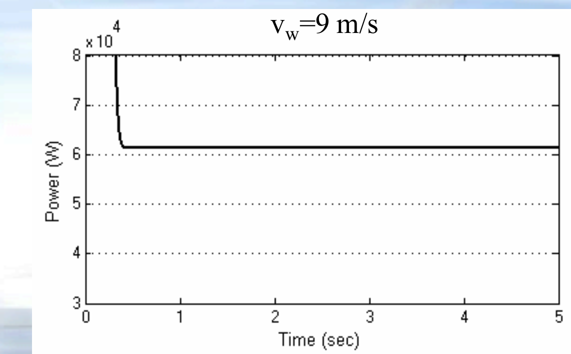
14.1 kW Output



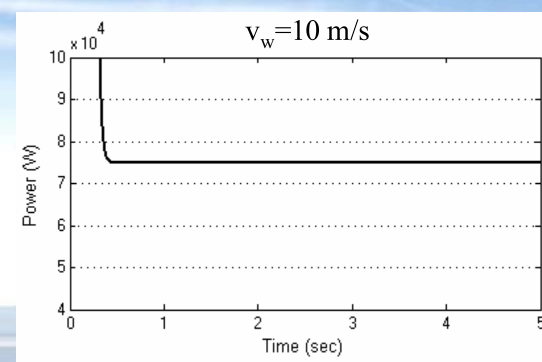
29.2 kW Output



46 kW Output

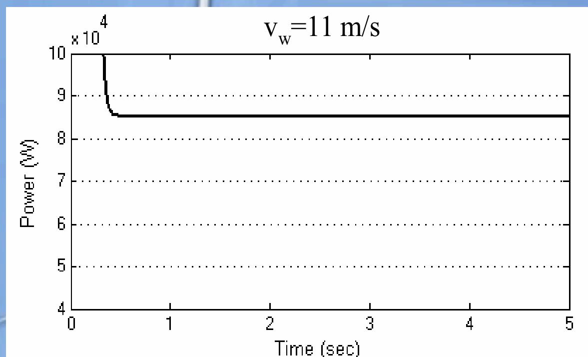


62.3 kW Output

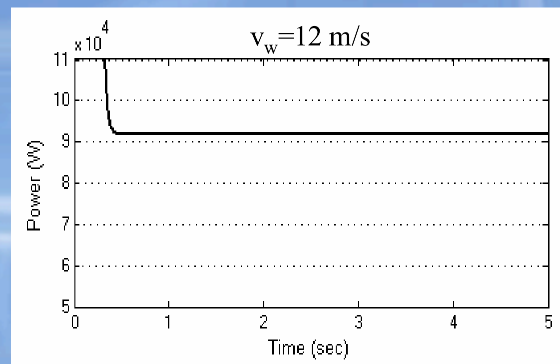


76.1 kW Output

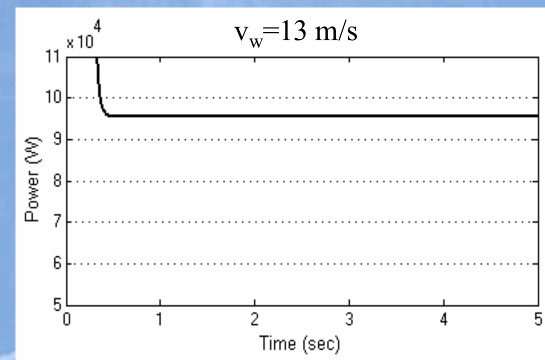
Modeling and Simulation of NW100 WT (cont.)



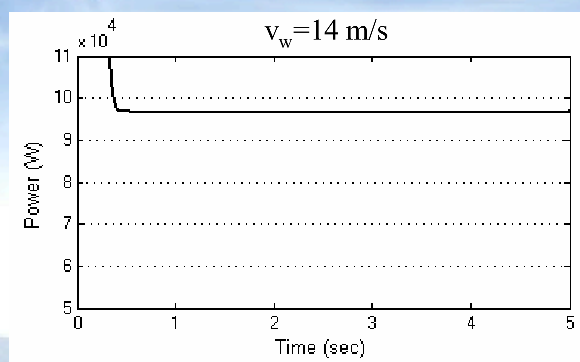
86.6 kW Output



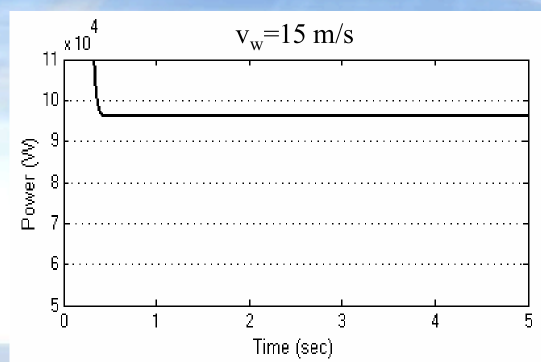
93.4 kW Output



97.1 kW Output



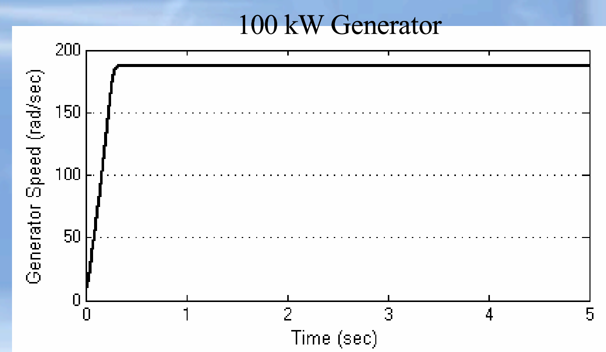
98.2 kW Output



98.2 kW Output

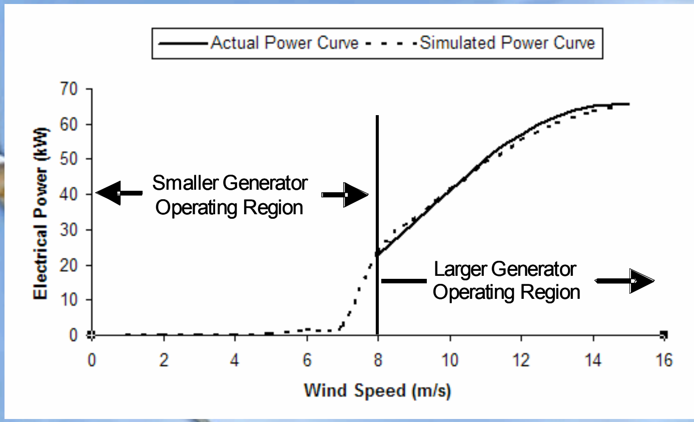
Modeling and Simulation of NW100 WT

100 kW Generator Rotational Speed

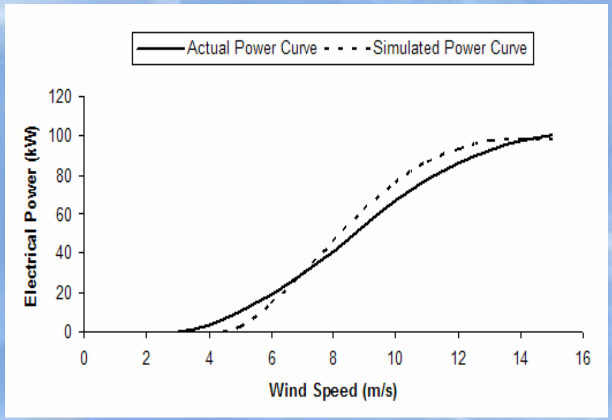


ω=183 rad/s

Comparison of Actual and Simulated Power Curves



Power Curves of WM15S WT



Power Curves of NW100 WT

Modeling of Alkaline type Electrolyzer (cont.)

- 30% KOH is added to increase the conductivity level of the electrolyte.
- Anode made of Ni, Co & Fe and Cathode made of Ni & C-Pt prevent corrosion and ensure good conductivity.
- For the same reason diaphragm is made up of NiO.

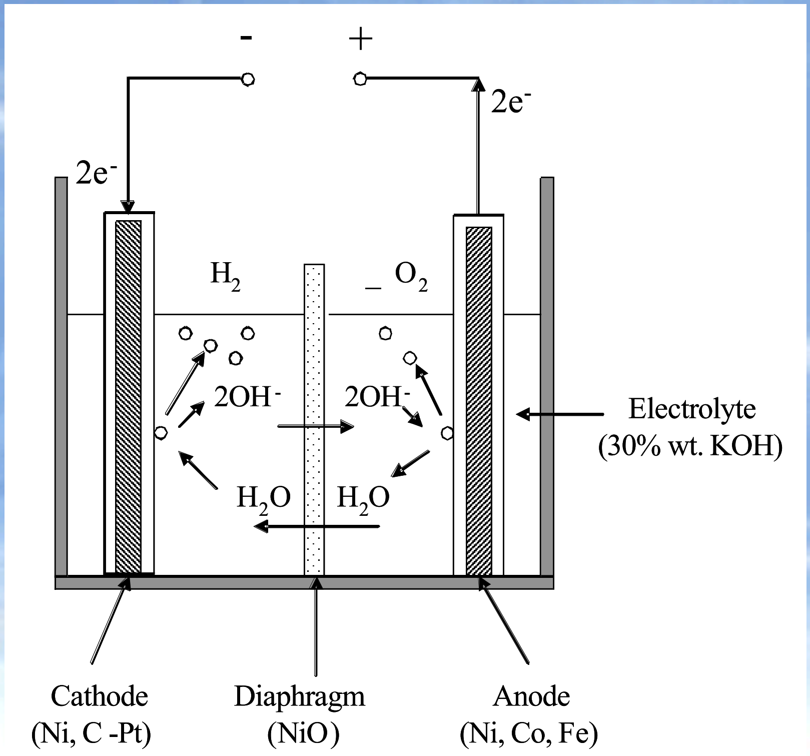


Figure: Internal structure of an alkaline electrolyzer.

Modeling of Alkaline type Electrolyzer (cont.)

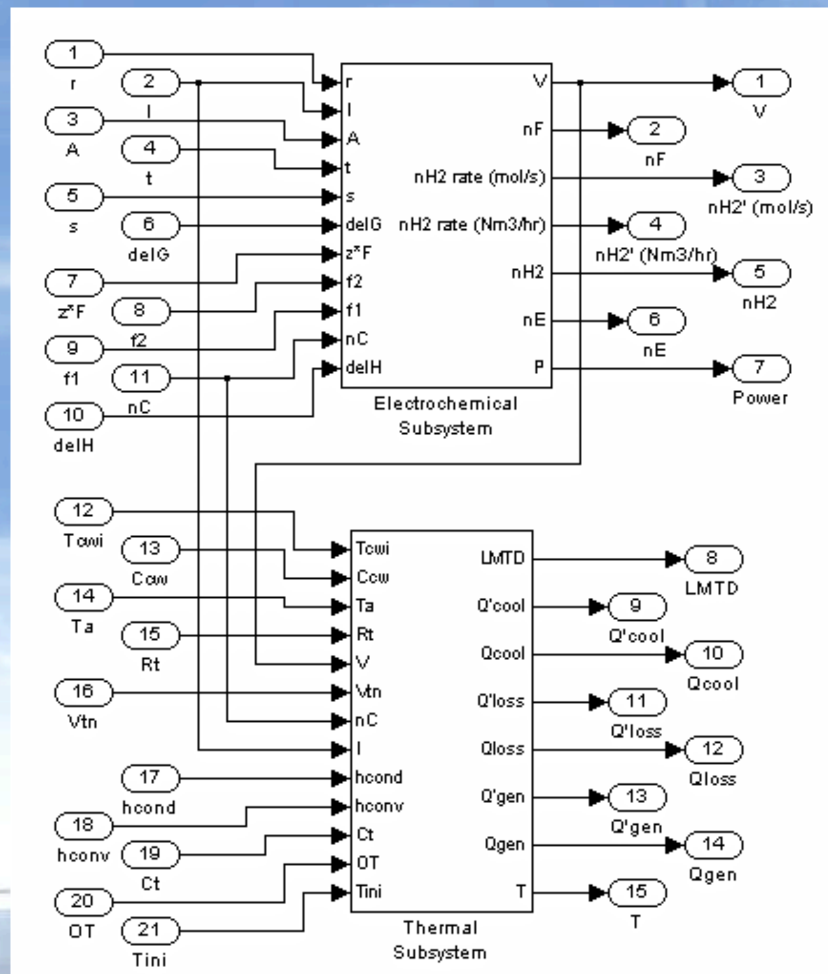


Figure: Simulink Model of 200 kW Electrolyzer.

Modeling of Alkaline type Electrolyzer (cont.)

- H_2 flow rate
- Cell voltage
- Faraday efficiency
- Energy efficiency

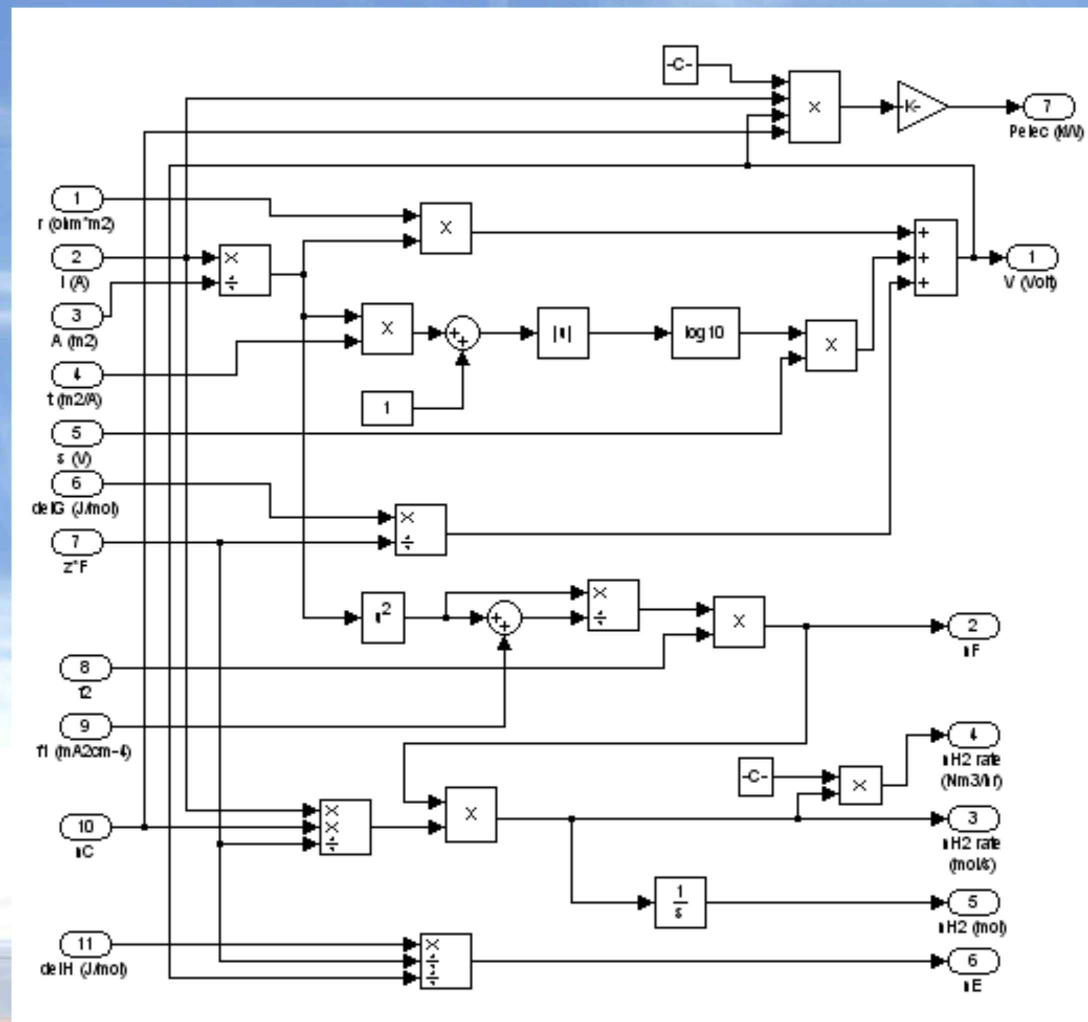


Figure: Electrochemical Model.

Modeling of Alkaline type Electrolyzer

- ➢ Heat generation
- ➢ Heat loss
- ➢ Cooling demand
- ➢ Temperature

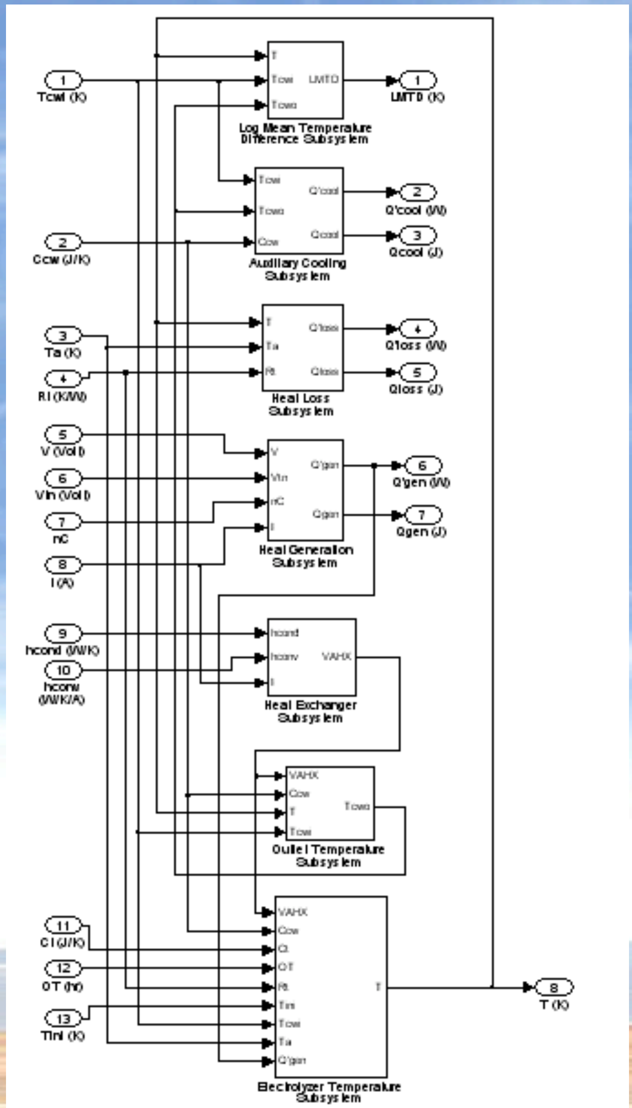


Figure: Thermal Model.

Simulations of Alkaline type Electrolyzer (cont.)

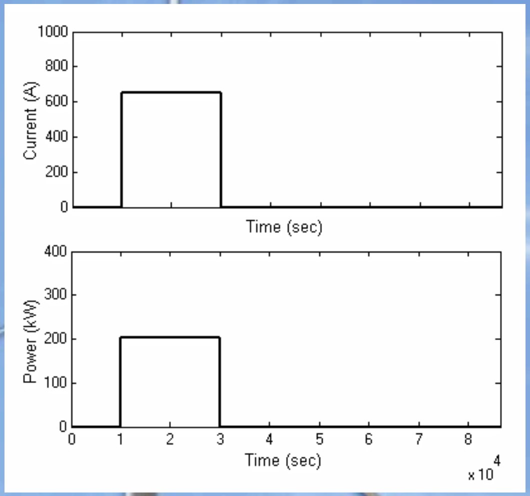


Figure: Current & Power.

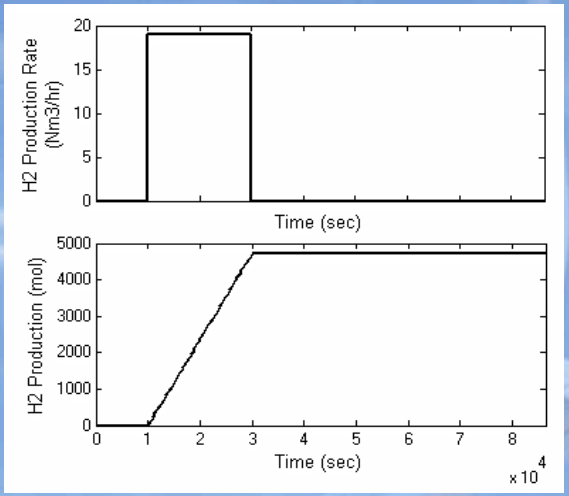


Figure: H_2 Generation.

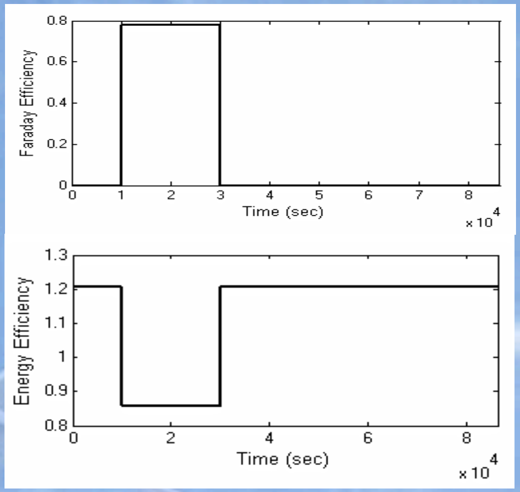


Figure: Faraday & Energy Efficiencies.

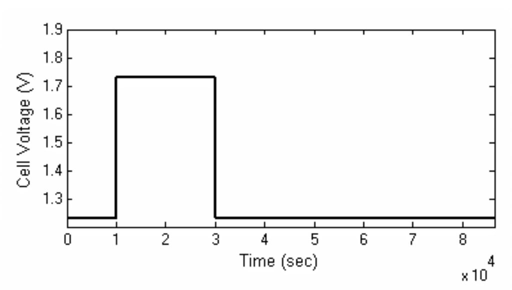


Figure: Cell Voltage.

Simulations of Alkaline type Electrolyzer

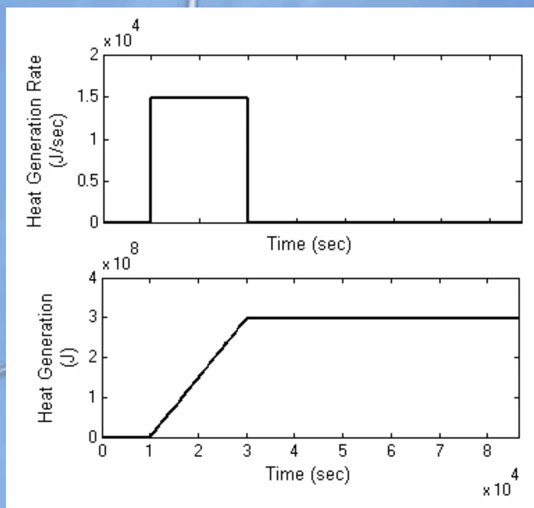


Figure: Heat Generation.

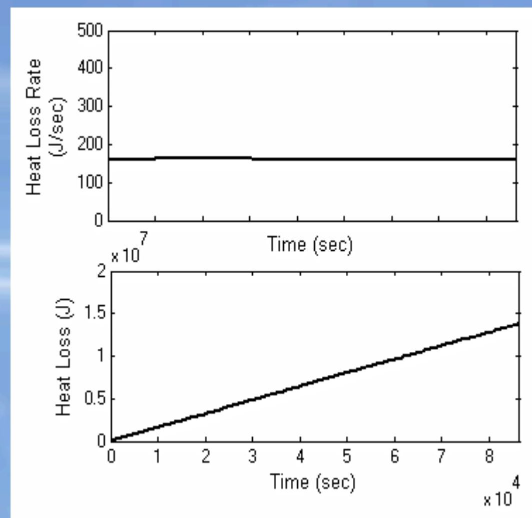


Figure: Heat Loss.

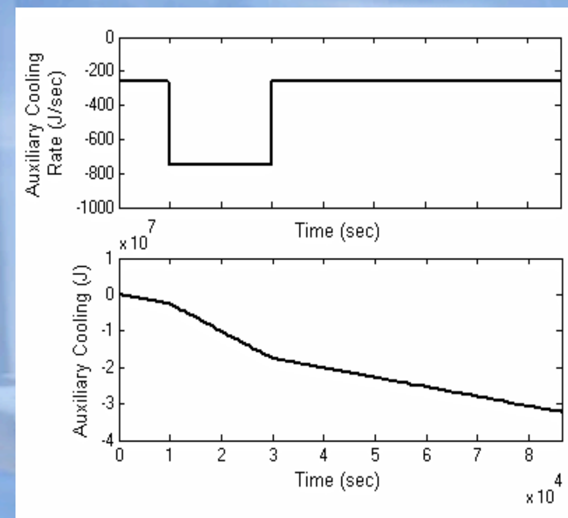


Figure: Auxiliary Cooling.

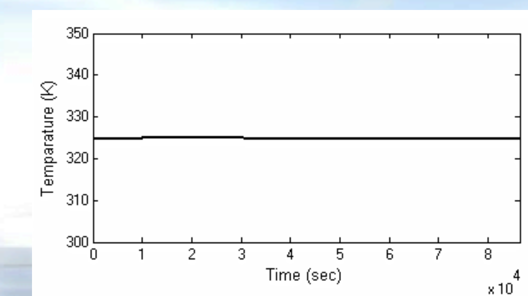


Figure: Temperature.

Modeling of H_2 Tanks

Figure: Three Hydrogen Tanks of 1000 Nm^3 combined Capacity .

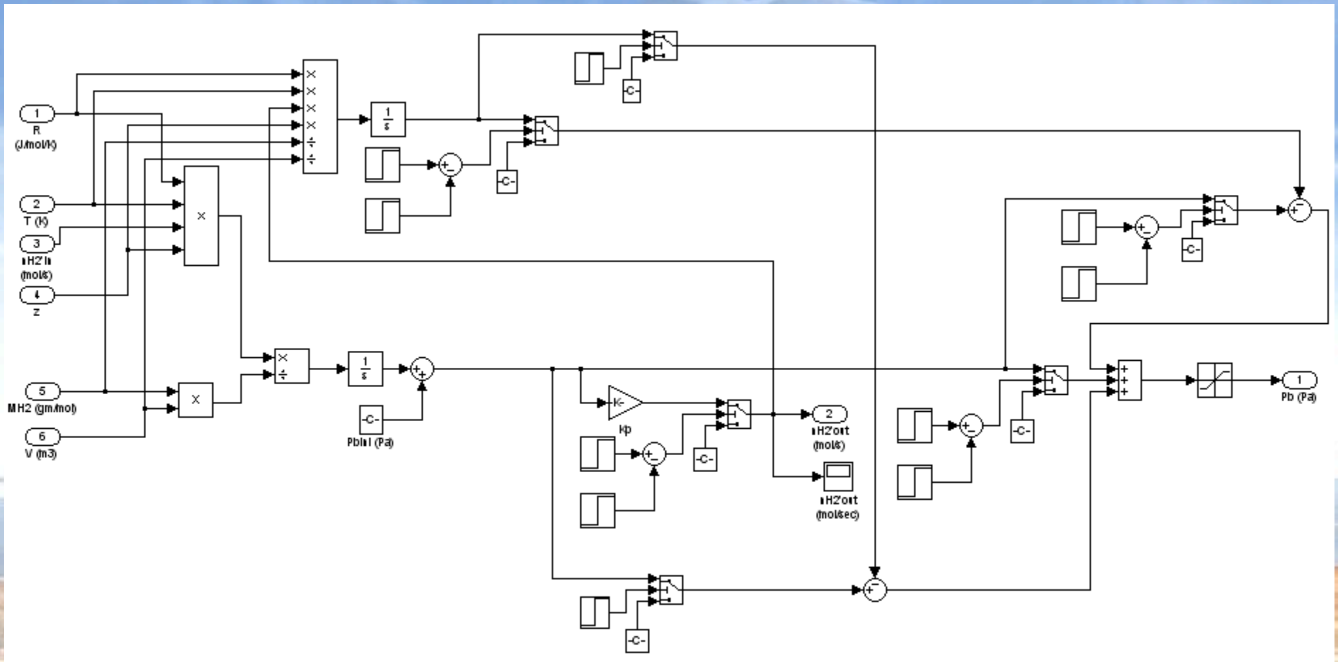


Figure: Simulink Model of H_2 Tank.

Simulations of H_2 Tanks

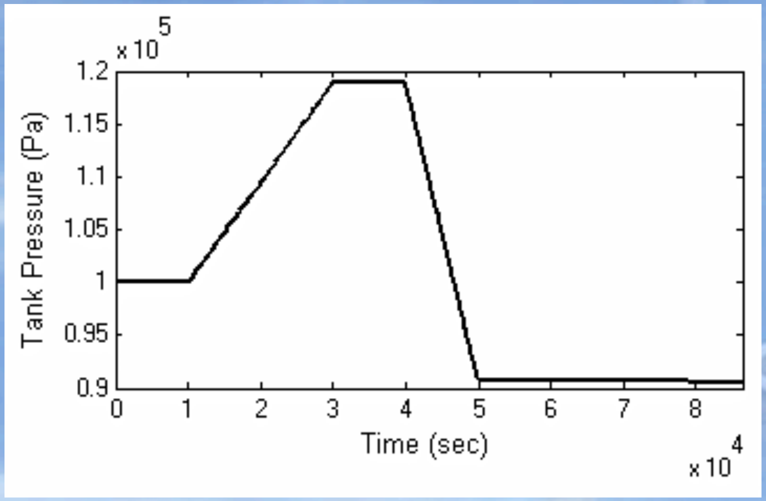


Figure: Pressure Change in the H_2 Tank.

Modeling of H_2 Engines

- Throttle body dynamics
- Manifold dynamics
- Rotational dynamics

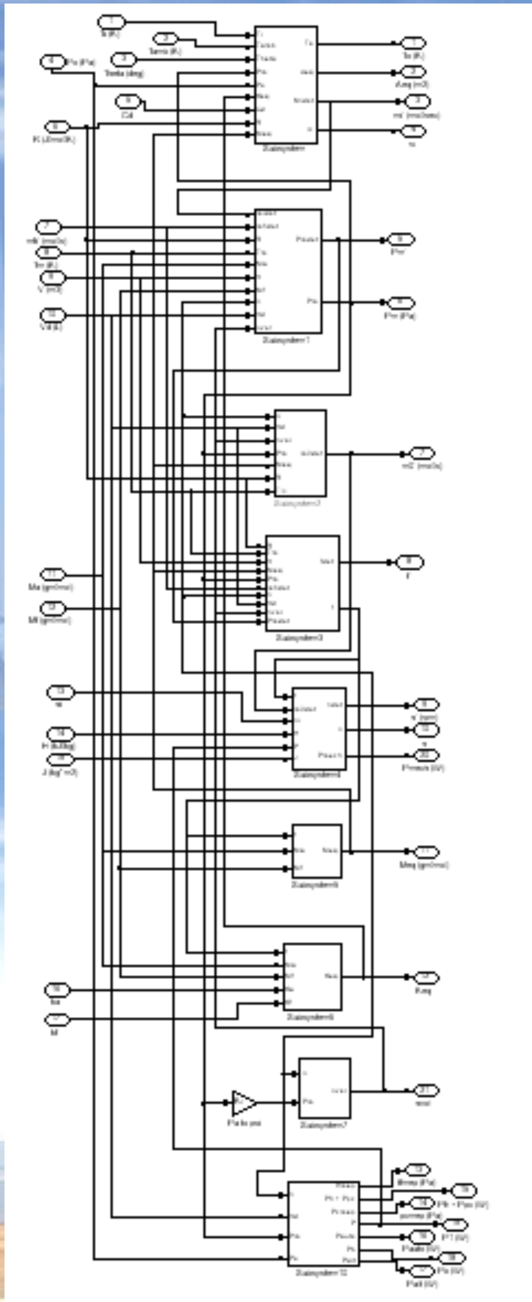


Figure: Simulink Model of H_2 Engines.

Simulations of H_2 Engines

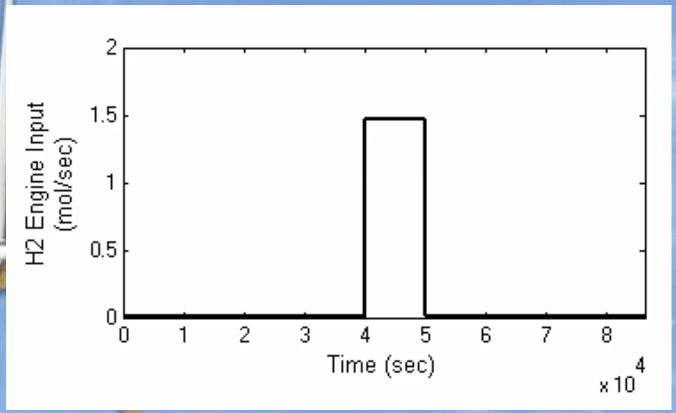


Figure: H_2 Flow Input to Engines.

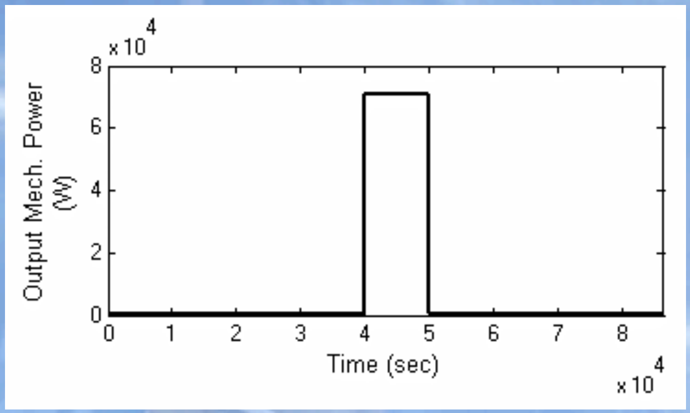


Figure: Mech. Power from Engines.

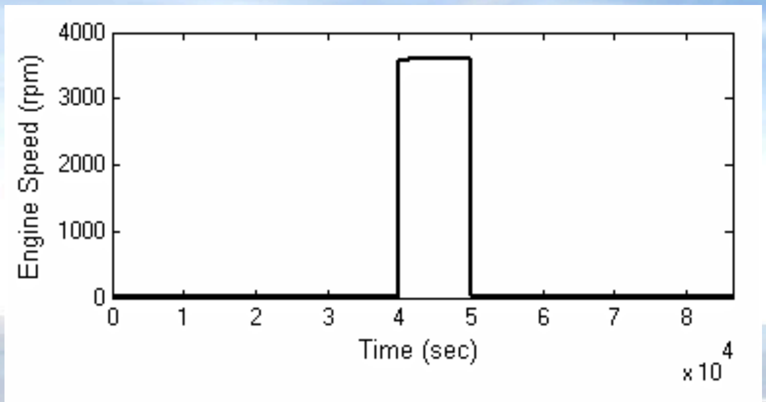


Figure: Synchronous Speed of the Engines.

Modeling of H_2 Generators

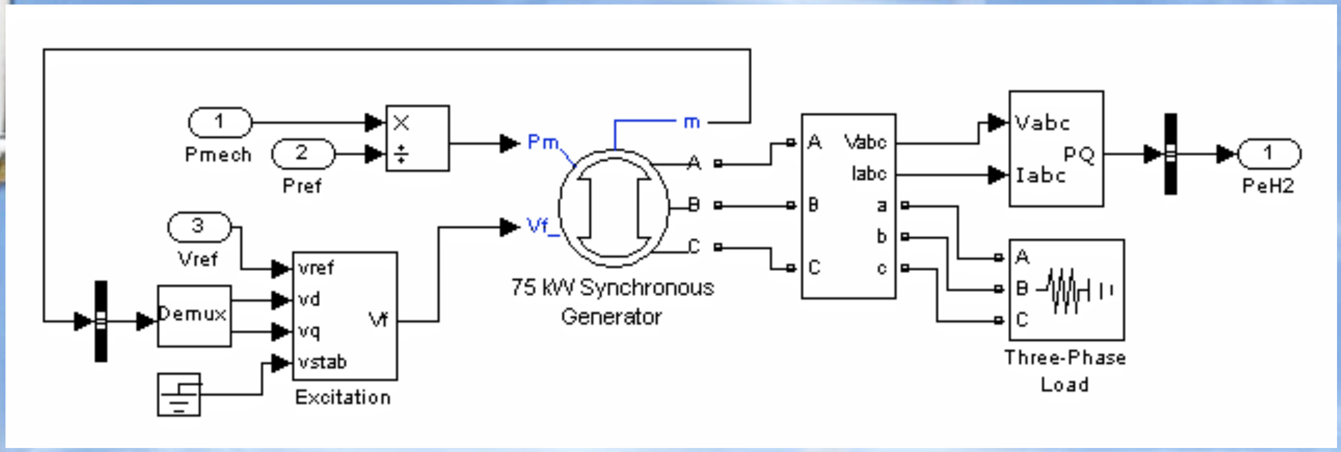


Figure: SimPower Model of H_2 Generator.

Simulations of H_2 Generator

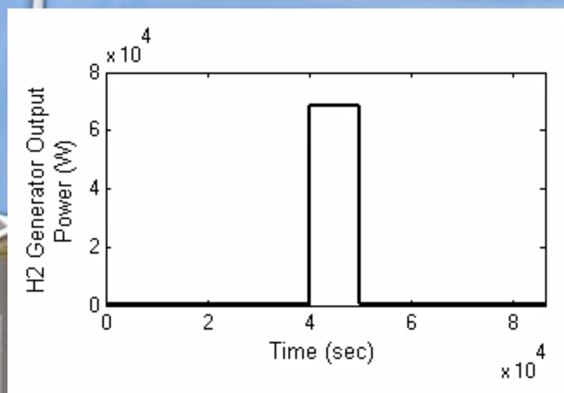


Figure: H_2 Generator Output Power.

Tank Output Flow Rate (mol/s)	Mechanical Power from Hydrogen Engine (kW)	Electrical Power Hydrogen Generator (kW)
1.472	70.70	68.5
1.300	62.50	60.5
1.150	55.25	53.5
1.000	48.00	46.5
0.850	40.83	39.6
0.700	33.63	32.6
0.550	26.42	25.6

Transient Analysis of Ramea Hybrid Power System

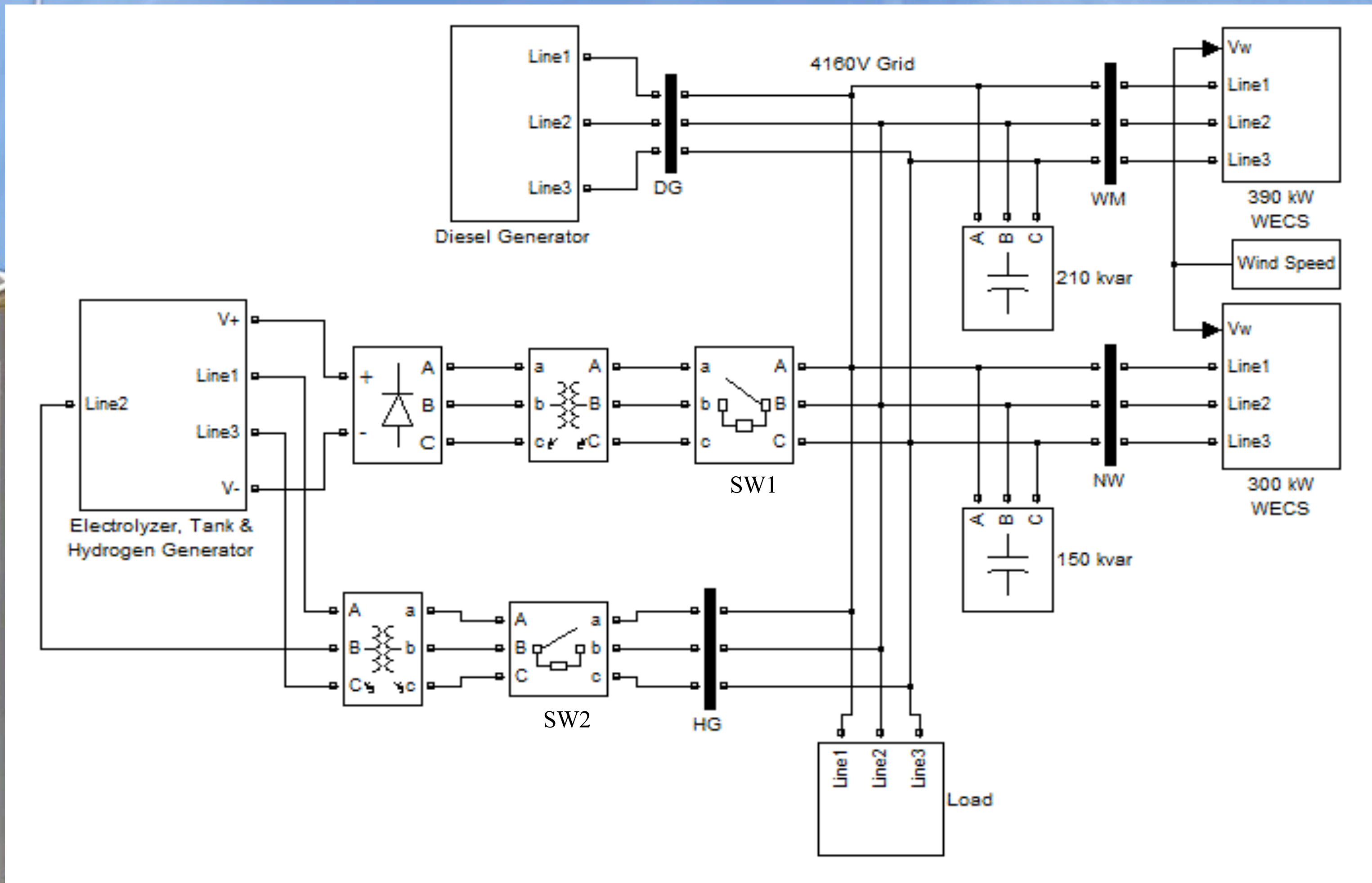


Figure: Ramea Hybrid Power System.

Modeling of Diesel Generators

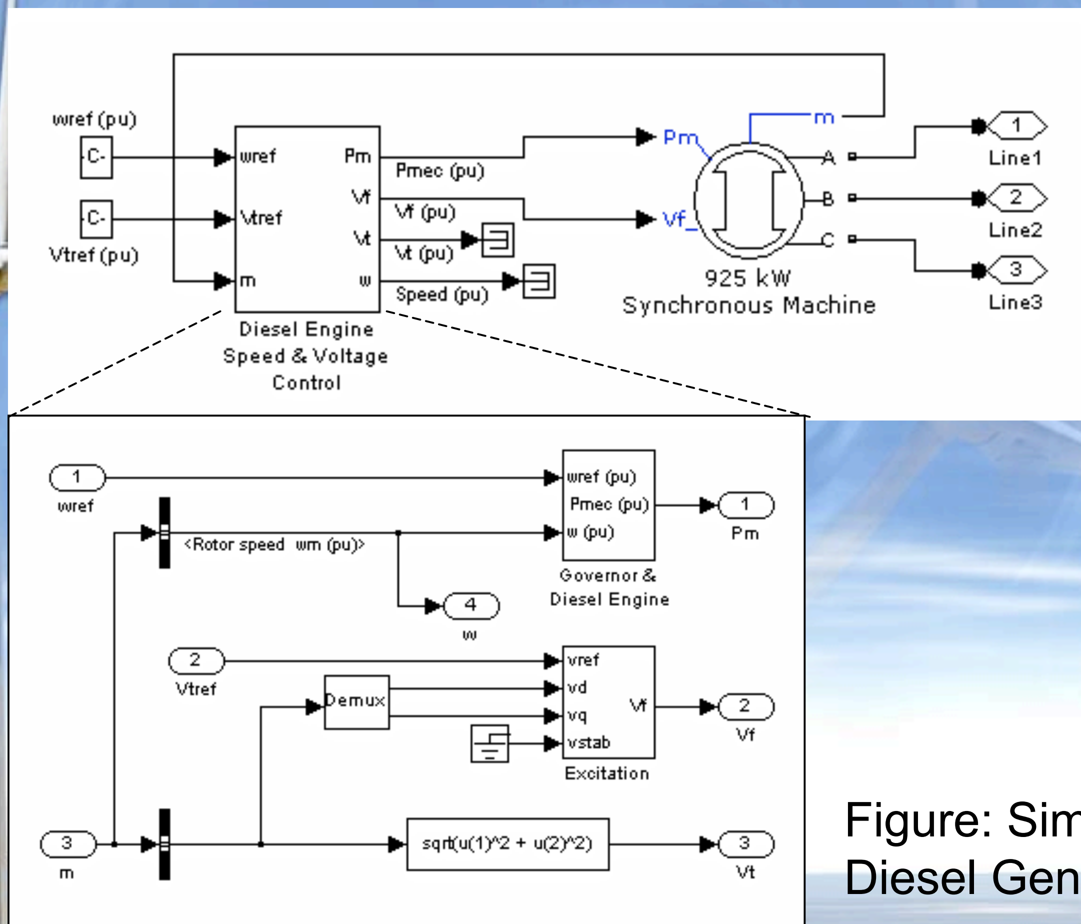


Figure: SimPower Model of Diesel Generator.

Modeling of Dump Load

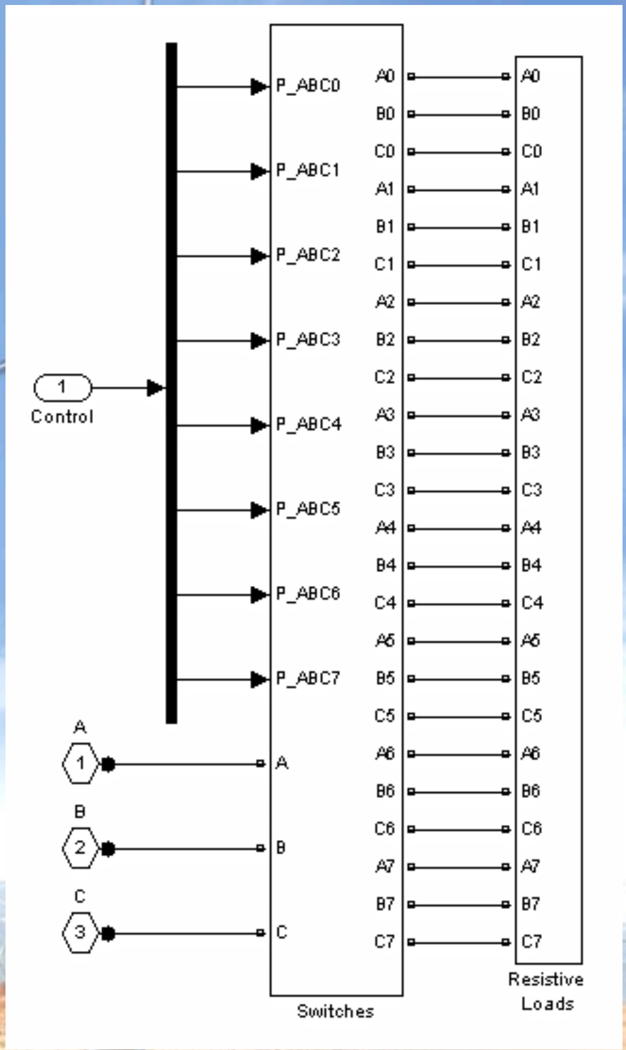
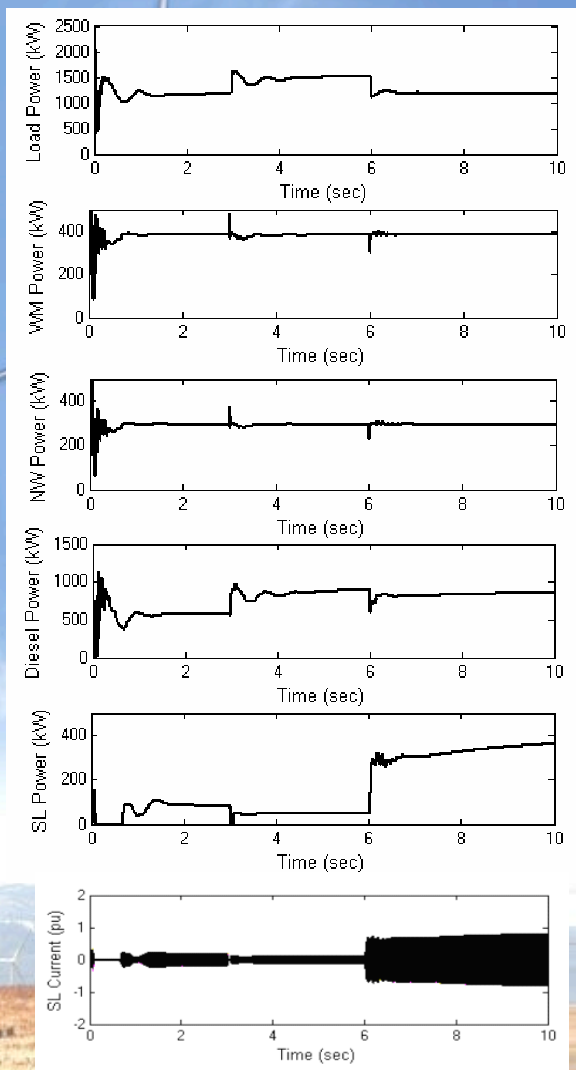


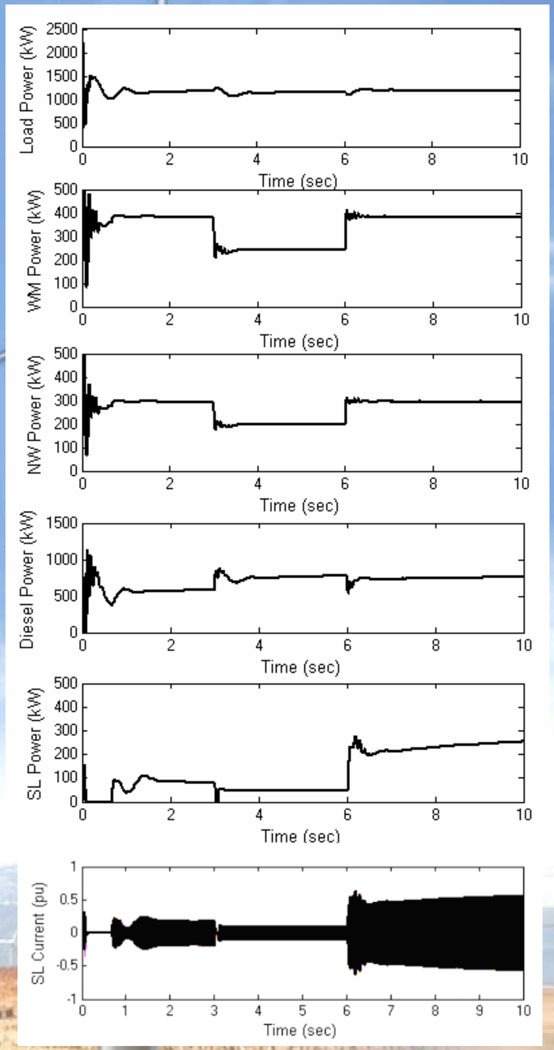
Figure: SimPower Model of Dump Load.

CS1: Simulation with Variable Load (1200/1600/1200 kW)



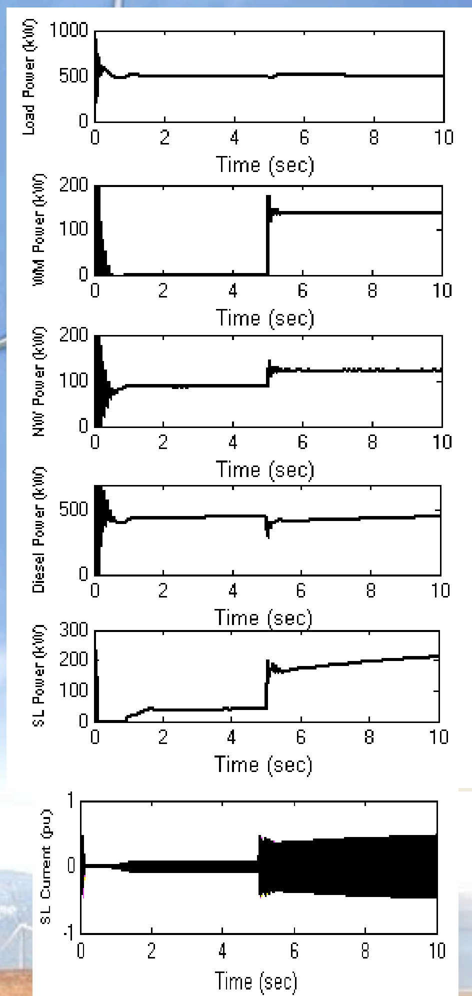
- Wind speed – 15 m/s.
- Dump load increases to minimize the effect of the main load declination.
- Secondary load current – 0.8 pu.

CS2: Simulation with Variable Wind Speed (15/10/15 m/s)



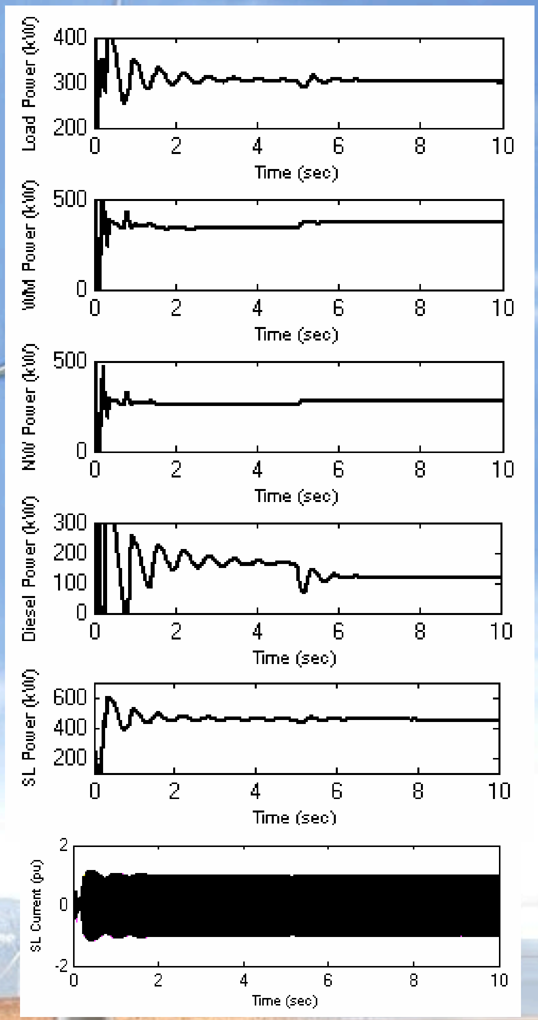
- Main load – 1200 kW.
- WTs respond to the wind speed change accordingly.
- In the second stage the additional load is met by diesel generator.
- SL has to increase as to minimize the effect of high wind generation.
- Secondary load current – 0.5 pu.

CS2: Simulation with Variable Wind Speed (7/8 m/s)



- Main load – 500 kW.
- WTs respond to the wind speed change accordingly.
- In the second stage the diesel power is reduced.
- SL has to increase as to minimize the effect of high wind generation.
- Secondary load current – 0.5 pu.

CS2: Simulation with Variable Wind Speed (12/13 m/s)



- ➢ Main load – 300 kW.
- ➢ WTs respond to the wind speed change accordingly.
- ➢ In the second stage the diesel power is reduced.
- ➢ SL has reached to its rated value.
- ➢ Secondary load current – 1 pu.

CS3: Simulation with Electrolyzer in Operation (cont.)

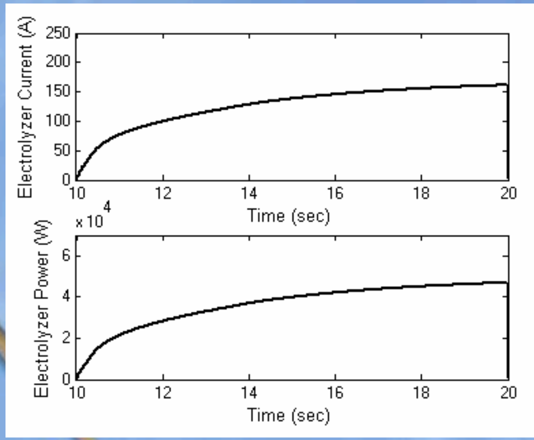


Figure: Current and Power.

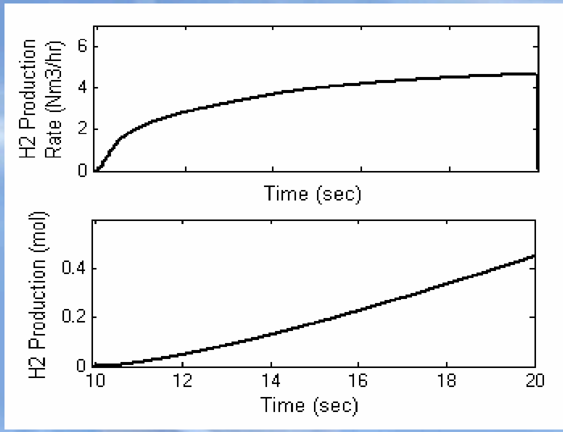


Figure: H_2 Production.

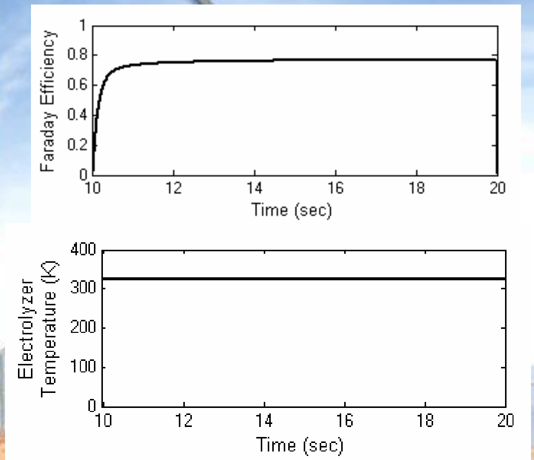
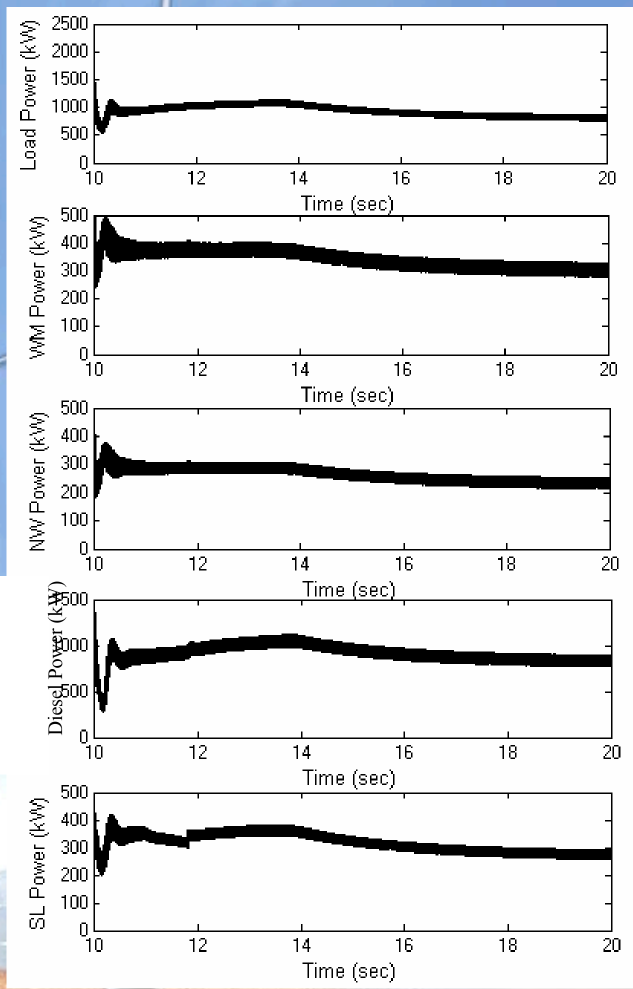


Figure: Faraday Efficiency and Temperature.

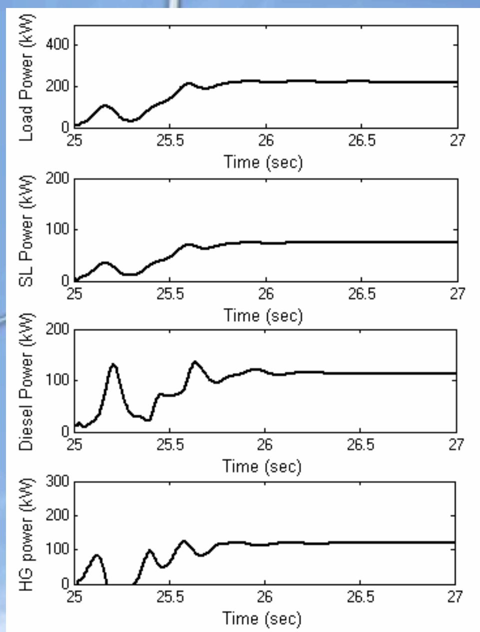
- Electrolyzer current – 160A.
- Electrolyzer power – 45 kW.
- H_2 production rate – 4.6 Nm^3/hr.
- Faraday efficiency – 78%.

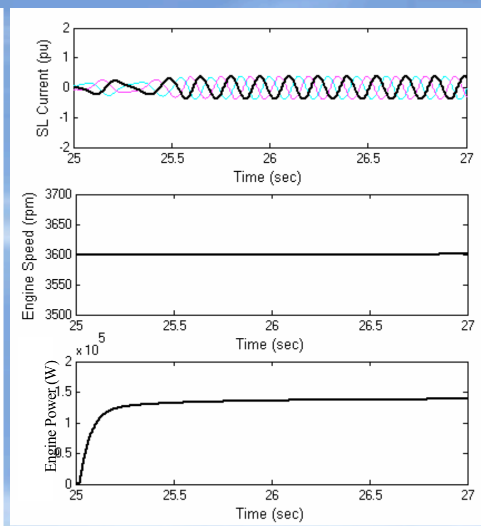
CS3: Simulation with Electrolyzer in Operation



- Main load – 1200 kW.
- WTs and diesel generator are operating at rated conditions.
- Secondary load – 400 kW.

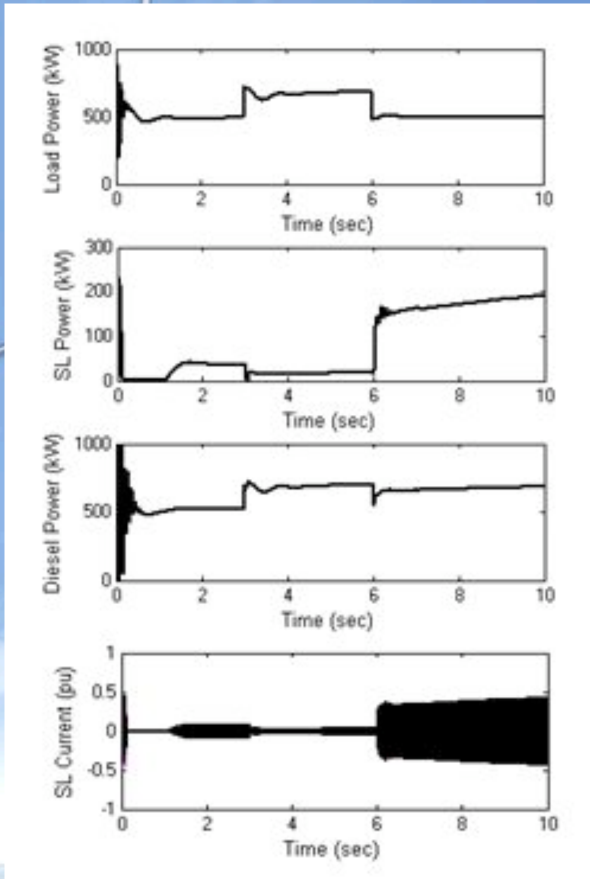
CS4: Simulation with HG in Operation





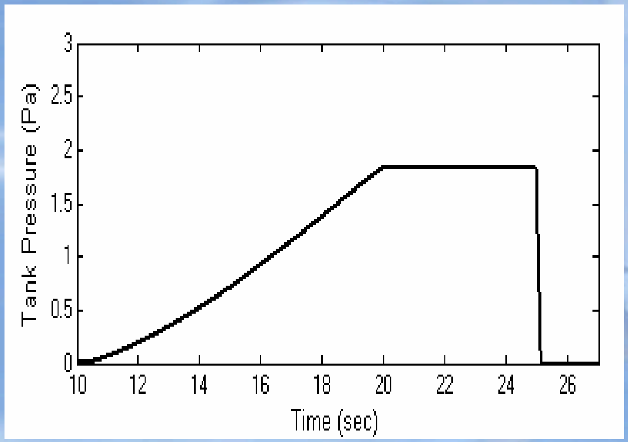
- Main load – 200 kW.
- WTs are operating below cut-in wind speed.
- Secondary load – 60 kW.
- Both diesel and H2 gensets are producing 130 kW individually.

CS5: Simulation with DG in Operation



- Main load – 500/700/500 kW.
- No wind generation
- No H_2 generation
- Diesel generation follows the load.
- SL increases to 200 kW.
- SL current – 0.5 pu.

Hydrogen Storage Dynamics



- 10-20 sec: Electrolyzer in operation.
- 20-25 sec: Both electrolyzer and H_2 generators are non-operating.
- 25-27 sec: H_2 generators in operation.

Conclusions

- Dynamic model of Wind-Diesel-Hydrogen based Ramea power system has been developed.
- Hydrogen as a storage medium is a novel approach adopted in this system.
- Introducing of new WECS is aiming at increasing the penetration level.
- The dump load used in this system played an important role in maintaining stability.

Future Works

- Introduce precise control mechanisms.
- Flywheel and pumped hydro as alternative storage systems.
- Design stand-alone energy systems for other remote communities.
- Energy consumed by the SL might be used for water heating, room heating, water pumping etc.


THANKS!
QUESTIONS?