DYNAMIC MODELING AND SUPERVISORY CONTROLLER DESIGN FOR A SMALL ISOLATED HYBRID SYSTEM WITH PUMPED HYDRO STORAGE

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Abstract

- New faster dynamic modeling method for a remote hybrid power system of Ramea, Newfoundland
- Simulation with the pumped hydro storage system replacing current low efficiency hydrogen electrolyzer and generator system
- Supervisory controller design with six case studies and detailed simulation results
- Different operational modes of diesel engine generator to estimate the fuel consumption, no of switching and system frequency deviation

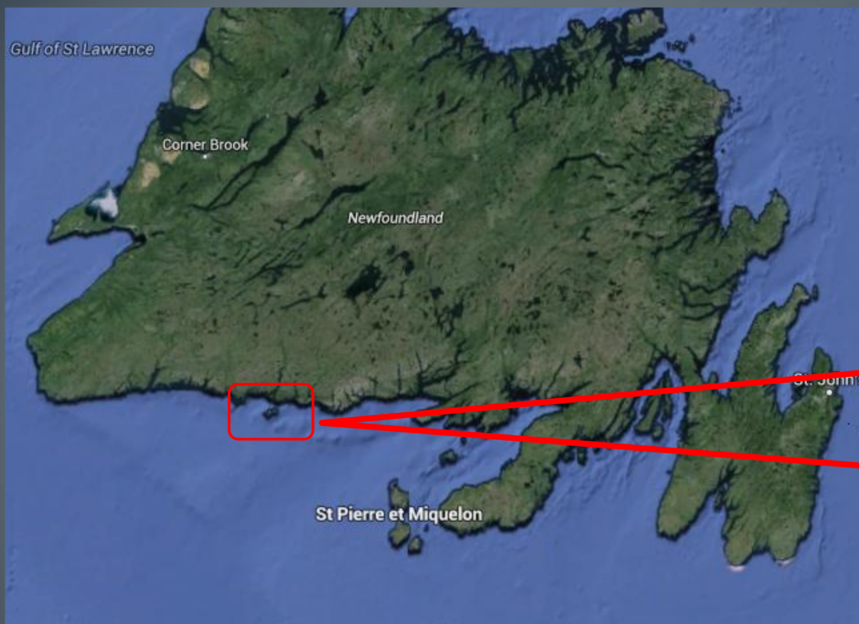
Presentation Overview

- **Introduction**
  - Ramea hybrid power system
  - Pumped hydro storage
- **Dynamic Modeling: All subsystems**
  - Wind turbines: Northern Power 100 and Windmatic 15s
  - Diesel engine generator
  - Centrifugal pump
  - Pelton wheel turbine
  - Sealed Lead Acid Battery
  - Electrical system and Supervisory controller
- **Simulations for six extreme cases of wind speed and load**
  - Simulation results and analysis
- **Diesel consumption analysis for high penetration system**
  - Simulation results and analysis
- **Conclusion, Contribution and Future work**
- **Questions**

Introduction

- Ramea Hybrid Power System
- Pumped Hydro Storage

Introduction:
Ramea Hybrid Power System

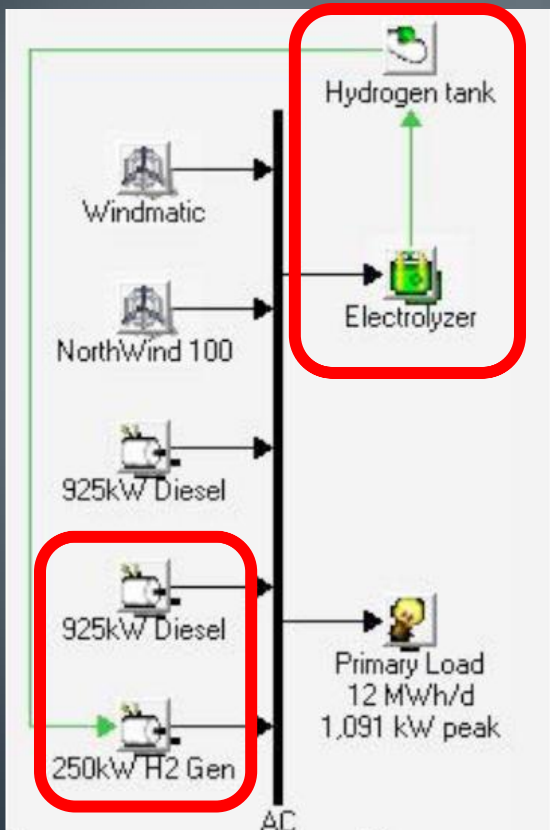


Newfoundland

Ramea Island

- Ramea, Newfoundland and Labrador is a small village located on Northwest Island, one of a group of five major islands located off the south coast of the island of Newfoundland, Canada
- The Island is approximately 3.1 km long by 1 km wide

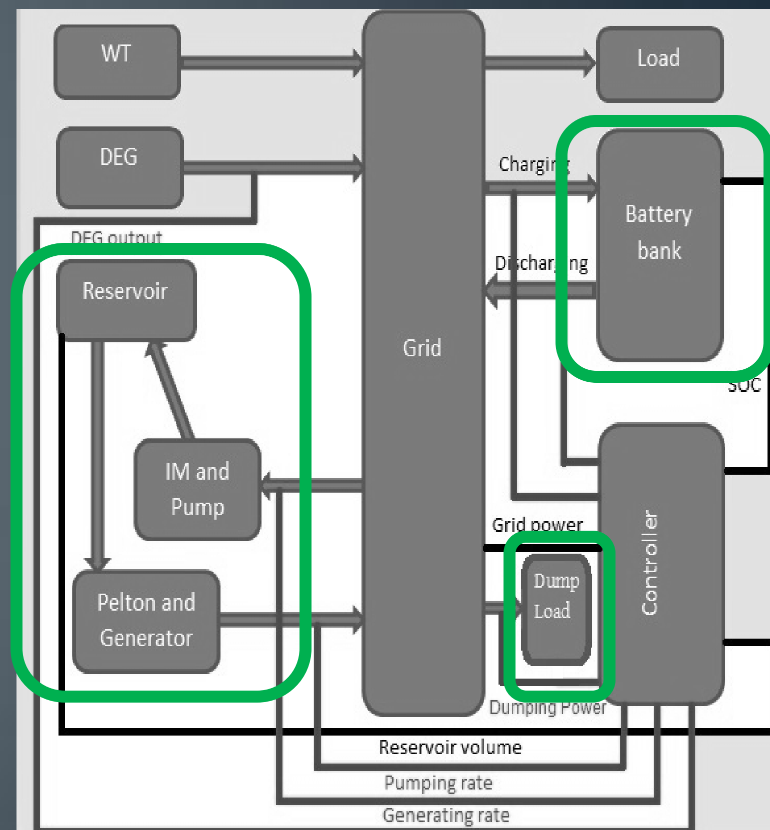
Introduction: Ramea Hybrid Power System



Existing hybrid power system

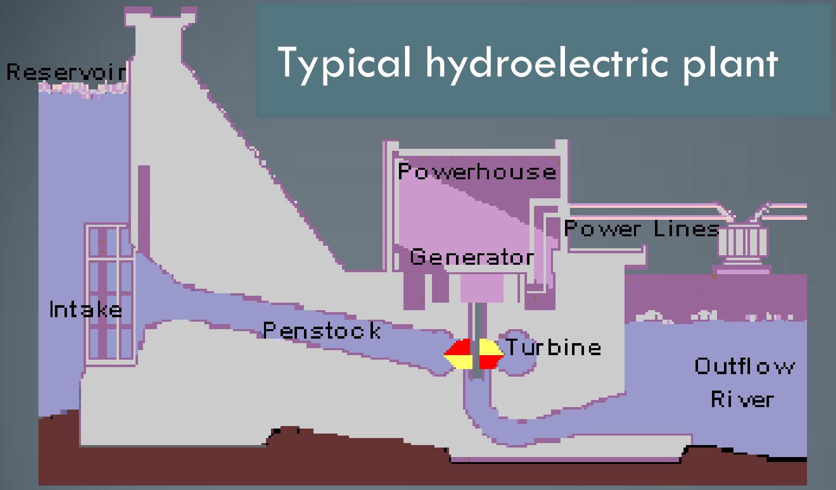
Components to be removed

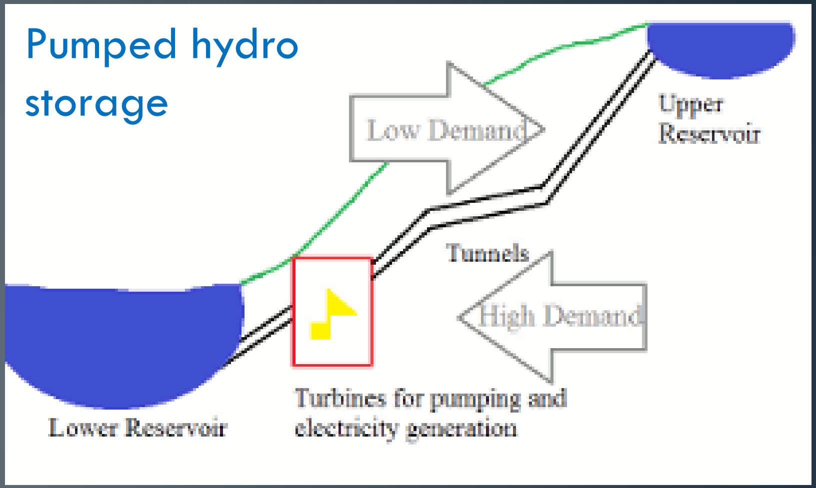
Components to be added



Proposed hybrid power system with pumped hydro storage

Introduction: Pumped Hydro Storage





- ✓ Pumped water when wind speed is high or/and load demand is low
- ✓ Bidirectional machine can be used to pump or generate but provides poor efficiency
- ✓ A centrifugal pump coupled with induction motor can be used to pump water
- ✓ Pelton wheel turbine is a good option as this system will rarely be operated at rated flow and this turbine has high part flow efficiency

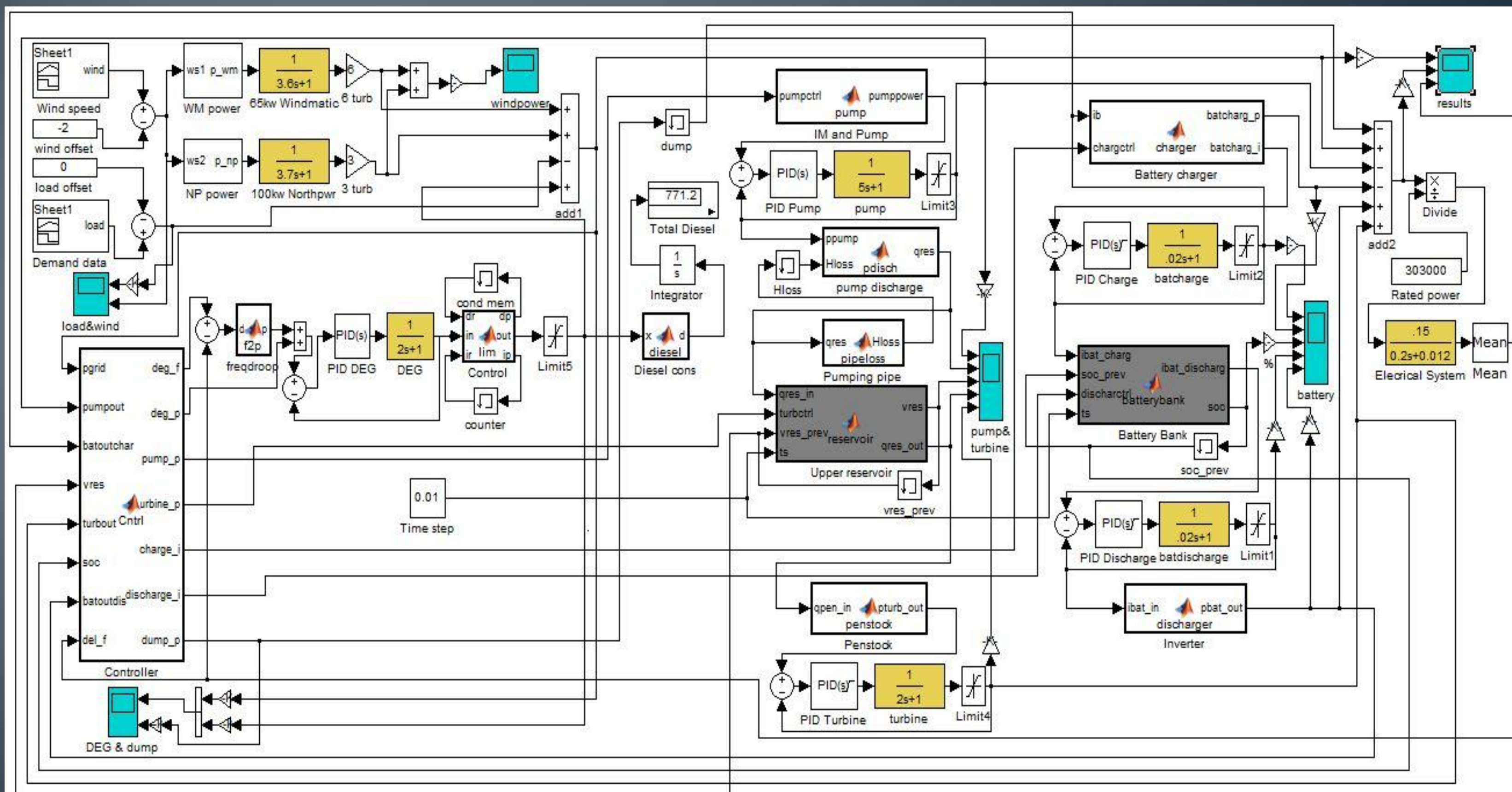
Introduction: Pumped Hydro Storage

- ✓ 2000m^2 reservoir area on top of the Man of war hill with 2m water depth
- ✓ 63m head with 4000m^3 reservoir

Dynamic Modeling: All subsystems

Wind turbines, Diesel engine generator, centrifugal pump, Pelton wheel turbine, battery

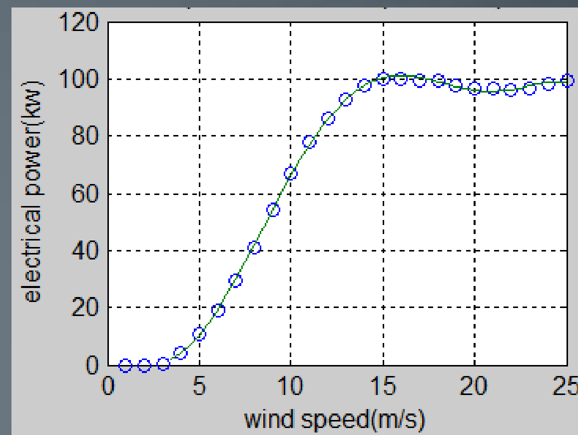
Dynamic Modeling: Whole system at a glance



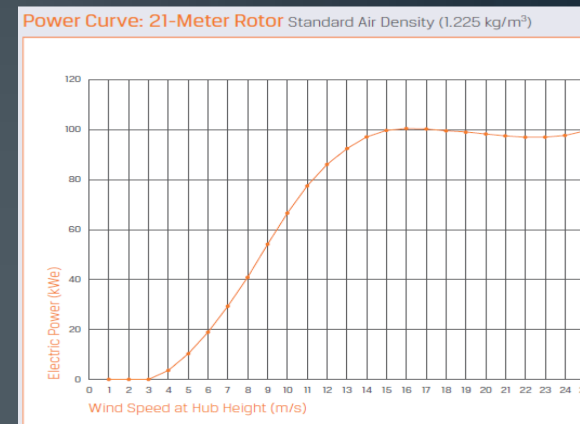
Simulink - MATLAB embedded function block based dynamic model of Ramea hybrid power system with pumped hydro storage, battery bank and controllable dump load

Dynamic Modeling:
Wind Turbines: Northern Power 100

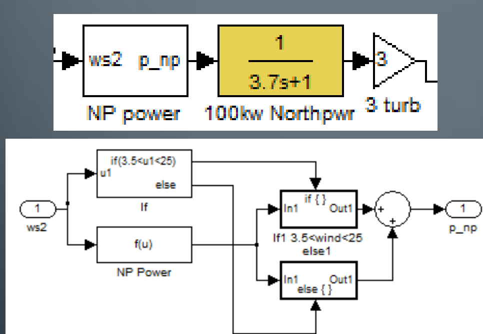
3*100kW Northern power 100 wind turbines in Ramea



Power curve in Matlab



Power curve for Northern Power 100 wind turbine



Dynamic model of Northern Power 100

$$H_{WT} \cong 1.87 * P_{WT}^{0.0597}$$

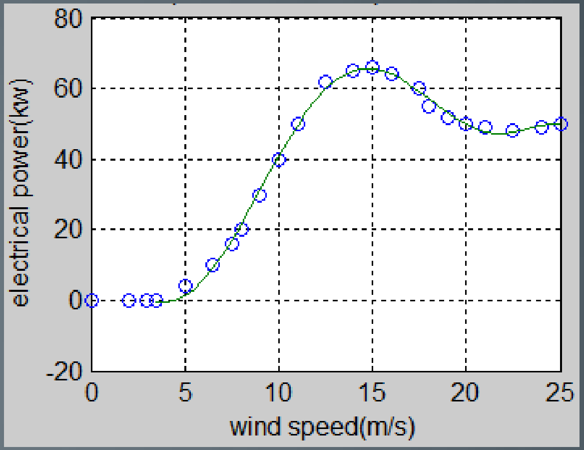
H_{WT} - the mechanical inertia time constant

P_{WT} - the power of the wind turbine in watts

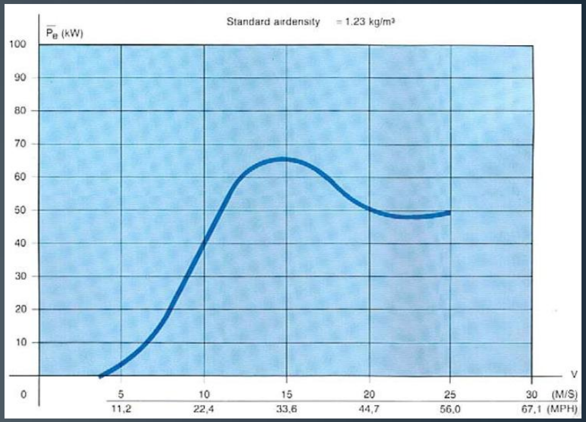
From calculation $H_{WT} = 3.7s$

Dynamic Modeling: Wind Turbines: Windmatic 15s

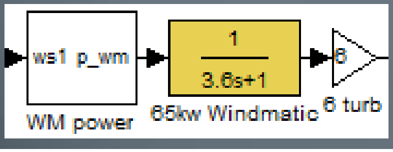
3*100kW Windmatic 15s wind turbines in Ramea

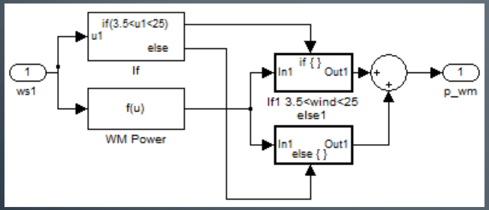


Power curve in Matlab



Power curve for Windmatic 15s wind turbine





Dynamic model of Windmatic 15s

$$H_{WT} \cong 1.87 * P_{WT}{}^{0.0597}$$

H_{WT} - the mechanical inertia time constant

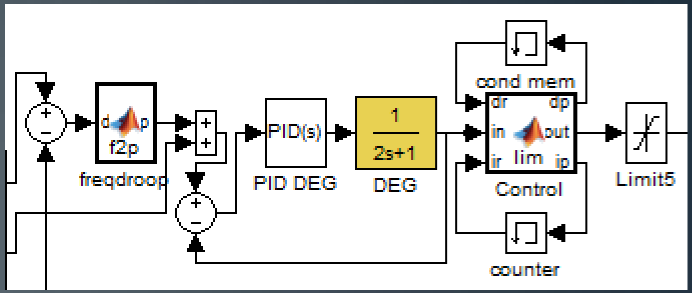
P_{WT} - the power of the wind turbine in watts

From calculation $H_{WT} = 3.6s$

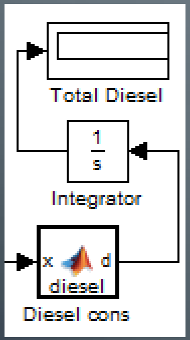
Dynamic Modeling: Diesel Engine Generator

$$J = \frac{S_n T_{DEG}}{{\omega_n}^2}$$

J - the moment of inertia
ω_n - the rated angular velocity
S_n - the DEG nominal apparent power
T_{DEG} - the acceleration time constant for S_n
Here, J = 20kg.m^2 results $T_{DEG} \cong 2$ s

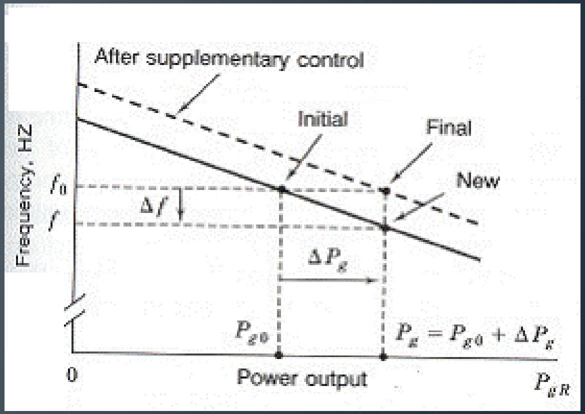


Dynamic model of diesel generator



D = 2E-14*x^2 + 5E-08*x + 0.0101

Diesel consumption measurement block and function



Frequency droop model

Dynamic Modeling: Centrifugal Pump

Overall efficiency considering all dynamic losses is 50%

Reynolds number
Re = 2000;

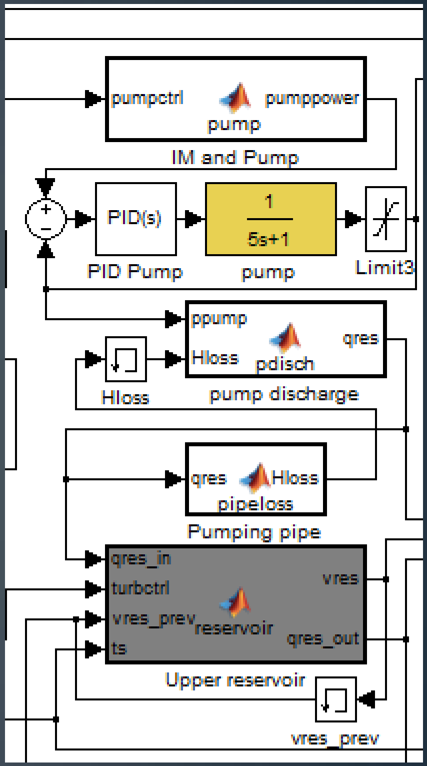
Darcy Friction Factor
flam=64/Re;

Darcy-Weisbach equation for head loss due to friction
hpipefric = (8*flam*Lpipe*qres^2)/(g*3.1416^2*Dpipe^5)

klossco is the loss coefficient for water meter
hlossmeter = klossco*(Velowaterpump^2)/(2*g)

Total dynamic head loss
Hloss = hpipefric + hlossmeter;

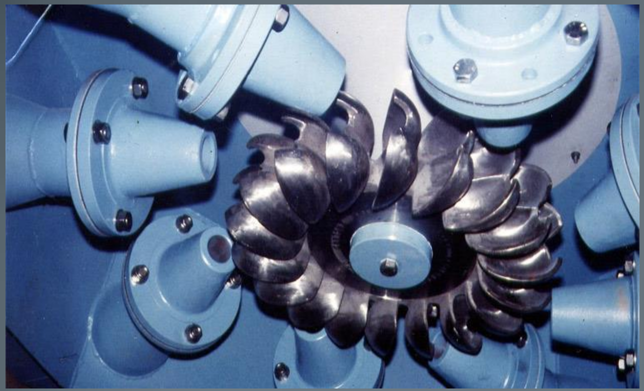
Centrifugal pump coupled with induction motor



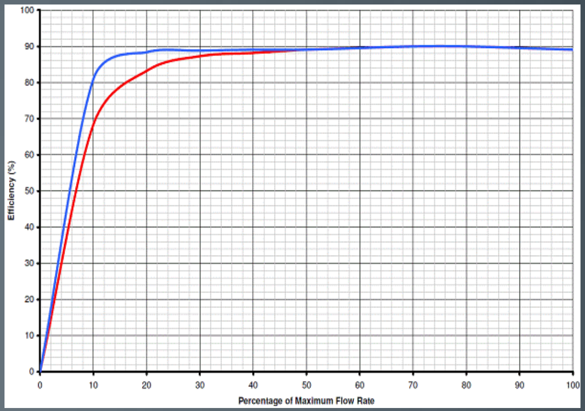
Dynamic model of pump and reservoir

- ❑ Operates from 30% to 100% of the rated value

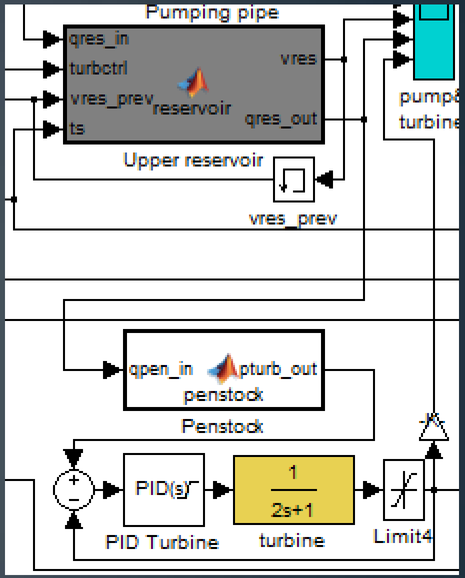
Dynamic Modeling: Pelton Wheel Turbine



Spare jet Pelton wheel turbine



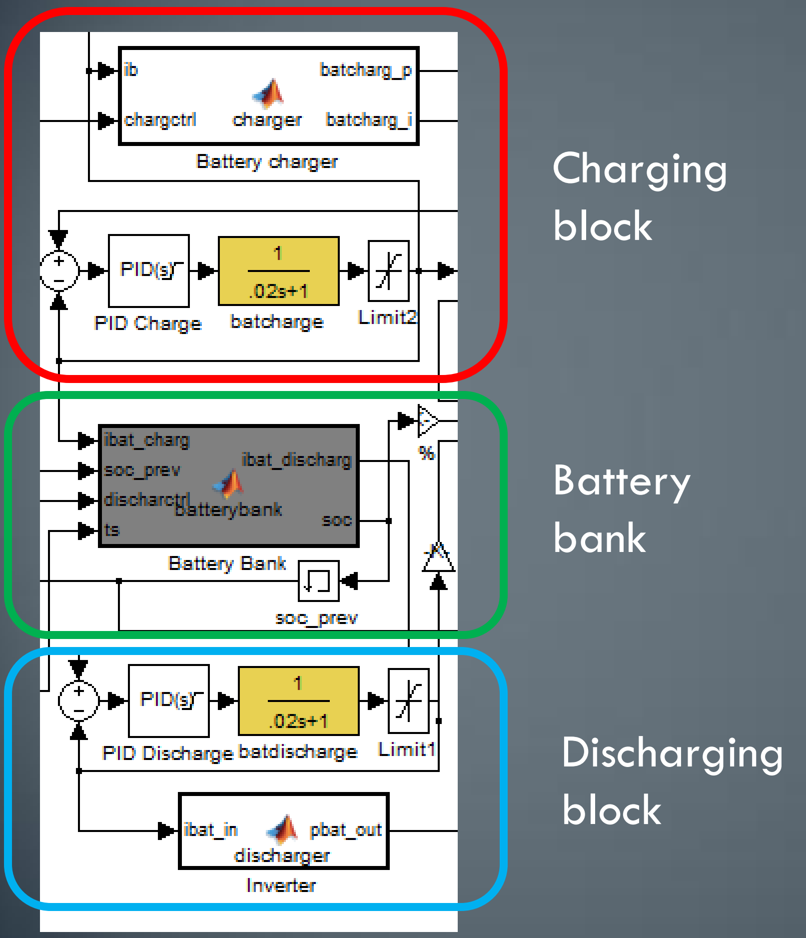
Part flow efficiency of a Pelton wheel turbine



Dynamic model of Pelton wheel turbine

- ❑ 150kW Pelton wheel turbine
- ❑ Overall efficiency is considered 70%
- ❑ Operates from 30% to 100% of the rated value

Dynamic Modeling: Sealed Lead Acid Battery



Dynamic model of battery bank

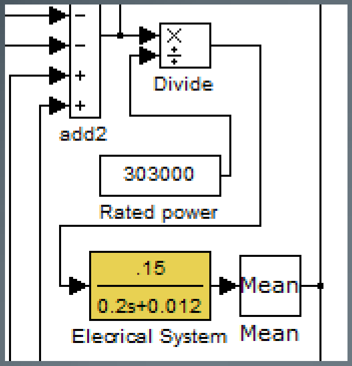
Individual capacity – 200Ahr
Battery per string – 20
Bus voltage – 240V DC (20*12V)
Number of string – 15
Number of battery – 300
Efficiency – 80%

- Maximum charging rate 10% of capacity i.e. 72kW
- Maximum discharge rate 33% of capacity i.e. 237.6kW
- For discharge rate higher than 20hr rate of battery 'Peukert's law' is applied.

$$\mathrm{It} = \mathrm{C}\left(\frac{C}{IH}\right)^{k-1}$$

- This battery bank can response in millisecond range

Dynamic Modeling: Electrical System and Supervisory Controller



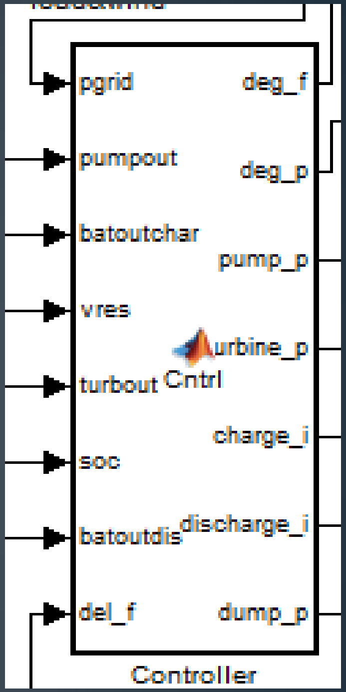
Dynamic model of the Electrical System

Electrical System

- M - System inertia constant (0.2)
- D - Load-damping constant (0.012)
- 0.05pu (5%) power deviation in grid will cause 0.01pu (1%) or 0.6Hz frequency deviation

Supervisory Controller

- In left side all are input parameters from the component blocks
- In right side all are output parameters to the component blocks
- Algorithm is implemented inside this block with C code



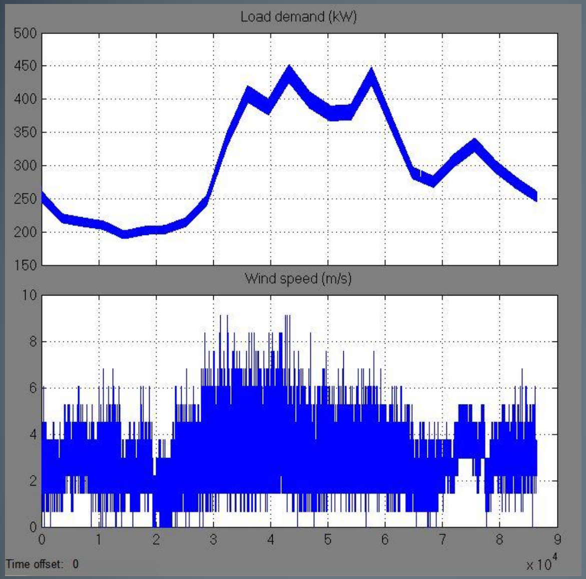
Dynamic model of the Supervisory controller

Simulation Results: Six extreme cases

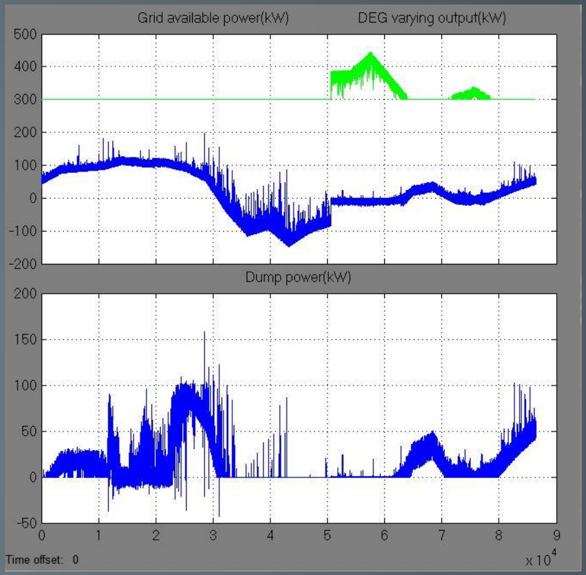
Simulation Results:
Wind speed and load demand conditions

Case	Load	Wind speed
1	Low (200kW to 330kW)	Low (0m/s to 9m/s)
2	Low (200kW to 330kW)	High (10m/s to 20m/s)
3	High (590kW to 990kW)	Low (0m/s to 9m/s)
4	High (590kW to 990kW)	High (10m/s to 20m/s)
5	Abrupt load change (500kW to 700kW at 200s and vice versa at 700s)	Steady in midrange (5m/s)
6	Steady in midrange (500kW)	Abrupt wind speed change (8m/s to 11m/s at 200s and vice versa at 700s)

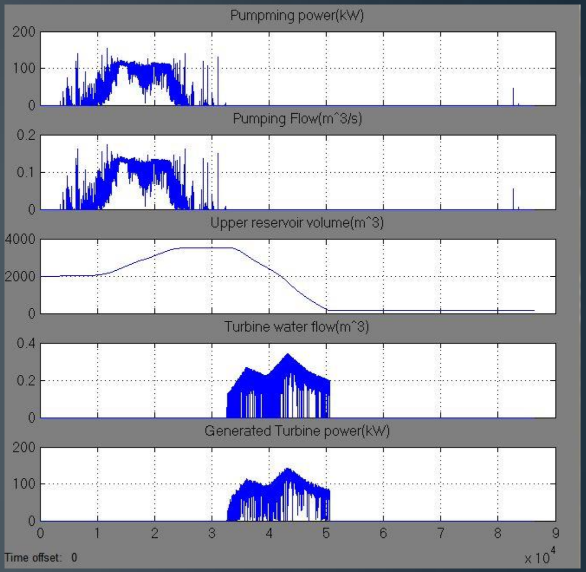
Simulation Results:
Case 1- Low load and Low wind speed



Load demand (kW) and wind speed (m/s) data for the case 1



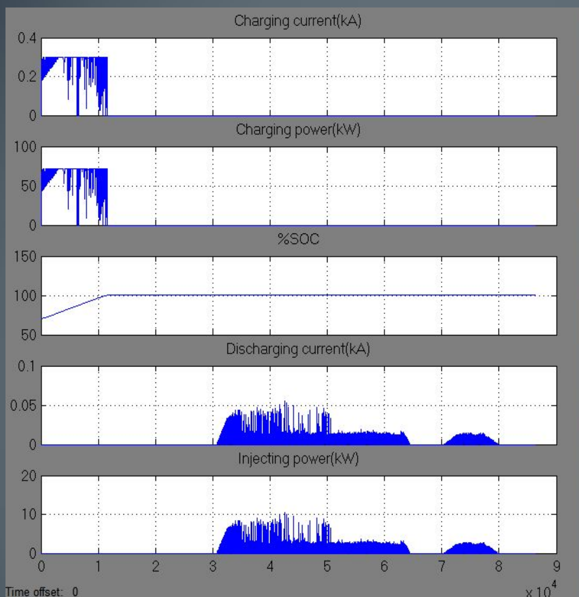
Grid available power (kW) and DEG varying output (kW) (with a minimum 300kW value) is shown and in the lower figure dump power (kW) is shown for the case 1



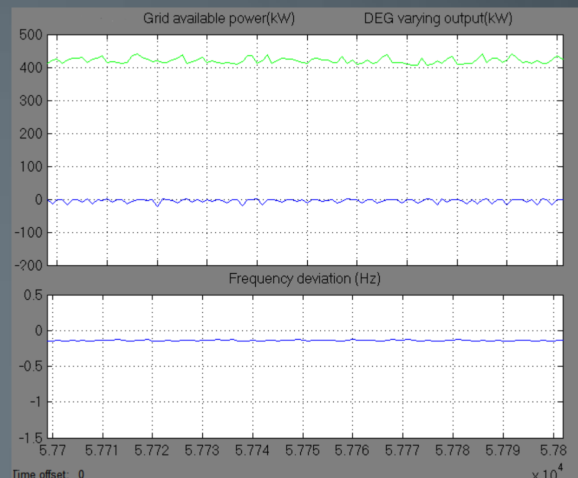
Pump power consumption (kW), pump water flow (m^3/s), the upper reservoir water volume (m^3), turbine water flow rate (m^3/s) and the turbine generated power (kW) for the case 1

Low (200kW to 330kW)	Low (0m/s to 9m/s)	1.3Hz

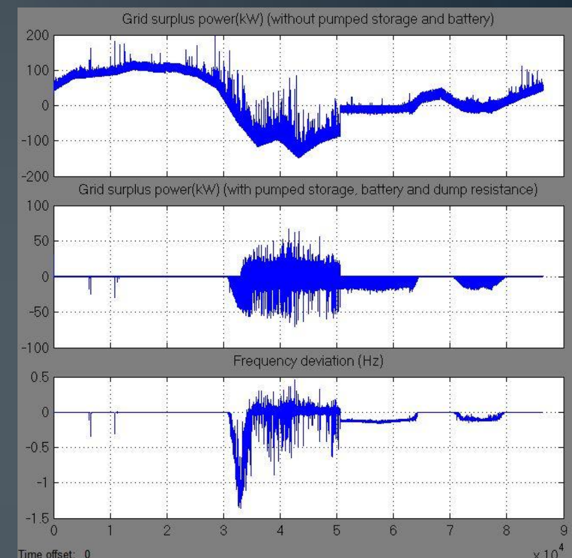
Simulation Results:
Case 1- Low load and Low wind speed



BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power to the grid (kW) due to the discharging of the battery are shown for the case 1



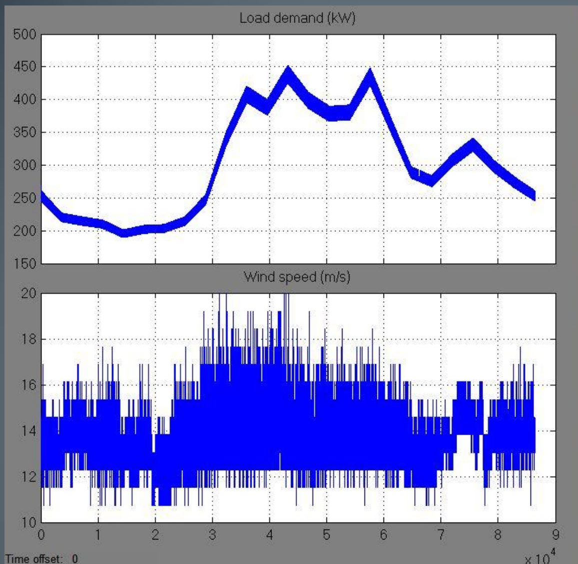
Simulation result has been zoomed from 57700s to 57800s to show the transients. In top figure, the grid available power (kW) and DEG varying output (kW) is shown and in the lower figure the resultant frequency deviation is shown for the case 1



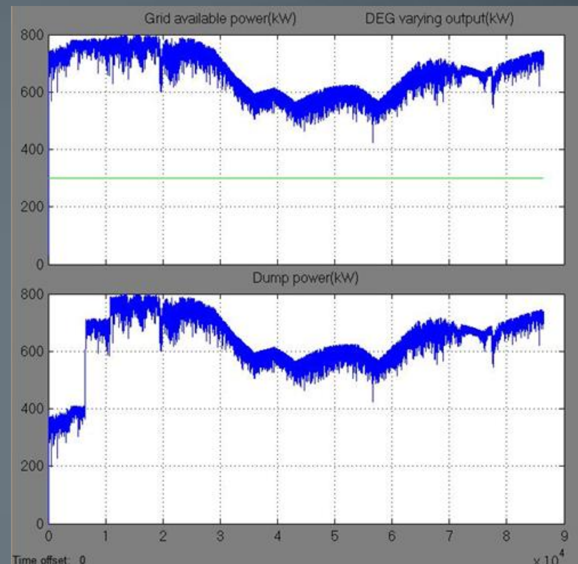
Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation for the case 1

Low (200kW to 330kW)	Low (0m/s to 9m/s)	1.3Hz

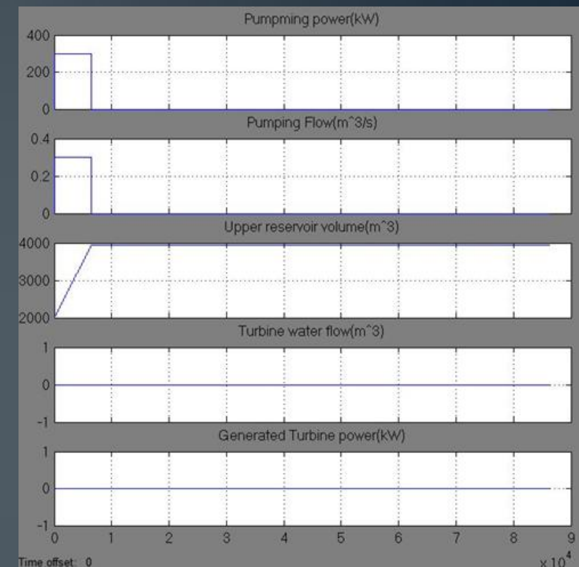
Simulation Results:
Case 2- Low load and High wind speed



Load demand (kW) and wind speed (m/s) data for case 2



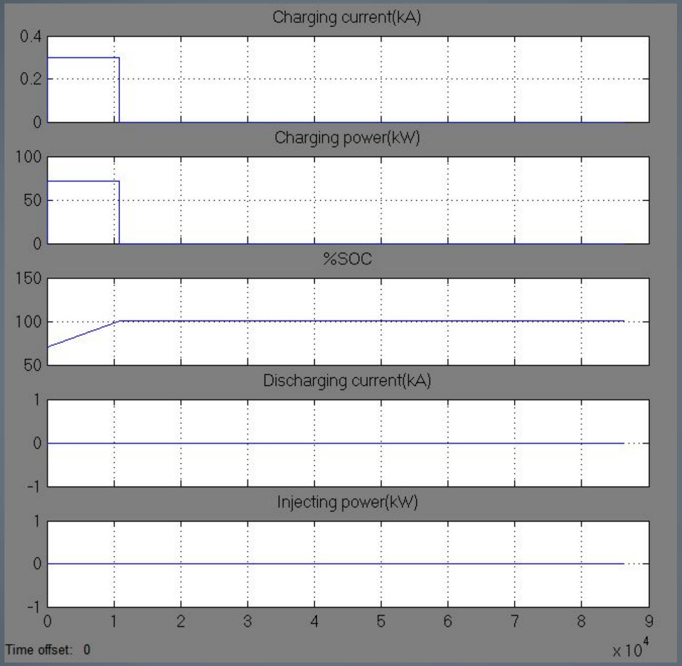
In the top part, grid available power (kW) and DEG output (kW) (with flat 300kW value) are shown and in the lower part dump power (kW) is shown for the case 2



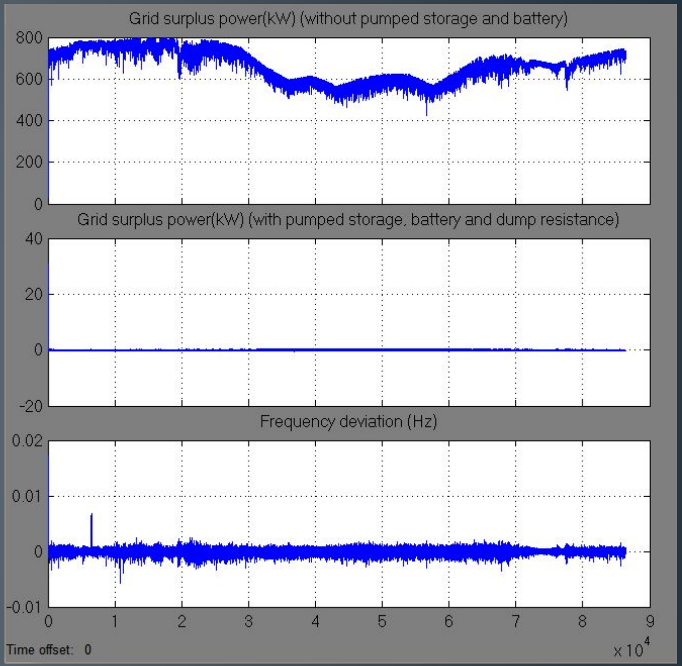
Pumping power (kW), pumping water flow rate (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) for the case 2

Low (200kW to 330kW)	High (10m/s to 20m/s)	~0Hz

Simulation Results:
Case 2- Low load and High wind speed



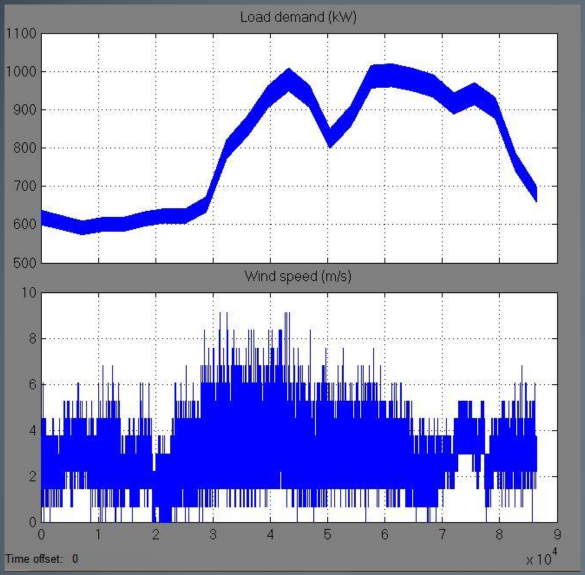
BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power injected to the grid (kW) due to the discharging of the battery are shown above for the case 2



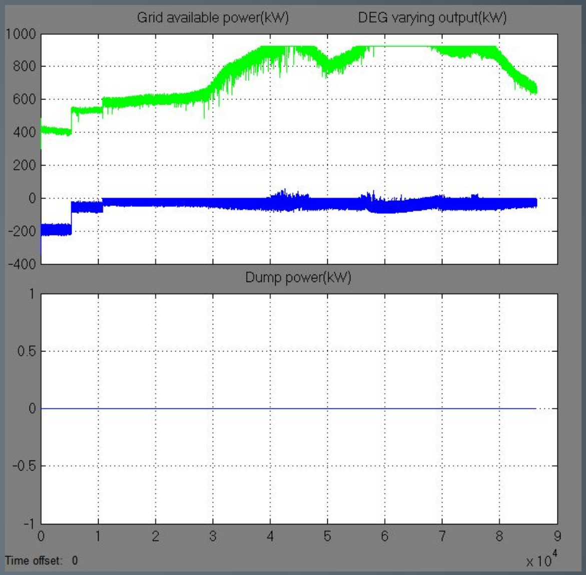
Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation are shown above for the case 2

Low (200kW to 330kW)	High (10m/s to 20m/s)	~0Hz

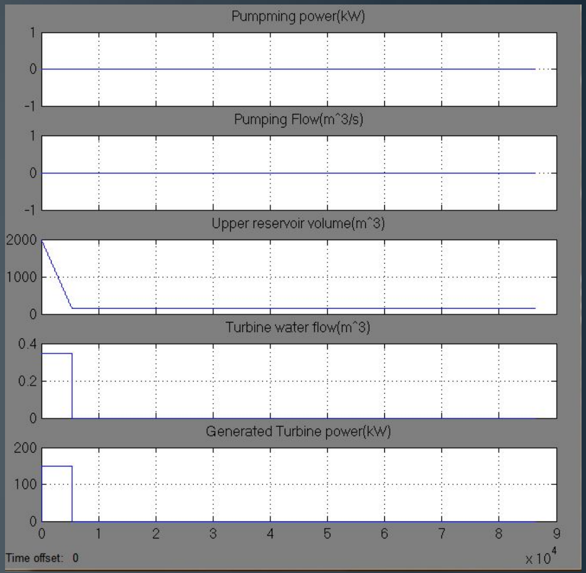
Simulation Results:
Case 3- High load and Low wind speed



Load demand (kW) and wind speed (m/s) data for the case 3



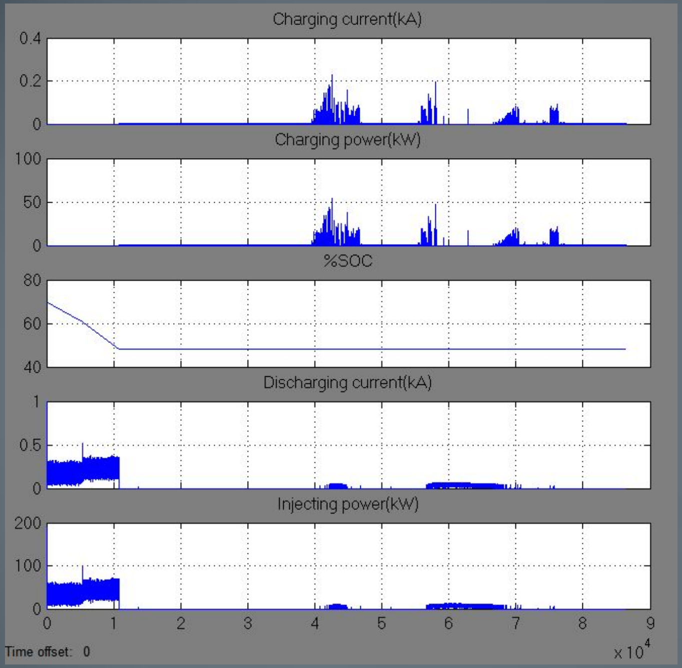
In top figure, grid available power (kW) and DEG varying output (kW) (from 400kW to 925kW) are shown and in the bottom part dump power (kW) is shown for the case 3



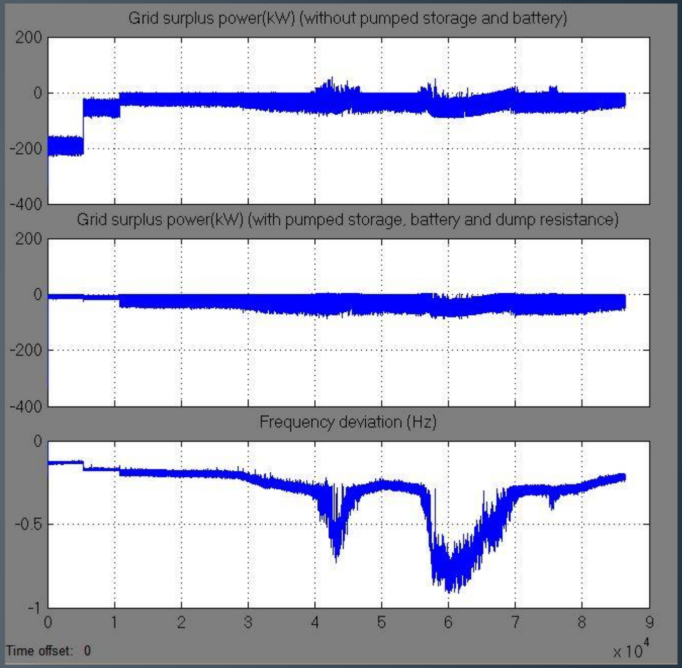
Pumping power (kW), pumping water flow (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) are shown for the case 3

High (590kW to 990kW)	Low (0m/s to 9m/s)	0.9Hz

Simulation Results:
Case 3- High load and Low wind speed



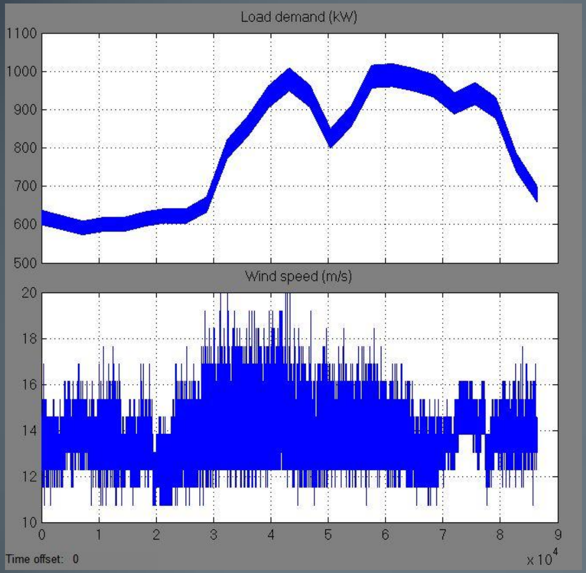
Charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and injected power to the grid (kW) due to the discharging of the battery are for the case 3



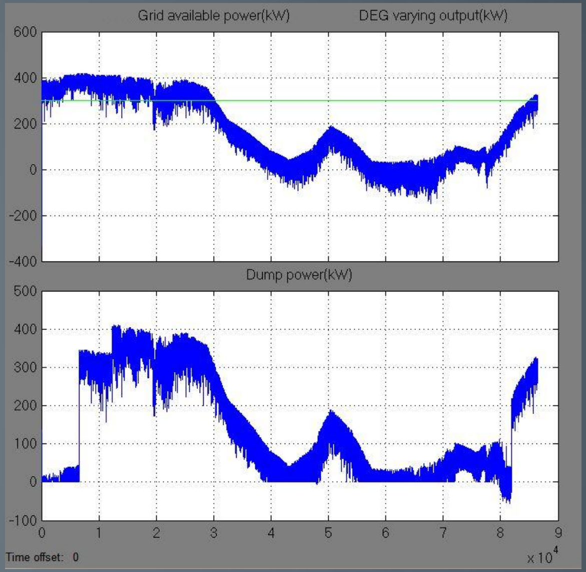
Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant system frequency deviation for the case 3

High (590kW to 990kW)	Low (0m/s to 9m/s)	0.9Hz

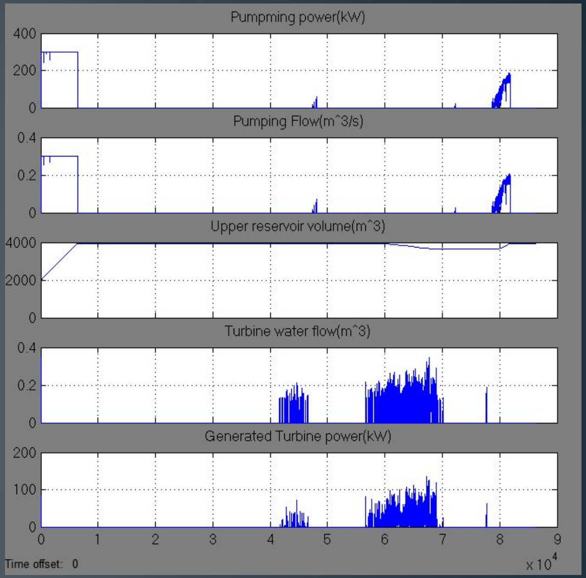
Simulation Results:
Case 4- High load and High wind speed



Load demand (kW) and wind speed (m/s) data for the case 4



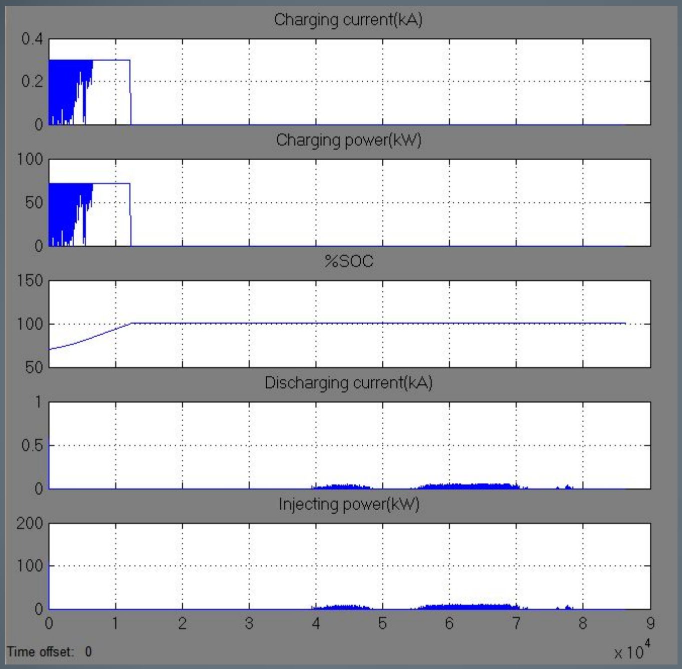
In top figure grid available power (kW) and DEG output (kW) (flat 300kW value) are shown and in the lower part dump power (kW) is shown for the case 4



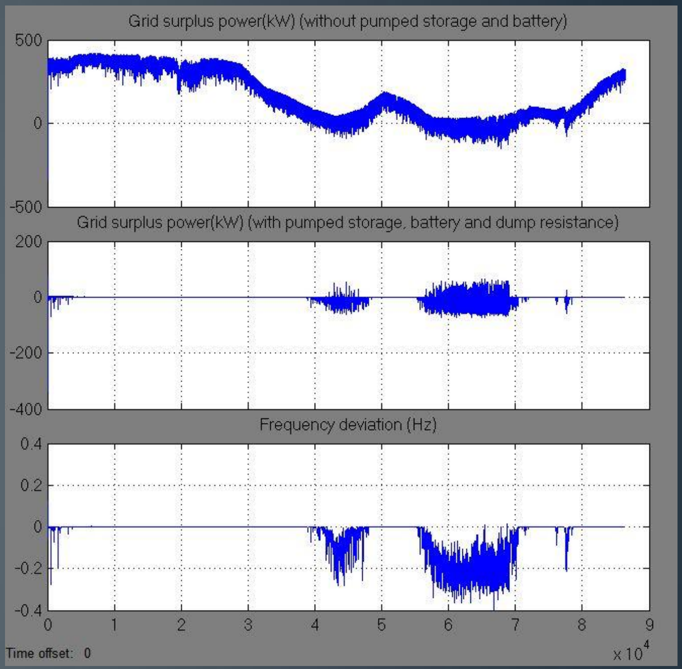
Pumping power (kW), pumping water flow (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) for the case 4 are shown above

High (590kW to 990kW)	High (10m/s to 20m/s)	0.4Hz

Simulation Results:
Case 4- High load and High wind speed



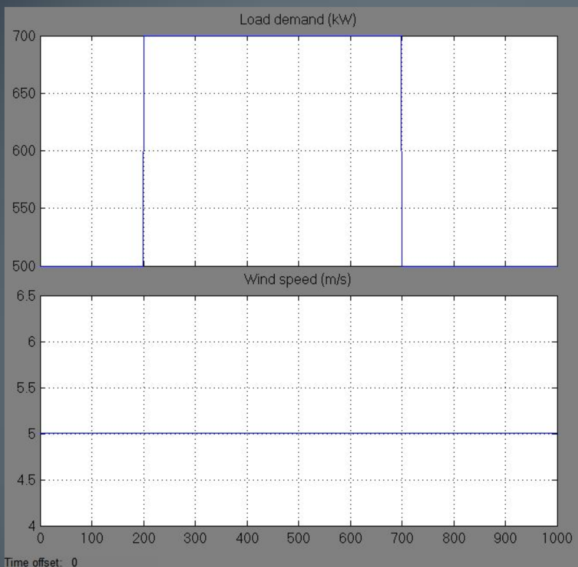
Charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power injected to the grid (kW) due to the discharging of the battery are shown above for the case 4



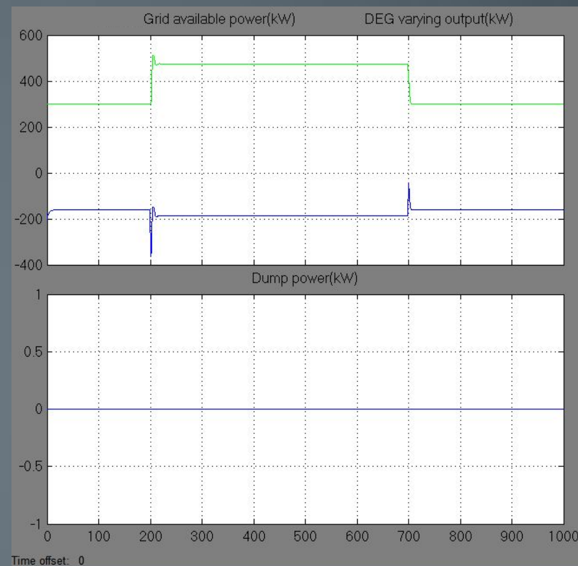
Grid surplus power (kW) with and without pumped storage, battery and dump load are shown above. The resultant frequency deviation is also plotted for the case 4

High (590kW to 990kW)	High (10m/s to 20m/s)	0.4Hz

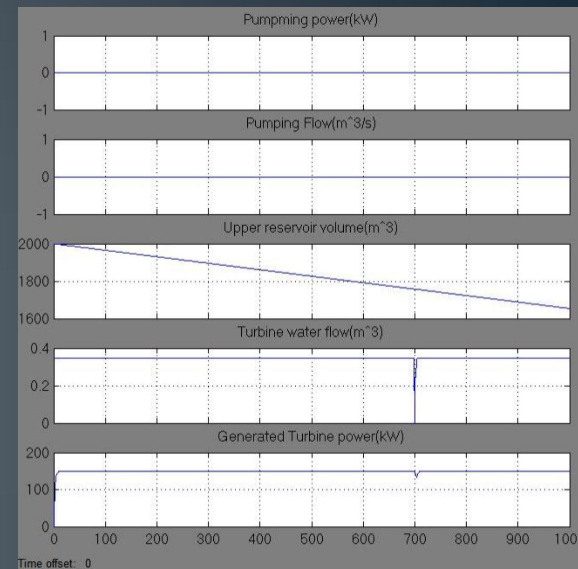
Simulation Results:
Case 5- Abrupt load and Steady wind speed



Load demand (kW) and wind speed (m/s) data for the case 5



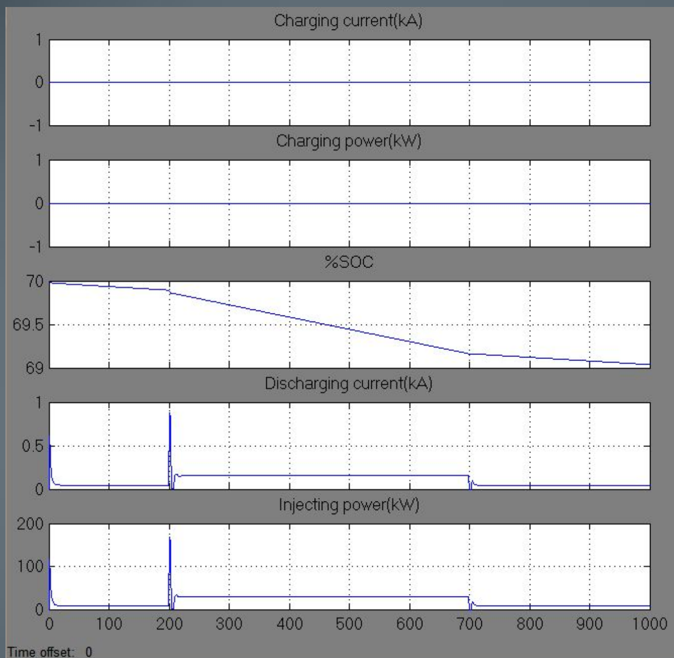
In top part, grid available power (kW) and DEG varying output (kW) (that changes from 300kW to 500kW) are shown. In the lower part dump load power (kW) is plotted for the case 5



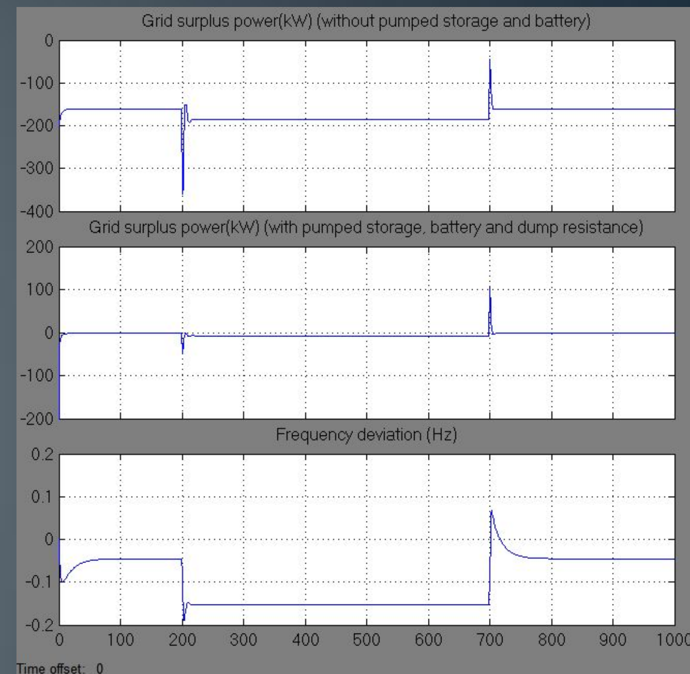
Pumping power (kW), pumping water flow (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) are plotted above for the case 5

Abrupt load change (500kW to 700kW at 200s and vice versa at 700s)	Steady in midrange (5m/s)	0.2Hz

Simulation Results:
Case 5- Abrupt load and Steady wind speed



BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and injecting power to the grid (kW) due to the discharging of the battery are plotted above for the case 5

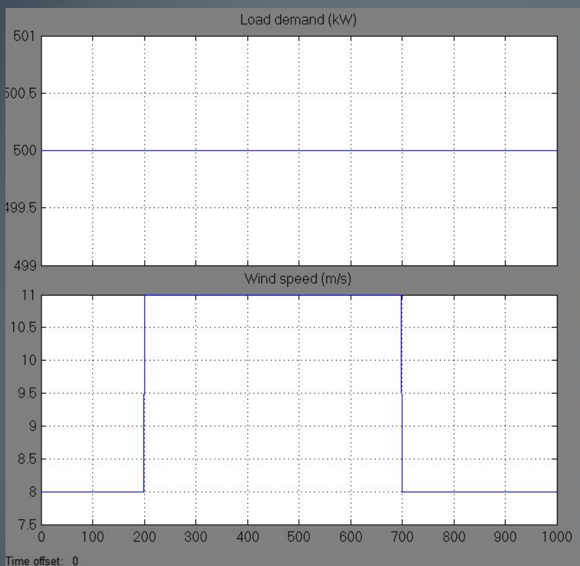


The grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation for the case 5

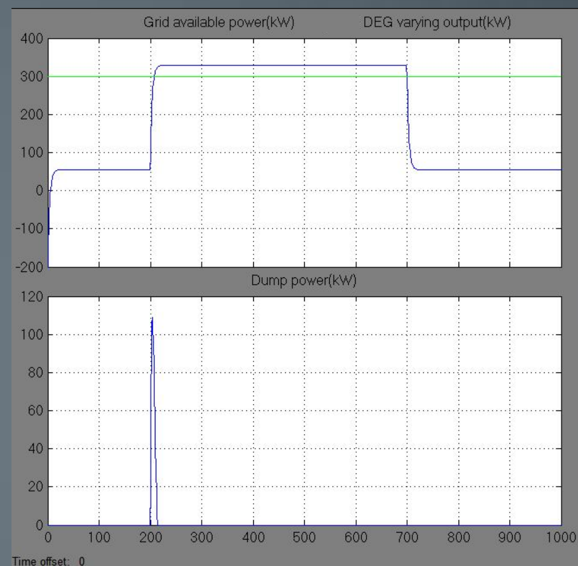
Abrupt load change (500kW to 700kW at 200s and vice versa at 700s)	Steady in midrange (5m/s)	0.2Hz

Simulation Results:

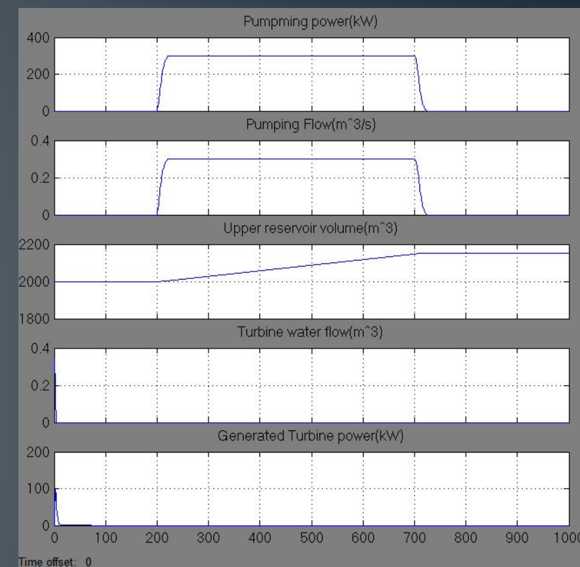
Case 6- Steady load and Abrupt wind speed



Load demand (kW) and wind speed (m/s) data for the case 6



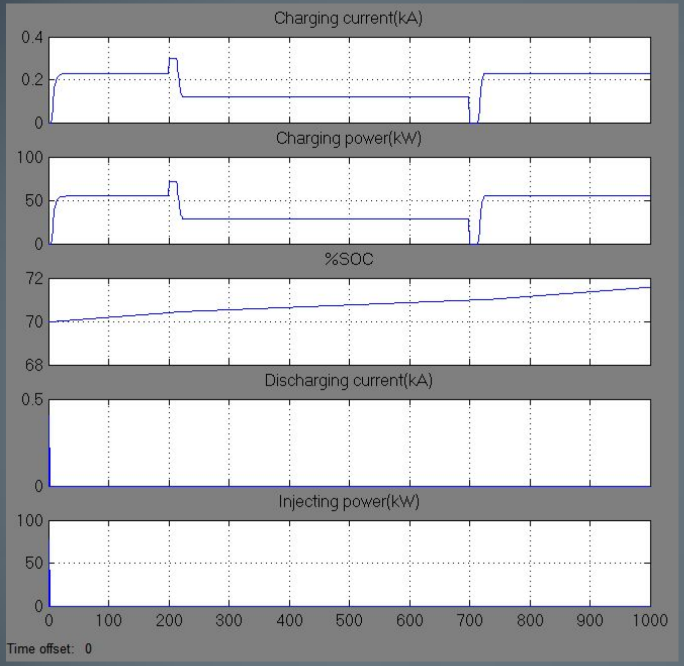
In the top part, grid available power (kW) and DEG varying output (kW) (with a flat 300kW) and in bottom part dump power (kW) is shown for the case 6



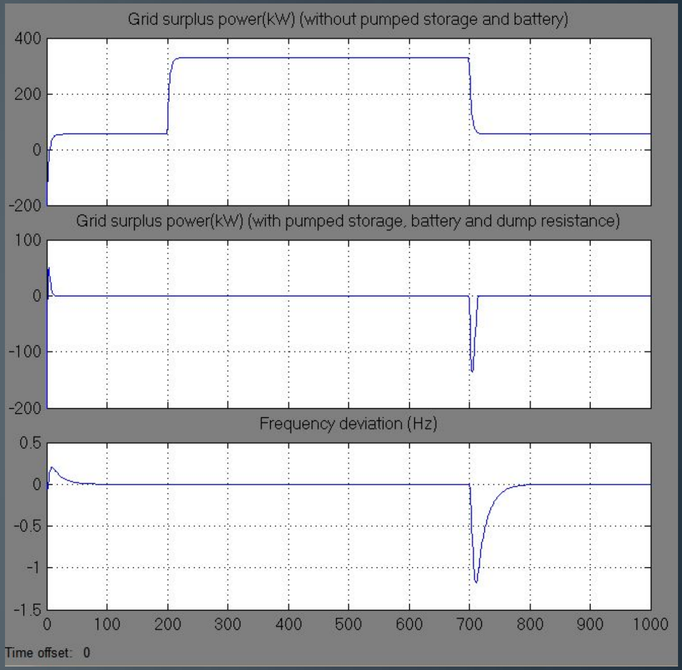
Pumping power (kW), pumping water flow (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) are shown above for the case 6

Steady in midrange (500kW)	Abrupt wind speed change (8m/s to 11m/s at 200s and vice versa at 700s)	1.1Hz

Simulation Results:
Case 6- Steady load and Abrupt wind speed



Charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and injected power to the grid (kW) due to the discharging of the battery are plotted above for the case 6



Grid surplus power (kW) with and without pumped storage, battery and dump resistance and the resultant frequency deviation are shown above for the case 6

Steady in midrange (500kW)	Abrupt wind speed change (8m/s to 11m/s at 200s and vice versa at 700s)	1.1Hz

Simulation Results: Outputs

Case	Load	Wind speed	Maximum frequency deviation
1	Low (200kW to 330kW)	Low (0m/s to 9m/s)	1.3Hz
2	Low (200kW to 330kW)	High (10m/s to 20m/s)	~0Hz
3	High (590kW to 990kW)	Low (0m/s to 9m/s)	0.9Hz
4	High (590kW to 990kW)	High (10m/s to 20m/s)	0.4Hz
5	Abrupt load change (500kW to 700kW at 200s and vice versa at 700s)	Steady in midrange (5m/s)	0.2Hz
6	Steady in midrange (500kW)	Abrupt wind speed change (8m/s to 11m/s at 200s and vice versa at 700s)	1.1Hz

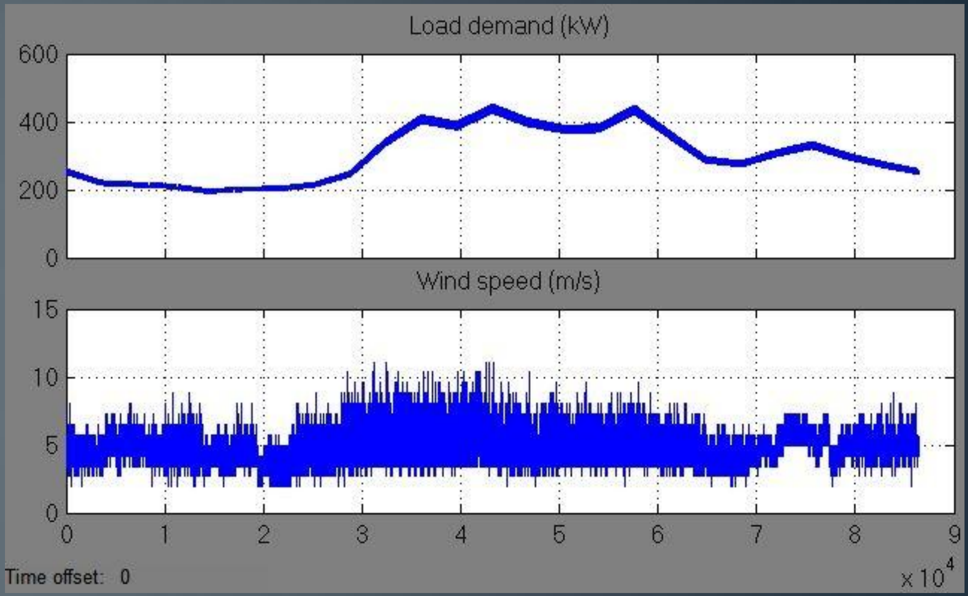
- For all conditions system frequency remain in acceptable range
- This deviations sustain for brief period only

Diesel consumption analysis for high penetration system

Simulation result and analysis

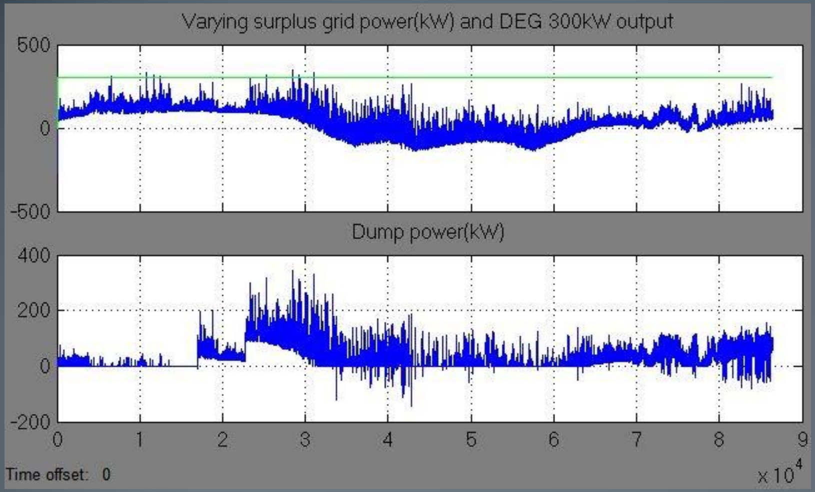
Diesel consumption analysis: Operation modes

MODES	DEG operation mode
Mode 1	Always ON
Mode 2	ON/OFF
	Continuous control
Mode 3	Minimum 10 min after last switching over

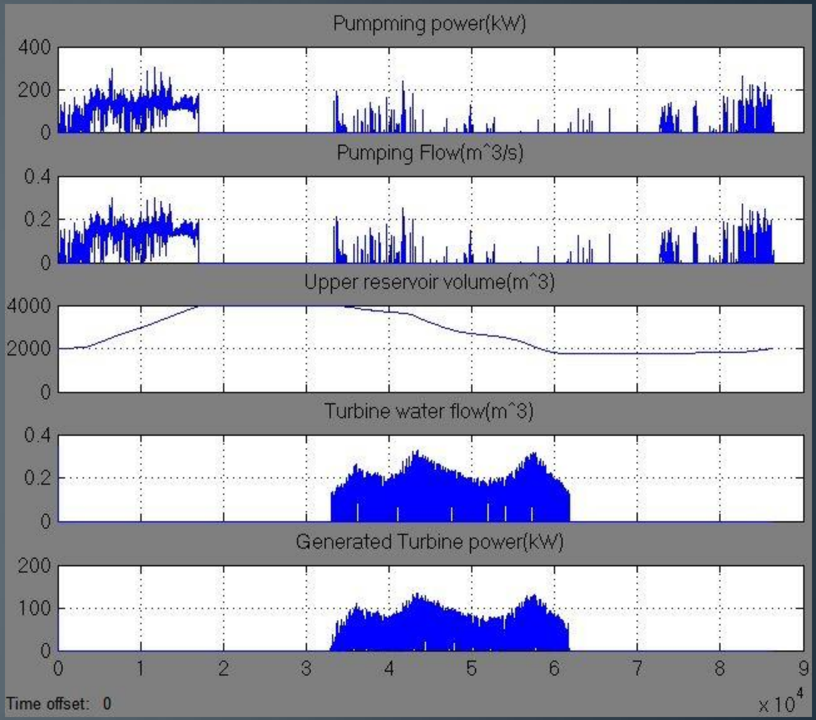


Load demand data and Wind speed data for one day (86400s), average wind speed 4.9ms^{-1} and load 303kW

Diesel consumption analysis: Simulation Outputs-Mode 1: Always ON

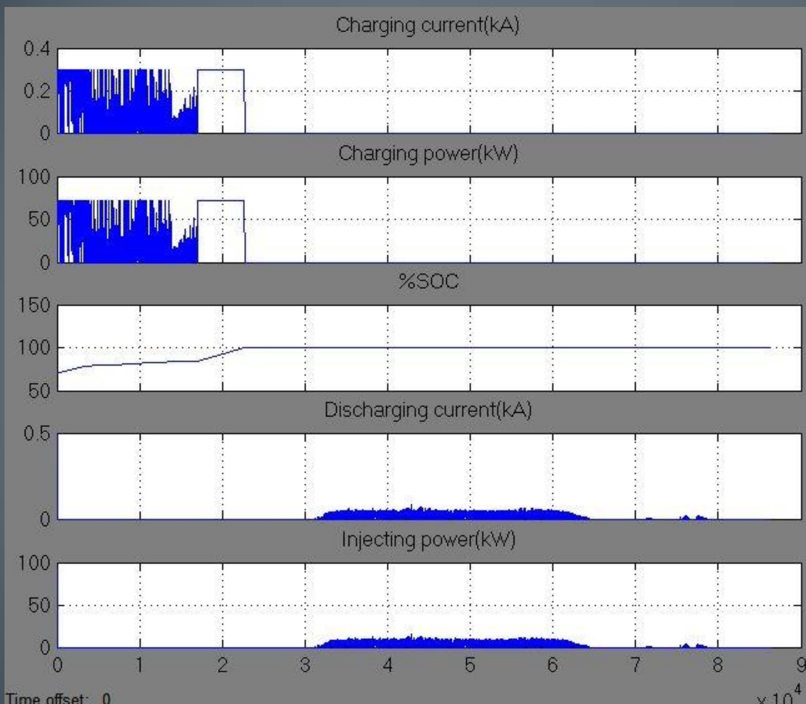


The grid available power (kW) and DEG output (kW) (with a minimum 300kW value) is shown and in the lower figure dump power (kW) is shown for mode 1

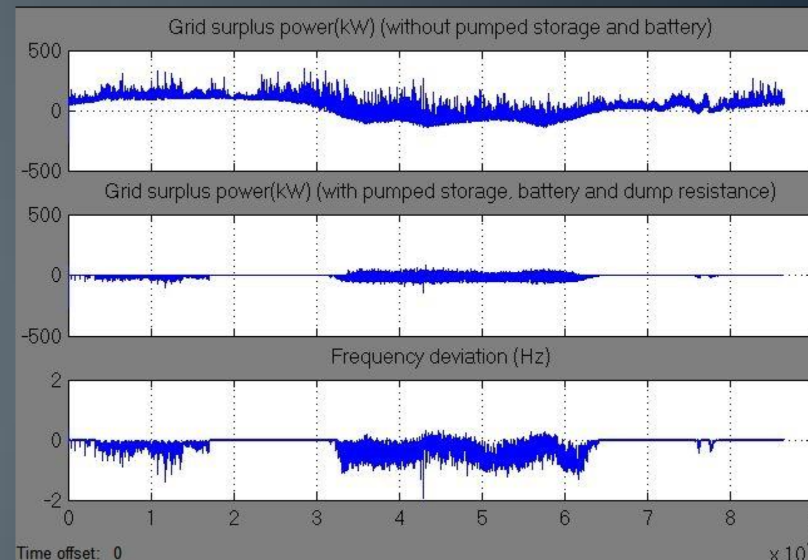


Pump power consumption (kW), pump water flow (m^3/s), the upper reservoir water volume (m^3), turbine water flow rate (m^3/s) and the turbine generated power (kW) for the Mode 1

Diesel consumption analysis: Simulation Outputs-Mode 1: Always ON

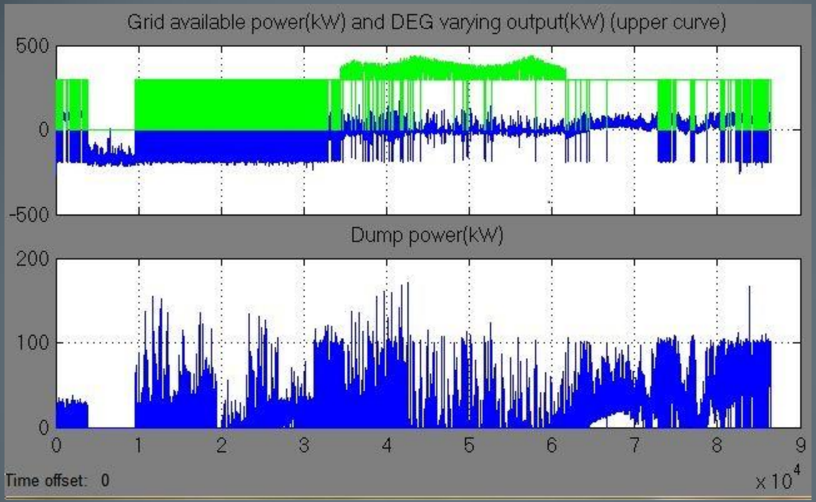


BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power to the grid (kW) due to the discharging of the battery are shown for the mode 1

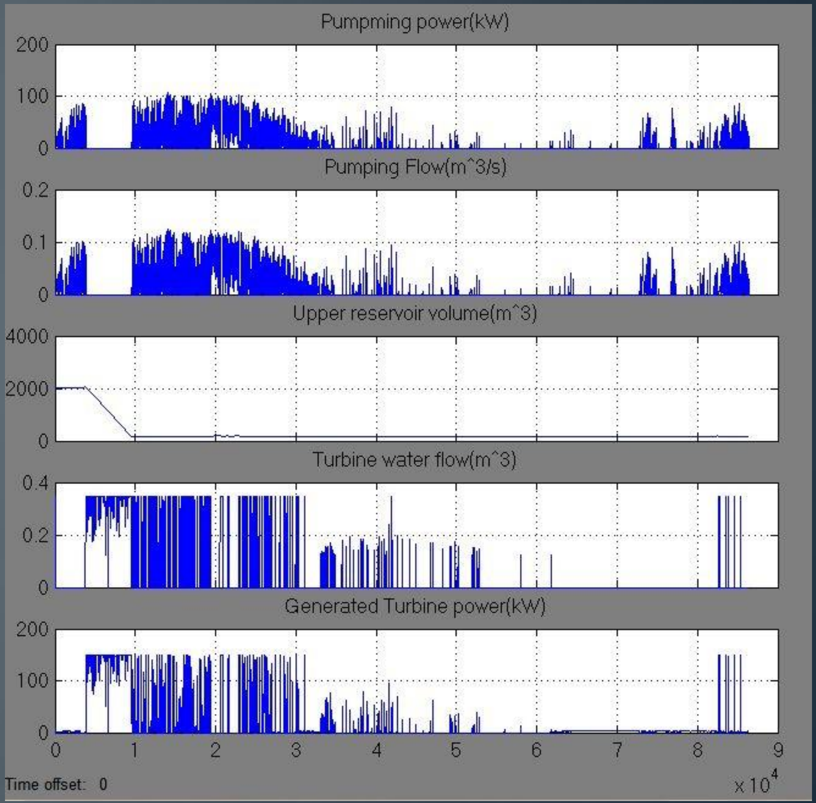


Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation for the mode 1

Diesel consumption analysis: Simulation Outputs-Mode 2: Diesel ON/OFF

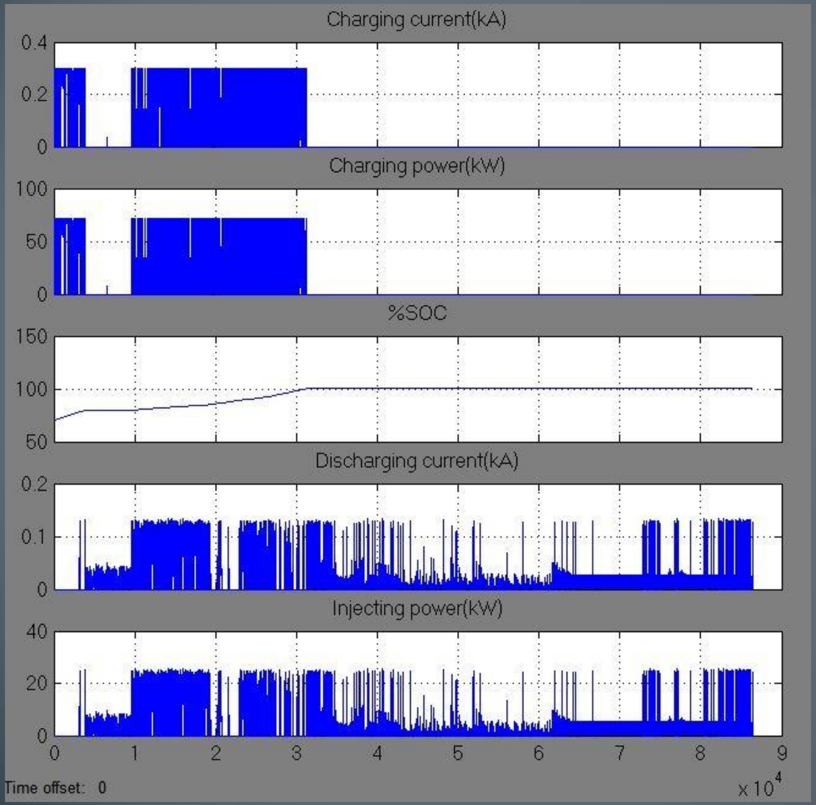


Grid available power (kW) and DEG output (kW) are shown and in the lower part dump power (kW) is shown for the mode 2

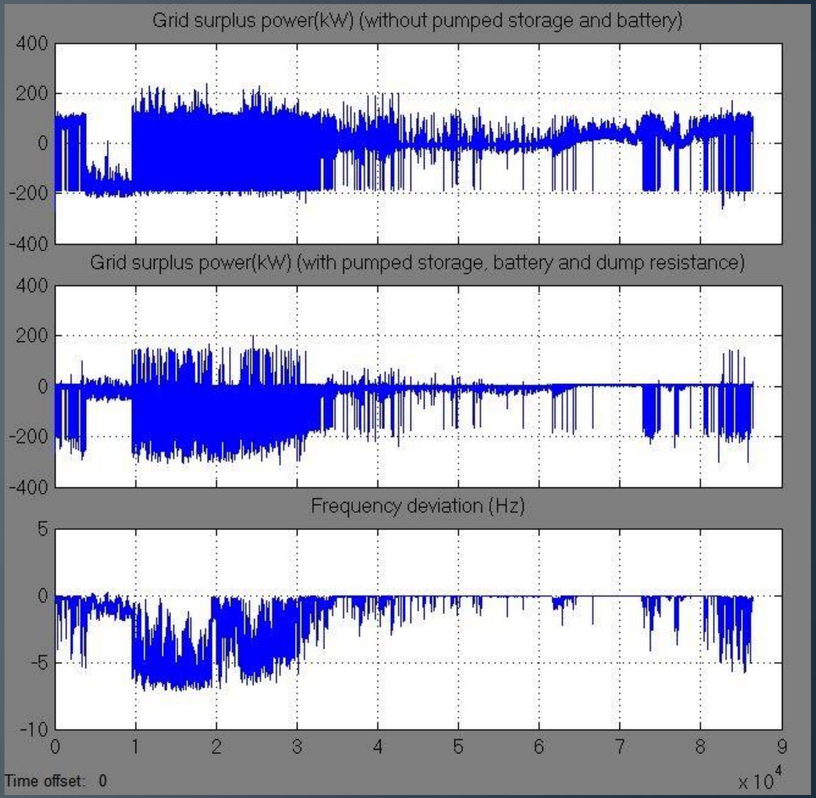


Pumping power (kW), pumping water flow rate (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) for the mode 2

Diesel consumption analysis: Simulation Outputs-Mode 2: Diesel ON/OFF

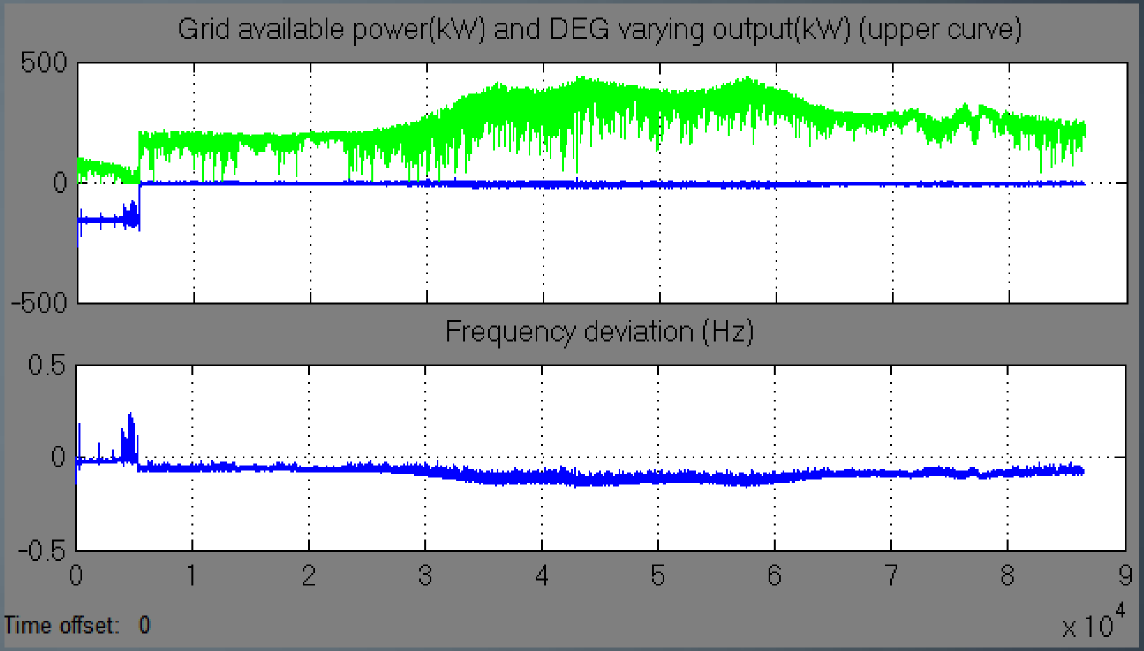


BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power injected to the grid (kW) due to the discharging of the battery are shown above for the mode 2



Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation are shown above for the mode 2

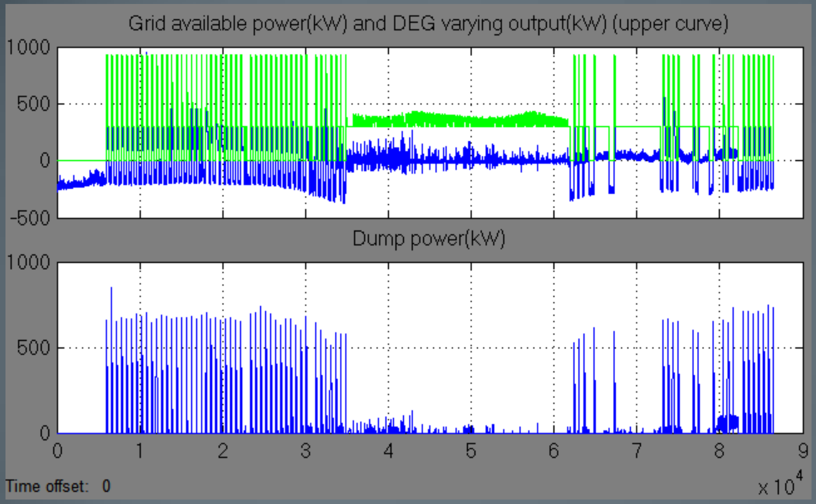
Diesel consumption analysis: Simulation Outputs-Mode 2: Cont. control



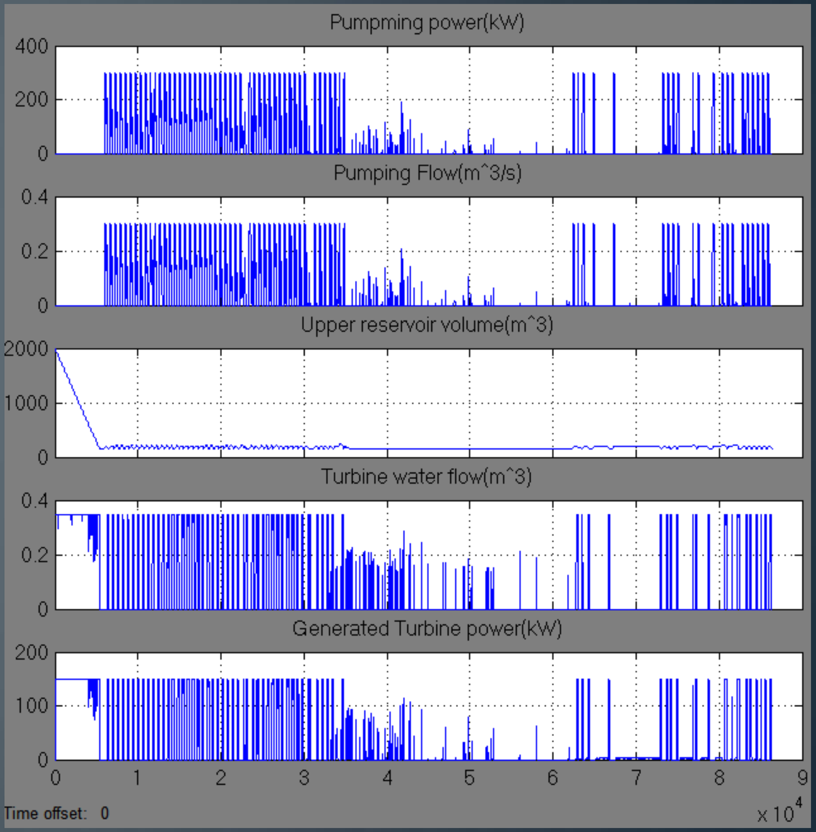
Grid available power (kW) and DEG output (kW) are shown and in the lower part the resultant frequency deviation (Hz) are shown for the continuous control of DEG in Mode 2

- Gives better system stability and consume almost same fuel as diesel ON/OFF mode
- Can be achieved by using a variable speed diesel with an AC-DC-AC link

Diesel consumption analysis: Simulation Outputs-Mode 3: Time constrained

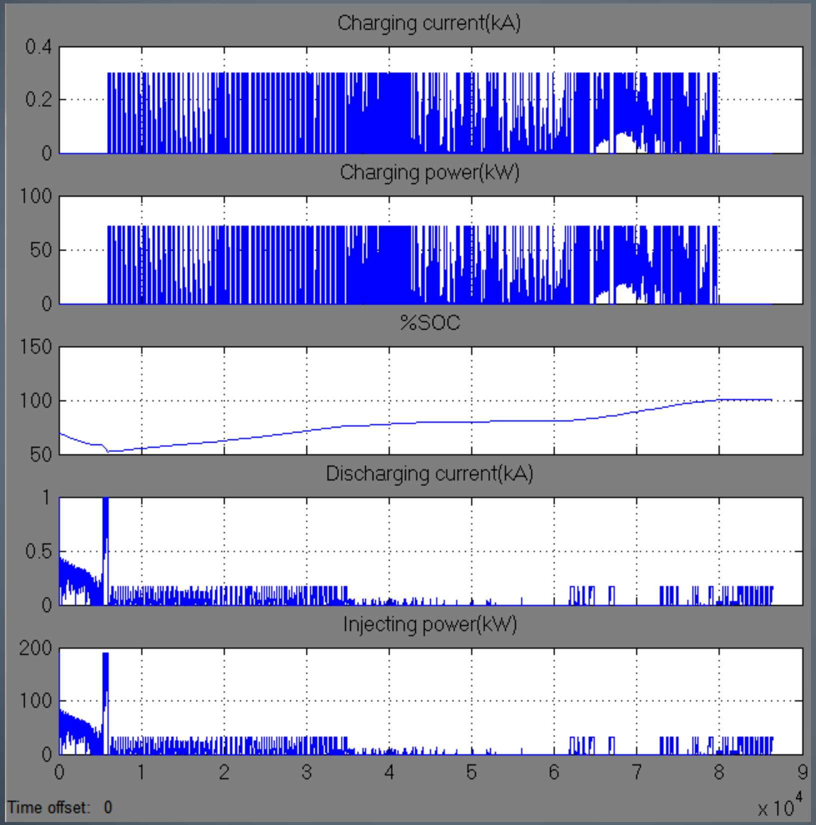


Grid available power (kW) and DEG output (kW) (with flat 300kW value) are shown and in the lower part dump power (kW) is shown for the mode 3

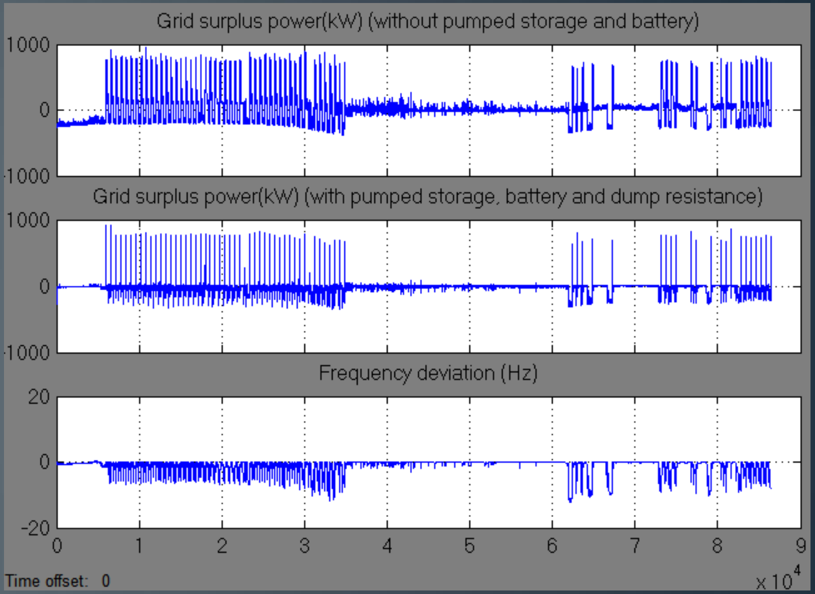


Pumping power (kW), pumping water flow rate (m^3/s), upper reservoir water volume (m^3), turbine water flow (m^3/s) and turbine generated power (kW) for the mode 3

Diesel consumption analysis: Simulation Outputs-Mode 3: Time constrained



BB charging current (kA), charging power (kW), percentage of state of charge, discharging current (kA) and the power injected to the grid (kW) due to the discharging of the battery are shown above for the mode 3



Grid surplus power (kW) with and without pumped storage, battery and dump load and the resultant frequency deviation are shown above for the mode 3

Diesel consumption analysis: Operation modes and results

MODES	DEG operation mode	Diesel Intake (Liter)	Maximum Frequency deviation (Hz)	No. of Switching
Mode 1	Always ON	2323	-1.5	0
Mode 2	ON/OFF	1866	-7	Many
	Continuous control	2039	-0.15	0
Mode 3	Minimum 10 min after last switching over	2110	-10	Less

Conclusion, Contribution and Future work

Conclusion, Contribution and Future work: Conclusion

✓ Faster simulation with simpler but detailed dynamic model and intelligent supervisory controller is possible

- A computer with Intel Core2Duo 2.1GHz processor and 4GB RAM takes only 30minutes to simulate any case for one day (86400 seconds)
- 1st order transfer function with all characteristics and dynamic losses

✓ Analyses for all extreme cases could be done

- Comprehensive case studies can be done with this dynamic model
- Analysis on different operational modes of diesel engine generator and their fuel consumption can be done

✓ Modified control of DEG is required for high penetration of wind energy

- Intelligent supervisory controller is required for complicated control strategies to operate the diesel engine generator

Conclusion, Contribution and Future work: Research Contribution

✓ Novel method for dynamic modeling

- Customized Simulink function blocks have been used
- Built-in Simulink blocks can be used with this function blocks

✓ Compatibility and flexibility

- For future extension of the hybrid system this model can be modified easily
- Different wind speed and load data can be used
- This model can be used to justify feasibility of a pumped hydro storage in a hybrid power system for a different location
- Changing any components requires only change on that particular block
- With adequate resources this model is able to simulate longer period of time e.g. few months to year

✓ Supervisory controller design and simulation

- Algorithm to control each components based on the capabilities, needs and priorities
- Complicated operation for diesel OFF high penetration operation

Conclusion, Contribution and Future work: Future Work

- ✓ Further development by integrating higher order models
  - Simulation time will increase considerably
  - May give better performance of the system and provide opportunity to analysis higher order transient responses.
- ✓ AC voltage and reactive power analysis
  - AC transient behavior e.g. phase angle, reactive power can be analyzed
  - Integration of synchronous condenser or variable capacitors can be done using
  - Controls of such system will be more complicated
- ✓ Other types of dynamic controllers
  - Fuzzy logic, neural network etc. can be used here as a future work to study possible improvement to the transient behavior of this model.
- ✓ This model can be experimented for other remote hybrid power systems and a detailed environmental impact analysis and economic analysis can also be done

Acknowledgements

- Dr. Tariq Iqbal
- The NSERC Wind Energy Strategic Network (WESNet); funded by industry and the Natural Sciences and Engineering Research Council of Canada (NSERC)
- School of Graduate Studies of MUN
- Faculty of Engineering and Applied Science of MUN
- My family and friends

Publications

- Paper published in the conference proceedings and presented in the *IEEE Newfoundland Electrical and Computer Engineering Conference* 2012, St. John's, Newfoundland and Labrador, Canada
- Poster presented on 3rd WESNet and CanWEA (Canadian wind Energy Association) poster sessions 2012
- Paper accepted for publishing in the *International Journal of Energy Science (IJES)*
- Paper accepted for presentation and publishing in the *conference IEEE Electrical Power and Energy Conference* 2013, Halifax, Nova Scotia, Canada.

Questions