Renewable Sources Based Micro-Grid Control Schemes and Reliability Modeling

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Doctor of Philosophy

By

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Outline

- **Introduction**
  - Micro-grid system and research objectives
- **Review and Critique**
  - Technology status and current research
- **System Behaviour Analysis**
  - System model, operational challenges and strategy
- **Controller Development and Evaluation**
  - Control challenges, designs, models, and tests
- **Reliability Assessment**
  - Reliability modeling and evaluation
- **Conclusion**
  - Contributions, future work and acknowledgment

- ***Introduction***
- Review and Critique
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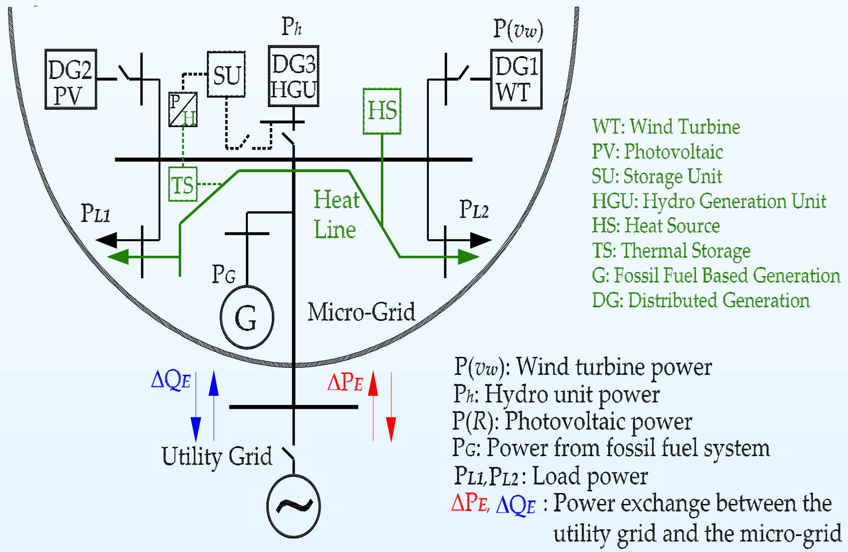
Micro-grid System

- Means of integrating a large number of distributed generation units



- *Why renewable source based micro-grid?*
- *What is renewable source based micro-grid?*

- Reliable power supply
- Power loss compensator
- Reduction in transmission system expansion
- Enhancement of renewable power penetration

Research Objectives

- To identify a system that contains renewable generations and has potential to operate in micro-grid
- To reveal the nature of technical issues related to stable operation of the micro-grid through system modeling
- To design and develop micro-grid controllers to maintain real and reactive power balance between generation and load during various operational modes of the micro-grid
- To develop a micro-grid test set up to verify the micro-grid controllers' performances
- To develop a micro-grid system reliability model to assess the reliability level of generating and supplying power by a micro-grid system that contains renewable generations

- Introduction
- ***Review and Critique***
- System Behaviour Analysis
- Controller Development and Evaluation
- Reliability Assessment
- Conclusion

Micro-Grid System: Technology Status

MG type	Source	RE fraction	Control			Storage	System
			$Cen.$	$Decen.$	$V\&f$		
GC [5]	RE & NRE	ND	Y	Y	Inverter	Assumed	Hypoth.
GC 1ϕ[35]	RE	100%	Y	Y	Inverter	Battery	Hypoth.
1^{st} NEDO[37]	RE & NRE	26%	ND	ND	Inverter	Battery	Hypoth.
2^{nd} NEDO[37]	RE	100%	ND	ND	Inverter	Battery	Hypoth.
3^{rd} NEDO[37]	RE & NRE	13%	ND	ND	Inverter	Battery	Hypoth.
GC [39]	RE & NRE	25%	ND	ND	Inverter	Assumed	Bench.
Isolated [3]	RE & NRE	ND	Y	Y	Generator	Hydrogen	Real
GC [41]	RE & NRE	60%	ND	Y	Inverter	ND	Hypoth.
GC[42]	RE & NRE	40%	ND	Y	Generator	Assumed	Hypoth.
GC [44]	RE	100%	ND	Y	Inverter	Battery	Hypoth.
GC [45]	RE	100%	ND	ND	ND	Hydro	Prop.
GC[3]	RE	100%	Y	ND	Generator	ND	Real

RE$\longrightarrow$ Renewable; NRE$\longrightarrow$ Non-renewable; ND$\longrightarrow$ Not defined; *Decen.*$\longrightarrow$ Decentralized; *Cen.*$\longrightarrow$ Centralized; Hypoth.$\longrightarrow$ Hypothetical; Bench.$\longrightarrow$ Benchmark; Prop.$\longrightarrow$ Proposed.

Modeling and Control of Micro-Grid System

- Micro-generations in a micro-grid system modeled without accounting the dynamics of the primary energy sources (simply assumed as a DC source)
- Micro-grid controller design without considering the dynamics and uncertainties of the input energy sources
- Because of the droop characteristics, the micro-grid system frequency and voltage might drop to such a value that all micro-generations will operate to newer values that are different from the nominal values
- Most of the past research has been carried out based on simulation study

Micro-grid Reliability Evaluation

- Reliability assessment of power generation and supply by a micro-grid system is not found in literature (System containing renewable micro-generation)

- Introduction
- Review and Critique
- ***System Behaviour Analysis***
- Controller Development and Evaluation
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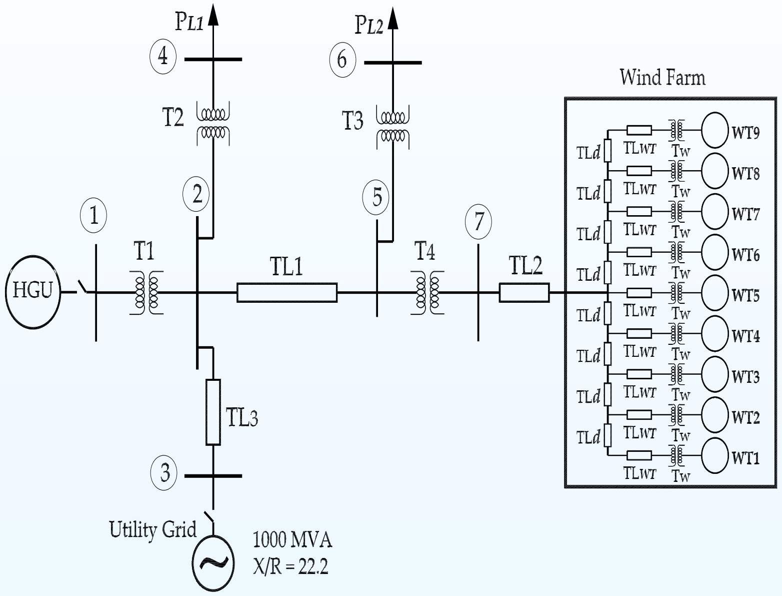
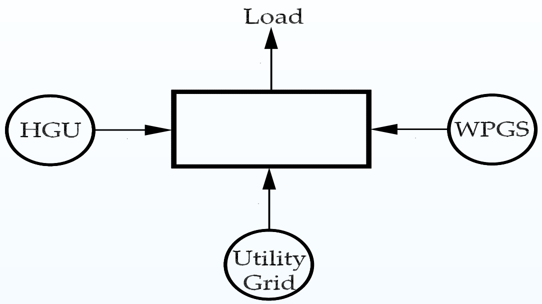
System Overview



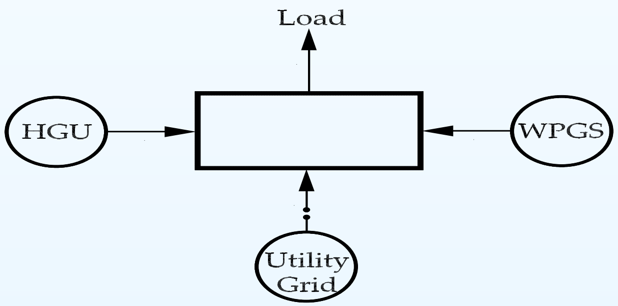
The power balance in the micro-grid system

$$\Delta P_E = P(v_\omega) + P_h - P_{L1} - P_{L2}$$

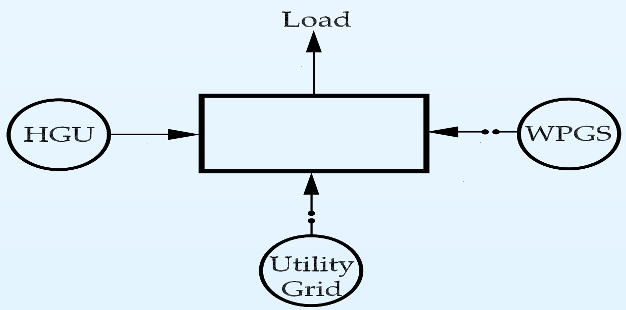
$$\Delta Q_E = Q(v_\omega) + Q_h - Q_{L1} - Q_{L2}$$



Grid connected system



Isolated system with wind power generation



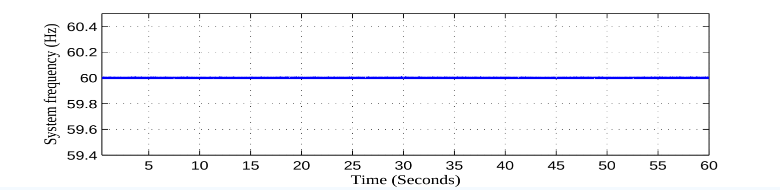
Isolated system without wind generation

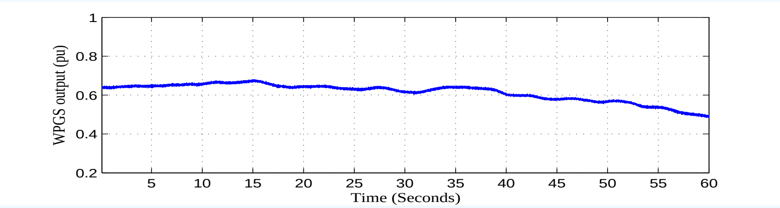
Component model of the micro-grid system

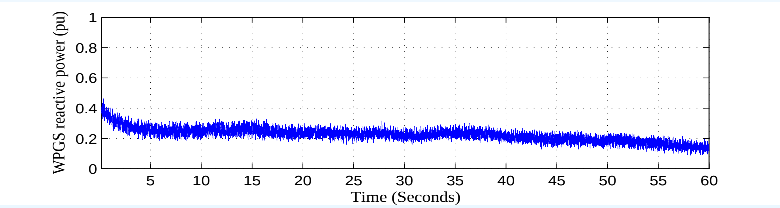
- 9 dynamic models of variable-speed wind energy conversion systems
- a variable pitch wind turbine, induction generator and converter control with maximum power extraction (*using 3.3-3.51*)
- a synchronous generator, a hydro turbine, and turbine governor and excitation system (*using 3.52-3.95*)
- line, transformer and load models are obtained from the Matlab/Simulink library
- Variable wind speed profile is the disturbance input to the wind turbine system
- Water flow is the input disturbance to the hydro turbine

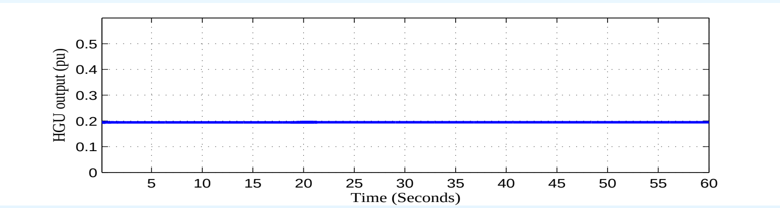
System performance

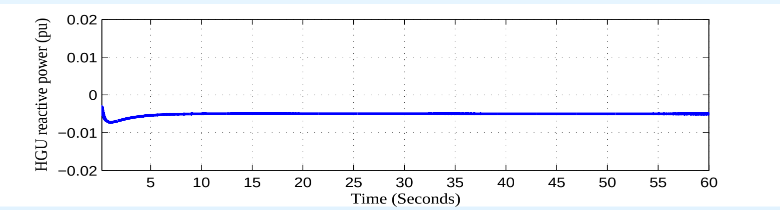
Grid connected system (Mode-I)

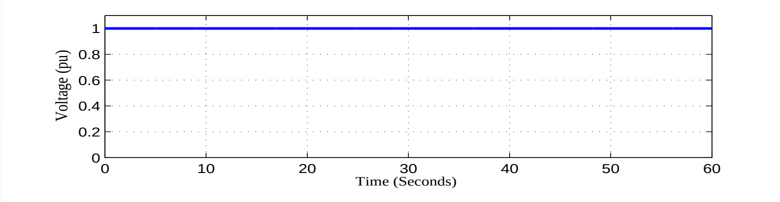


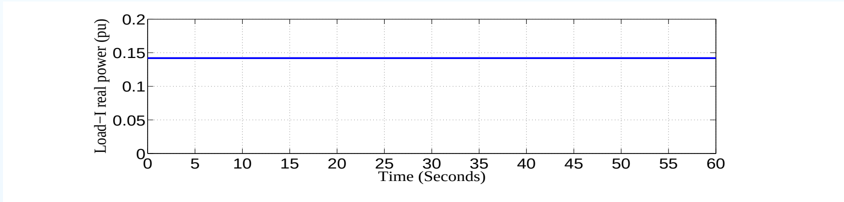


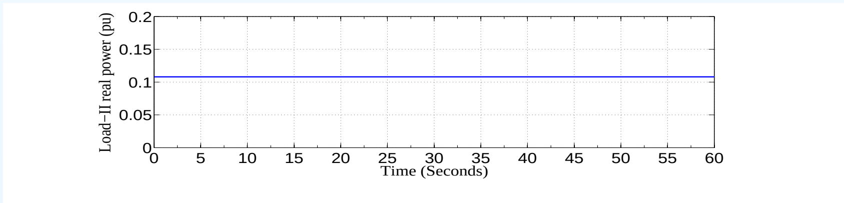








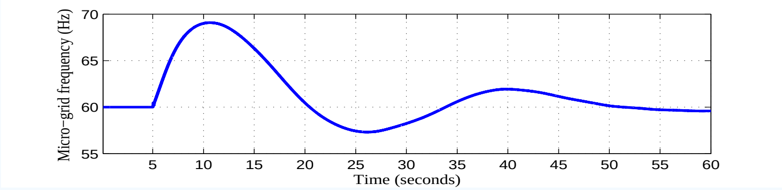


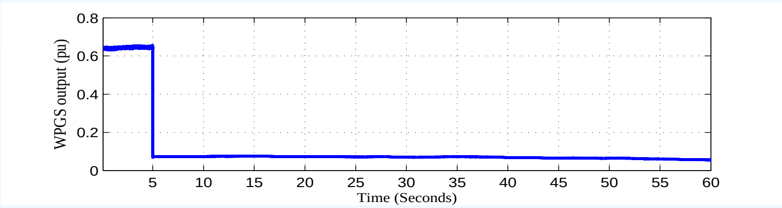


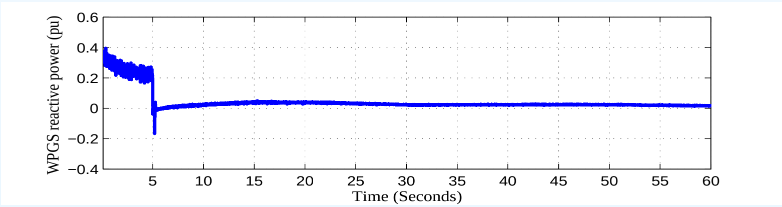
- System voltage and frequency maintained by the utility grid
- HGU operates at its rated value, however, WPGS output varies as wind varies

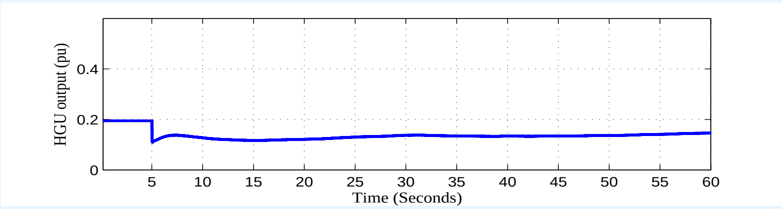
System performance

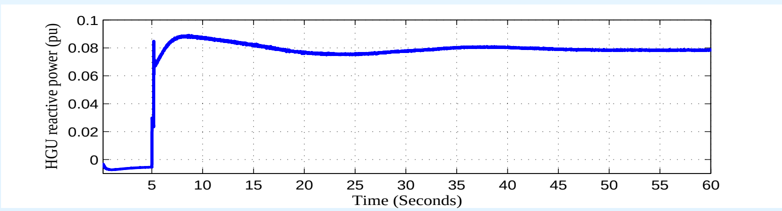
Isolated system with wind power generation (Mode-II)

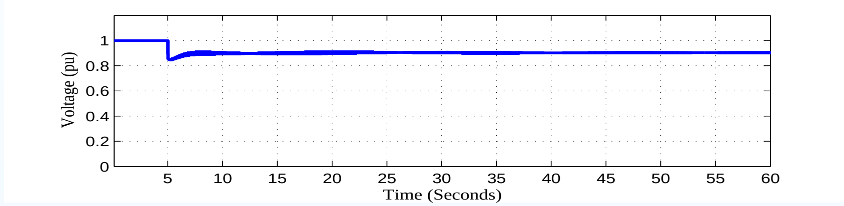


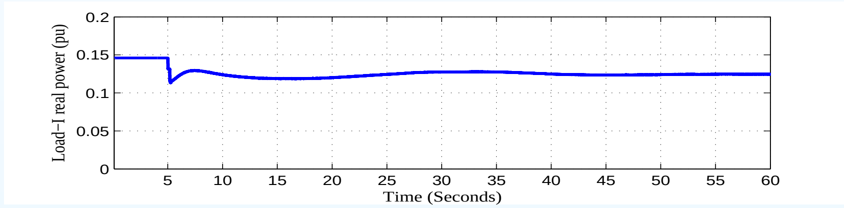


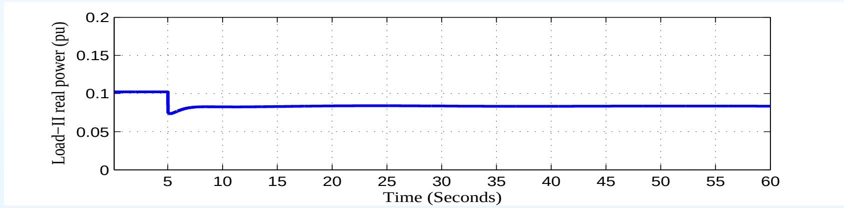








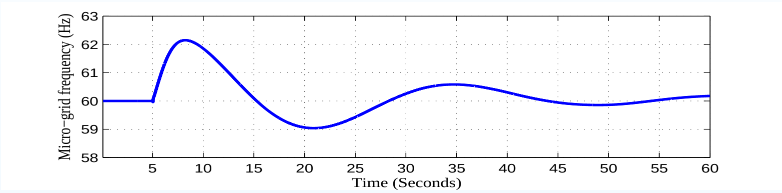


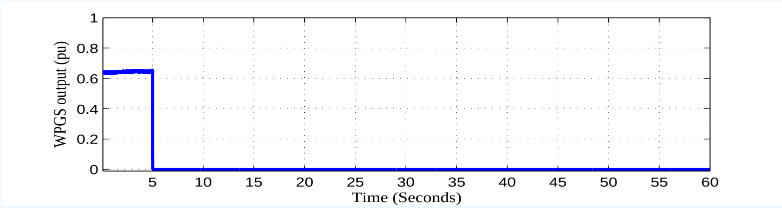


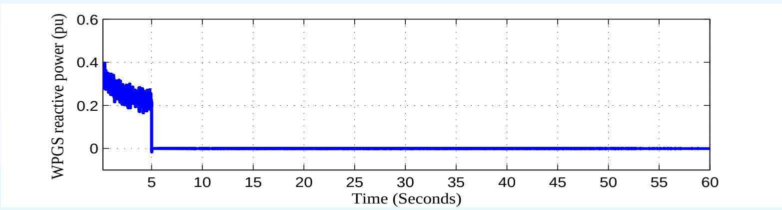
- System frequency deviation is significantly high, causing the generator to trip.
- Lack of sufficient reactive power results in lower system voltage.

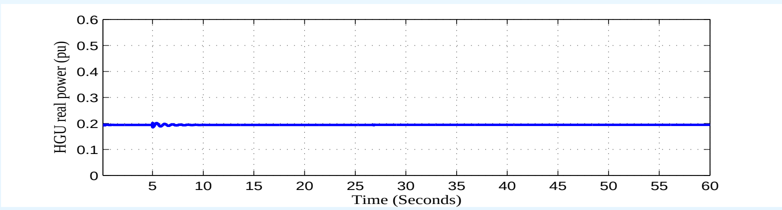
System performance

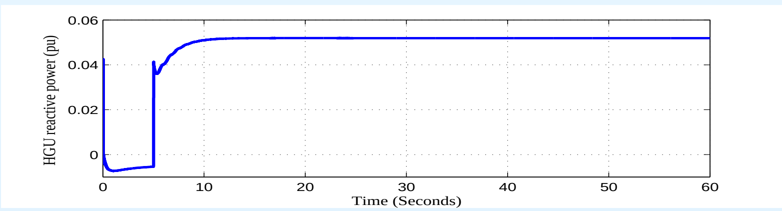
Isolated system without wind power generation (Mode-III)

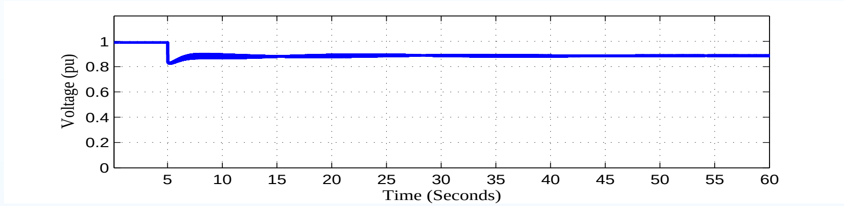


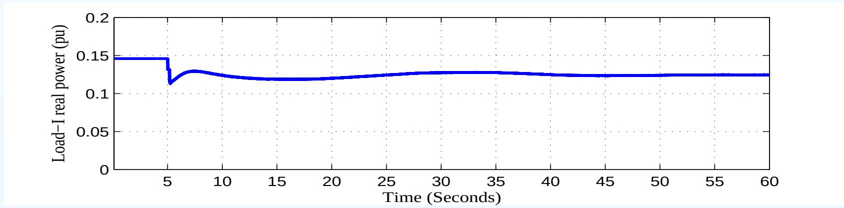


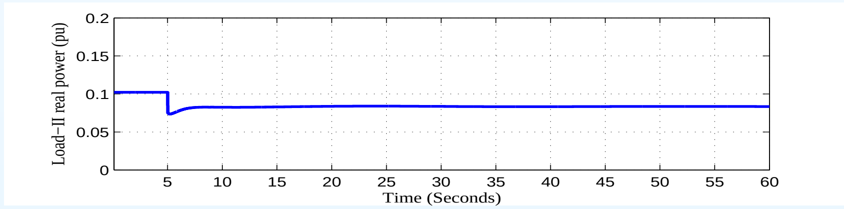






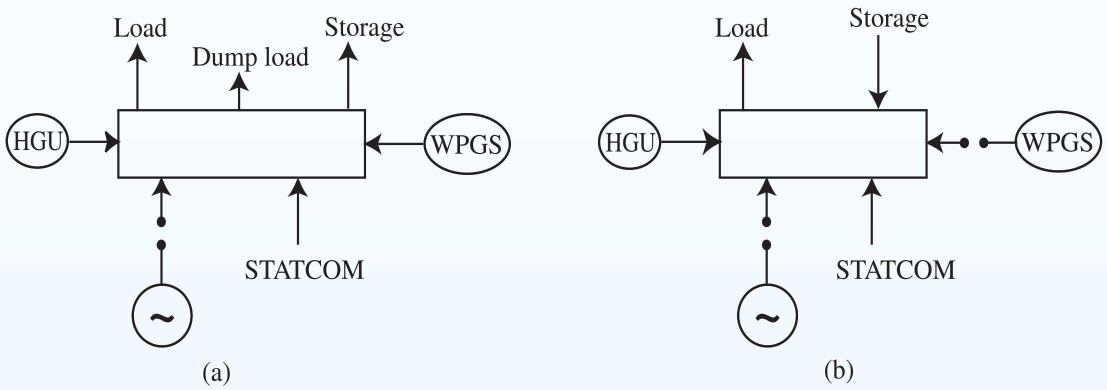






- The system frequency deviation is less compared to Mode-II.
- Insufficient reactive power causes the system voltage to drop to lower value than the rated value.

Micro-grid operational and control requirements



(a) Isolated micro-grid with wind power generation

- active power shaping using dump load and storage
- reactive power adjustment using statcom

(b) Isolated micro-grid without wind power generation

- active and reactive or only active power adjustment from storage
- reactive power adjustment using statcom and active power adjustment from storage

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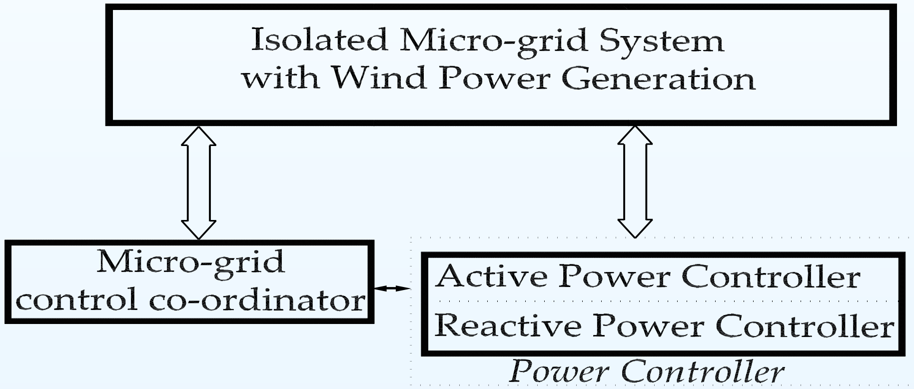
Controller: Isolated micro-grid with wind power generator

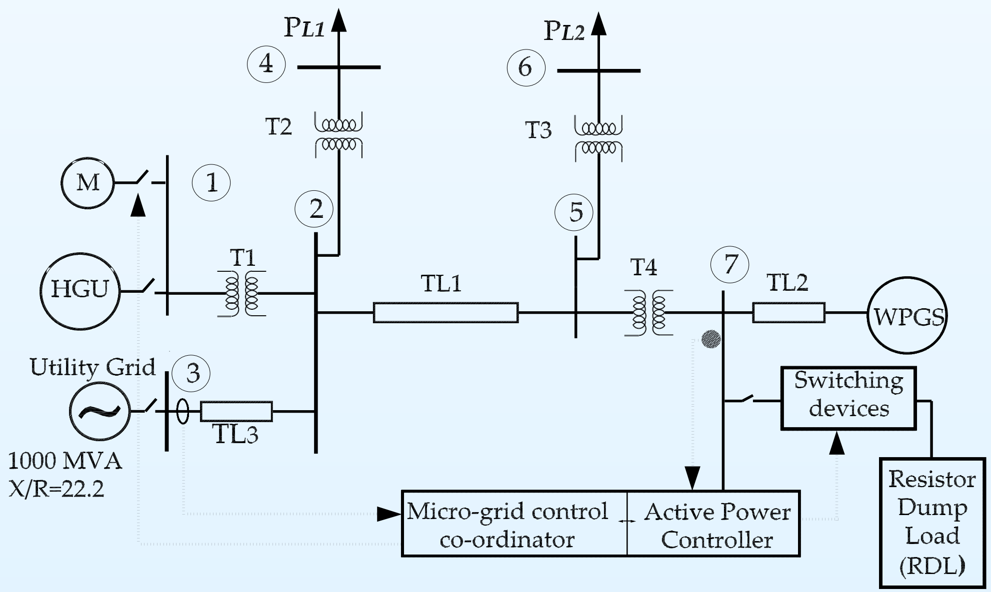
- Control overview



- Objective
  - To adjust the active power such that the micro-grid frequency is maintained at its rated value and shows acceptable steady-state and transient performance

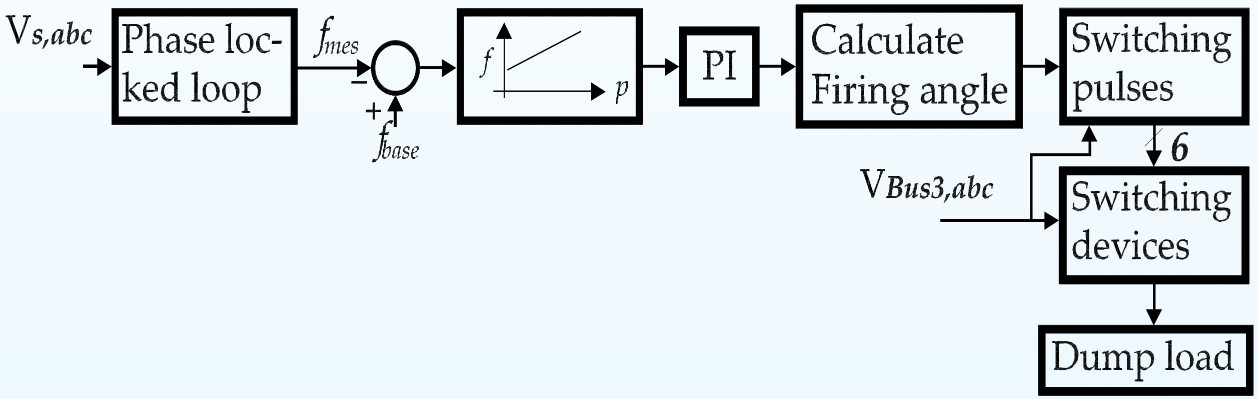
Controller: Isolated micro-grid with wind power generator

- Design considerations
  - Operate the wind turbines at their optimal efficiency
  - Large scale energy storage
  - Increase overall system efficiency
- Active power controller



Controller: Isolated micro-grid with wind power generator

- Active power controller



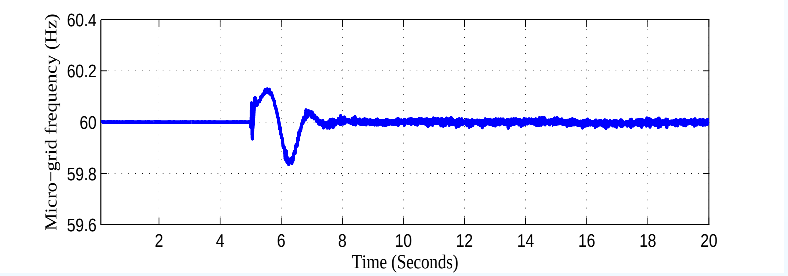
  - $\Delta P = -\frac{1}{D_c}(f_{base} - f_{mes})$
  - control signal, $u_{cs} = \Delta P \left(k_p + \frac{k_i}{s}\right)$
  - firing angle $\alpha = \begin{cases} -69 \times u_{cs} + 87^0 & \text{for } 1 \geq u_{cs} \geq 0 \\ 69 \times u_{cs} + 87^0 & \text{for } 0 \geq u_{cs} \geq -1 \end{cases}$

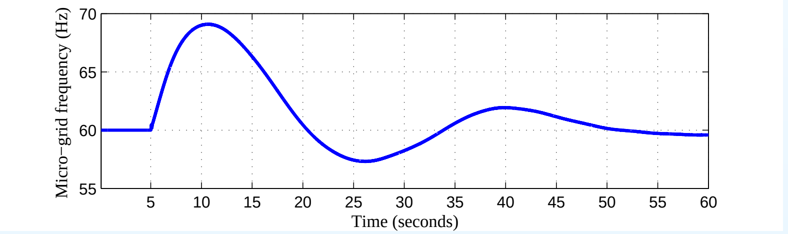
Controller: Isolated micro-grid with wind power generator

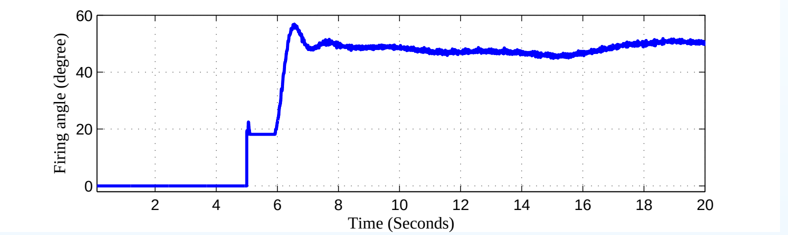
- Active power controller: *Overall model*
  - implemented in Matlab/Simulink
  - maximum possible power generation and load in micro-grid determines the size of the dump load
  - disturbance inputs are utility grid disconnection, stochastically varying wind velocity, step increase or step decrease in load power
  - control variable is the micro-grid system frequency
  - manipulated variable is the current, and output variable is the thyristor firing angle

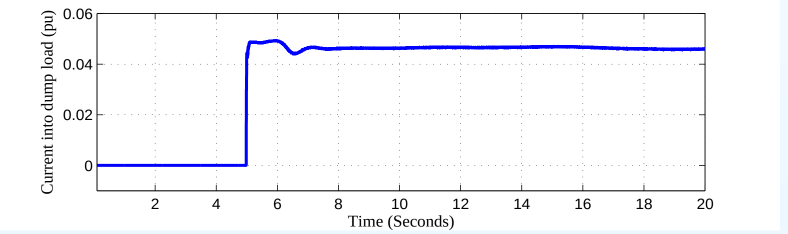
Controller: Isolated micro-grid with wind power generator

- Active power controller: *Performances*
  - Micro-grid frequency
  - Firing angle and dump load current





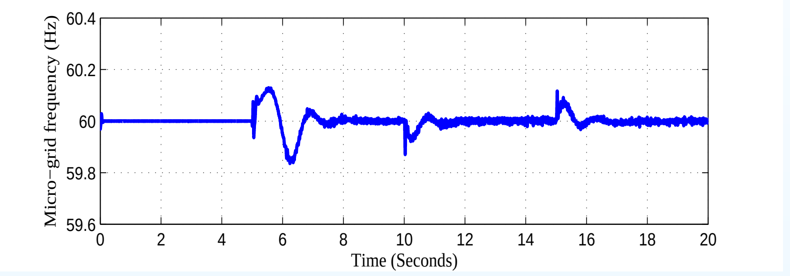


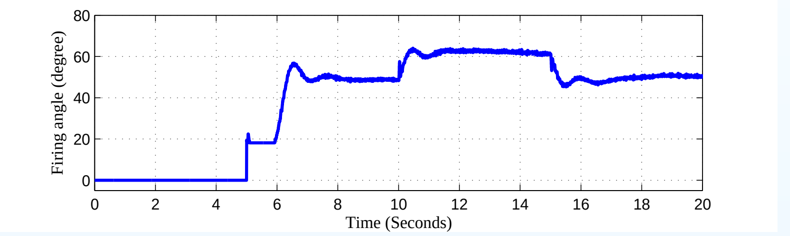


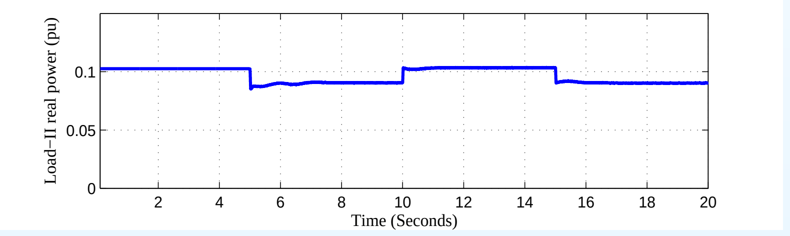
- Micro-grid system frequency deviates within acceptable range during the utility-grid disconnection
- The system frequency retains its rated value in subsequent operation
- Fast and stable change in controller output allows smooth variation in manipulated variable

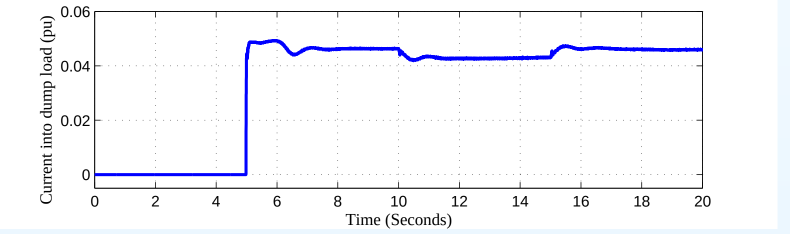
Controller: Isolated micro-grid with wind power generator

- Active power controller: *Performances*
  - Micro-grid frequency
  - Firing angle and dump load current





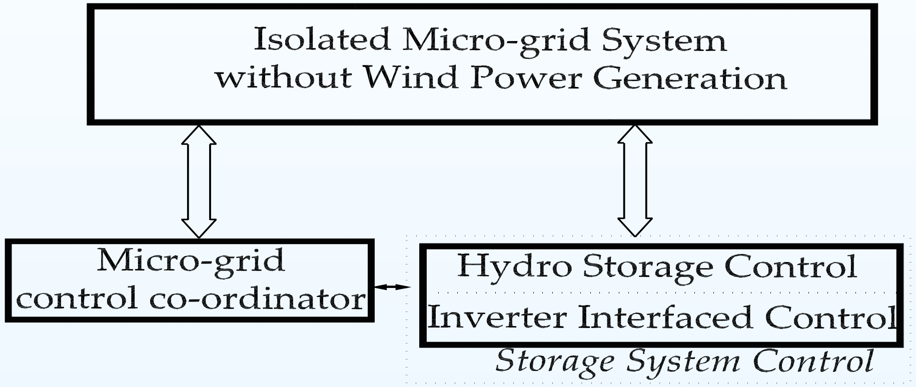




- Step change in load is chosen according to the load variation characteristics in the system
- The system frequency settles back to its rated value after a load disturbance
- Dynamically stable; change in controller output leads to stable power adjustment.

Controller: Isolated micro-grid without wind generator

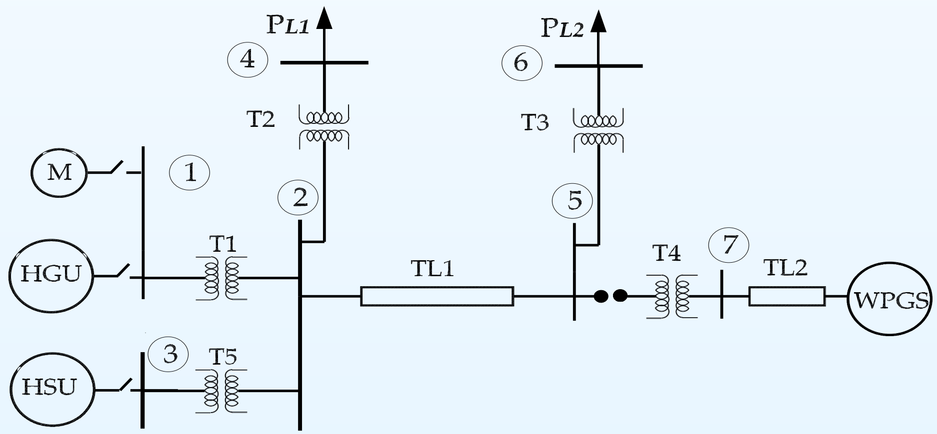
- Control overview



- Objective
  - To regulate frequency and voltage of the isolated micro-grid system during insufficient wind
- Design considerations
  - Insufficient wind speed results no power from wind generators
  - Effective response time to accommodate new power commands

Controller: Isolated micro-grid without wind generator

- Pumped hydro storage
  - Capable of storing large amount of power
  - Available reservoir can be utilized to pump water
- Pumped hydro storage: *Design and Control*

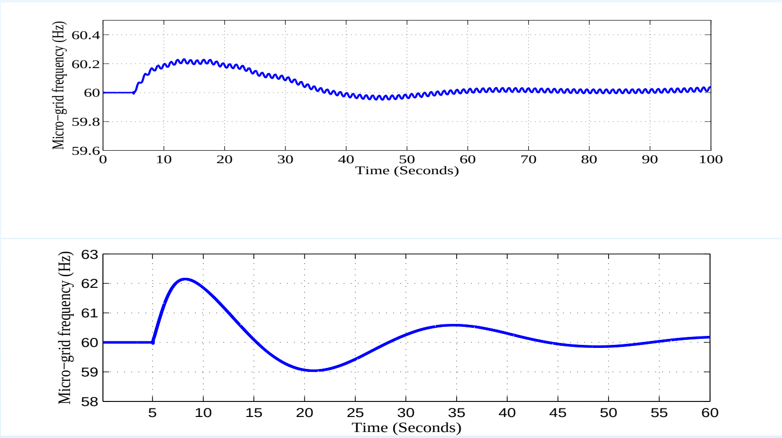


  - Topological similarity is applied to choose the control of the HSU
  - Modify the controllers parameter to achieve the control objective

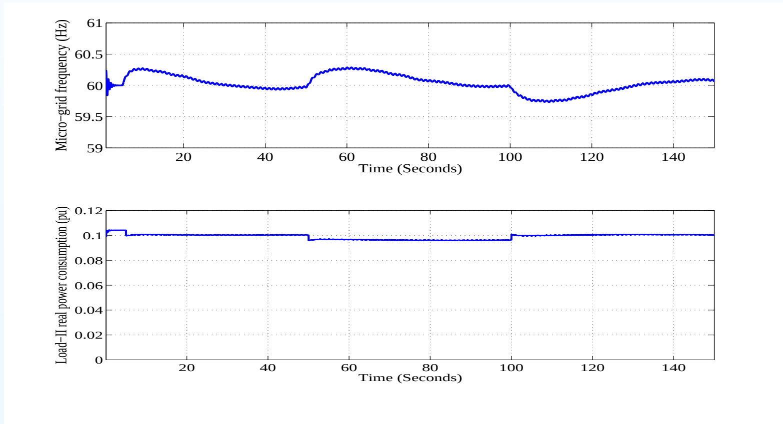
Controller: Isolated micro-grid without wind generator

Hydro storage control: *Overall model and performance*

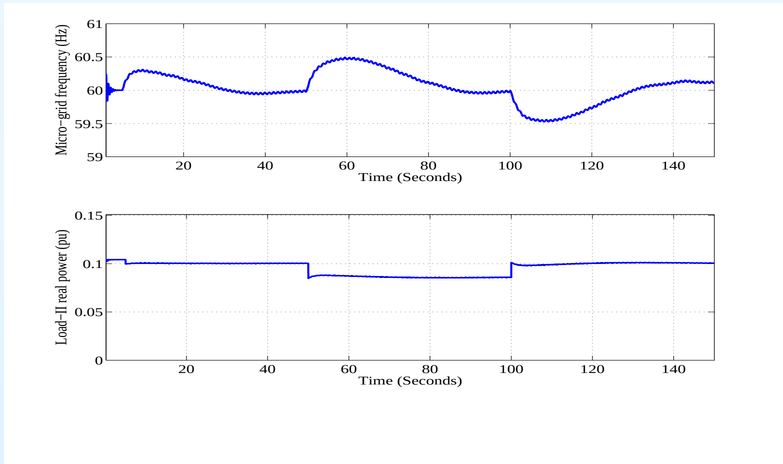
- implemented in Matlab/Simulink
- disturbance inputs are utility-grid disconnection and step change in load
- control variable is the micro-grid system frequency



- step change by 2% of load

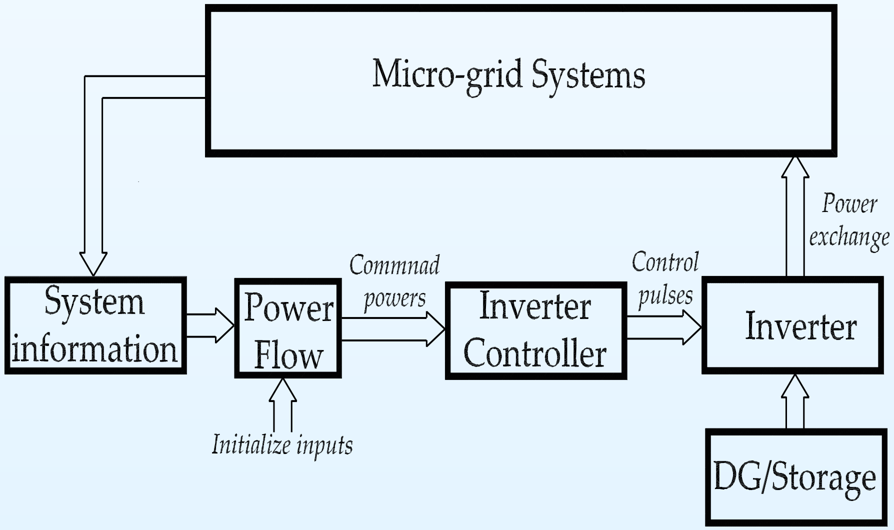


- step change by 7.5% of load



Controller: Isolated micro-grid without wind generator

- Design considerations
  - Effective on-demand, discrete time power adjustment
  - Fast and stable response to accommodate new power commands
- Controller overview
  - Power flow based micro-grid controller (PFMC)



Controller: Isolated micro-grid without wind generator

Power Flow Based Micro-grid Controller

- $d - q$-axis Power Flow
  - Available PF methods analyze power systems assuming that they have to be perfectly balanced 3ϕ and active power generated by each PV bus is known
  - Such assumptions may not be accurate for buses with DG unit that operates in various modes and produces power from stochastically varying primary energy sources
  - The random variation in primary energy sources can also lead to bus type conversion.
  - DG output powers can be determined using $d - q$-axis voltage and current components on the output side of the converter

Controller: Isolated micro-grid without wind generator

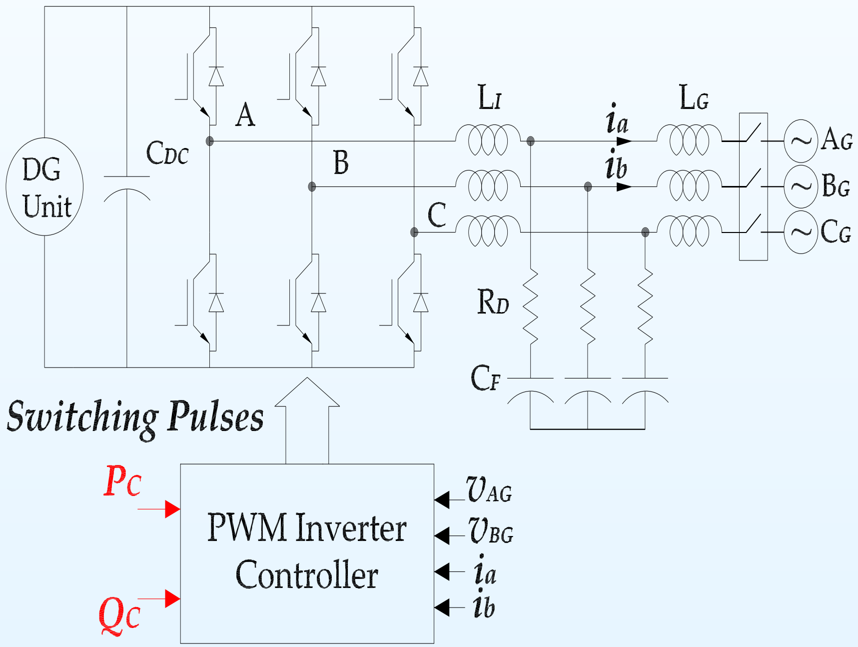
Power Flow Based Micro-grid Controller

- Formulation of $d-q$-axis Power Flow
  - Mathematical analysis and formulation of $d-q$-axis power flow is performed according to (4.13-4.43)
- Implementation of the $d-q$-axis Power Flow in Controller
  - The step by step procedure to implement the $d-q$-axis power flow into the controller is described in section 4.4.2 in the thesis
  - Outcomes of the power flow calculation determine the command power, P_C and Q_c for the inverter controller

Controller: Isolated micro-grid without wind generator

Power Flow Based Micro-grid Controller

- Inverter control

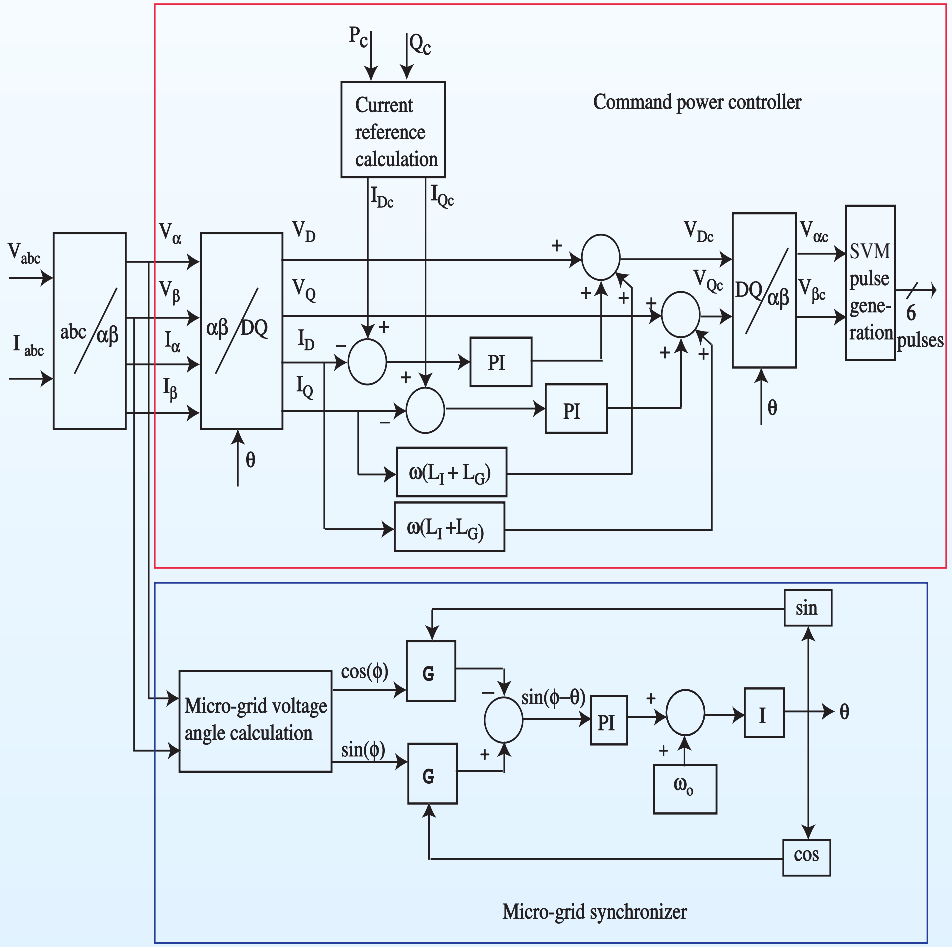


- Power from storage to an input of the micro-grid side inverter is assumed as a DC source
- Focus is to control the inverter to maintain command power flow from storage to the micro-grid
- Also synchronization between the storage and micro-grid

Controller: Isolated micro-grid without wind generator

Power Flow Based Micro-grid Controller

- Inverter control structure



- Current references:

$$I_{Dc} = \frac{P_c - V_Q I_{Qc}}{V_D}$$

$$I_{Qc} = \frac{Q_c V_D + P_c V_Q}{V_D^2 + V_Q^2}$$

- Micro-grid voltage angle

$$cos\phi = \frac{V_\alpha}{V_\alpha^2 + V_\beta^2}$$

$$sin\phi = \frac{V_\beta}{V_\alpha^2 + V_\beta^2}$$

- $sin(\phi - \theta)$ can be reduced to a value that allows synchronization based on the fact that $sin(\phi-\theta) \cong (\phi-\theta) = \Delta\theta$

Controller: Isolated micro-grid without wind generator

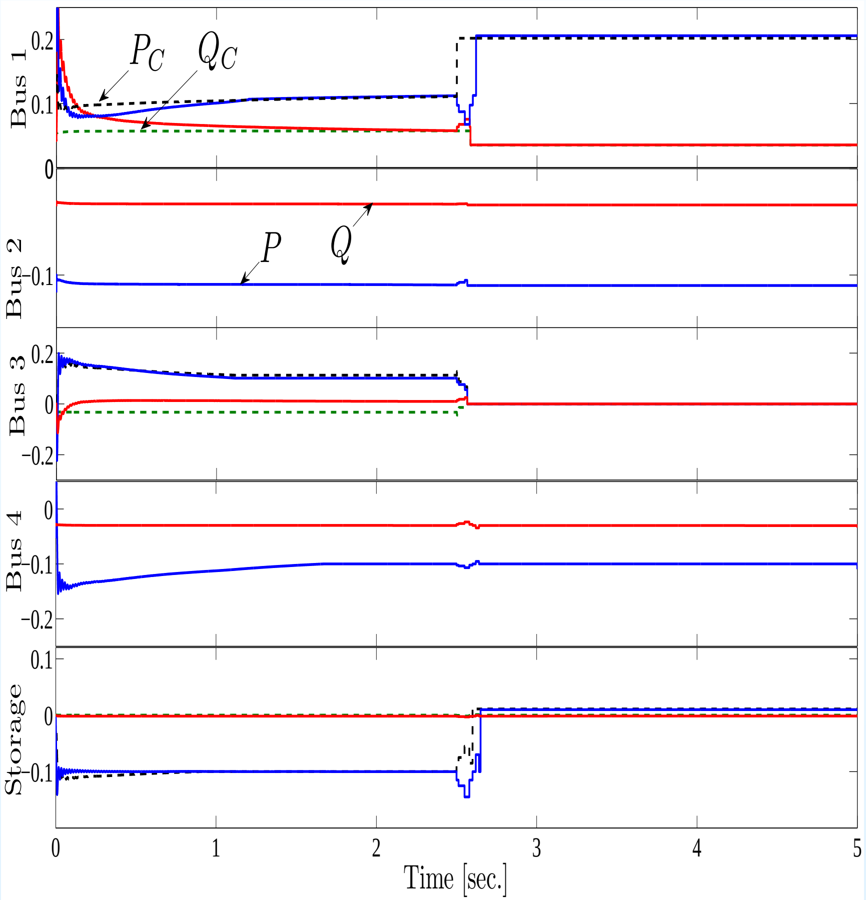
Power Flow Based Micro-grid Controller: *Overall model*

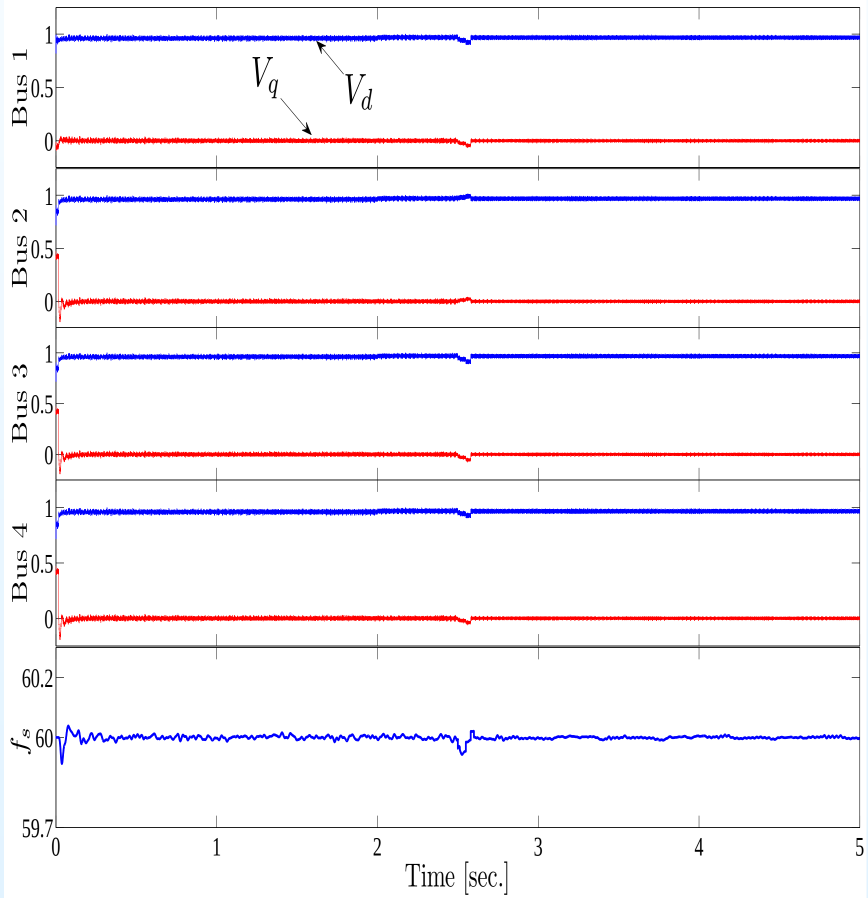
- Implemented in Matlab/Simulink
- $d-q$-axis power flow is realized using a Matlab code
- Inverter control is accomplished using Simulink model
- Closed loop study is carried out by employing $d-q$-axis power flow and the control of the inverter
- Control performances represent the dynamic condition of the micro-grid system along with power adjustment in the system
- Simulation study is performed for grid-connected and isolated modes of operation

Controller: Isolated micro-grid without wind generator

Power Flow Based Micro-grid Controller: *Performances*

- Isolated micro-grid with wind generator disconnection

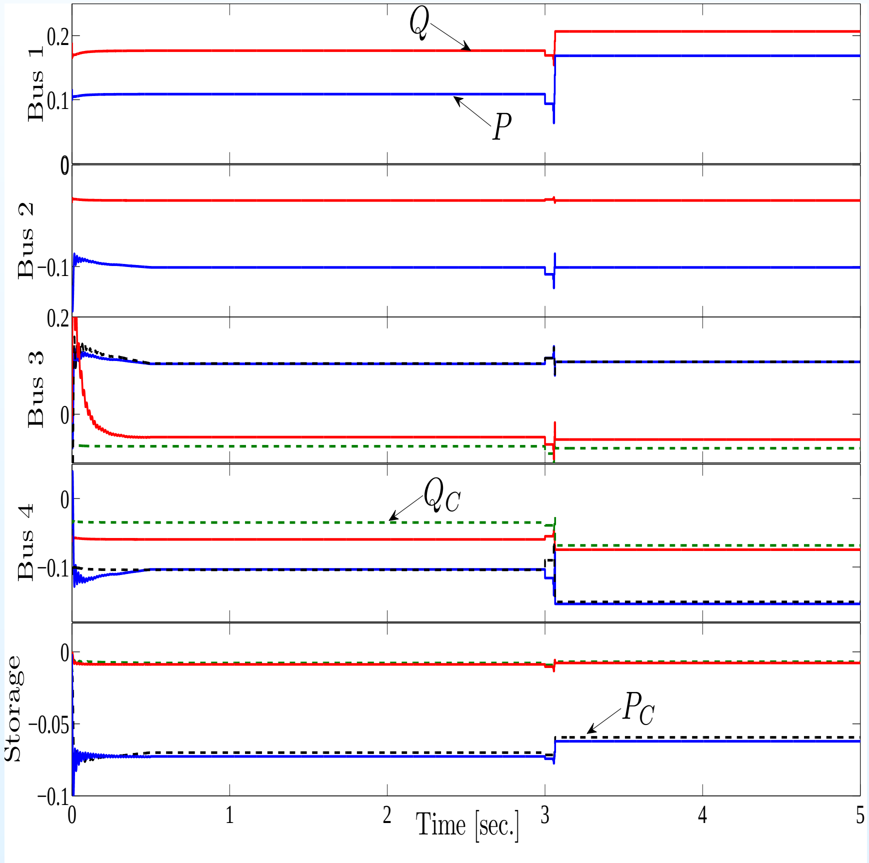


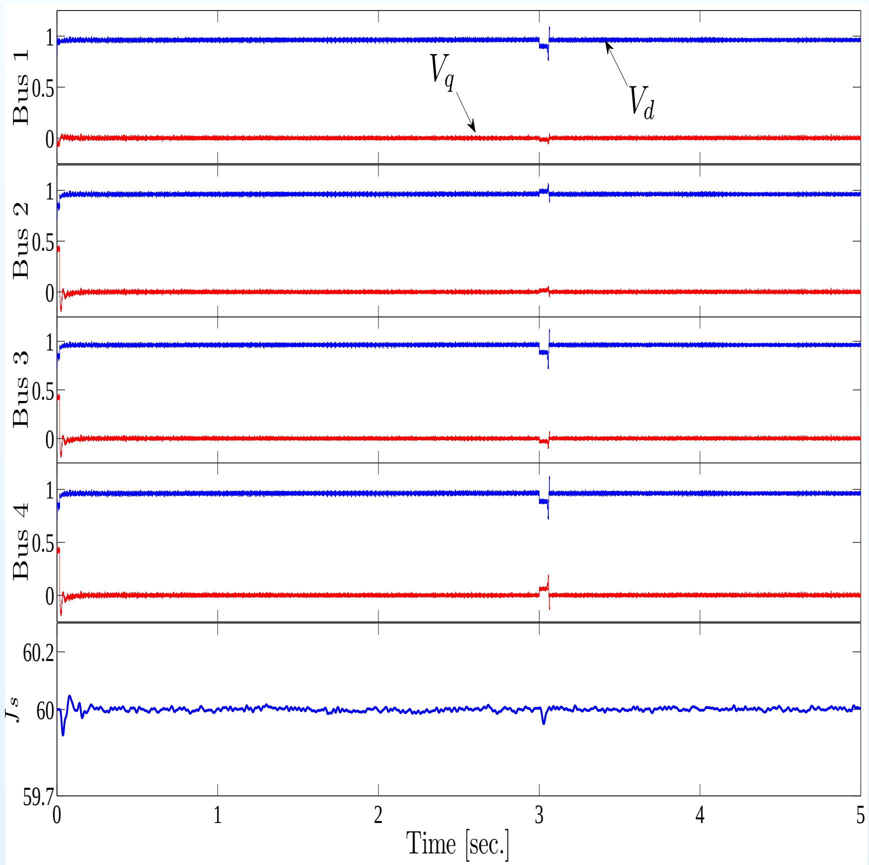


Controller: Isolated micro-grid with wind generator

Power Flow Based Micro-grid Controller: *Performances*

- Isolated micro-grid with step increase in load

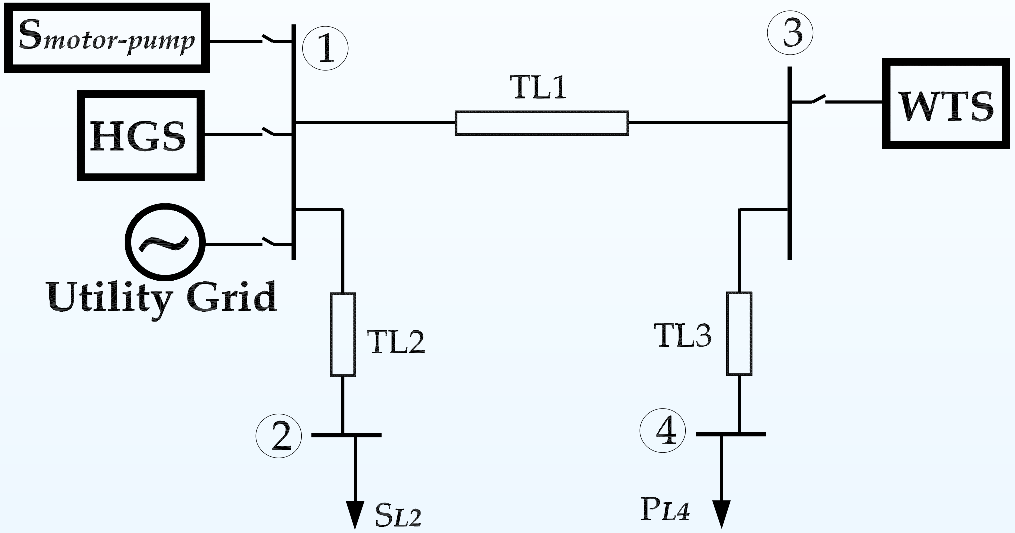




Controller Development: Summary

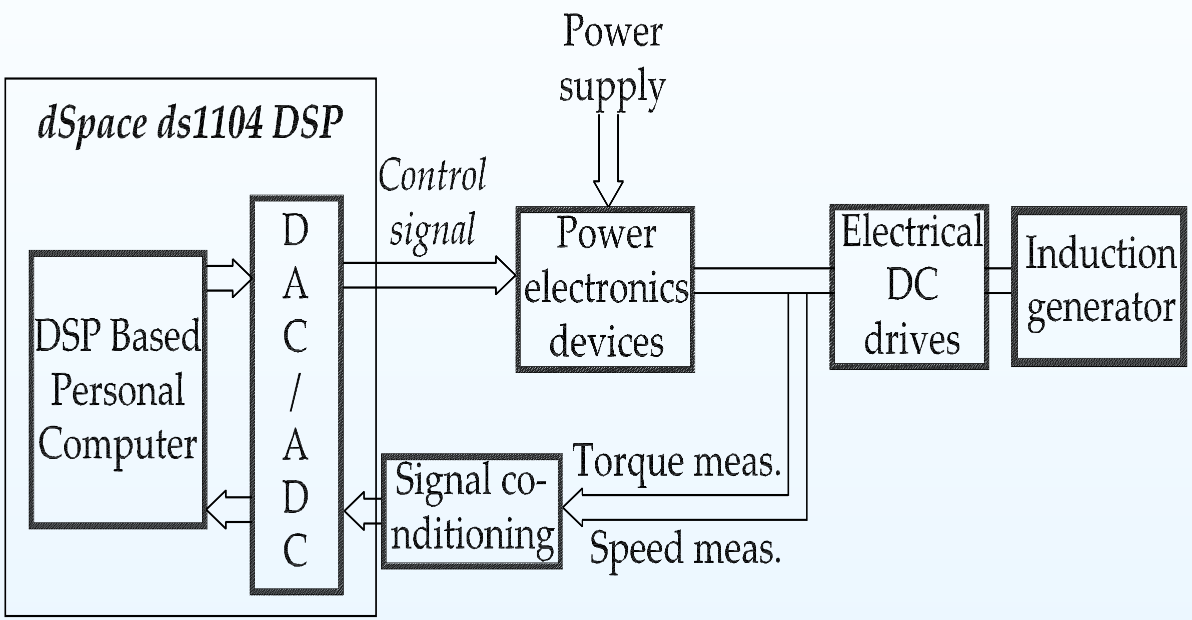
- The developed active power controller is capable of maintaining power balance between generation and load under various operating conditions
- The operation of an isolated micro-grid with HSU is studied and discussed
- An alternative control scheme is developed based on power flow analysis and current controlled inverter for the storage unit
- PFMC shows the ability to initiate accurate and fast actions to adjust power between generation and load
- The accuracy of the PFMC is observed from the micro-grid frequency and bus voltages under different operating conditions

Micro-grid Test Setup: Overview



- Validate the outcome obtained by simulation for the developed controller
- Micro-grid test setup (MTS) is accomplished using the lab facilities
- Four bus system because it is assumed that the voltage level is the same in the test setup

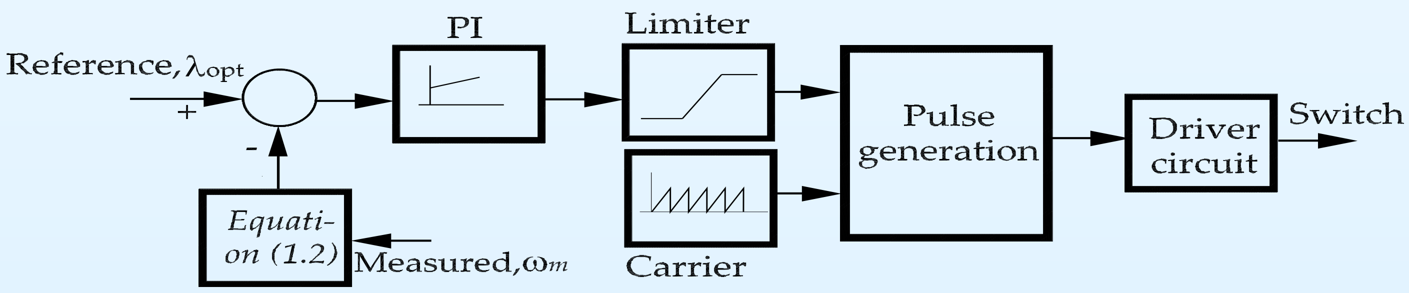
Micro-grid Test Setup: Wind Turbine Emulator (WTE)



- A separately excited DC motor is emulated to represent a wind turbine rotor.
- The inertia of the DC motor and induction generator is assumed to be the inertia of the wind turbine rotor.
- DSP based PC is utilized to implement the wind turbine model and characteristics

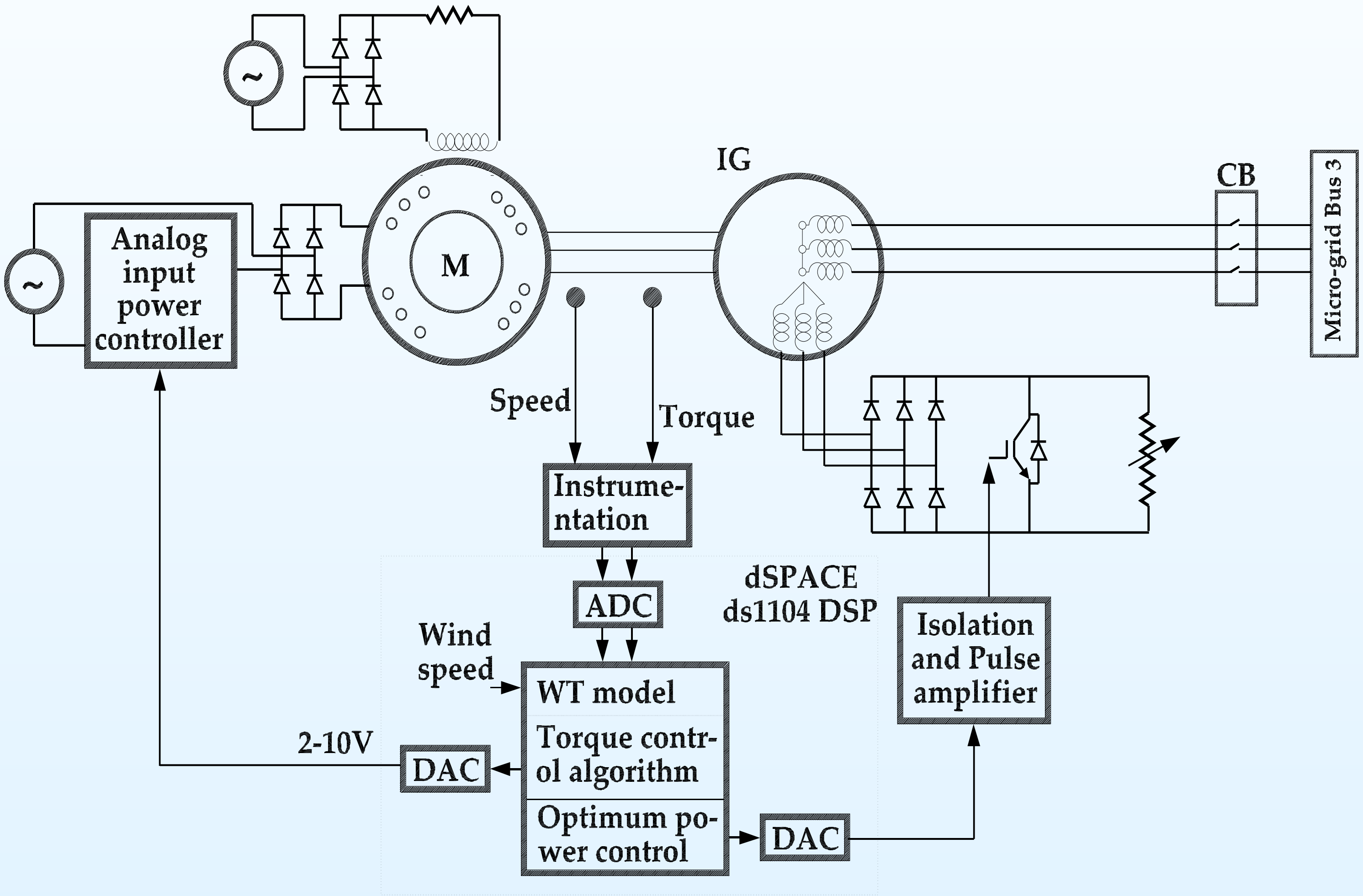
Micro-grid Test Setup: Wind Turbine Emulator (WTE)

- Wind turbine model
  - Turbine output power: $P_{mech} = \frac{1}{2}\rho A v_w^3 C_p(\lambda)$
  - Tip speed ratio: $\lambda = \frac{\omega_m r_t}{v_w}$
  - Average torque: $T_{av} = \frac{1}{2}\rho A v_w^2 C_q(\lambda) r_t$
  - Torque coefficient:
    $C_q = -0.02812 + 0.038576\lambda - 0.0045912\lambda^2 + 0.0001489\lambda^3$
- Torque control algorithm
  - Recursive discrete PI controller
- Optimum power controller



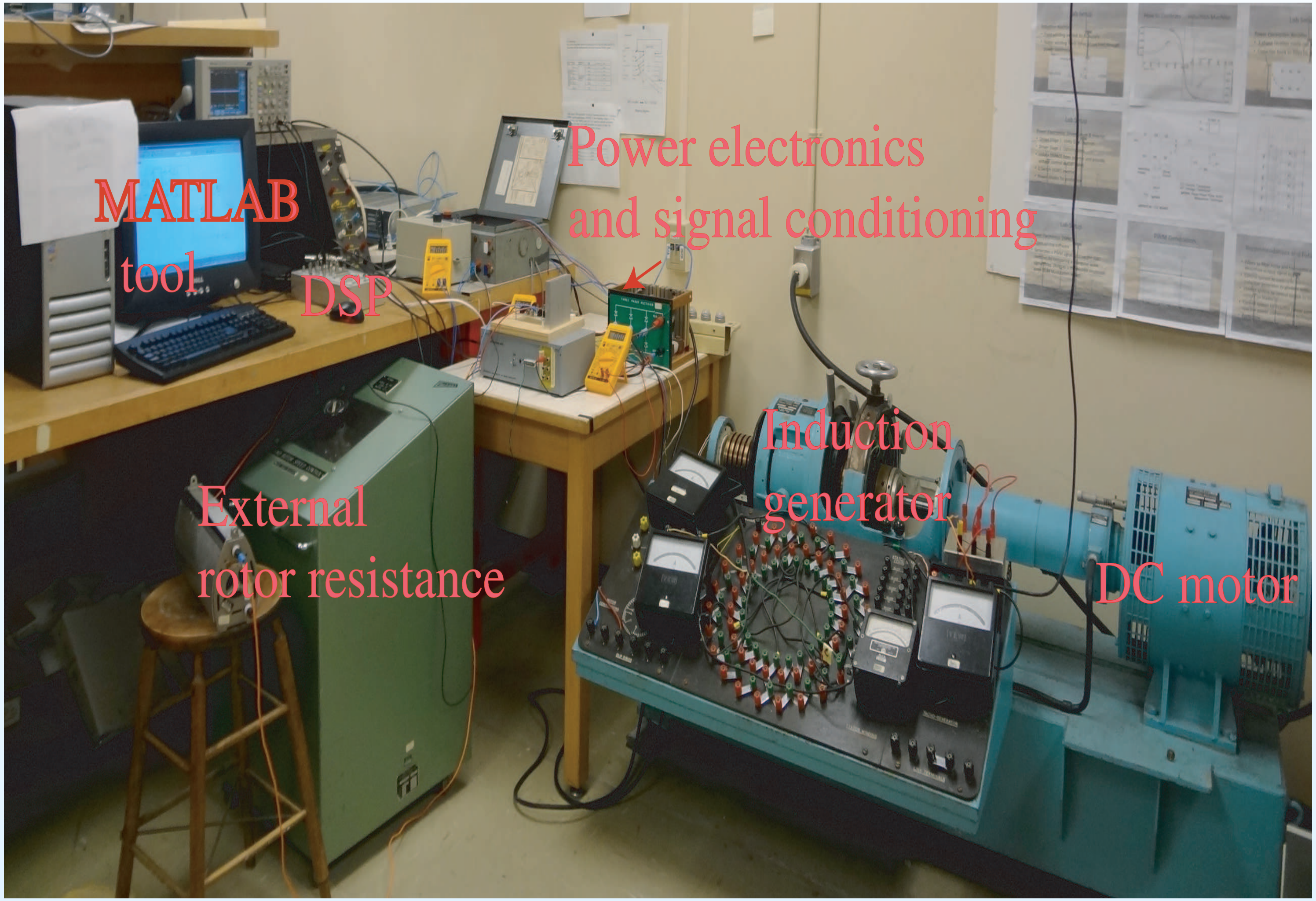
Micro-grid Test Setup: WTE Implementation

- Laboratory layout for the WTE



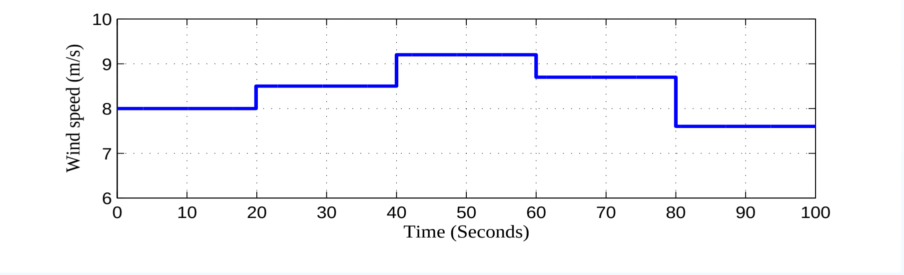
Micro-grid Test Setup: WTE Implementation

- Photograph of the laboratory wind turbine system

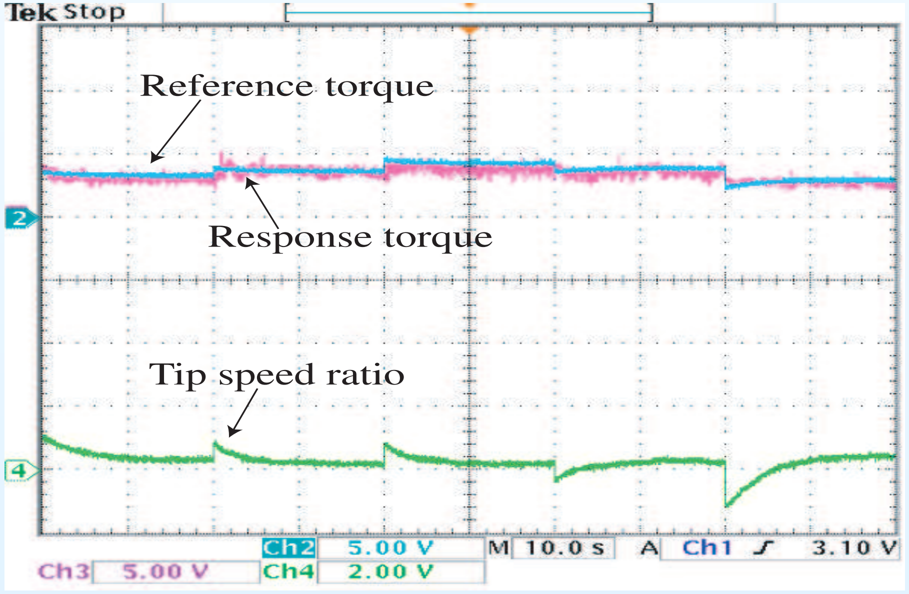


Micro-grid Test Setup: WTE Implementation

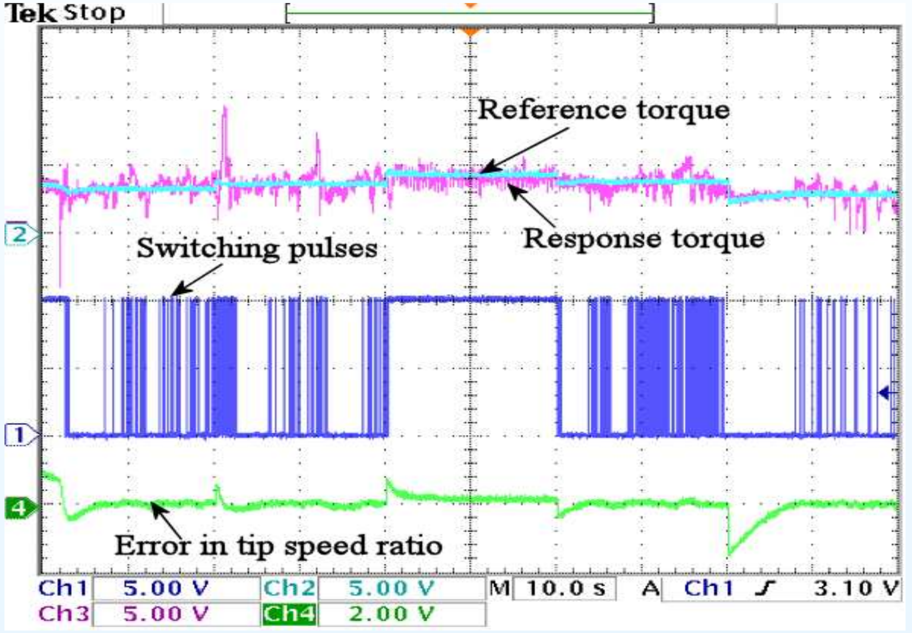
- *Experimental Performances*



Wind speed profile



WTE performance without OPC

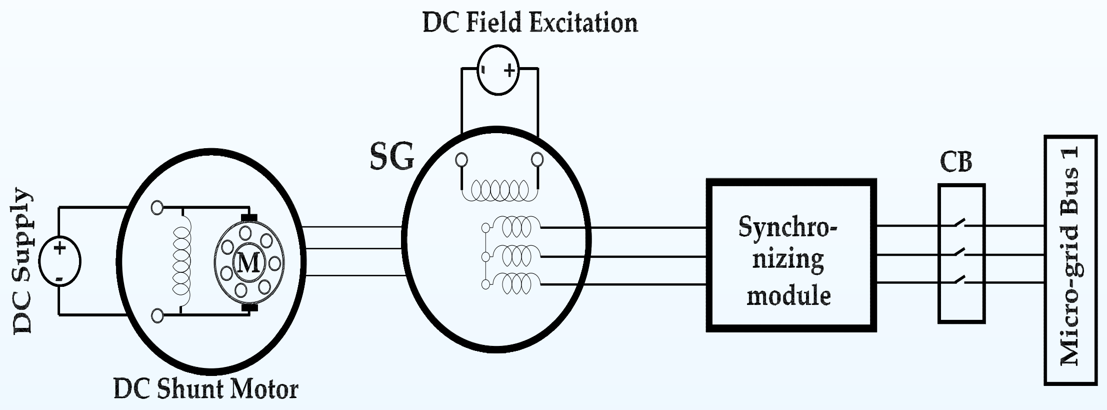


WTE performance with OPC

- Almost exact fit between DC motor actual torque and the reference torque produced by the wind turbine model.

Micro-grid Test Setup: Other Hardware Components

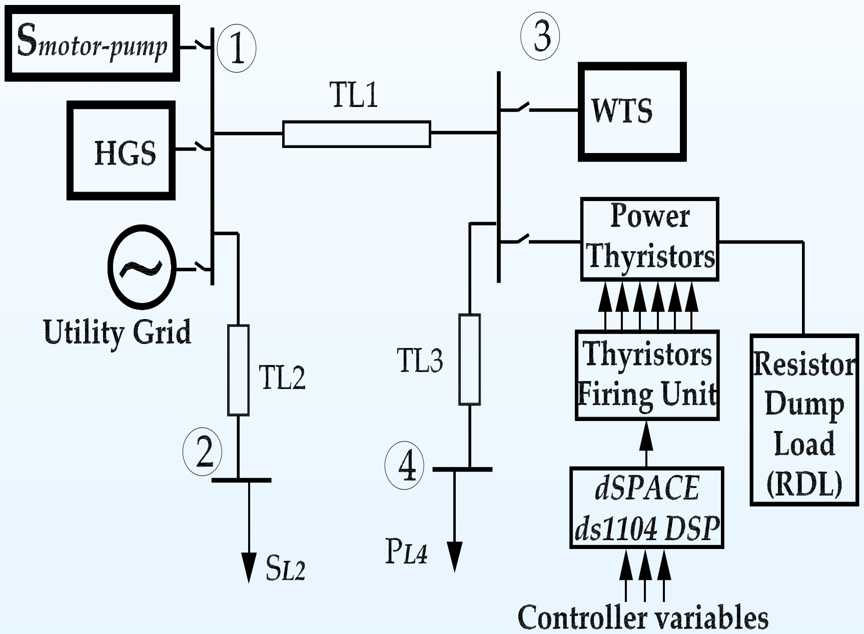
- Hydro Generation Simulator



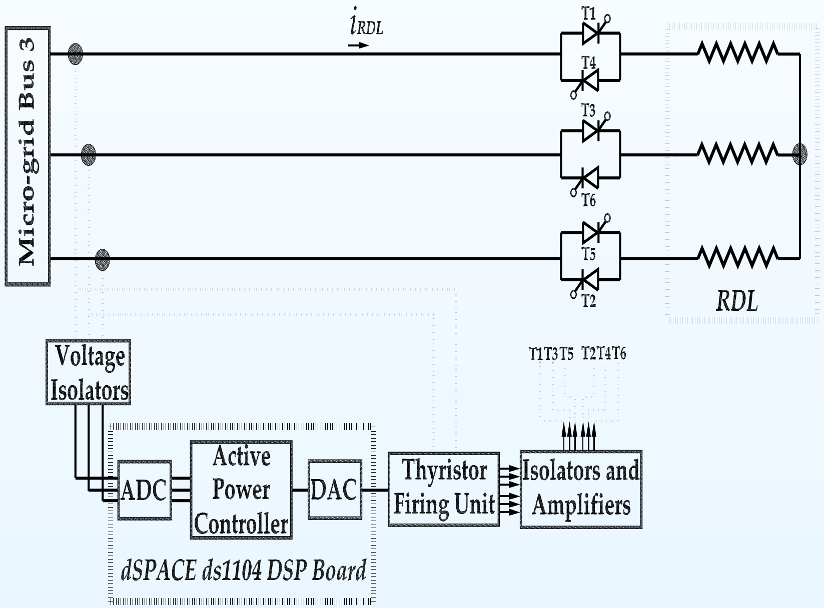
- A 3ϕ, 208 V, 60 Hz supply is used as the utility grid.
- A 3ϕ, 10 A circuit breaker is used as the link between MTS and the utility grid.
- 6, 2 and 2.5 m long cables represent the line.
- Two loads are $SL2 = (750 + j251)$W and $PL4 = 1.24kW$
- Motor load, $S_{motor-pump}$= 0.5kVA

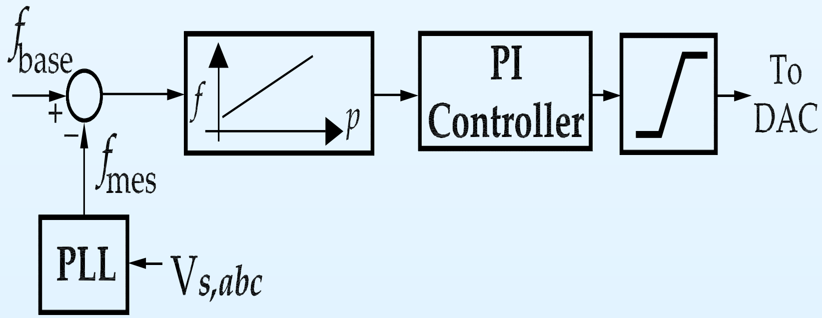
Active Power Controller Implementation

- Experimental Layout



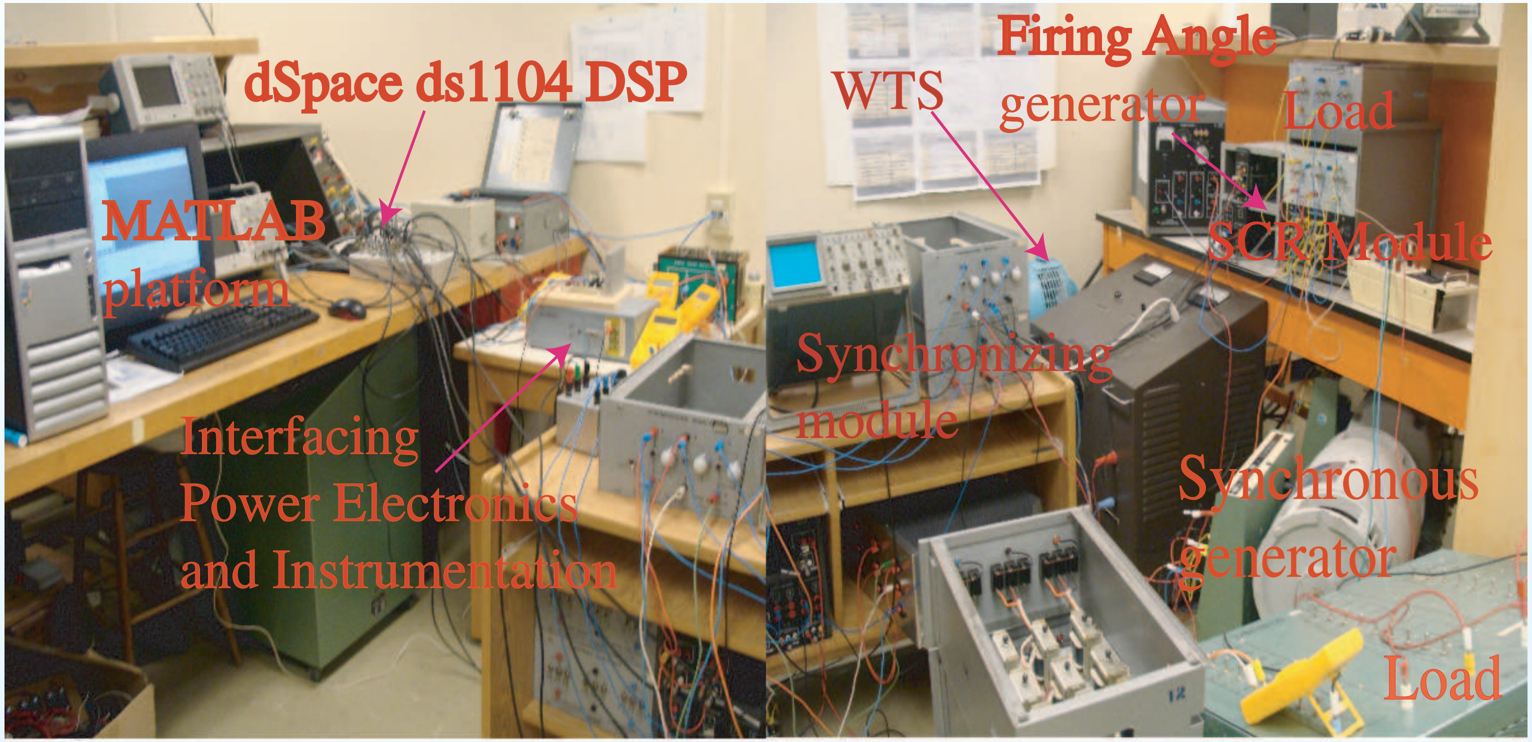
- Controller Hardware





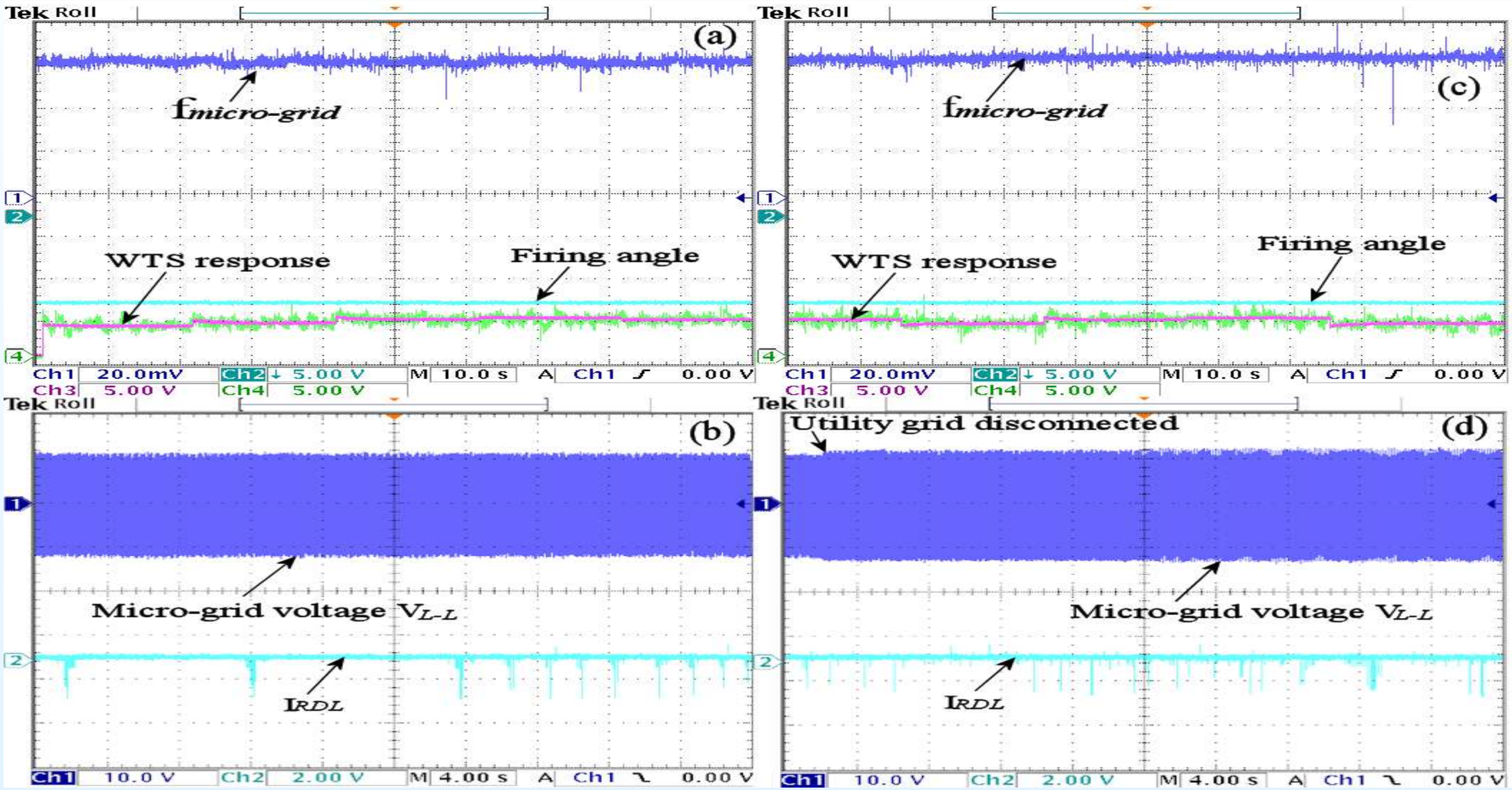
Active Power Controller Implementation

- Experimental Hardware



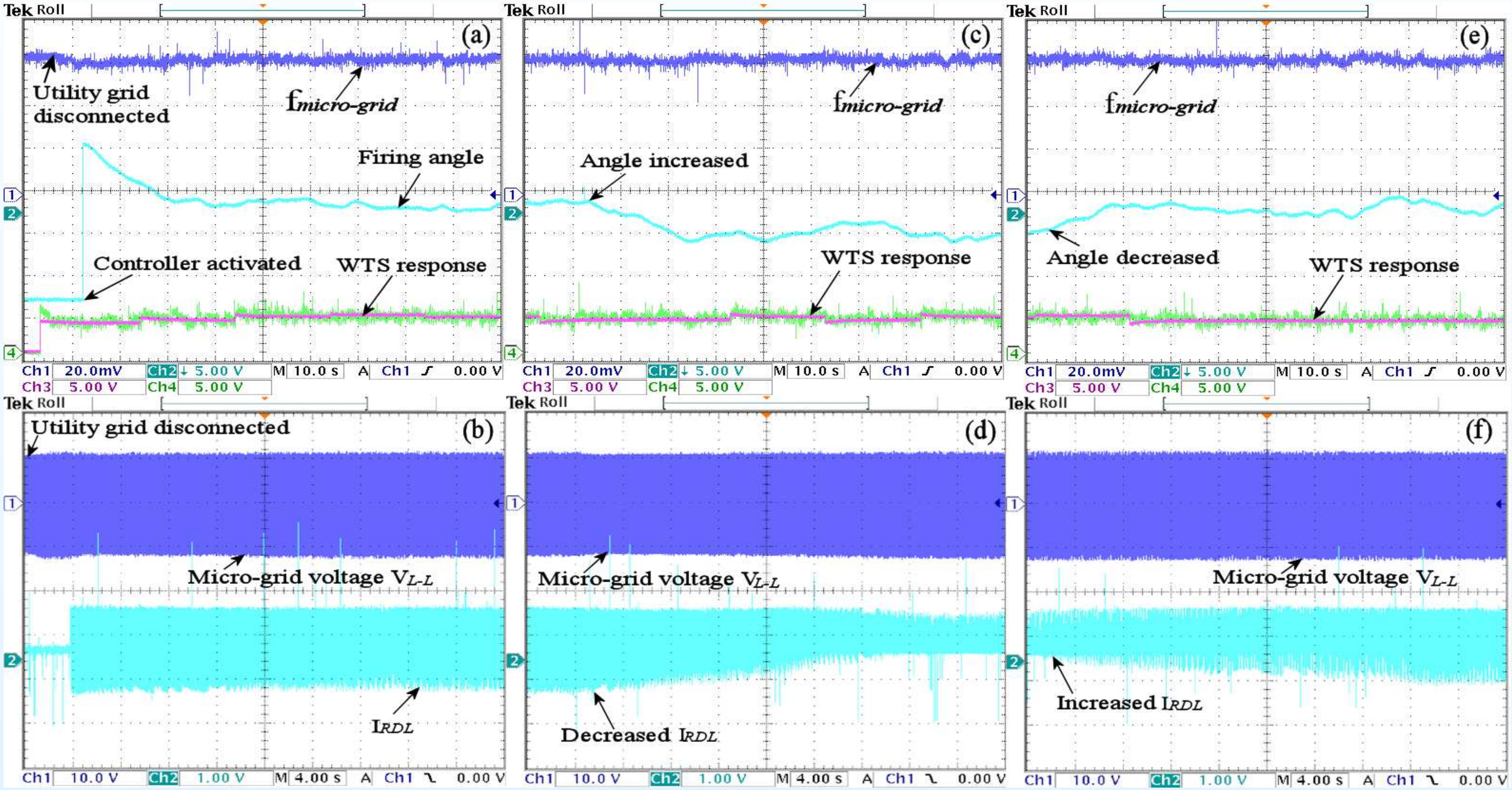
Active Power Controller Implementation

- *Experimental Performances: without control*



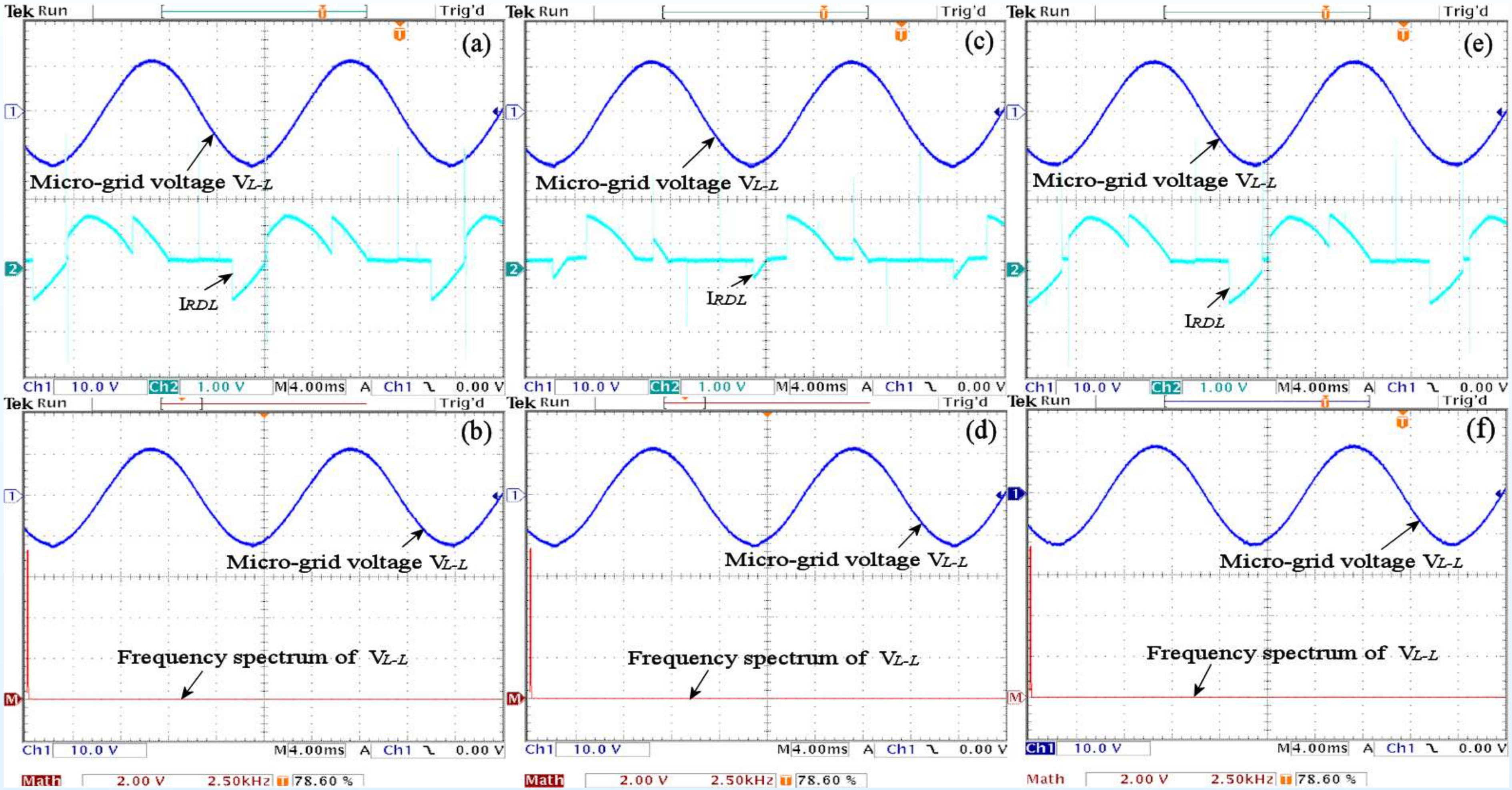
Active Power Controller Implementation

- *Experimental Performances: with control*



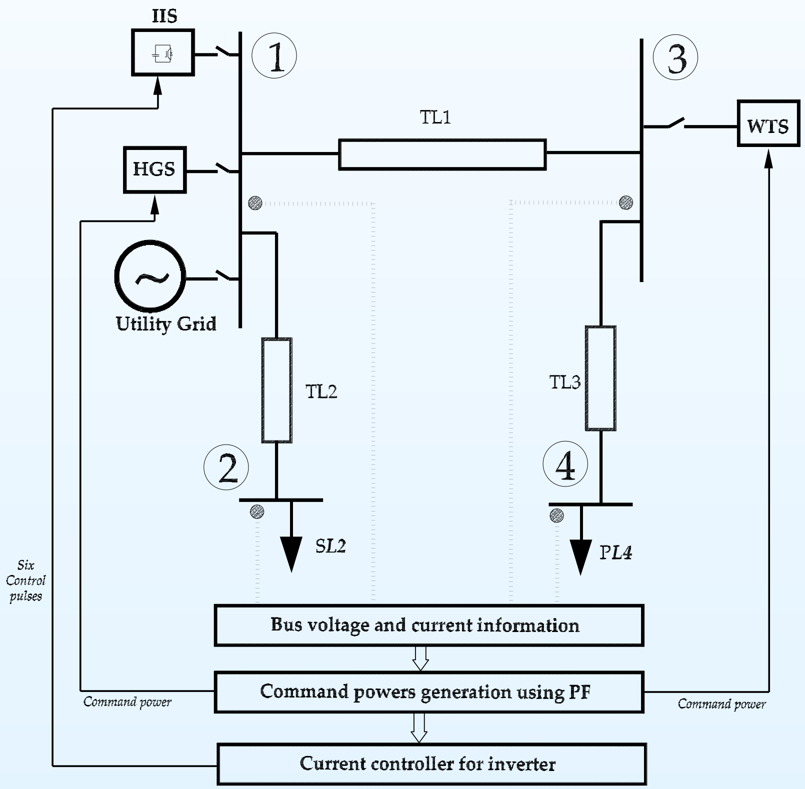
Active Power Controller Implementation

- *Experimental Performances: with control*

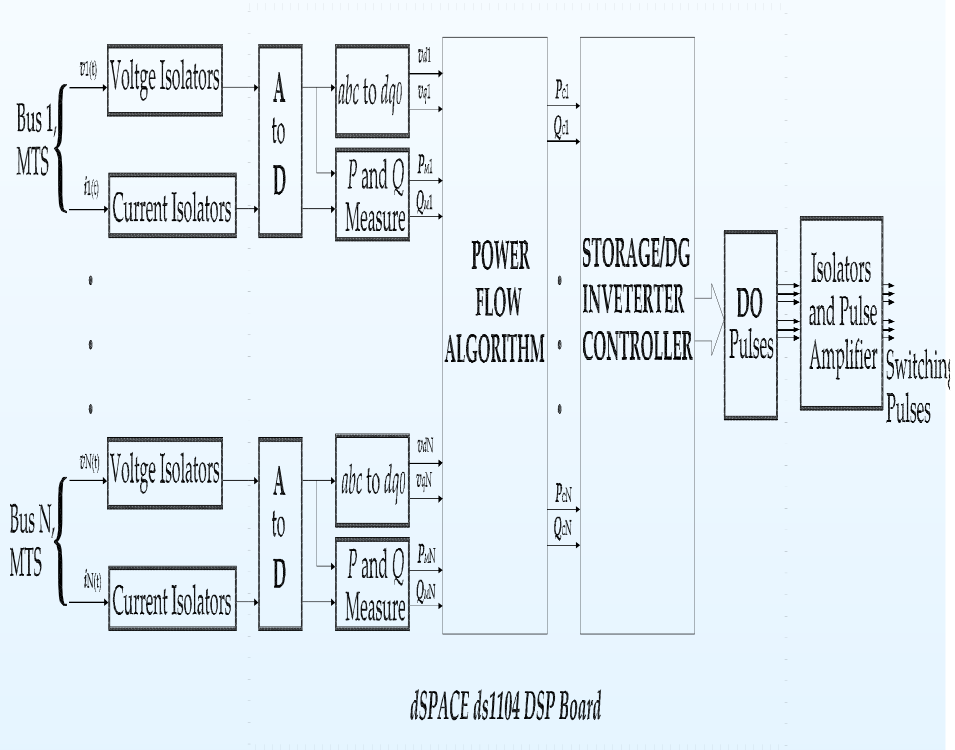


Power Flow Based Micro-Grid Controller Implementation

- Schematic of Experimental Layout

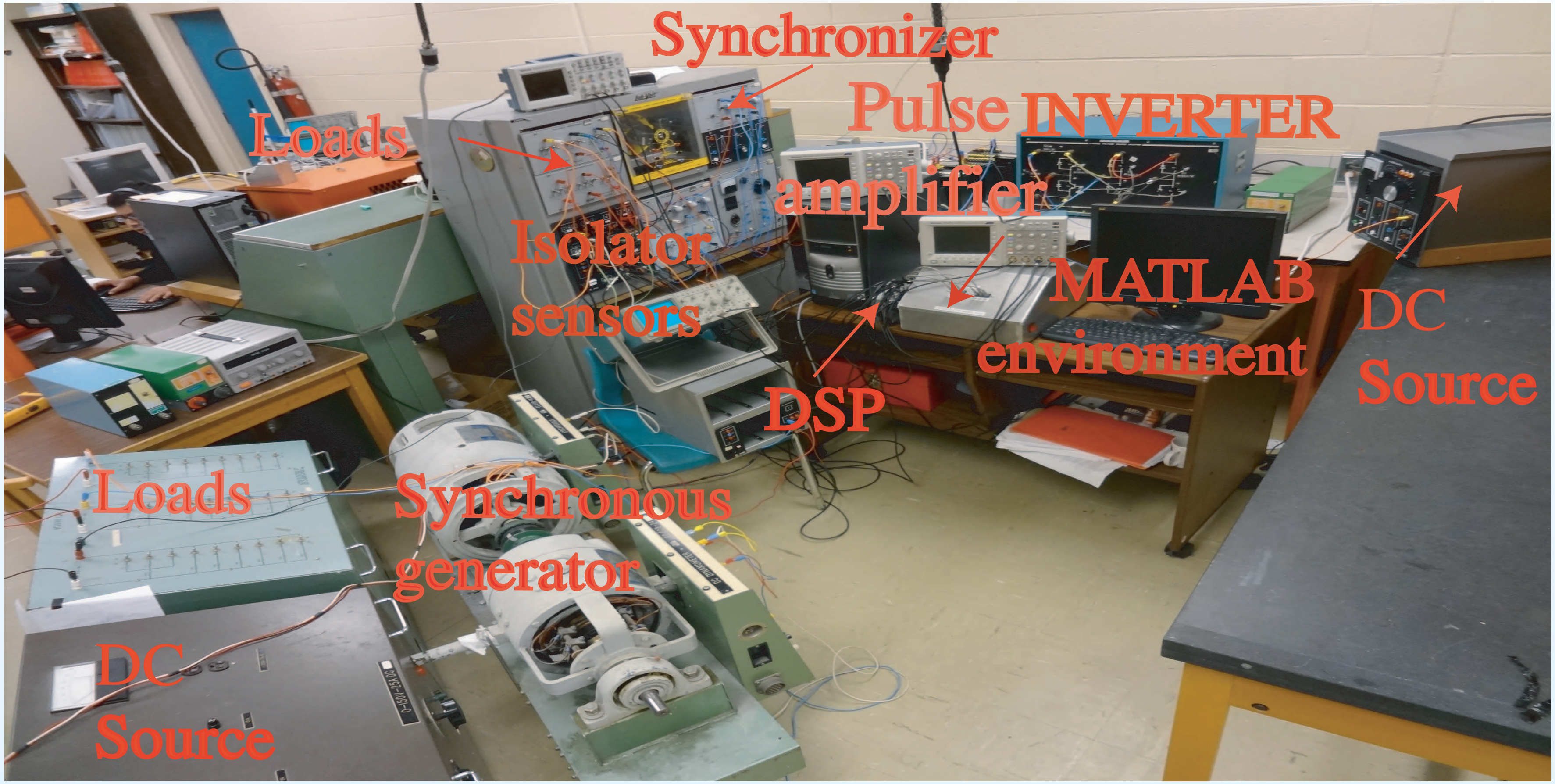


- Controller Hardware Detail



Power Flow Based Micro-Grid Controller Implementation

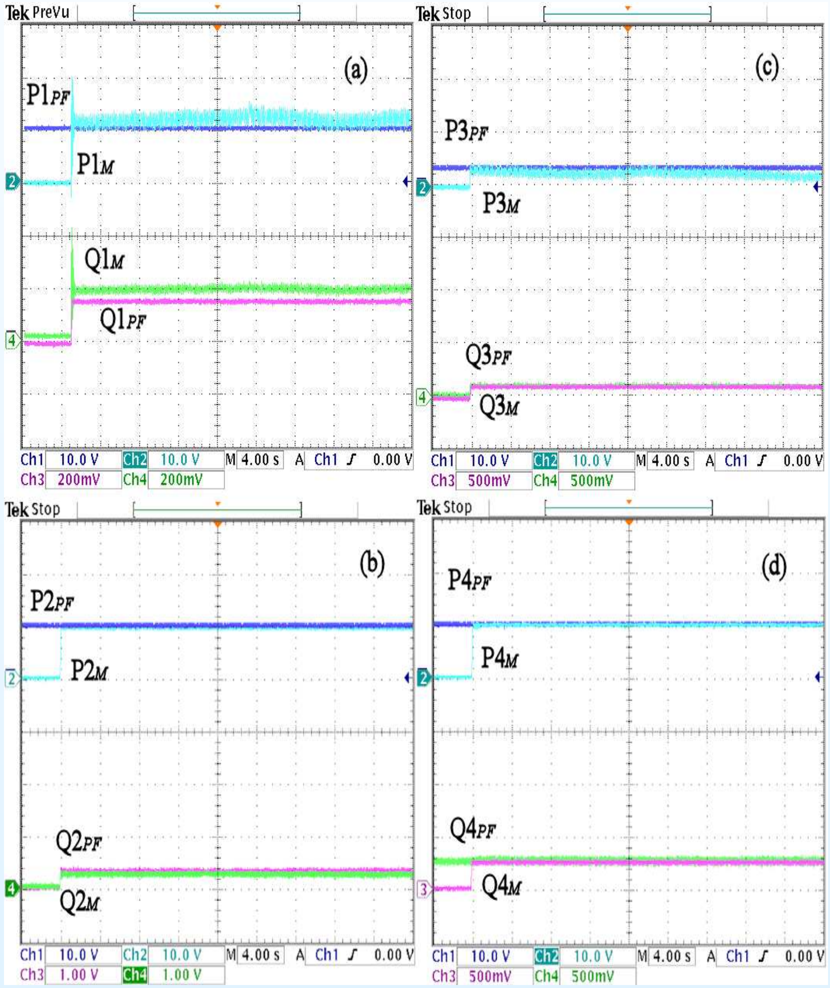
- Experimental Hardware Setup

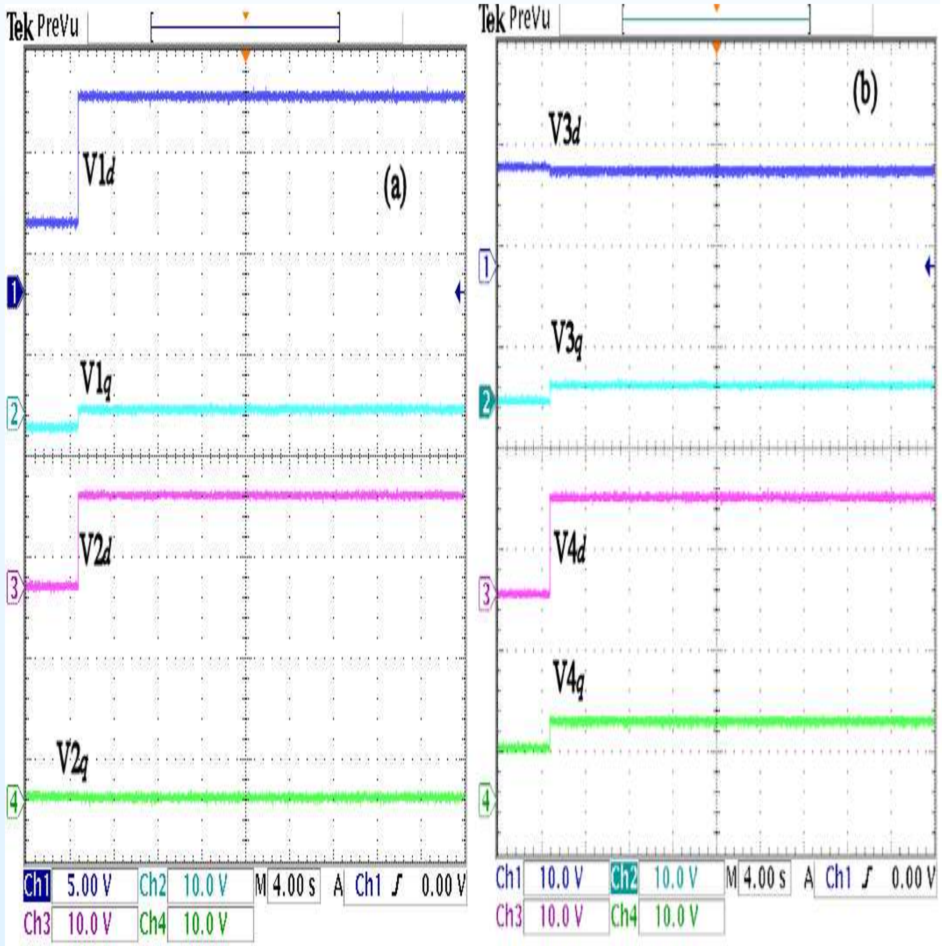


Power Flow Based Micro-Grid Controller Implementation

Isolated micro-grid without wind generator

- Performances: Bus Powers
- Performance: Bus Voltages

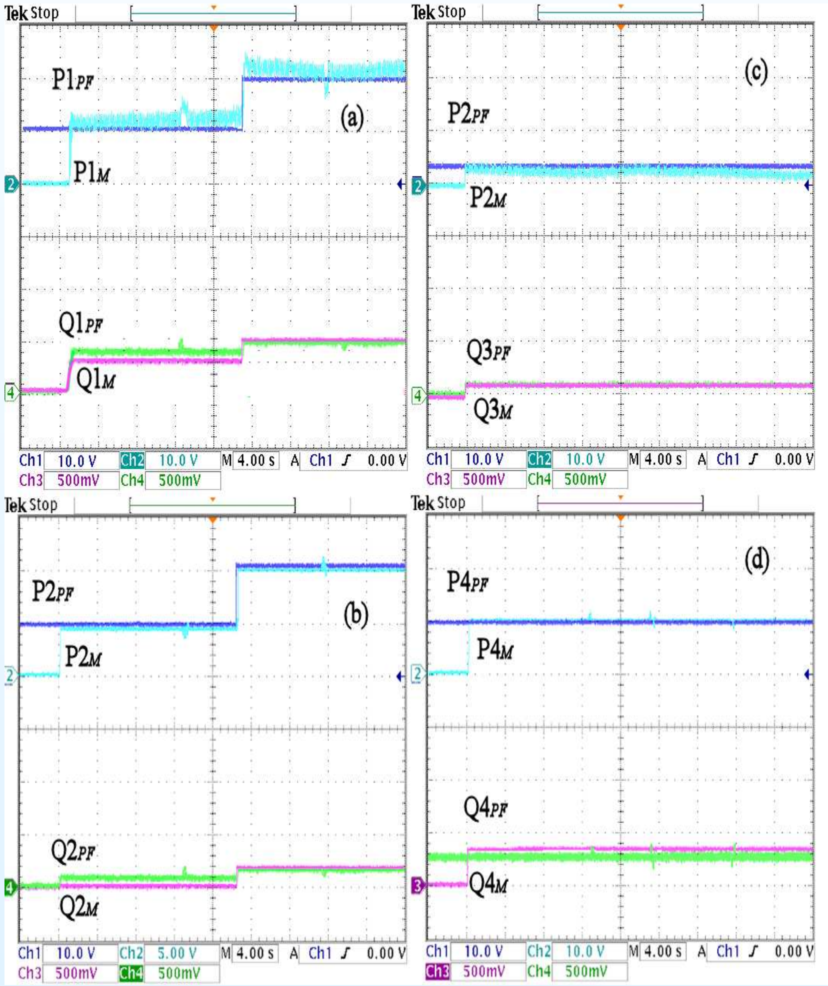


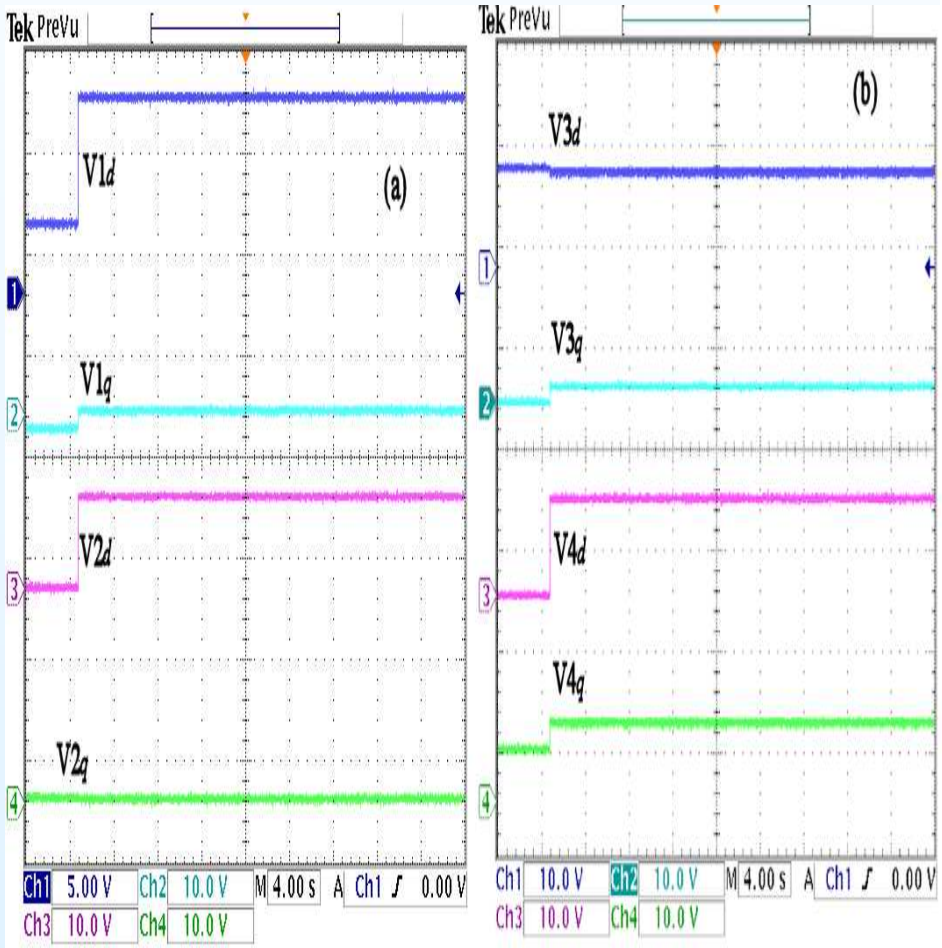


Power Flow Based Micro-Grid Controller Implementation

Isolated micro-grid with step change in load

- Performances: Bus Powers
- Performance: Bus Voltages





Controller Evaluation: Summary

- Scaled version laboratory prototype of a micro-grid system is presented
- WTE is developed to represent a variable speed wind turbine system
- The implementation and performances of an active power controller is presented
- Power flow based micro-grid controller is implemented and the performance results are presented
- All the tests results show the same pattern as those found through simulation study

- Introduction
- Review and Critique
- System Behaviour Analysis
- Controller Development and Evaluation
- ***Reliability Assessment***
- Conclusion

Why is micro-grid system reliability necessary?

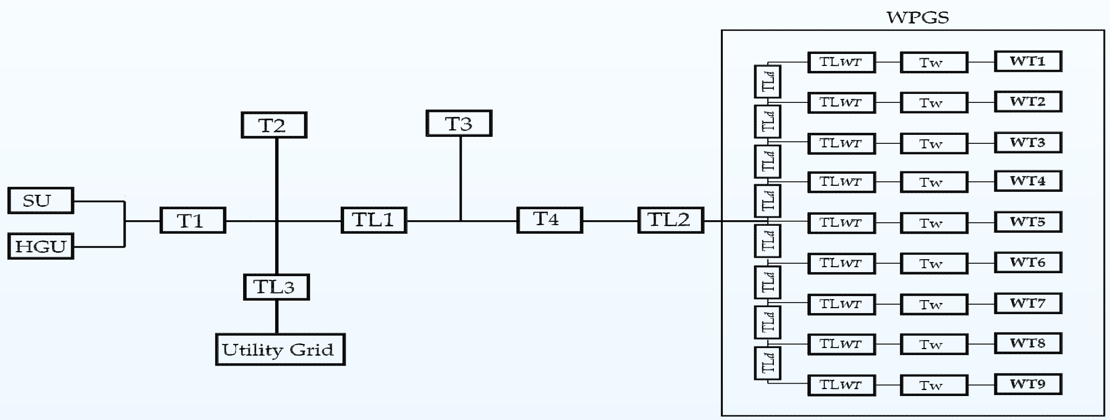
- Wind speed profile and the power generation by the wind turbine are highly dependednt on a specific site
- Reliability calculation should be carried out for the entire wind speed range that a wind turbine system operates and also for the complete wind energy conversion system

Assumptions

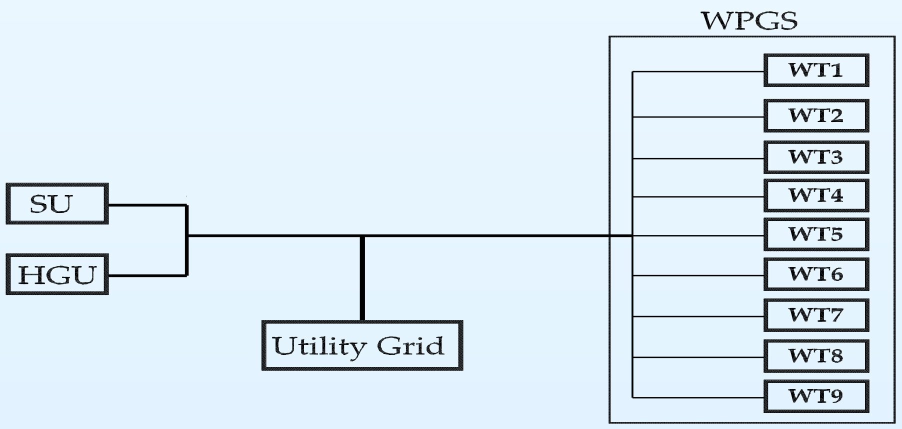
- Power generation by the hydro unit is assumed to be highly reliable
- Inverter interfaced storage is also assumed with better reliability of generating power

Micro-Grid System Reliability: Model

- Detail reliability block diagram (RBD)

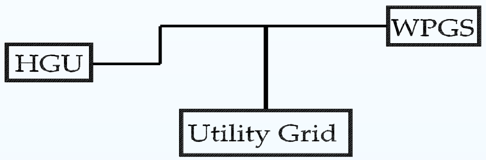


- Simplified reliability block diagram

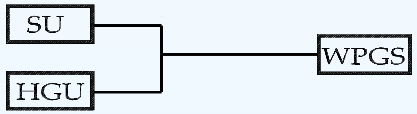


Micro-Grid System Reliability: Model

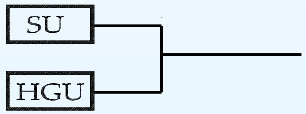
- RBD for micro-grid Modes



(a)

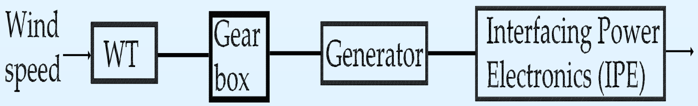


(b)



(c)

- Wind turbine system



(a) Mode-I:

$$R_{MSR_{M1}} = \left[1 - (1 - R_{wts})^N (1 - R_{HGU})(1 - R_{ug})\right]$$

(b) Mode-II:

$$R_{MSR_{M2}} = \left[1 - (1 - R_{wts})^N (1 - R_{HGU})\right]$$

(c) Mode-III:

$$R_{MSR_{M3}} = [1 - (1 - R_{HGU})(1 - R_{SU})]$$

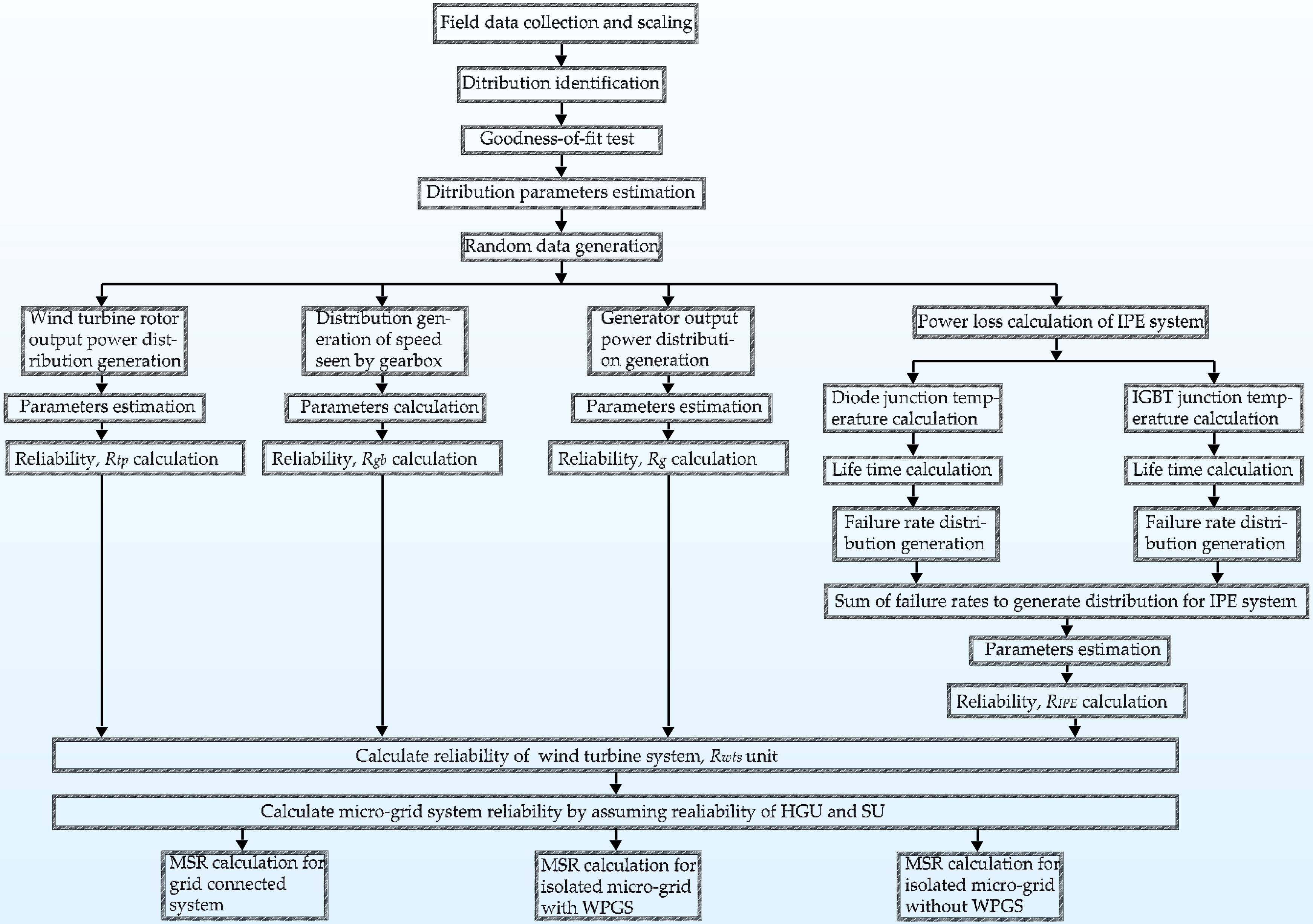
Wind turbine system

$$R_{wts} = R_{tp} \times R_{gb} \times R_g \times R_{IPE}$$

WPGS

$$R_{WPGS} = \left[1 - (1 - R_{wts})^N\right]$$

Micro-Grid System Reliability: Model Implementation



Reliability Results

- Sub-systems reliability in a variable speed wind turbine system

DG units	Reliability
WT rotor, R_{tp}	0.9068
Gear box, R_{gb}	0.9107
Generator, R_g	0.9266
IPE system, R_{IPE}	0.8144

- The reliability of generating power by various sub-systems of a variable speed wind turbine is acceptable
- Interfacing power electronic sub-system is less reliable among all the subsystems

Reliability Results

- DG units reliability

DG units	Reliability
WT system, R_{wts}	0.6232
WPGS, R_{WPGS}	0.9998
HGU, R_{HGU}	0.85
SU, R_{SU}	0.8144
Utility grid, R_{UG}	0.85

- Micro-grid system reliability

Micro-grid operational modes	Reliability
Grid connected mode	$R_{MSR_{M1}}$
	.9999
Isolated micro-grid with WPGS:	$R_{MSR_{M2}}$
number of WT systems in WPGS (1, 2, 3, 4)	0.94, 0.97, 0.99, 0.997
Isolated micro-grid without WPGS	$R_{MSR_{M3}}$
	0.97

- Introduction
- Review and Critique
- System Behaviour Analysis
- Controller Development and Evaluation
- Reliability Assessment
- ***Conclusion***

Summary

- The possibility of constructing a micro-grid system that contains only renewable sources has been practically demonstrated
- Detail modeling of the micro-grid sub-systems/systems has been conducted to understand the operational and control issues and needs
- Active power controller has been developed, tested and validated for isolated micro-grid operation
- Power flow based micro-grid controller has been developed, tested and validated for an isolated micro-grid operation
- A micro-grid test setup has been developed for experimental testing of micro-grid controllers
- Reliability assessment of a renewable source based micro-grid system has been conducted

Future Work

- Voltage control scheme development for an isolated micro-grid with wind generator system
- Further investigation using power flow based control for multiple generation unit control
- Addition of other renewable micro-generations such as ocean and solar power generation to the micro-grid system
- Development of hydro generation simulator would improve the micro-grid test set up
- Detail reliability assessment for other micro-generations in the micro-grid system
- Micro-grid protection

Contributions

- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Modeling and Analysis of a Micro-grid System Powered by Renewable Energy Sources", Accepted to publish in The Open Renewable Energy Journal, Vol. 6, 2013.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Design and Performance Testing of an Active Power Controller for the Operation of a Micro-grid", Revised and submitted, Renewable Energy Journal, 2012.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Frequency Regulation for a Micro-grid System Based on Renewable Power Generation", Accepted for special issue in The Open Renewable Energy Journal, 2011.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Reliability Analysis of Micro-grid System Powered by Renewable Energy Sources", Under review with the IEEE Systems Journal, 2012.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Experimental Investigation of a Micro-grid Power Controller", in Proc. IEEE Electrical Power and Energy Conference, EPEC’2011, Winnipeg, MB, Canada, 2011.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Reliability Assessment of a Micro-grid System", in Proc. IEEE Electrical Power and Energy Conference, EPEC’2011, Winnipeg, MB, Canada, 2011.

Contributions (cont’d)

- R. Ahshan, S. Saleh, M. T. Iqbal, and George K. I. Mann, “Development of a Micro-grid Controller Employing a Load Flow Analysis", in Proc. IEEE Electrical Power and Energy Conference, EPEC’2011, Winnipeg, MB, Canada, 2011.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Micro-grid System Based on Renewable Power Generation Units", in Proc. IEEE Canadian Conf. on Electrical and Computer Engineering, CCECE’2010, Calgary, AB, Canada, 2010.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Development of a Micro-Grid Prototype", Presented at the Aldrich Interdisciplinary Conference, 2011, Memorial University, St. John’s, NL, 2011.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Simulation of a 27 MW Wind Farm in Newfoundland", in Proc. IEEE Newfoundland Electrical and Computer Engineering Conf., NECEC’2010, St. John’s, NL, Canada, 2010.
- R. Ahshan, M. T. Iqbal, George K. I. Mann, and John E. Quaicoe, “Wind, Hydro and Pumped Hydro Storage Based Micro-grid for Newfoundland", in Proc. IEEE Newfoundland Electrical and Computer Engineering Conf., NECEC’2010, St. John’s, NL, Canada, 2010.

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- School of Graduate Studies, MUN
- Technical Services, MUN

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