Modeling and Comparison of Dynamics of AC and DC Coupled Remote Hybrid Power Systems

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Research Overview

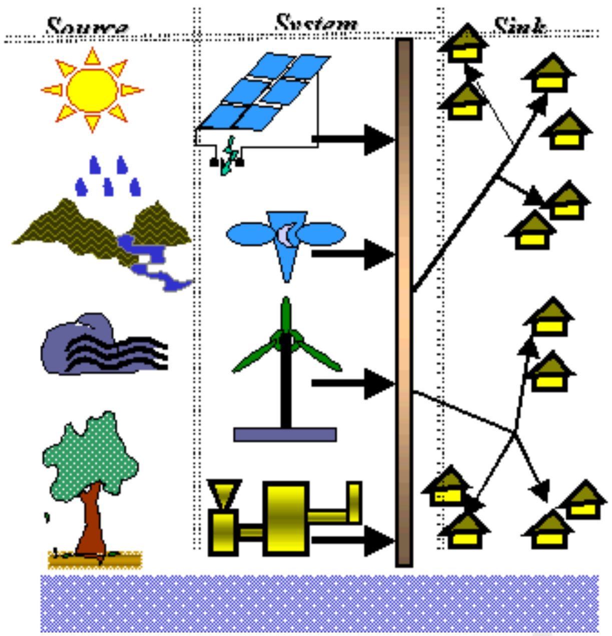
- Many community around the world use diesel generator based stand-alone power system
- Rising fuel costs and environmental concerns make the use of renewable energy in stand alone systems increasingly attractive.
- In this research an AC based and an DC based hybrid power system are designed and analyzed.
- A comparison is made based on steady-state and dynamic analysis
- In some case DC coupled hybrid system is better than AC coupled hybrid system.

Research Aims

- Design an AC and a DC coupled Hybrid power system
- Optimal sizing of system components
- Steady- state analysis
- Simulink/Matlab models
- Dynamic and Transient analysis
- Comparison of AC and DC coupled hybrid power system

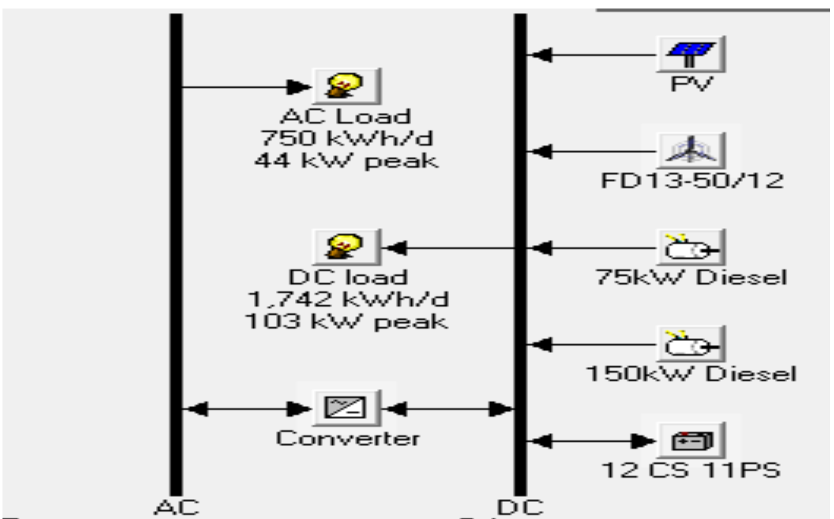
HYBRID POWER SYSTEM

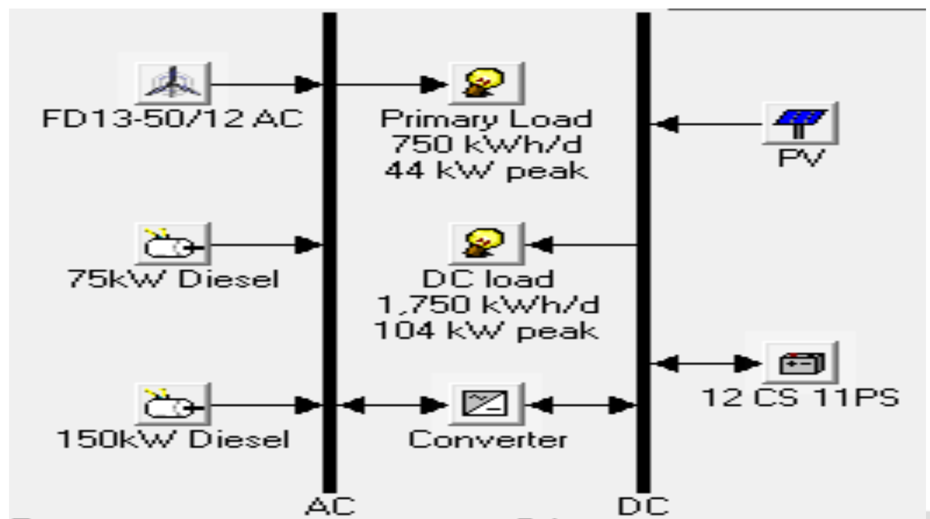
- A system consisting of two or more energy sources used together to provide increased system efficiency and a well balanced energy supply.
- May be a combination of *renewable* sources (solar, hydro, wind, biomass) and *non-renewable* sources (fossil fuels).



Types of Hybrid Power System

- DC (Direct Current) coupled
- AC (Alternating Current) coupled

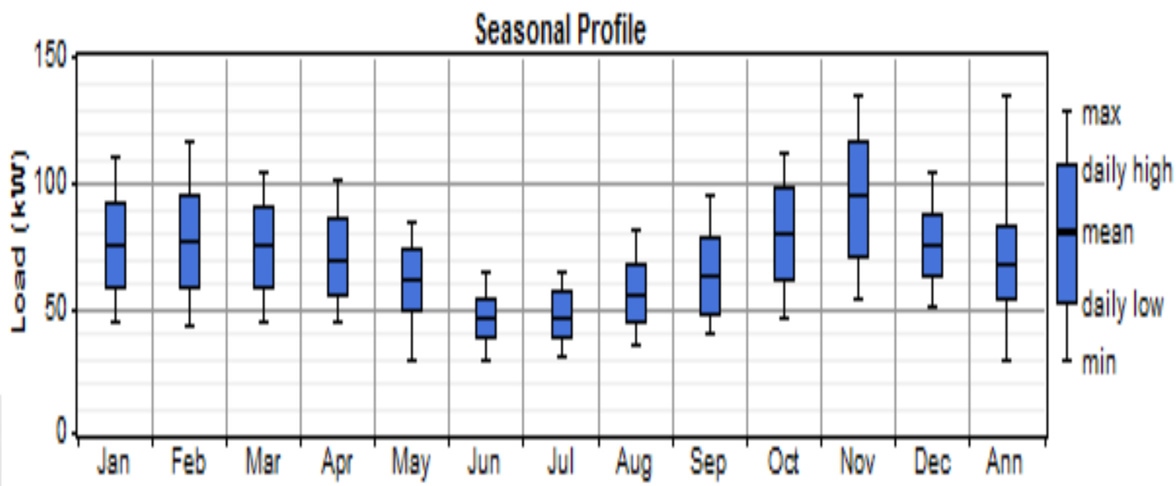




Energy Planning

Load profile

- Load of small community of about 160-180 residents is considered
- Daily demands– 2500 kWh
- Peak load - 207 kW
- Load factor 0.503



RENEWABLE RESOURCES -Wind Profile

WESNet

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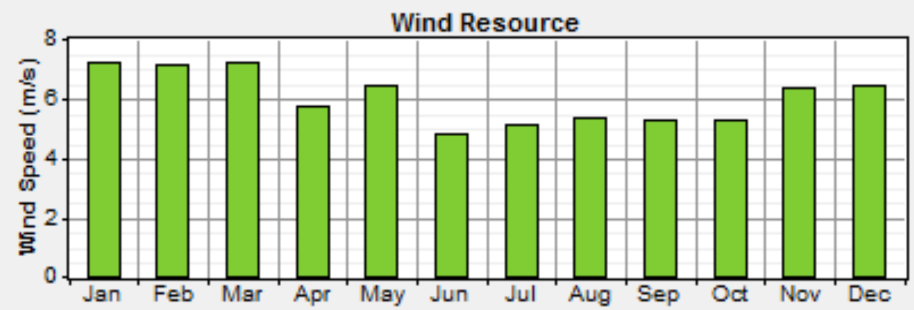
- Based on data collected from (www.climate.weatheroffice.gc.ca) Wind speeds at an elevation of 50 m above sea level and scaled for 10 m height.
- Average annual wind speed – 6.041m/s
- Averages higher in winter months than summer months
- Correlates with higher loads in winter months

Month	Wind Speed (m/s)
January	7.228
February	7.170
March	7.190
April	5.738
May	6.464
June	4.787
July	5.132
August	5.333
September	5.310
October	5.316
November	6.390
December	6.479

Annual average: 6.041



Other parameters

Altitude (m above sea level)	0
Anemometer height (m)	10

Variation With Height...

Advanced parameters

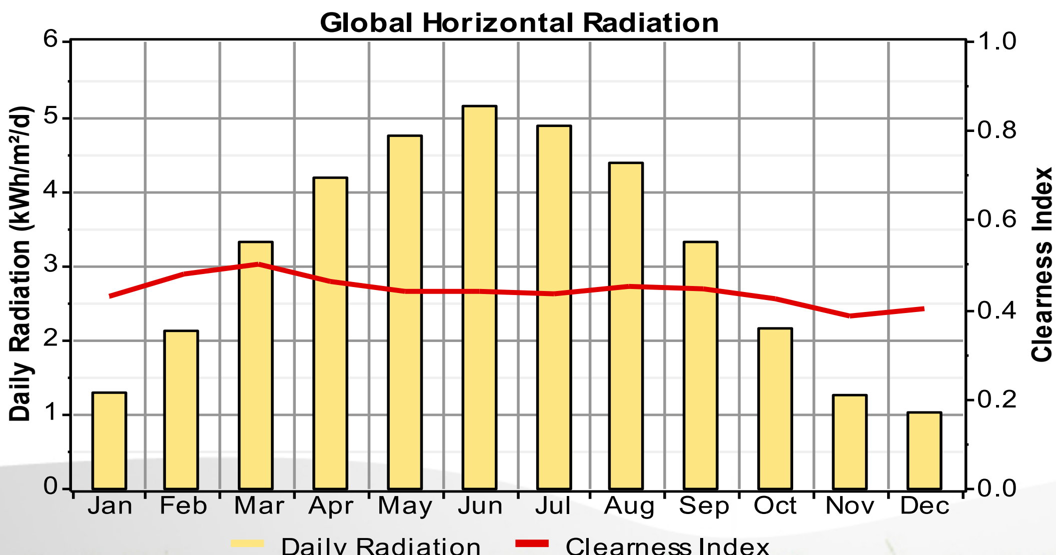
Weibull k	1.91
Autocorrelation factor	0.937
Diurnal pattern strength	0.028
Hour of peak windspeed	24

RENEWABLE RESOURCES –Solar Resource

- Based on data collected from NASA
- Solar radiation values are exported for latitude of 47° on monthly basis.
- Average solar energy 3.15kWh/m2-d.
- Averages are higher in May, June and July.

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.433	1.280
February	0.479	2.110
March	0.501	3.310
April	0.465	4.180
May	0.439	4.740
June	0.444	5.140
July	0.437	4.880
August	0.455	4.390
September	0.447	3.310
October	0.426	2.150
November	0.388	1.270
December	0.402	1.020
Average:	0.448	3.153

Scaled annual average (kWh/m²/d) 3.15



HYBRID SYSTEM DESIGN

System Components

- Photovolatic System
- Wind turbines
- Diesel Generators
- Battery Bank
- Converter

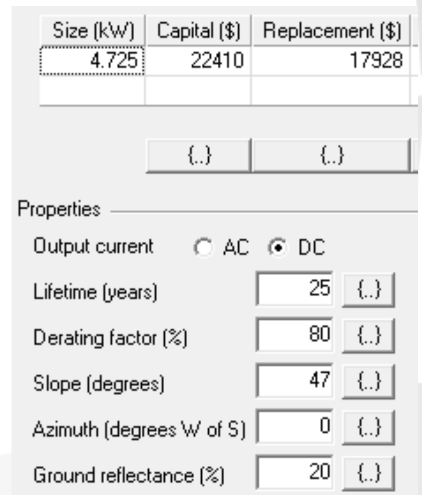
Type of Load

- 30% AC and 70% DC load
- 100% AC load

HYBRID SYSTEM DESIGN – Photovolatic System

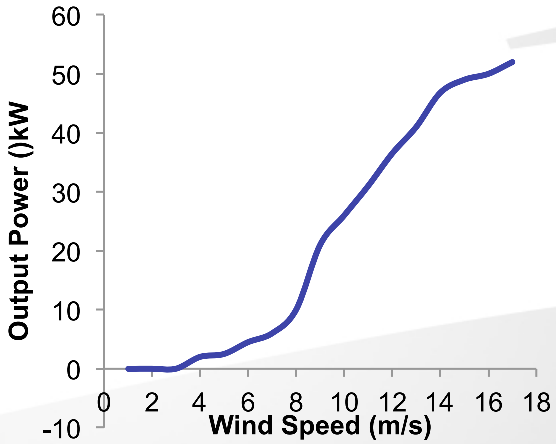
- 175W, 24 V Solar panel
- Can withstand high loads such as heavy accumulations of snow and ice.
- Deliver maximum power output even under reduced light conditions.
- Price for one panel $830

Rated power	SW175
Peak power	175W
Peak power voltage	35.8V
Peak power current	4.89A
Open circuit voltage	44.4V
Short circuit current	5.30A
Fuse Rating	15A



HYBRID SYSTEM DESIGN –Wind Turbine

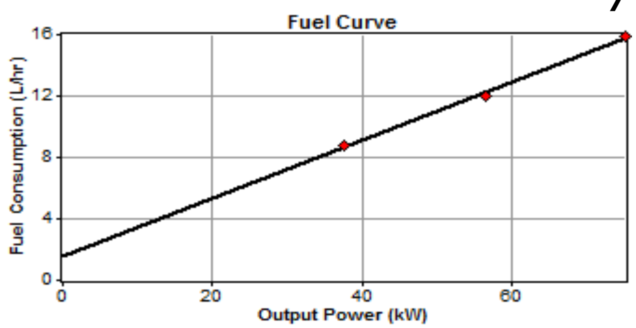
- FD13-50/12 ; cut-in wind speed – 3m/s, cut-out – 25 m/s
- Economically feasible at average speeds of 5 m/s
- 3 blade upwind turbine, PMG generator
- 50 KW rated power
- 13m diameter, 25m hub height

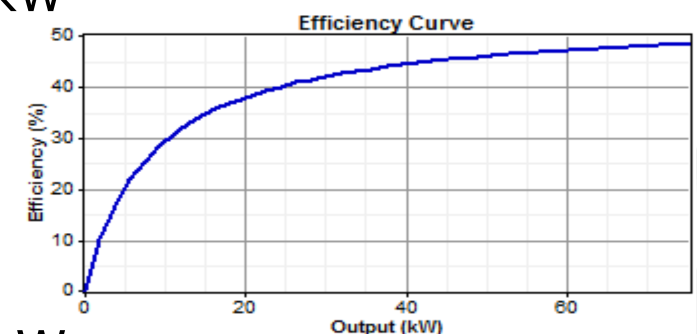


HYBRID SYSTEM DESIGN –Diesel Generators

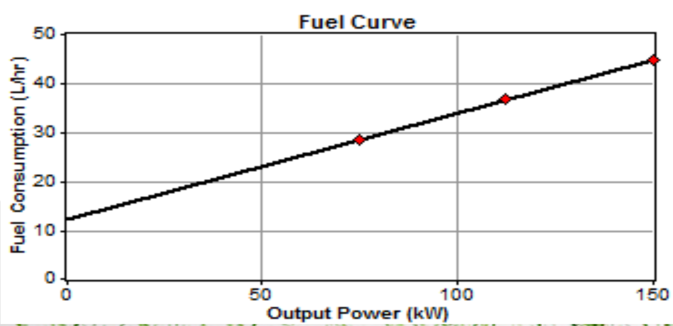
- Two different size (75 kW and 150 kW)
- Life time 35000hrs and 40000hrs respectively

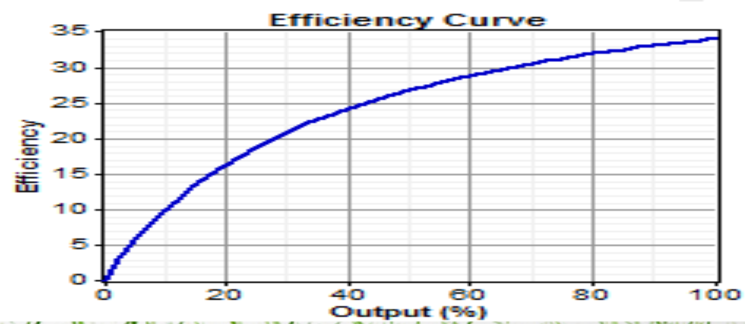
75 kW





150 kW





HYBRID SYSTEM DESIGN –Battery Bank/Converter

- Surrette 12-Cs-11-Ps – lead acid, deep cycle battery
- 12V battery, 54 in series for a 648V bus
- Nominal Capacity 503Ah (6.04 kWh)
- Optimal converter size based on HOMER simulation were 60 kW and 120kW

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	1070	856	30.00
	{..}	{..}	{..}

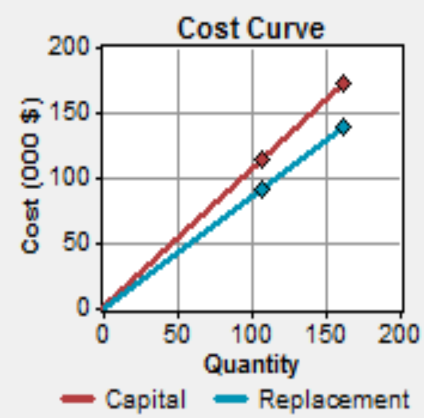
Sizes to consider

Strings
0
2
3

Advanced

Batteries per string 54 (648 V bus)

☐ Minimum battery life (yr) 4 {..}

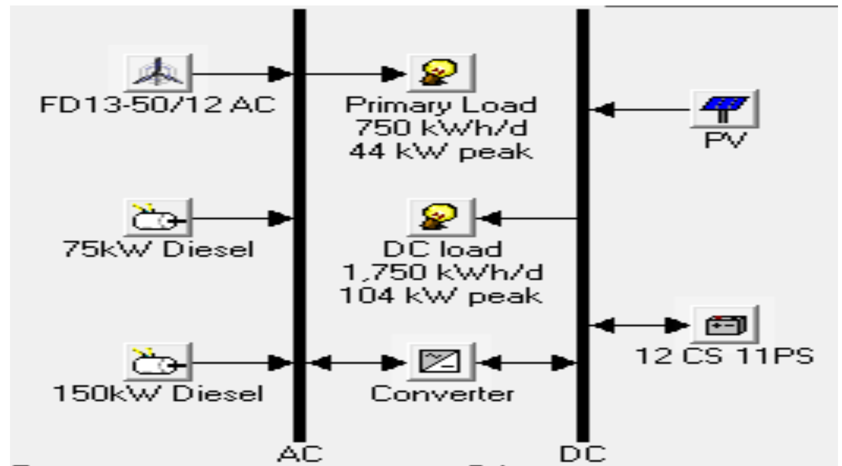


HYBRID SYSTEM DESIGN – System Architecture (30% AC & 70% DC Load)

- AC (Alternating current) coupled system:

System Architecture:

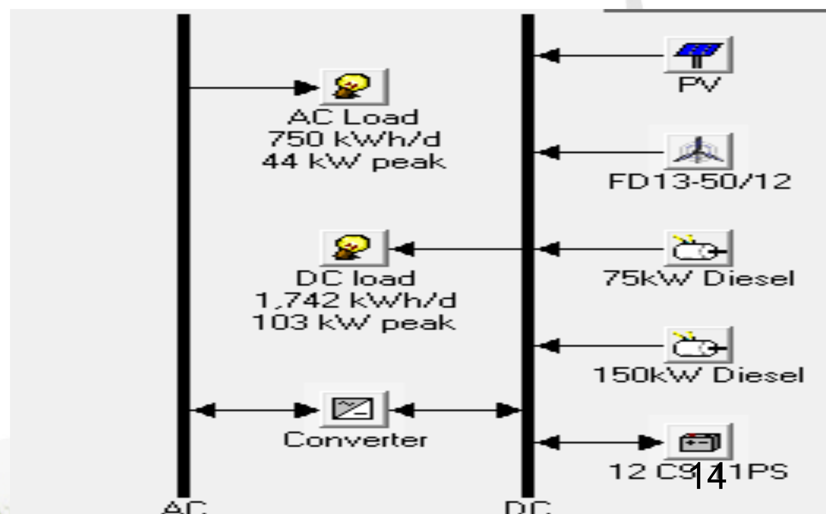
Wind Turbine	: Five FD13-50/12
Diesel Generator	: One 75kW and one 150kW
PV	: 33 kW
Converter	: 120kW
Battery	: 108 (12CS11PS)



- DC (Direct current) coupled system:

System Architecture:

Wind Turbine	: Five FD13-50/12
Diesel Generator	: One 75kW and one 150kW
PV	: 4.725 kW
Converter	: 60kW
Battery	: 108 (12CS11PS)



HYBRID SYSTEM DESIGN – Simulation Results

- AC coupled system with 30% AC & 70 % DC Load :

PV (kW)	XLS	D75 (kW)	D150 (kW)	12CS 1...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D75 (hrs)	D150 (hrs)
33....	5	75	150	108	120	$ 1,738,260	180,033	$ 4,039,688	0.346	0.60	127,057	4,528	1,477
23....	6	75	150		120	$ 1,842,050	243,156	$ 4,950,395	0.424	0.63	179,686	3,944	4,825

- DC coupled system with 30% AC & 70 % DC Load :

PV (kW)	XLS	D75 (kW)	D150 (kW)	12CS 1...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D75 (hrs)	D150 (hrs)
4.725	5	75	150	108	60	$ 1,567,970	174,044	$ 3,792,835	0.326	0.60	122,102	4,576	1,421
18....	5	75	150		60	$ 1,519,640	222,455	$ 4,363,359	0.375	0.60	167,464	2,173	4,807

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HYBRID SYSTEM DESIGN – Simulation Results

AC coupled system with 100% AC Load

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 3.15 | Wind Speed (m/s) 6.04 | Diesel Price ($/L) 1.2

Double click on a system below for simulation results.

Categorized

PV (kW)	XLS	D75 (kW)	D150 (kW)	12 CS 1...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D75 (hrs)	D150 (hrs)
4.725	4	75	150	108	180	$ 1,372,970	182,424	$ 3,704,959	0.318	0.55	121,925	4,892	1,346
4.725	4	75	150		180	$ 1,257,410	229,212	$ 4,187,509	0.359	0.54	162,441	3,425	4,102

DC coupled system with 100% AC Load

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 3.15 | Wind Speed (m/s) 6.04 | Diesel Price ($/L) 1.2

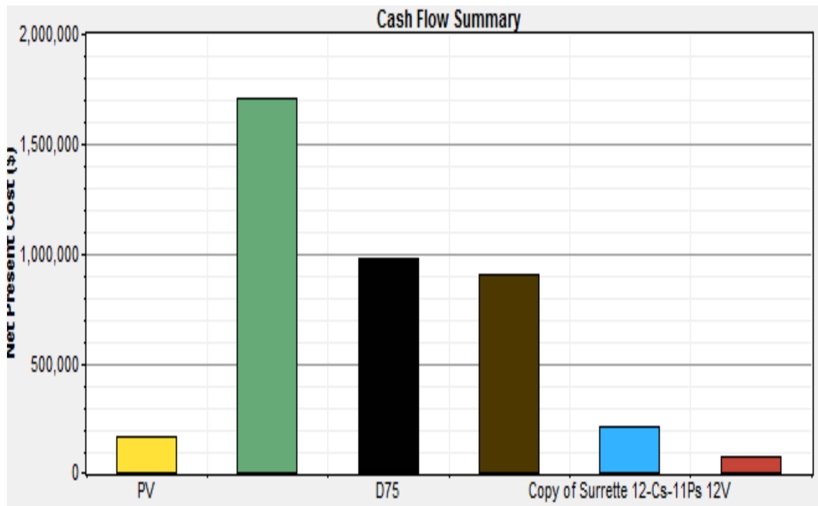
Double click on a system below for simulation results.

Categ

PV (kW)	XLS	D75 (kW)	D150 (kW)	12 CS 1...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D75 (hrs)	D150 (hrs)
4.725	4	75	150	108	180	$ 1,372,970	187,054	$ 3,764,154	0.323	0.54	125,659	4,877	1,432
4.725	4	75	150		180	$ 1,257,410	235,564	$ 4,268,711	0.366	0.53	167,467	3,321	4,273

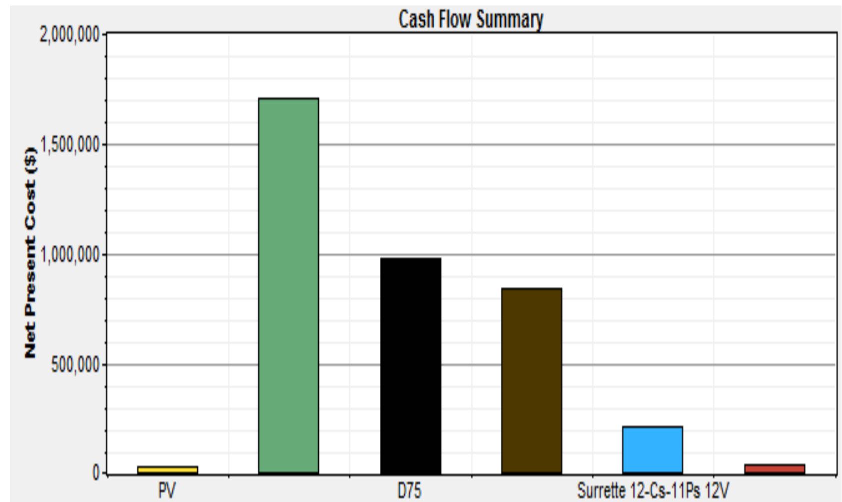
HYBRID SYSTEM DESIGN – Cost Summary (30% AC & 70% DC Load)

AC coupled system:



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	157,700	0	4,498	0	0	162,198
FD13-50/12 AC	1,325,000	0	383,501	0	0	1,708,501
75kW Diesel	30,000	26,051	4,341	923,608	-3,568	980,432
150kW Diesel	40,000	0	28,322	838,664	-573	906,413
Copy of Surrette 12-Cs-1	115,560	68,777	41,418	0	-19,745	206,009
Converter	70,000	0	6,136	0	0	76,136
System	1,738,260	94,828	468,216	1,762,273	-23,887	4,039,690

DC coupled system:

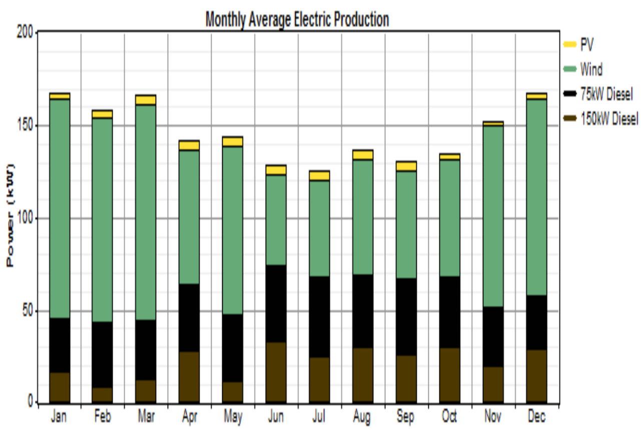


Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	22,410	0	639	0	0	23,049
FD13-50/12	1,325,000	0	383,501	0	0	1,708,501
75kW Diesel	30,000	26,262	4,387	917,613	-3,408	974,854
150kW Diesel	40,000	0	27,248	775,940	-834	842,354
Surrette 12-Cs-11Ps 12v	115,560	68,777	41,418	0	-19,745	206,009
Converter	35,000	0	3,068	0	0	38,068
System	1,567,970	95,039	460,261	1,693,554	-23,988	3,792,836

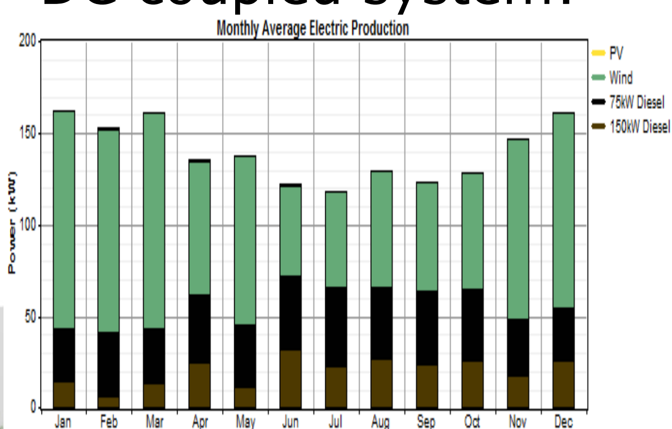
HYBRID SYSTEM DESIGN –

Electrical Production (30% AC & 70% DC Load)

AC coupled system:



DC coupled system:



System Components	Electrical production of DC System		Electrical production of AC System	
	(kWh/yr)	%	(kWh/yr)	%
PV array	5,213	0	36,657	3
Wind turbines	730,987	60	730,987	57
75kW Diesel	311,734	25	314,417	25
150kW Diesel	177,782	15	195,454	15
Total	1,225,716	100	1,277,515	100

Comparison: Based on Component Required

- 100 % AC Load

Component	AC Based System	DC Based System
PV	4.725 kW	4.725 kW
W.T	4 * 50 kW	4 * 50 kW
D-75 kW	1* 75 kW	1* 75 kW
D-150 kW	1 * 150kW	1 * 150kW
Battery	108 number	108 number
Converter	180 kW	180 kW

- 30 % AC and 70% DC load

Component	AC Based System	DC Based System
PV	33 kW	4.725 kW
W.T	5 * 50 kW	5 * 50 kW
D-75 kW	1* 75 kW	1* 75 kW
D-150 kW	1 * 150kW	1 * 150kW
Battery	108 number	108 number
Converter	120 kW	60 kW

Comparison: Based on Cost

100 % AC Load

Cost Type	AC Based System	DC Based System
Initial Capital cost($)	13,72,970	13,72,970
Operating cost ($/Y)	182,424	187,054
Total NPC ($)	3,704,959	3,764,154
COE (%/kWh)	0.318	0.323

30 % AC and 70% DC load

Cost Type	AC Based System	DC Based System
Initial Capital cost($)	17,38,260	15,67,970
Operating cost ($/Y)	180,033	174,044
Total NPC ($)	4,039,688	3,792,835
COE (%/kWh)	0.346	0.326

Comparison: Based on Diesel Use and Corresponding Emission

100 % AC Load

	AC System	DC System
Diesel (L)	121,925	125,659
Pollutant	**Emission (Kg/Yr)**	**Emission (Kg/Yr)**
CO_2	321,070	330,901
CO	793	817
UHCs	87.8	90.5
PM	59.7	61.6
SO_2	645	665
NO_x	7,072	7,288

30 % AC and 70% DC load

	AC System	DC System
Diesel (L)	127,057	122,102
Pollutant	**Emission (Kg/Yr)**	**Emission (Kg/Yr)**
CO_2	334,583	321,536
CO	826	794
UHCs	91.5	87.9
PM	62.3	59.8
SO_2	672	646
NO_x	7,369	7,082

WESNet

NSERC CRSNG

Comparison: Based on Renewable Energy fractions

100 % AC Load

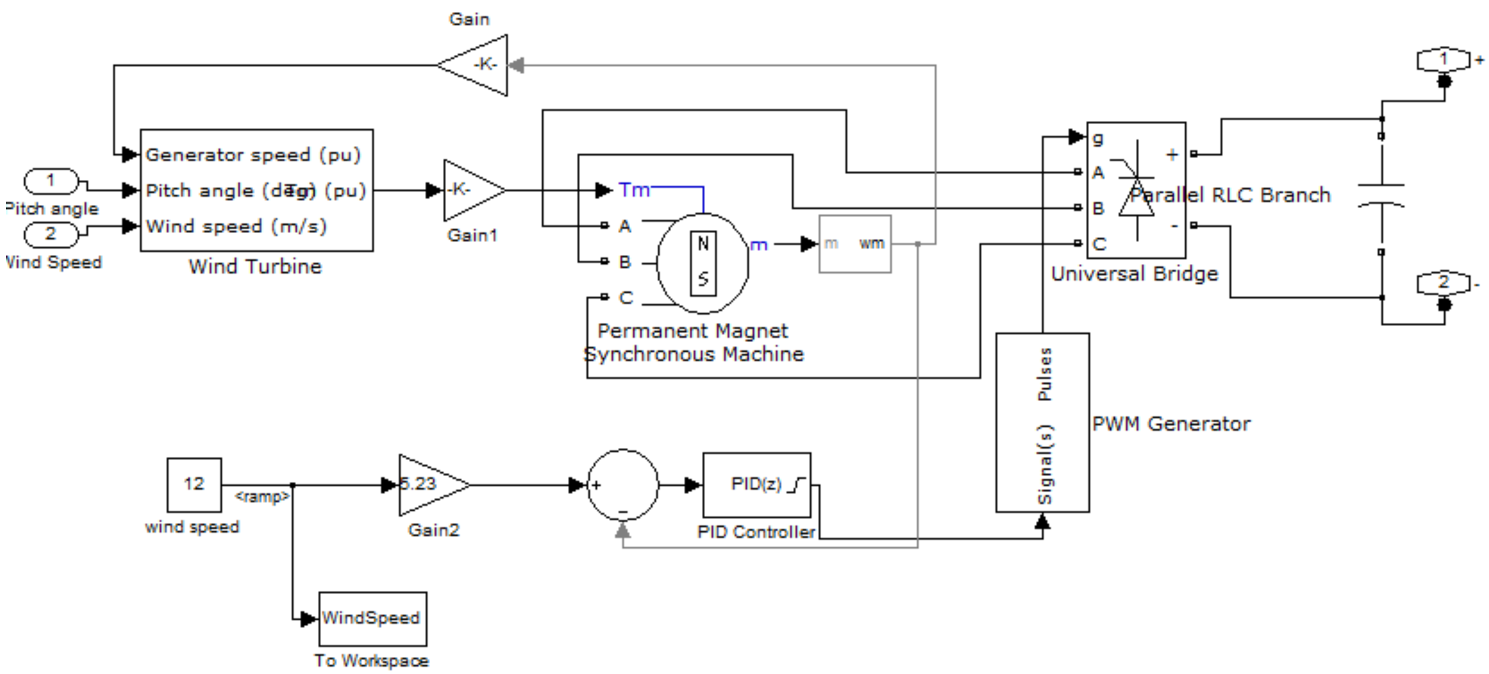
	AC System	DC System
Renewable Fractions	55 %	54 %

30 % AC and 70% DC load

	AC System	DC System
Renewable Fractions	60 %	60 %

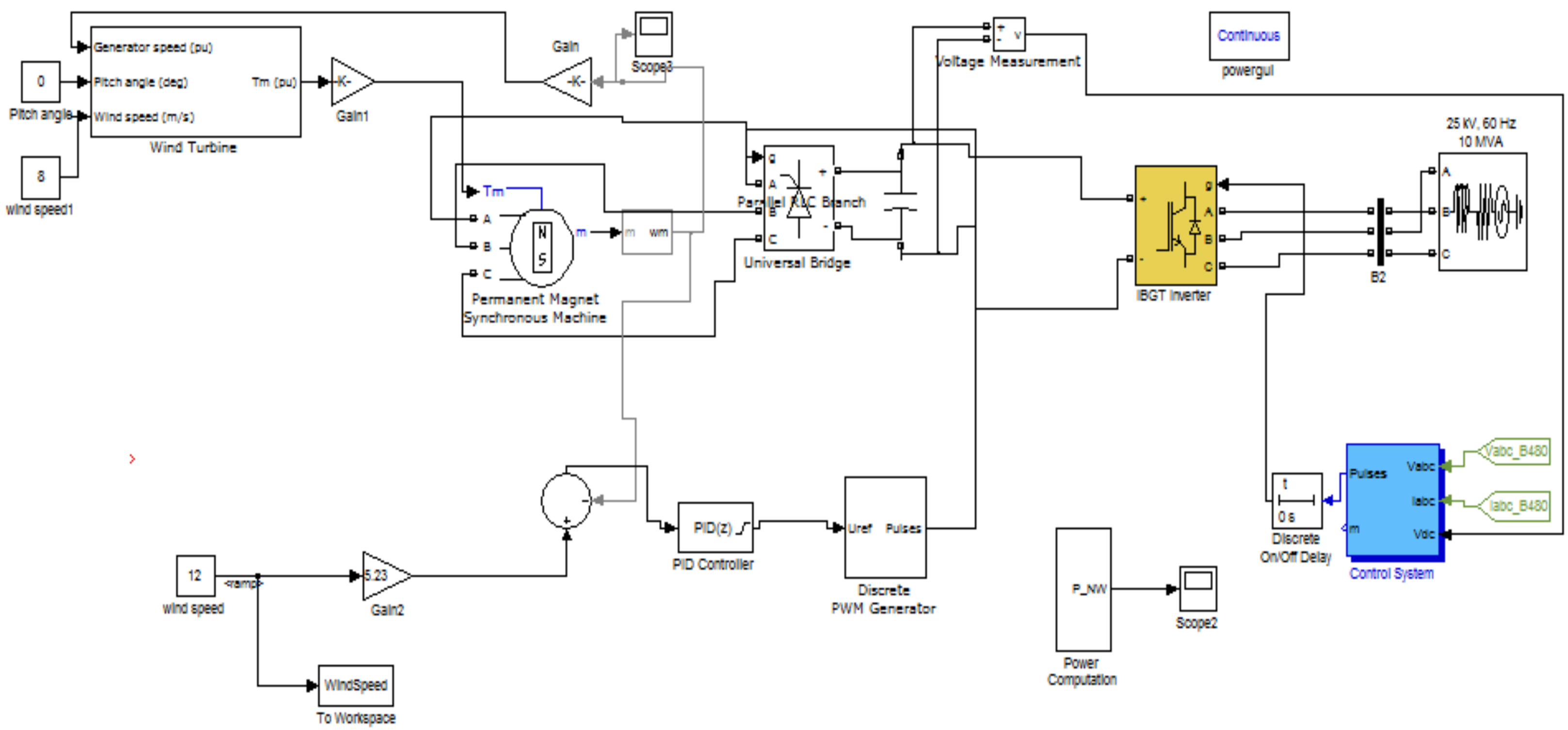
Matlab/ Simulink Model of WT

Model of PMG based WECS for DC System



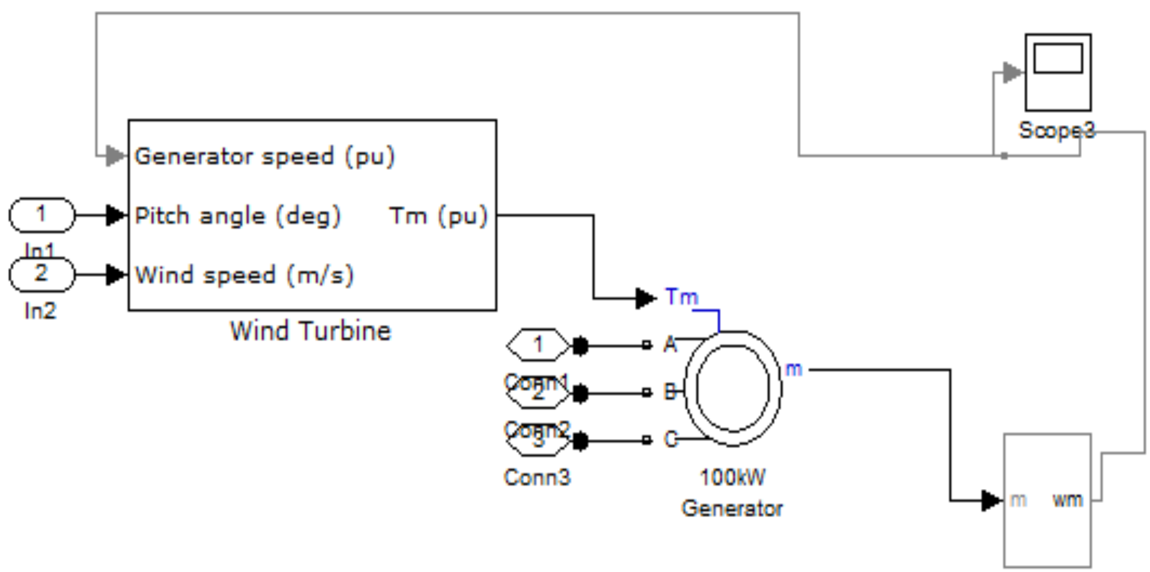
Matlab/ Simulink Model of WT (cont.)

Model of PMG based WECS for AC System

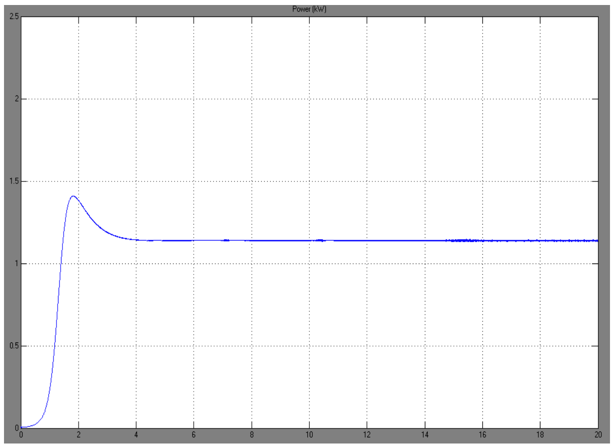


Matlab/ Simulink Model of WT (cont.)

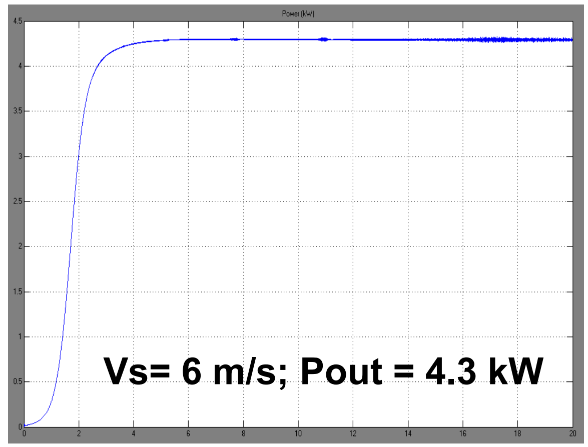
Model of induction generator based WECS for AC system.



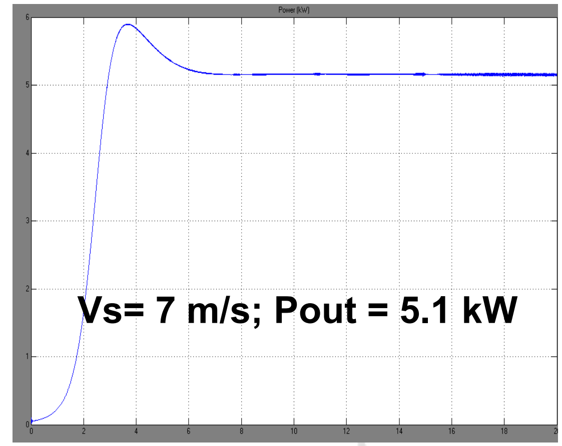
Matlab/ Simulink Model of WT (cont.)



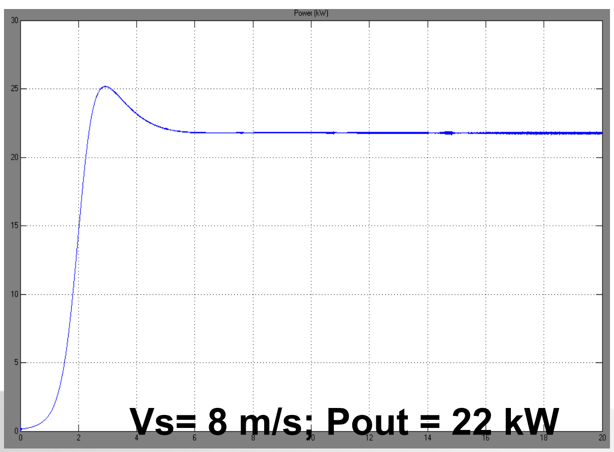
Vs= 5 m/s; Pout = 1.2 kW



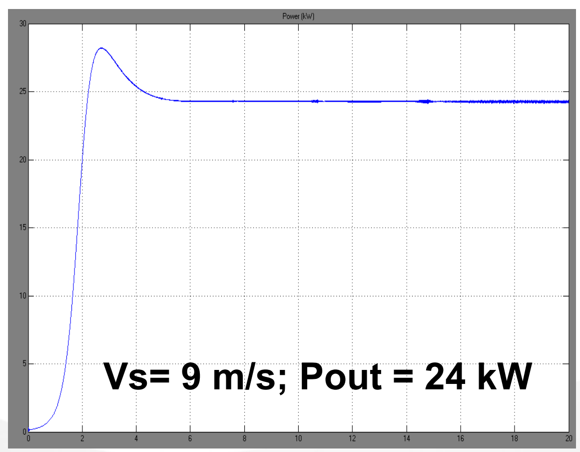
Vs= 6 m/s; Pout = 4.3 kW



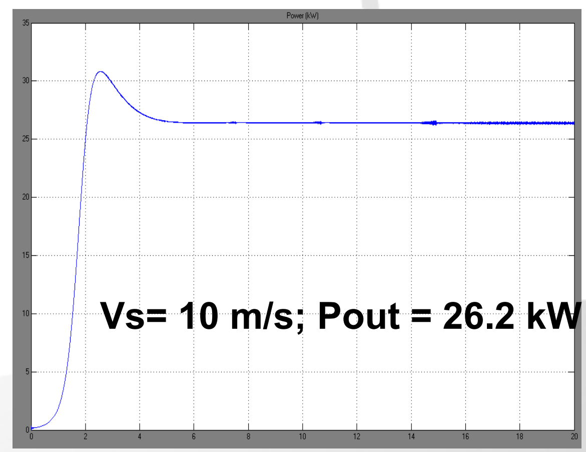
Vs= 7 m/s; Pout = 5.1 kW



Vs= 8 m/s; Pout = 22 kW

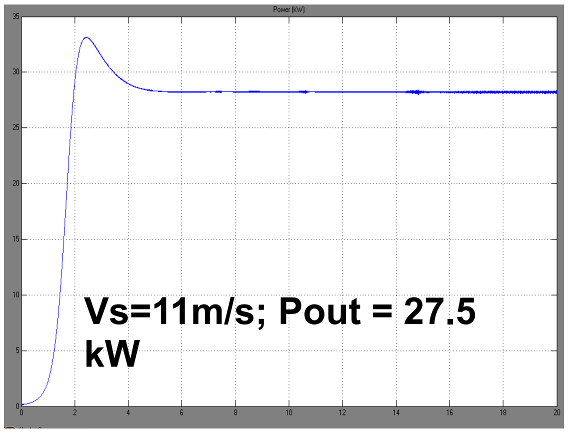


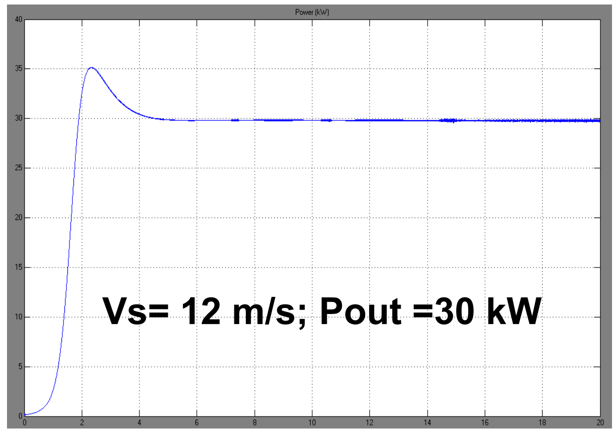
Vs= 9 m/s; Pout = 24 kW

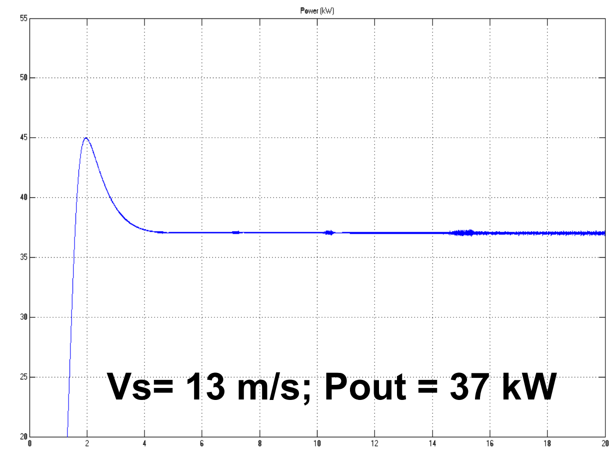


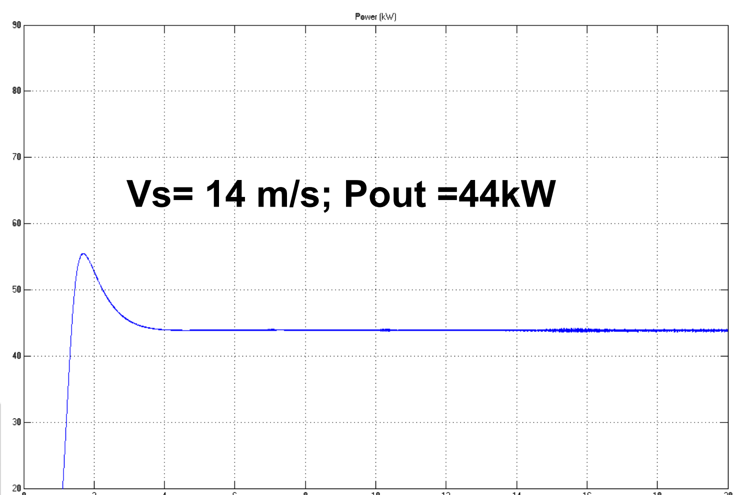
Vs= 10 m/s; Pout = 26.2 kW

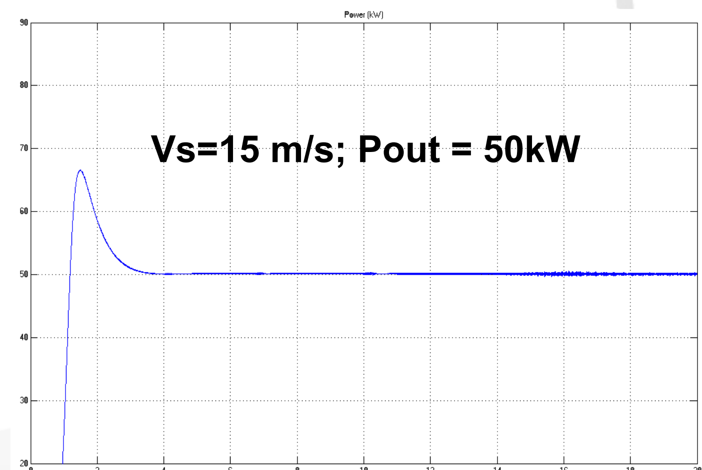
Matlab/ Simulink Model of WT (cont.)



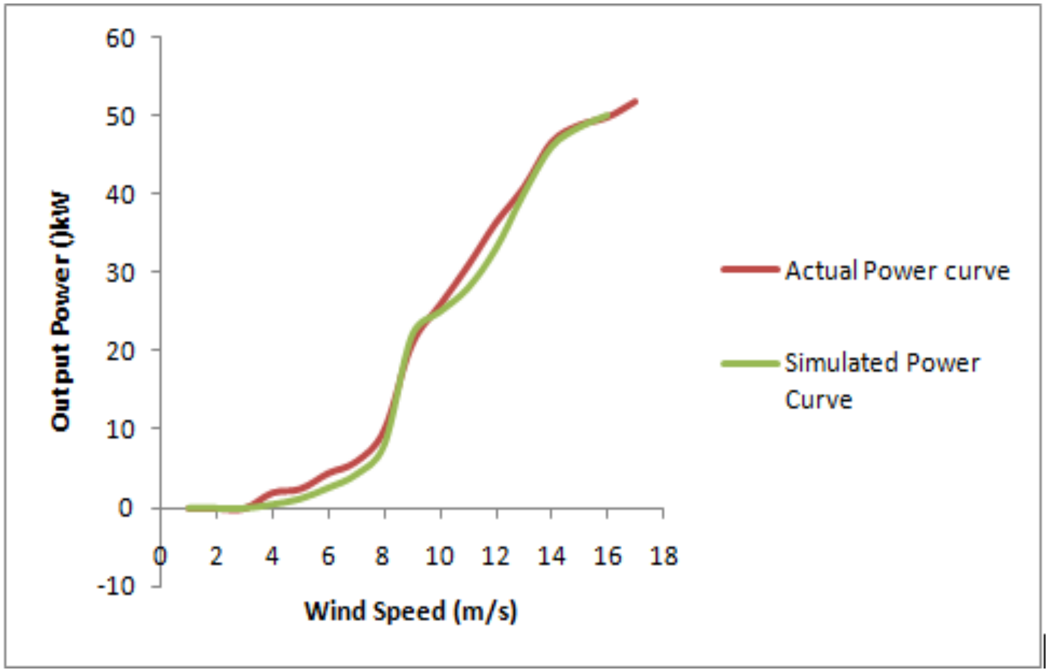








Comparison of the Power Curves Found from Simulation Results and from the Manufacturer

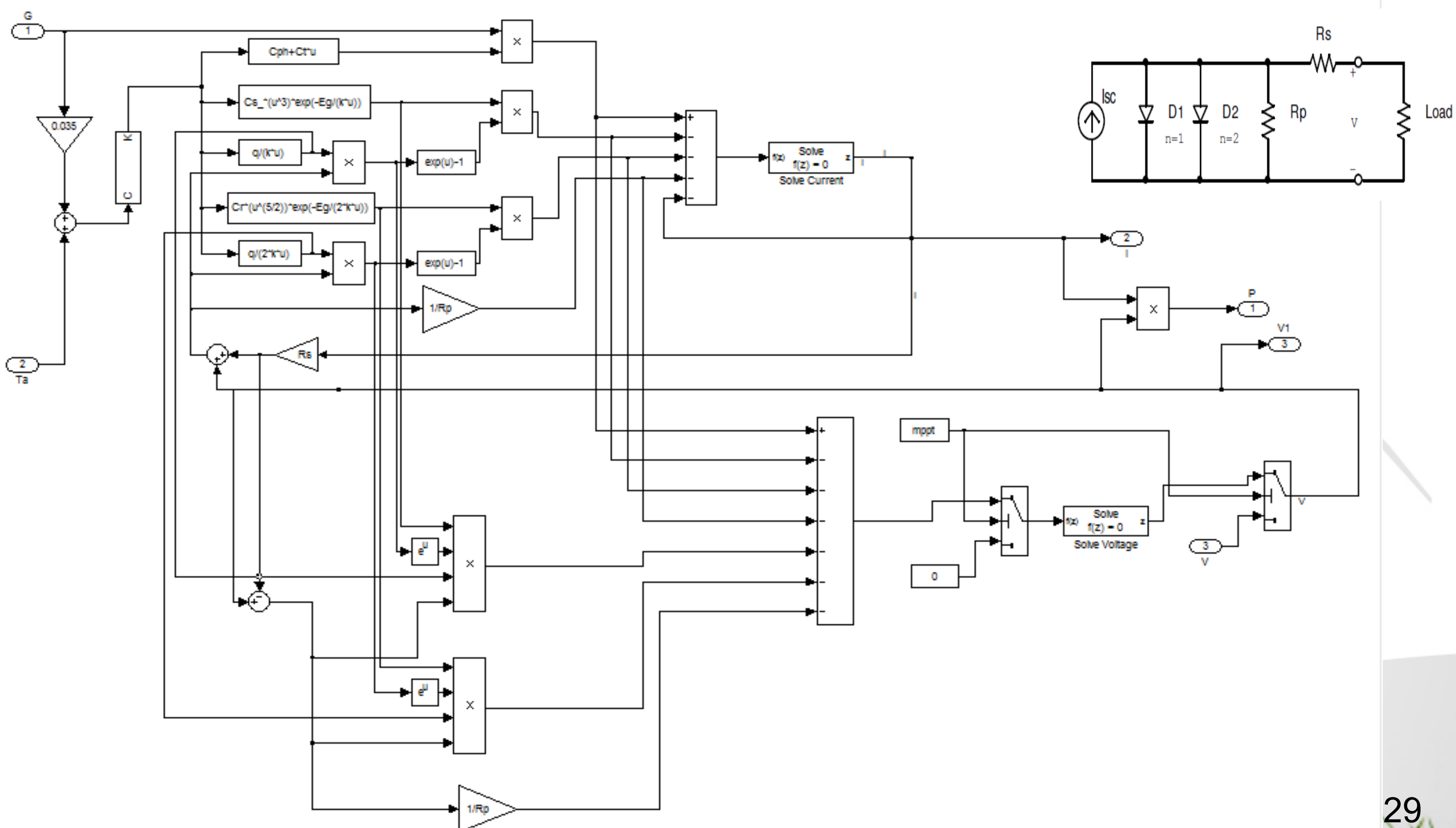


Matlab/ Simulink Model of PV System

Two Diode Solar Cell Model

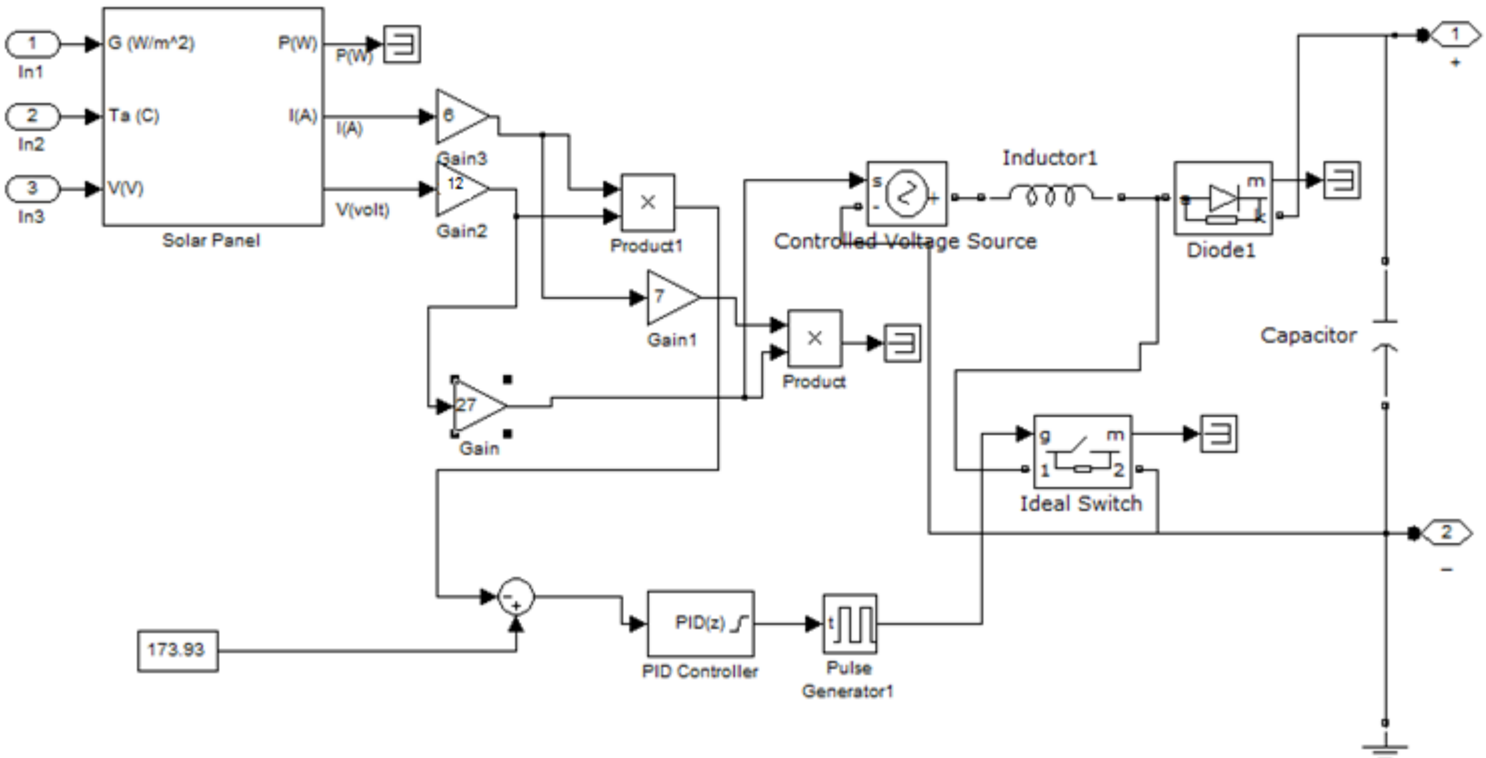
$$I = I_{sc} - I_o\left[e^{q\left(\frac{V+IR_s}{nkT}\right)} - 1\right]$$

$$I = I_{sc} - I_{01}\left[e^{q\left(\frac{V+I.R_s}{kT}\right)} - 1\right] - I_{02}\left[e^{q\left(\frac{V+I.R_s}{2kT}\right)} - 1\right] - \left(\frac{V+I.R_s}{R_p}\right)$$

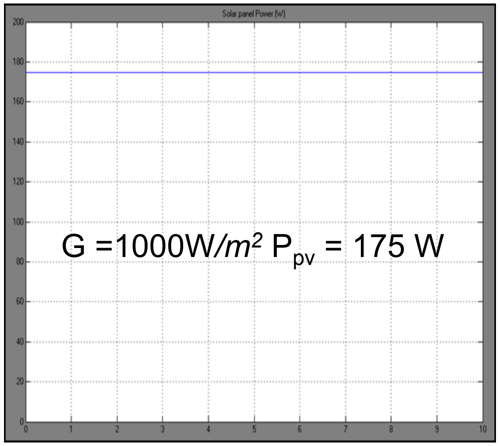


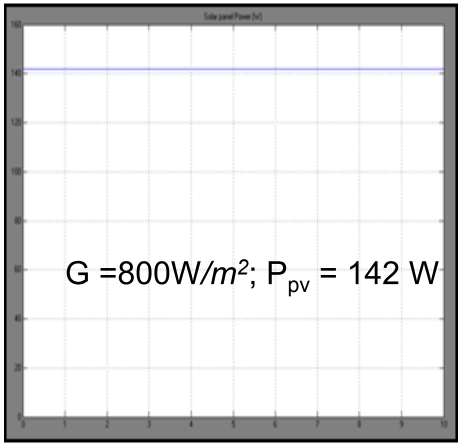
Matlab/ Simulink Model of PV System (Cont.)

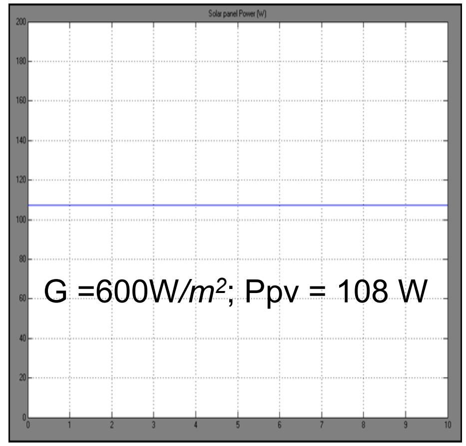
Modeling of Solar panel

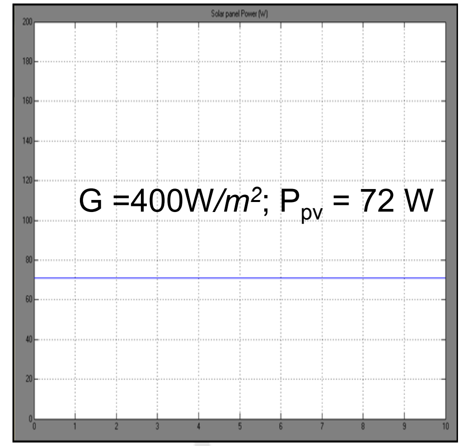


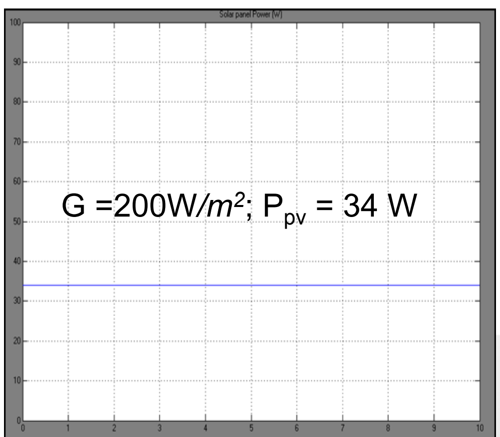
Power Generation in Solar Panel at Different Solar Irradiance (Cont.)

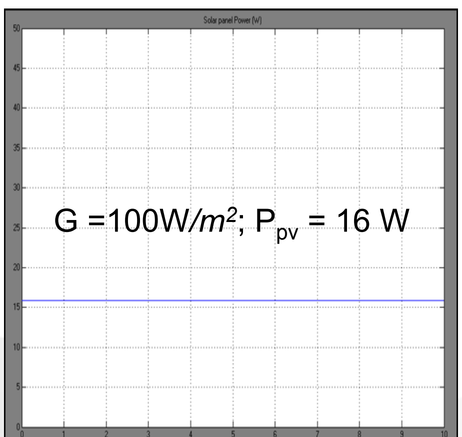


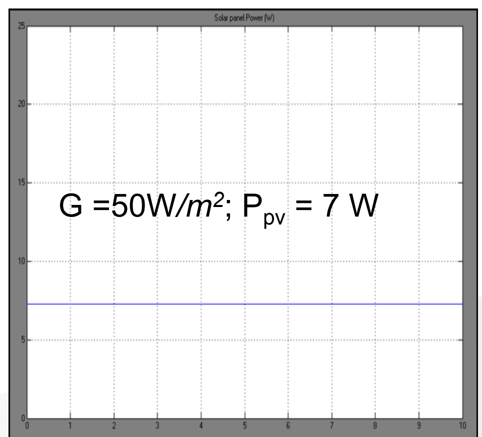


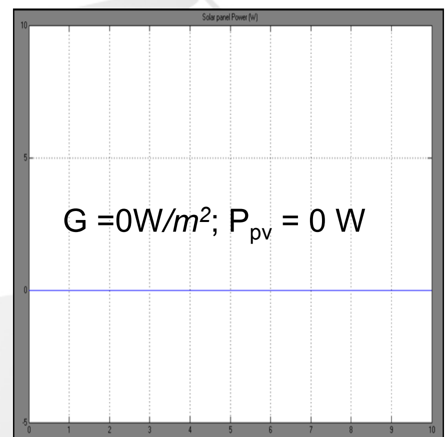




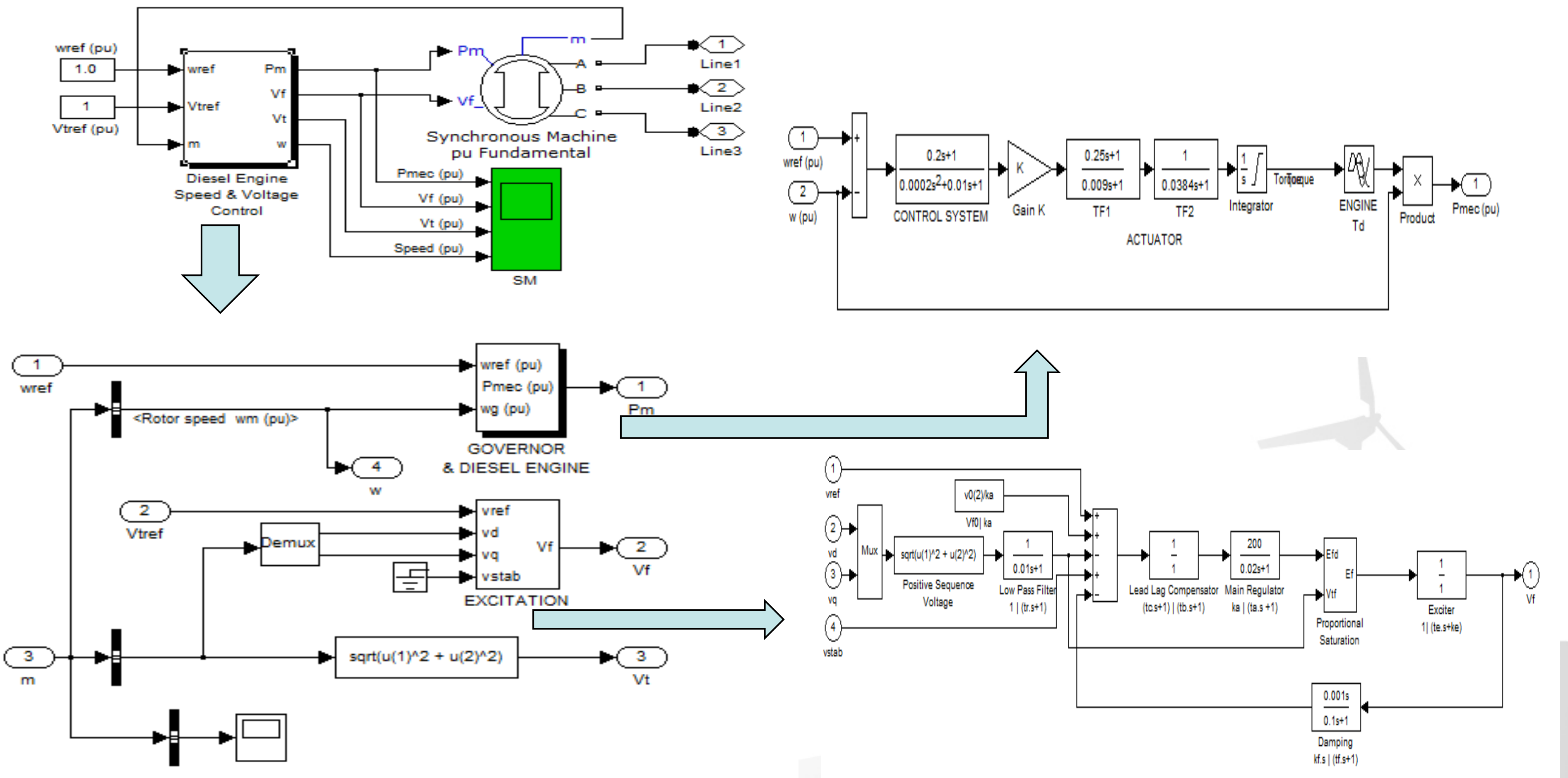




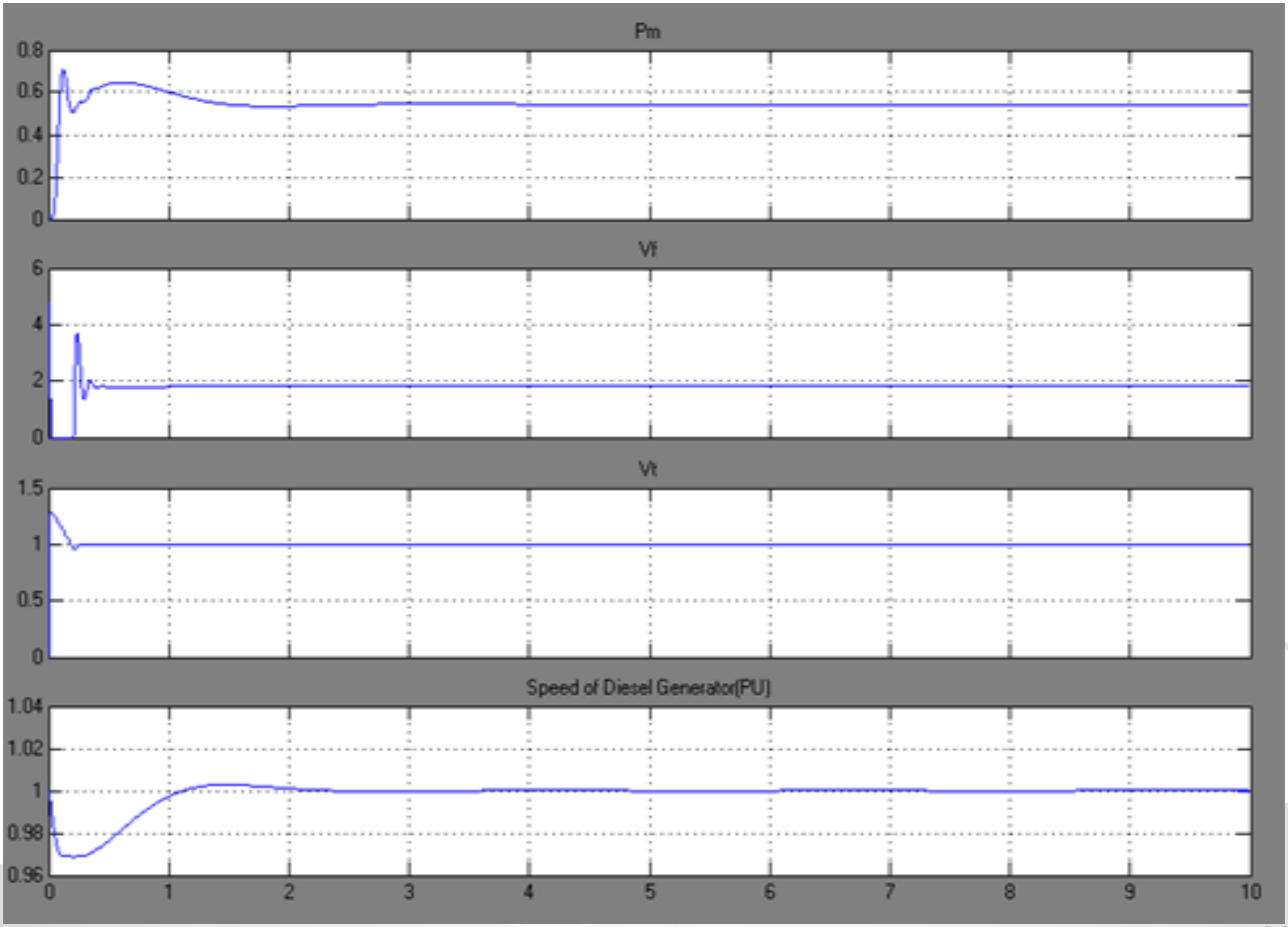




Matlab/ Simulink Model of Diesel Generator



Simulation Result of Diesel Generator



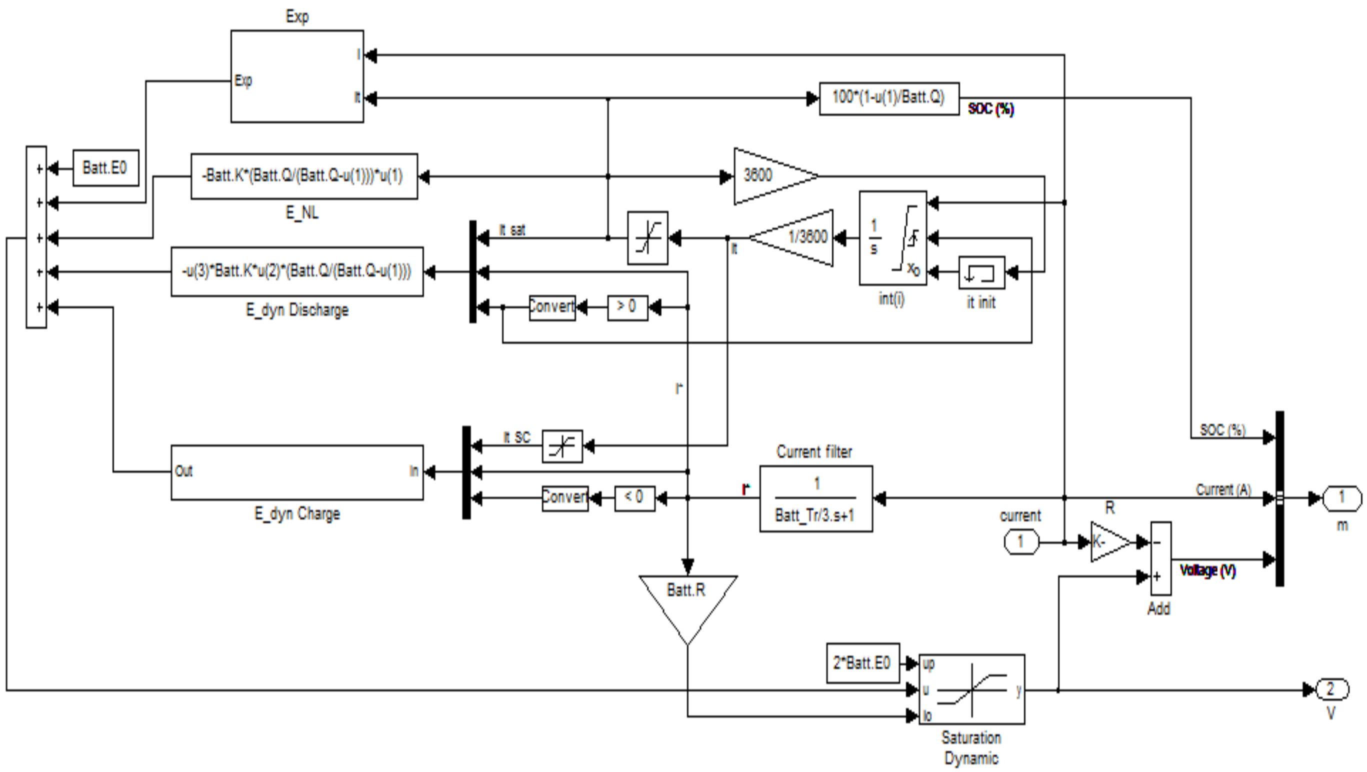
Matlab/ Simulink Model of Battery

Discharge model $i^* > 0$

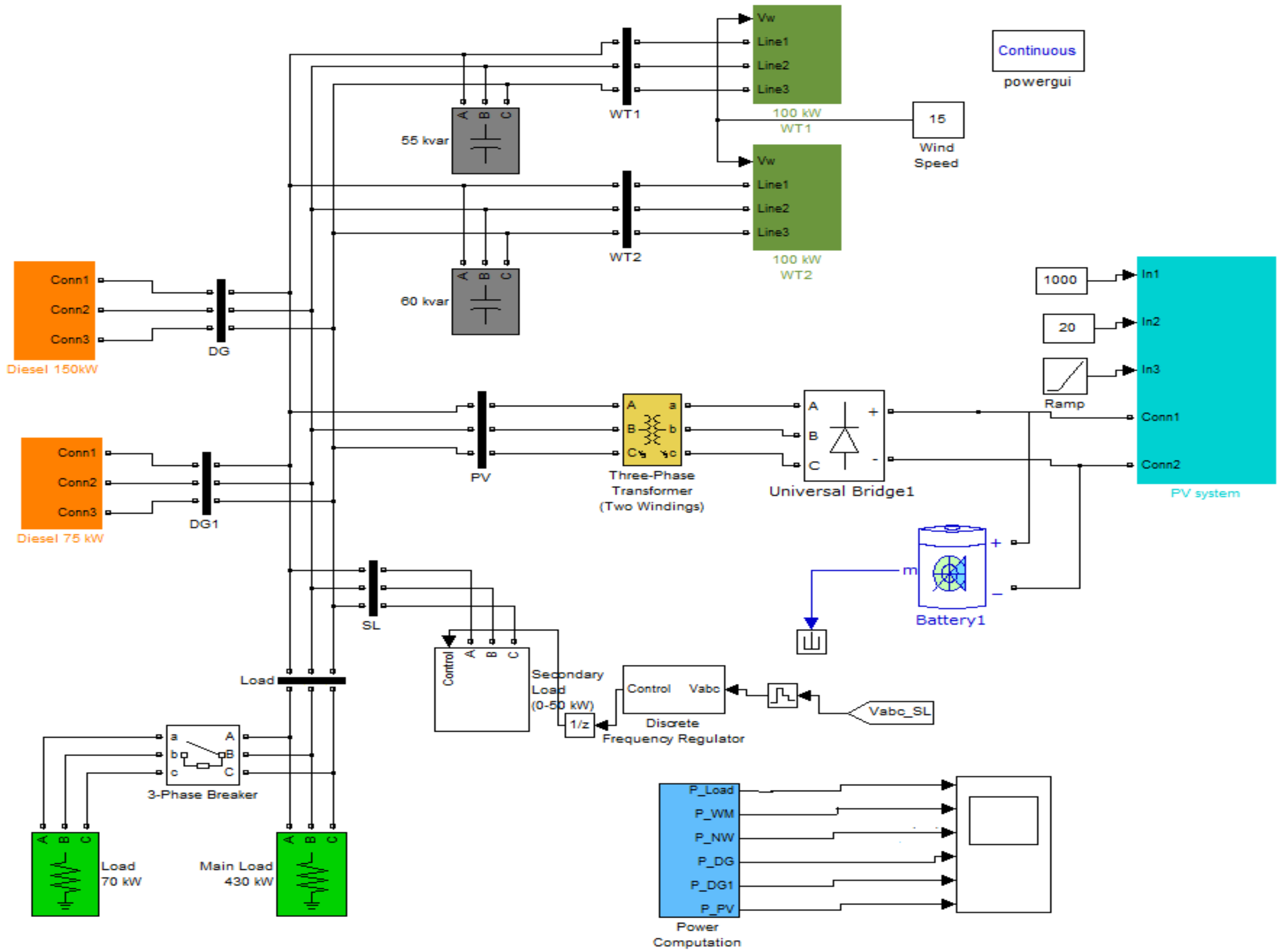
$$f_1(it, i^*, i, Exp) = E_0 - K\frac{Q}{Q-it}\cdot i^* - K\frac{Q}{Q-it}\cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot 0\right)$$

Charge model $i^* < 0$

$$f_2(it, i^*, i, Exp) = E_0 - K\cdot\frac{Q}{it+0.1\cdot Q}\cdot i^* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot\frac{1}{s}\right)$$

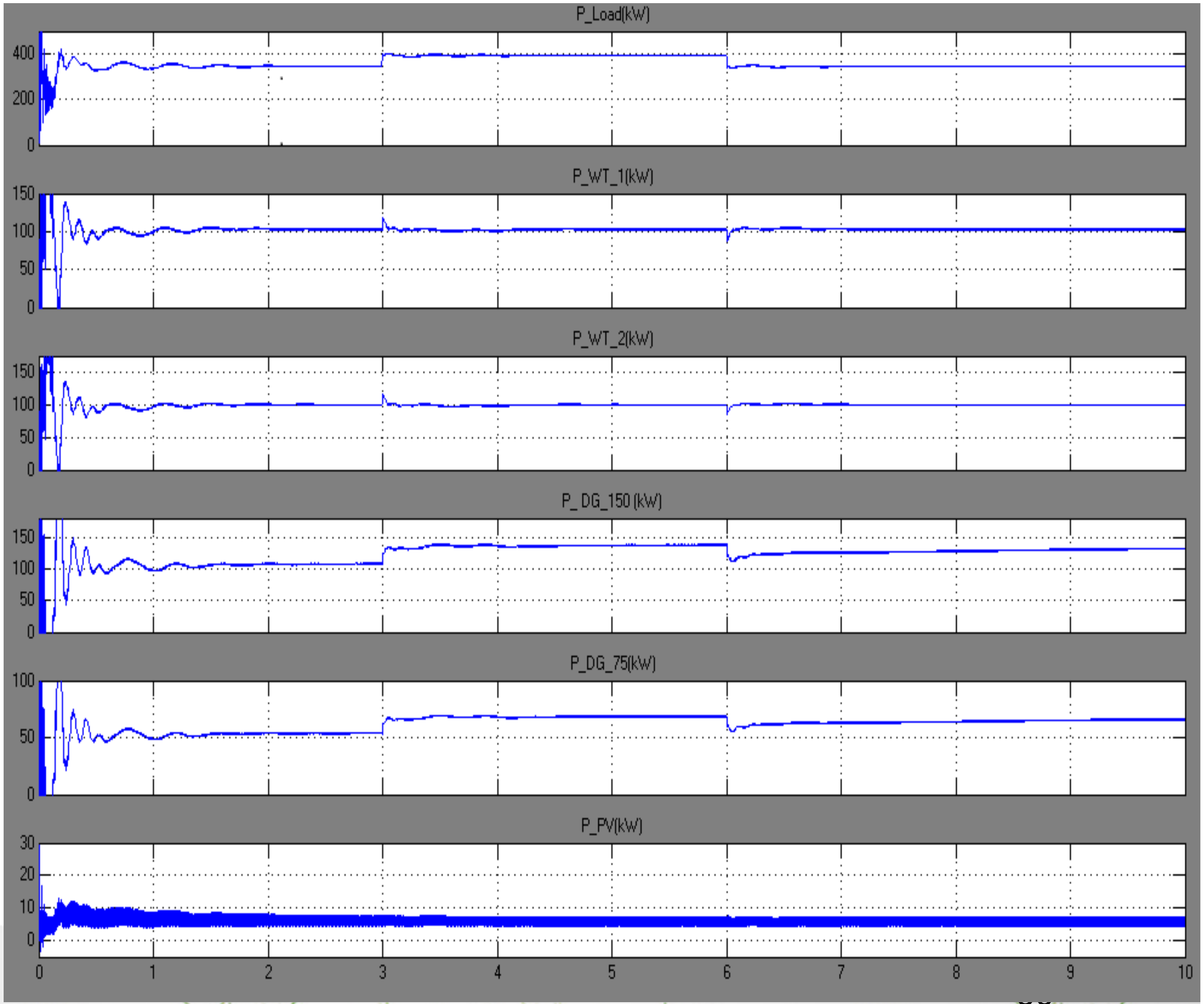


Transient Analysis of AC Coupled Hybrid Power System



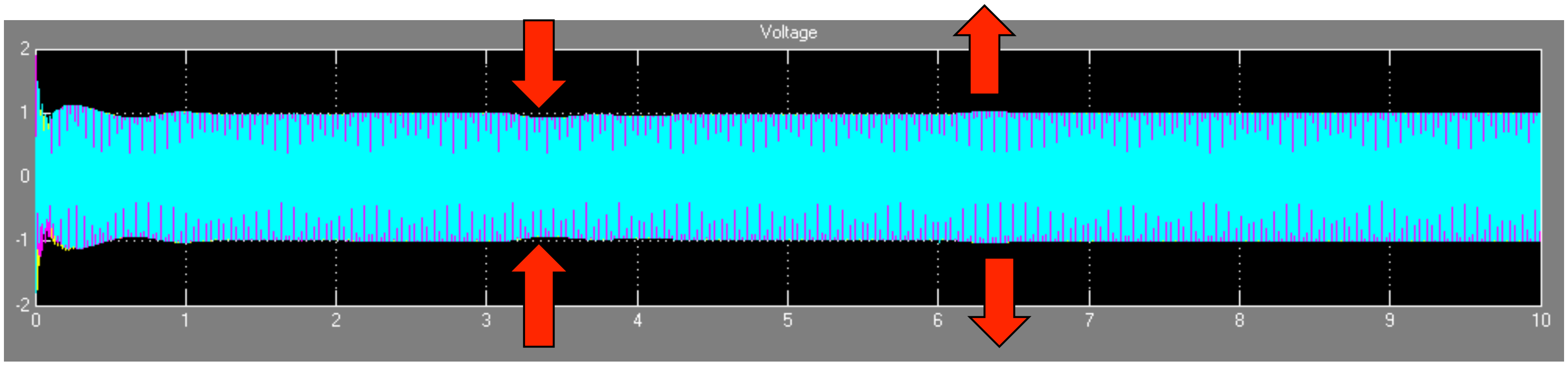
CS1: Simulation With Fixed Wind Speed Variable Load

- ❖Load 350/400/350 kW
- ❖Wind Speed 15 m/s
- ❖No change in WT power
- ❖DGs respond with main load variation



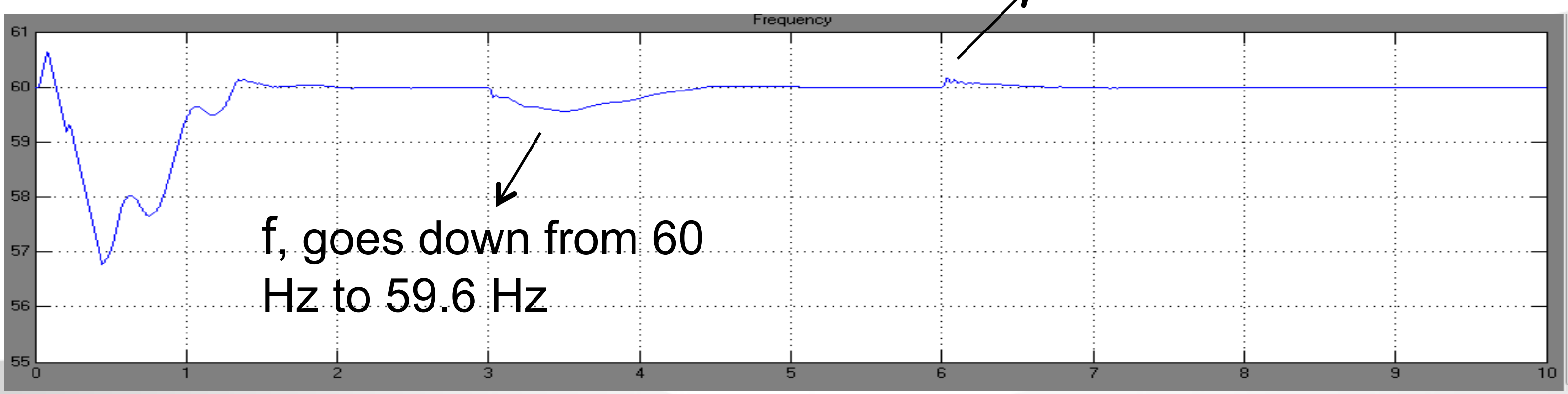
CS1: Simulation With Fixed Wind Speed Variable Load (cont.)

- **Effect of change of load on voltage and Frequency**



Effect on Voltage

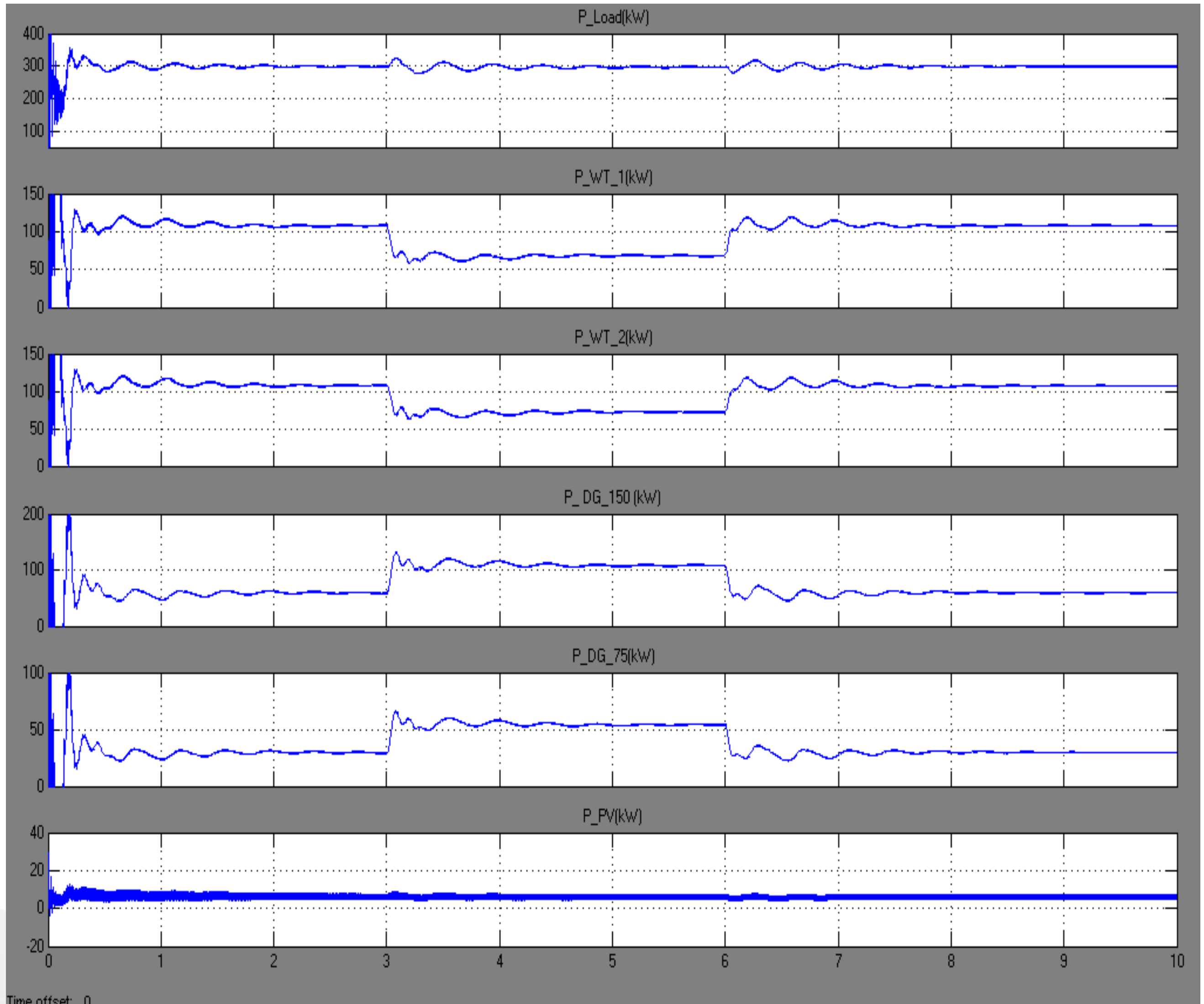
f, rises from 60 Hz to 60.1 Hz



Effect on Frequency

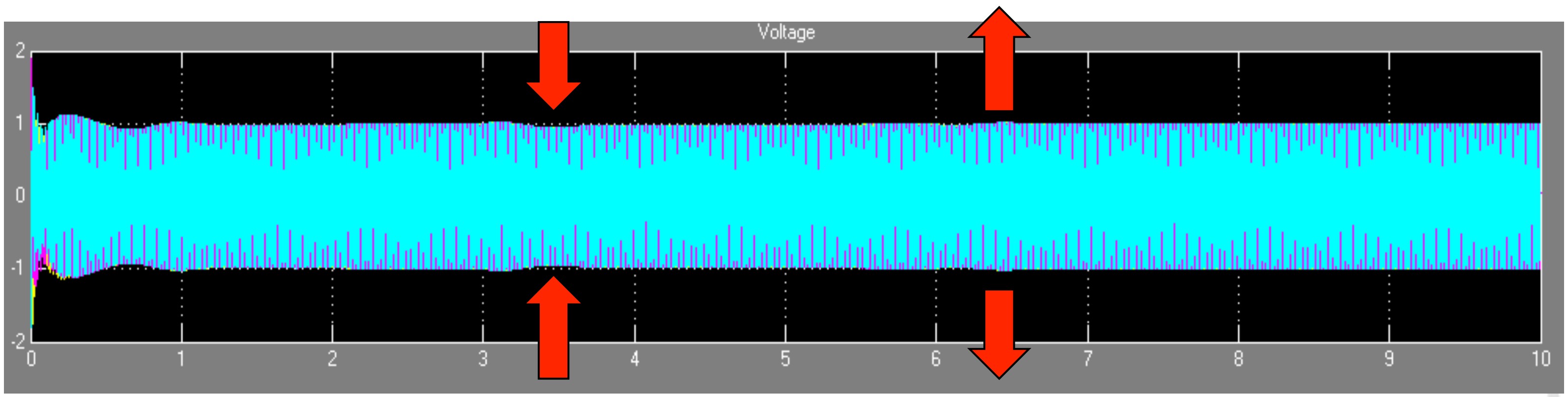
CS2: Simulation With Fixed Load Variable Wind Speed

- Load 300kW
- Wind Speed 15/10/14 m/s
- WTs respond to wind speed change
- When wind generation drop, DGs met up additional load

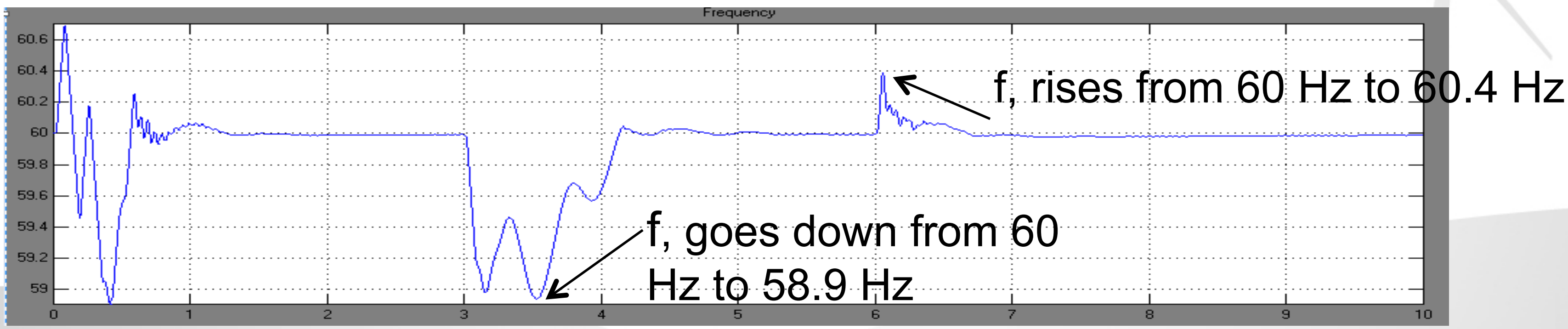


CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

Effect of change of Wind Speed on voltage and Frequency



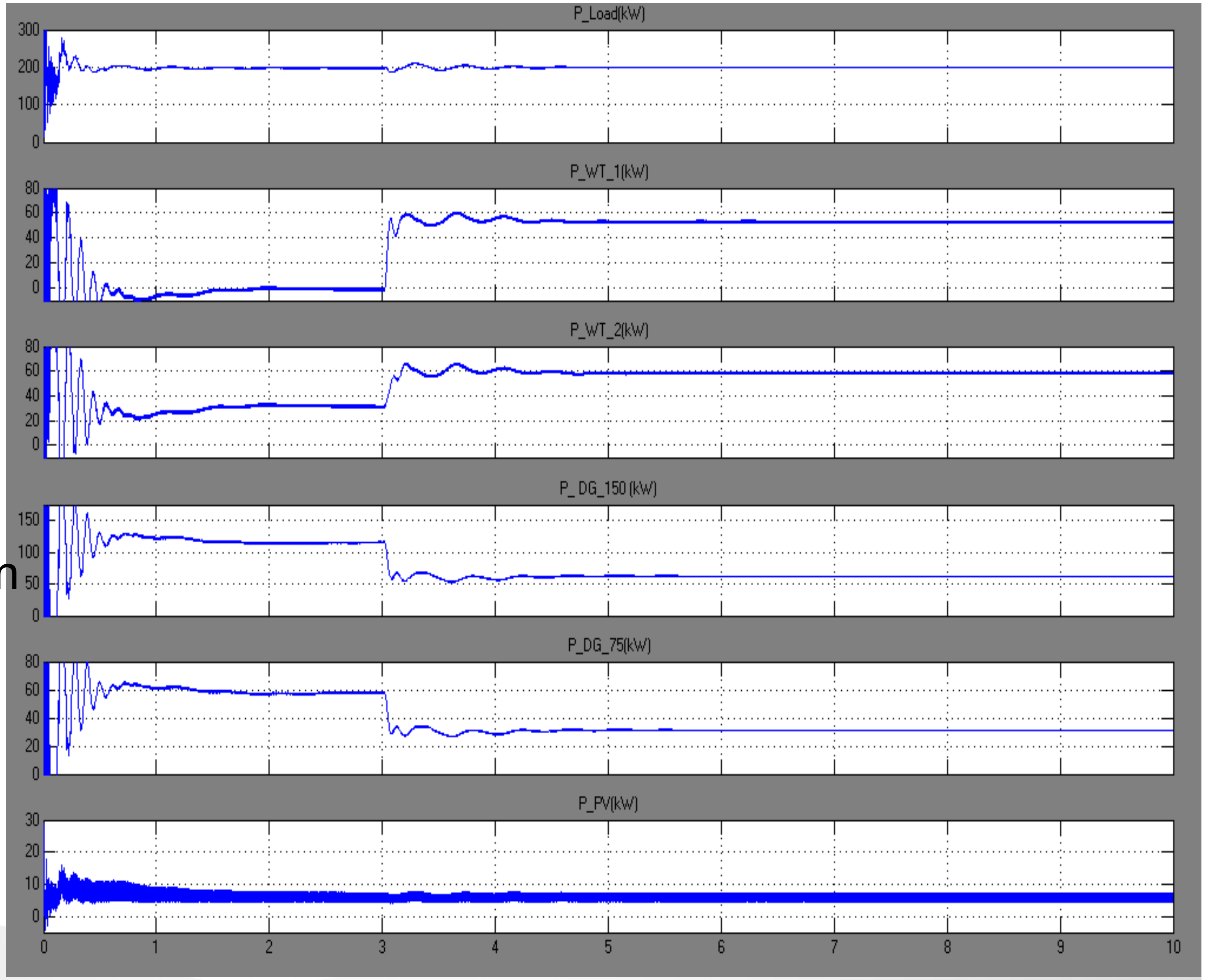
Effect on Voltage



Effect on Frequency

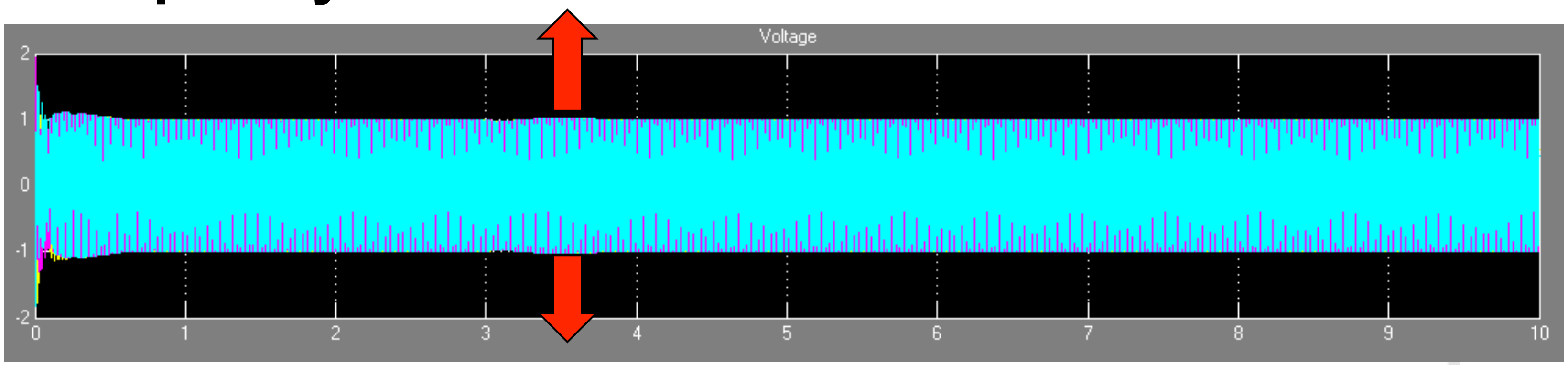
CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

- ❖Load 200kW
- ❖Wind Speed 7/9 m/s
- ❖WTs respond to wind speed change
- ❖When wind generation rises, Diesel generation drop automatically.

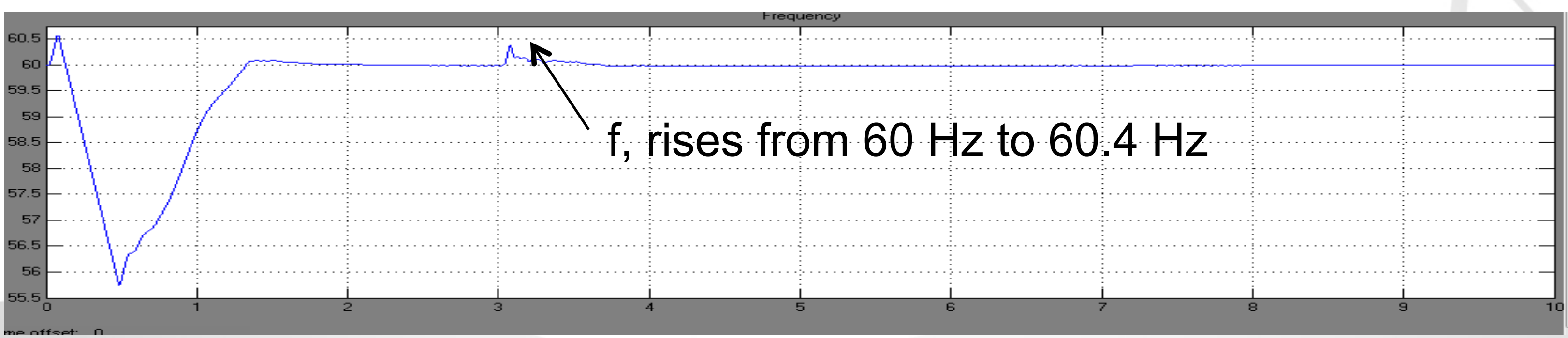


CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

Effect of change of Wind Speed on voltage and Frequency



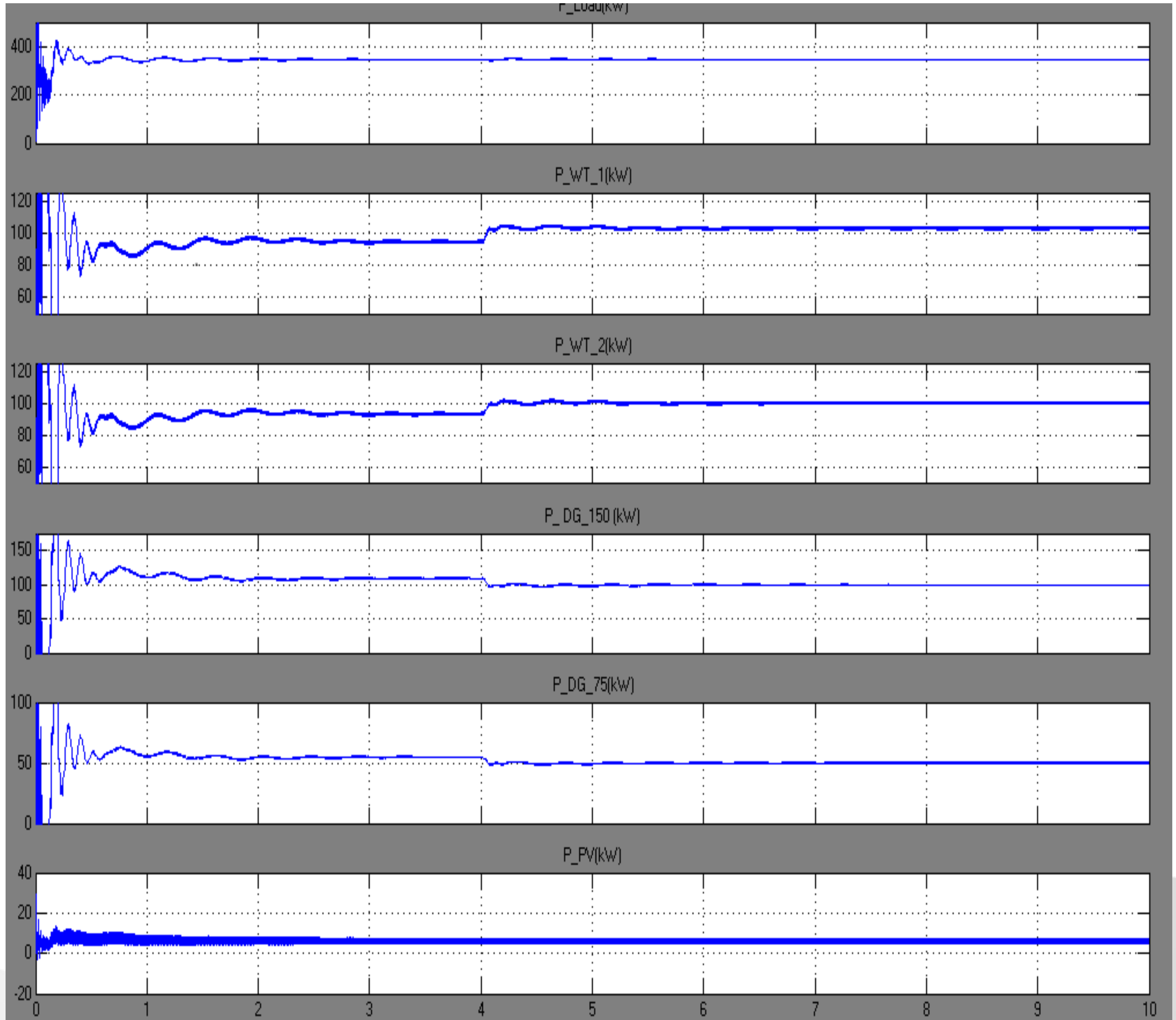
Effect on Voltage



Effect on Frequency

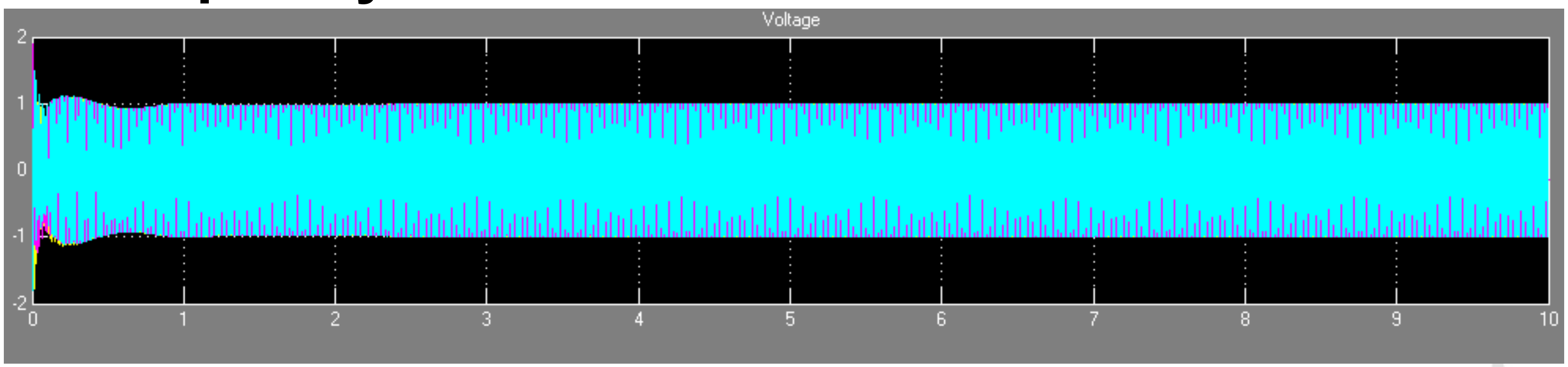
CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

- Load 350kW
- Wind Speed 14/15 m/s
- WTs respond to wind speed change
- When wind generation rises, Diesel generation drop automatically.

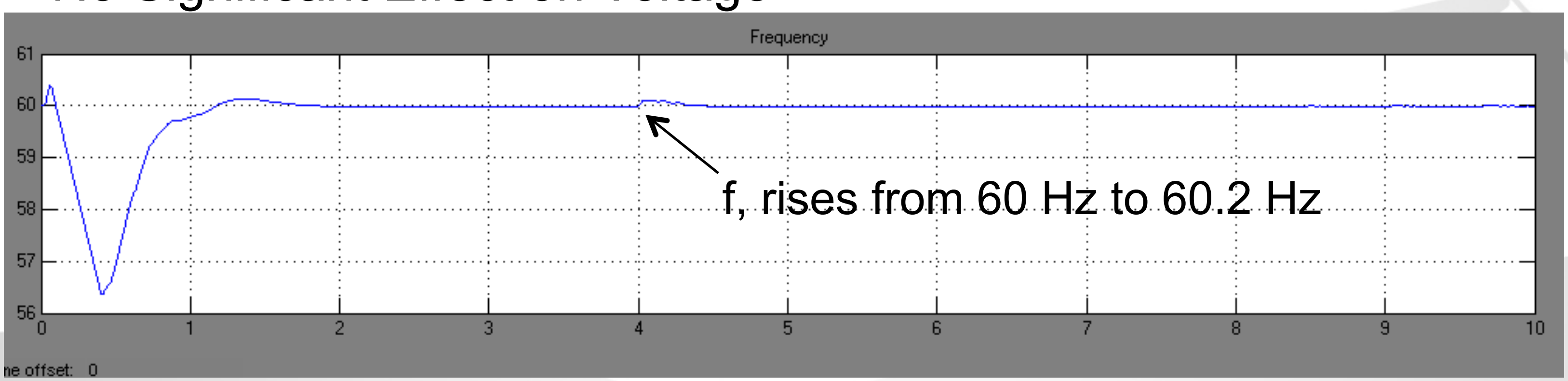


CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

Effect of change of Wind Speed on voltage and Frequency



No Significant Effect on Voltage



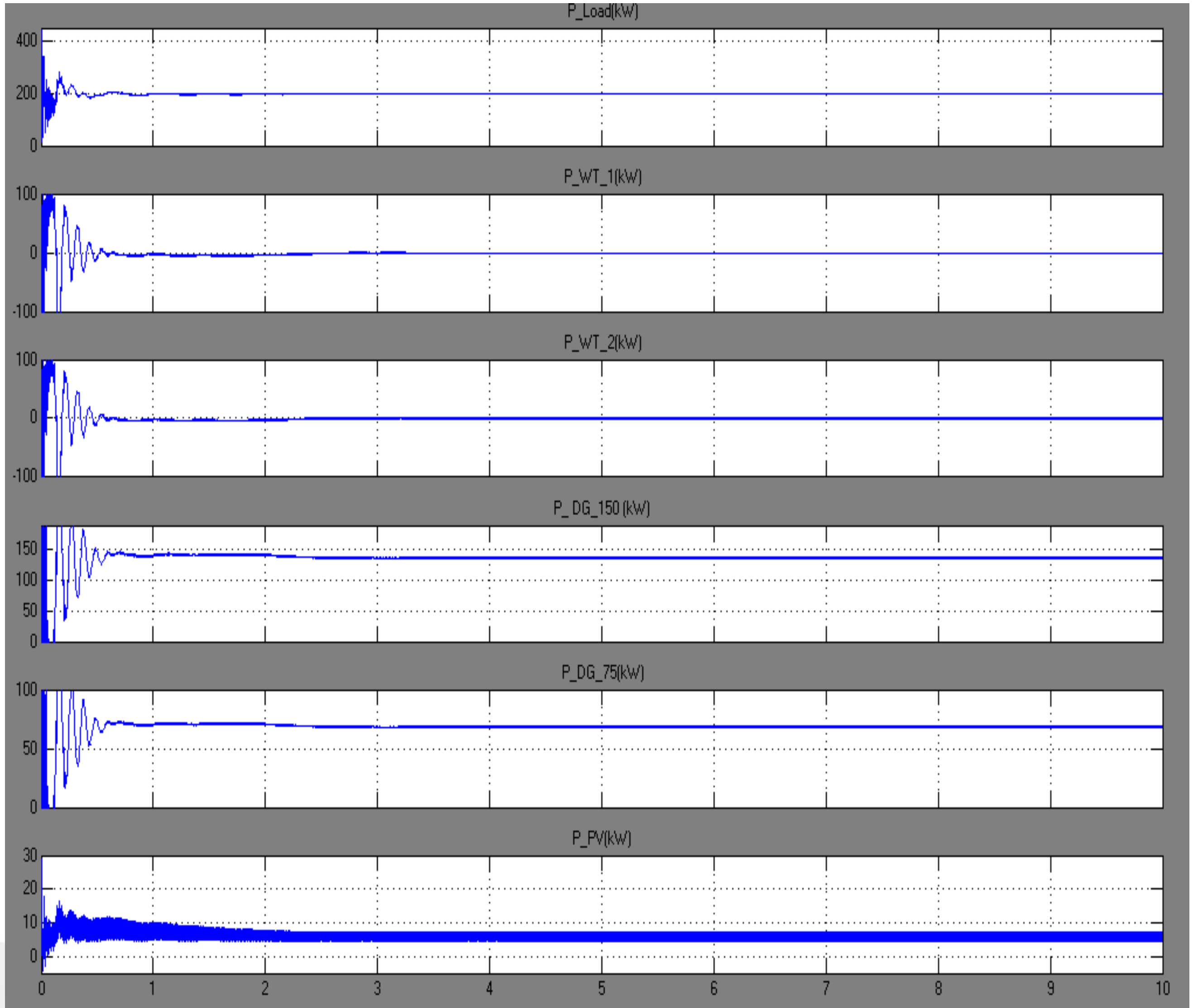
Effect on Frequency

CS3: Simulation With Diesel Generator and Photovoltaic System(cont.)

❖Load 200kW

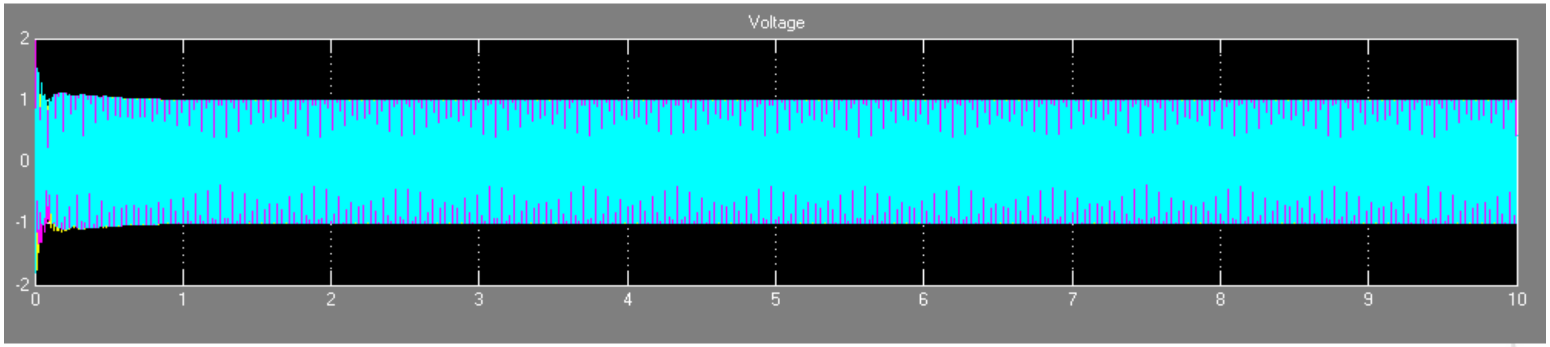
❖ Zero Wind Speed

❖Load is met by DGS and PV.

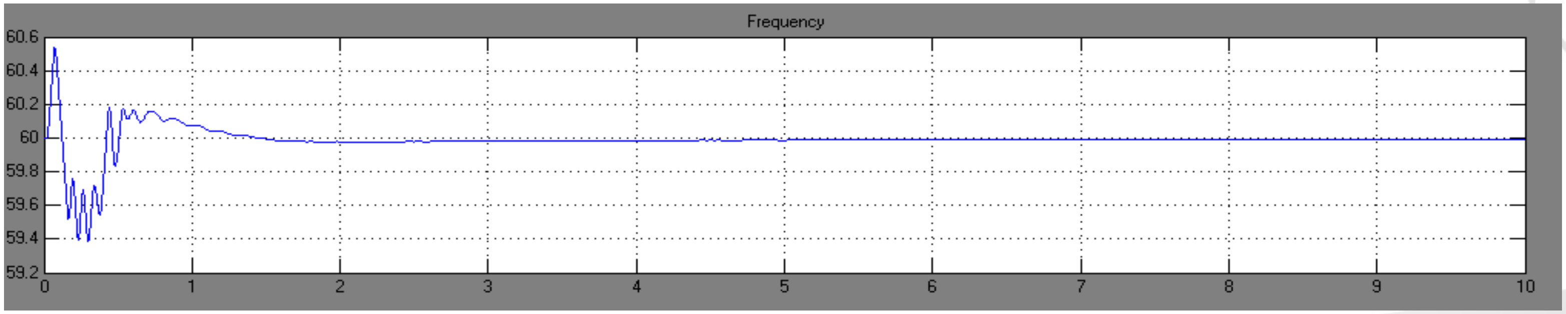


CS3: Simulation With Diesel Generator and Photovoltaic System(cont.)

Effect on voltage and Frequency



No Effect on Voltage as expected



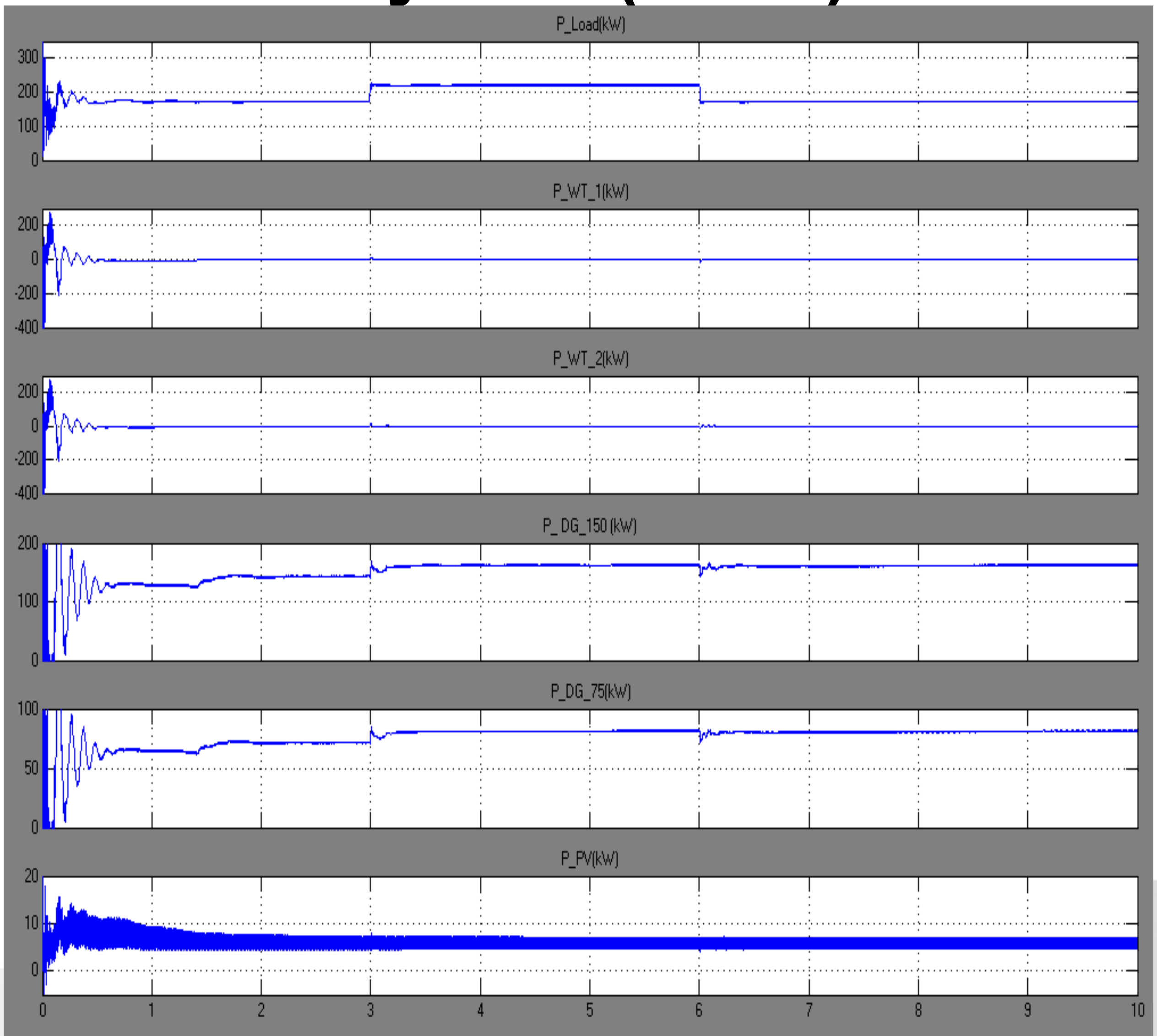
No Effect on Frequency as expected

CS3: Simulation With Diesel Generator and Photovoltaic System(cont.)

❖Load 175/225/175kW

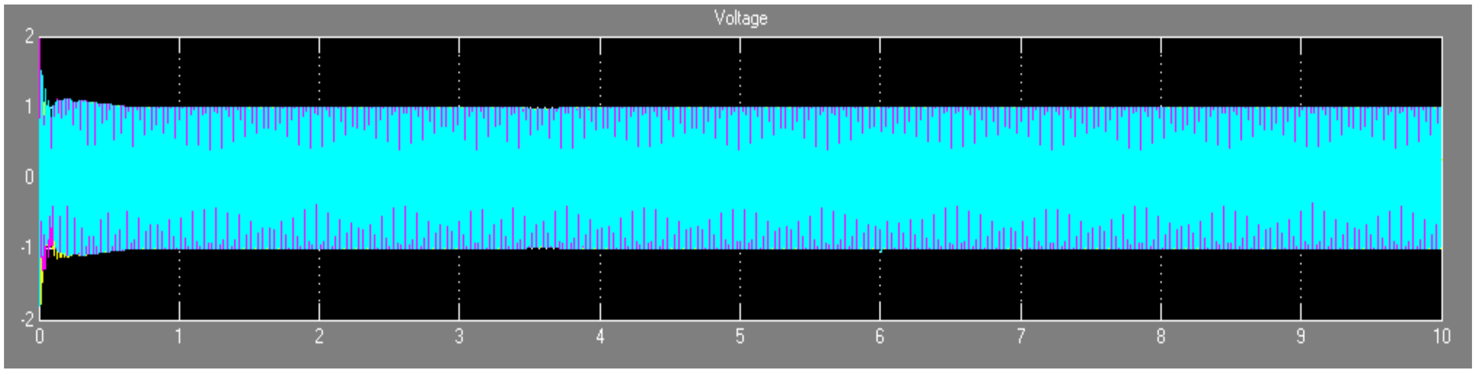
❖ Zero Wind Speed

❖Diesel generation follows the load

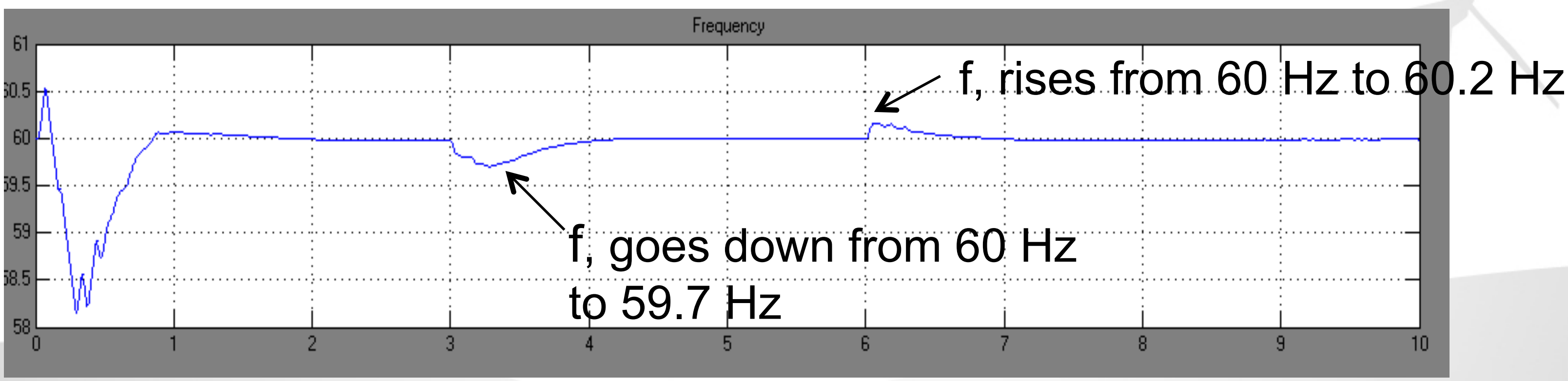


CS3: Simulation With Diesel Generator and Photovoltaic System

Effect on voltage and Frequency

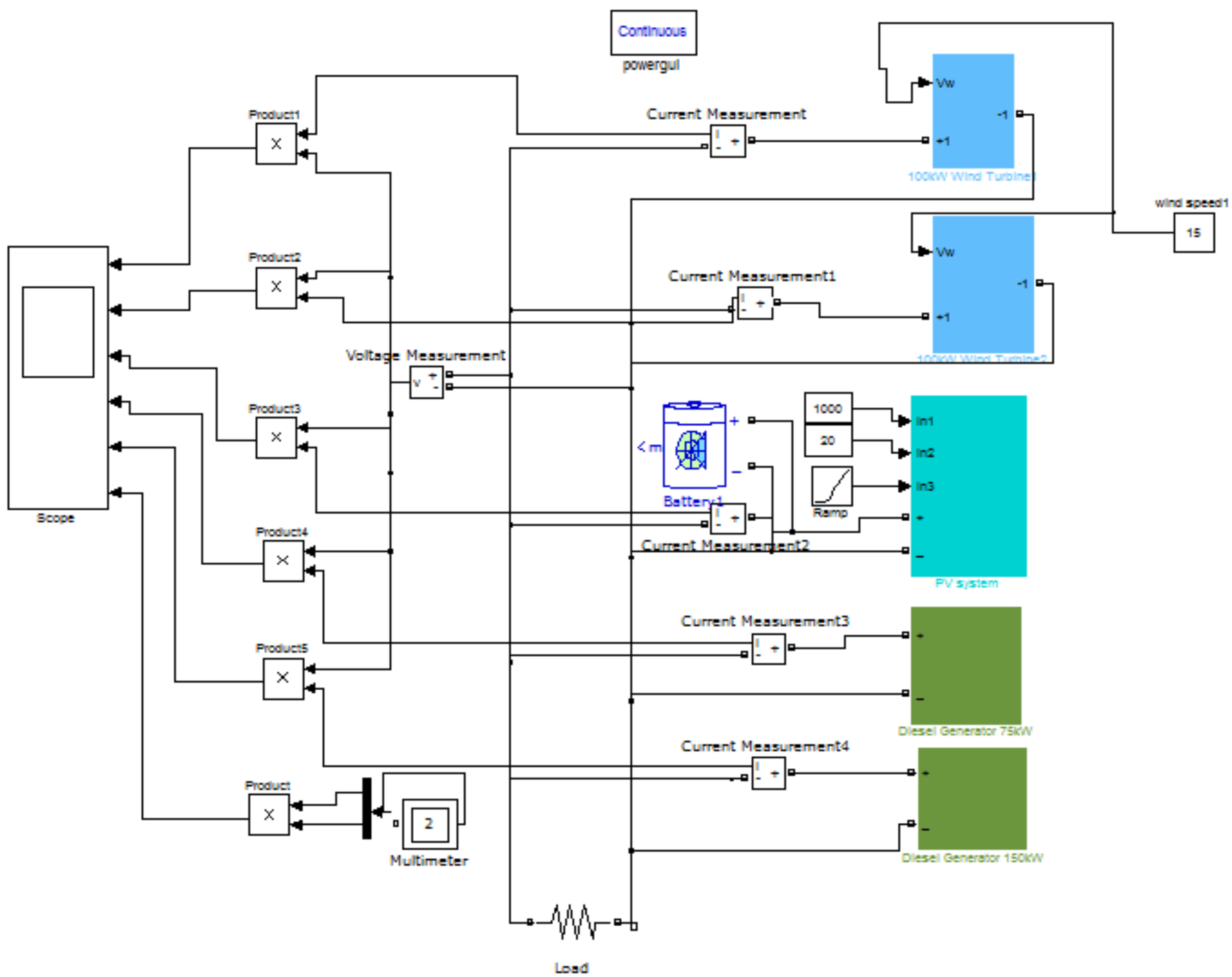


Effect on Voltage

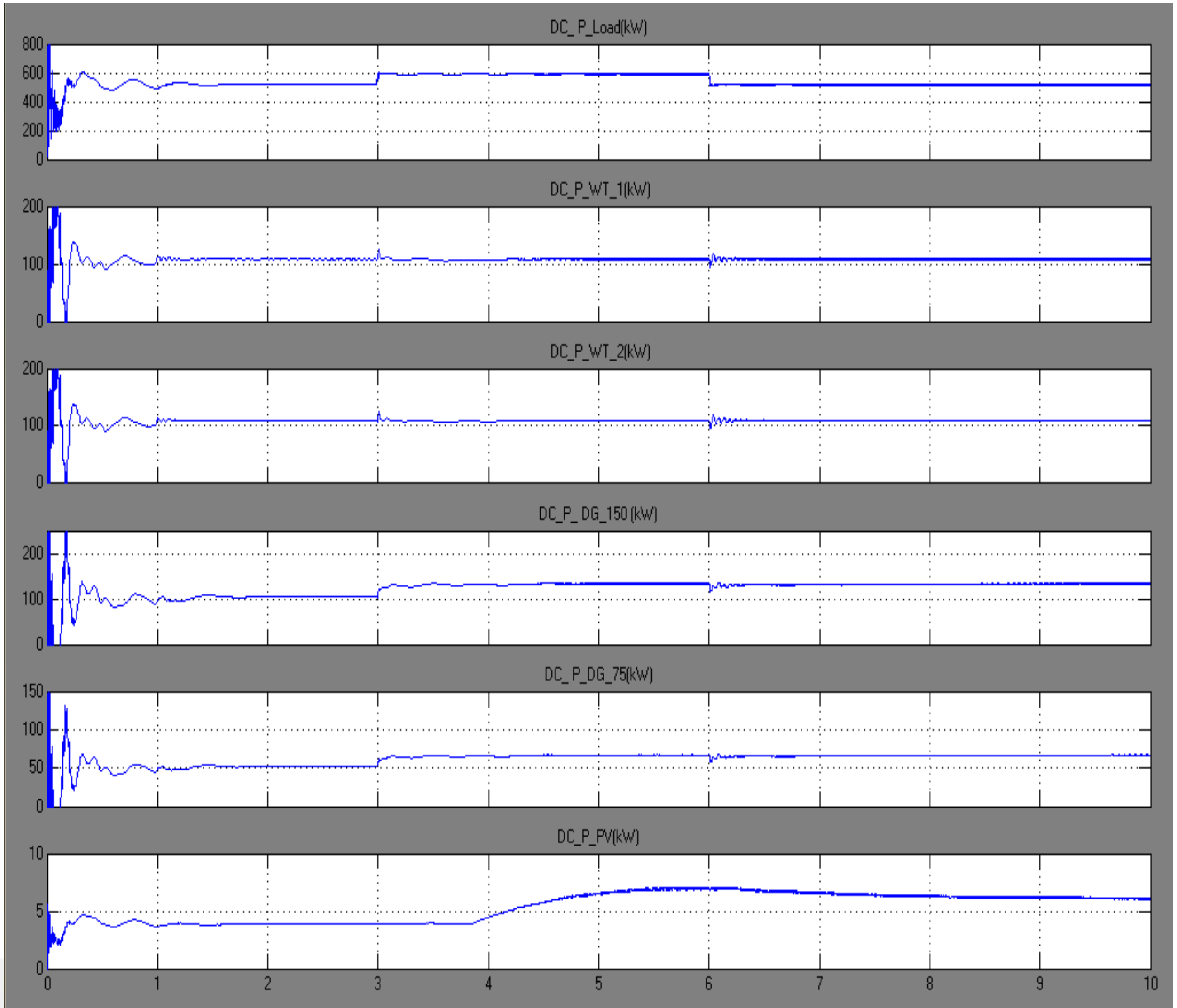


Effect on Frequency

Transient Analysis of DC Coupled Hybrid Power System



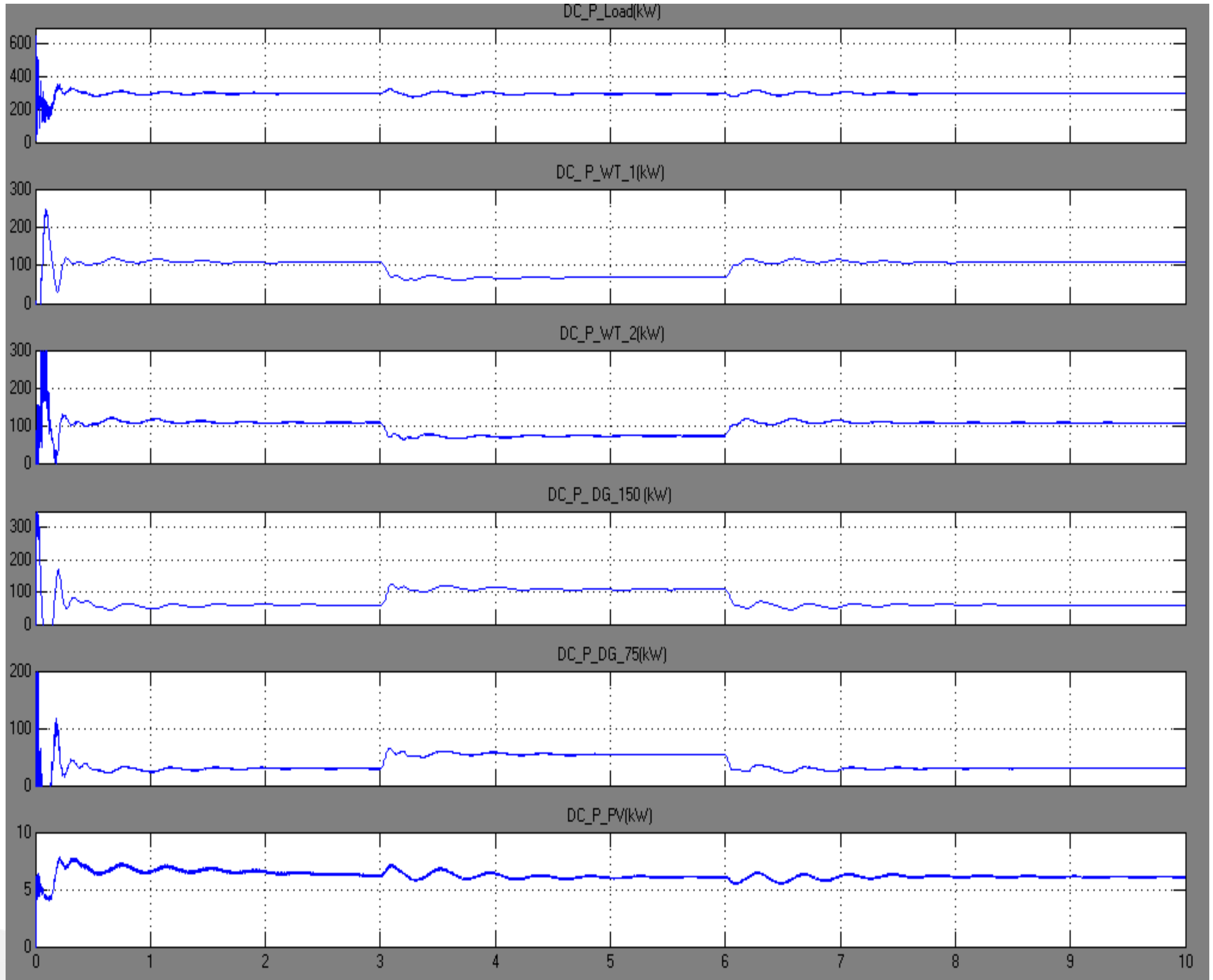
CS1: Simulation With Fixed Wind Speed Variable Load



- ❖Load 550/600/550 kW
- ❖Wind Speed 15 m/s
- ❖No change in WT power
- ❖DGs respond with main load variation
- ❖Power quality of PV is better than AC

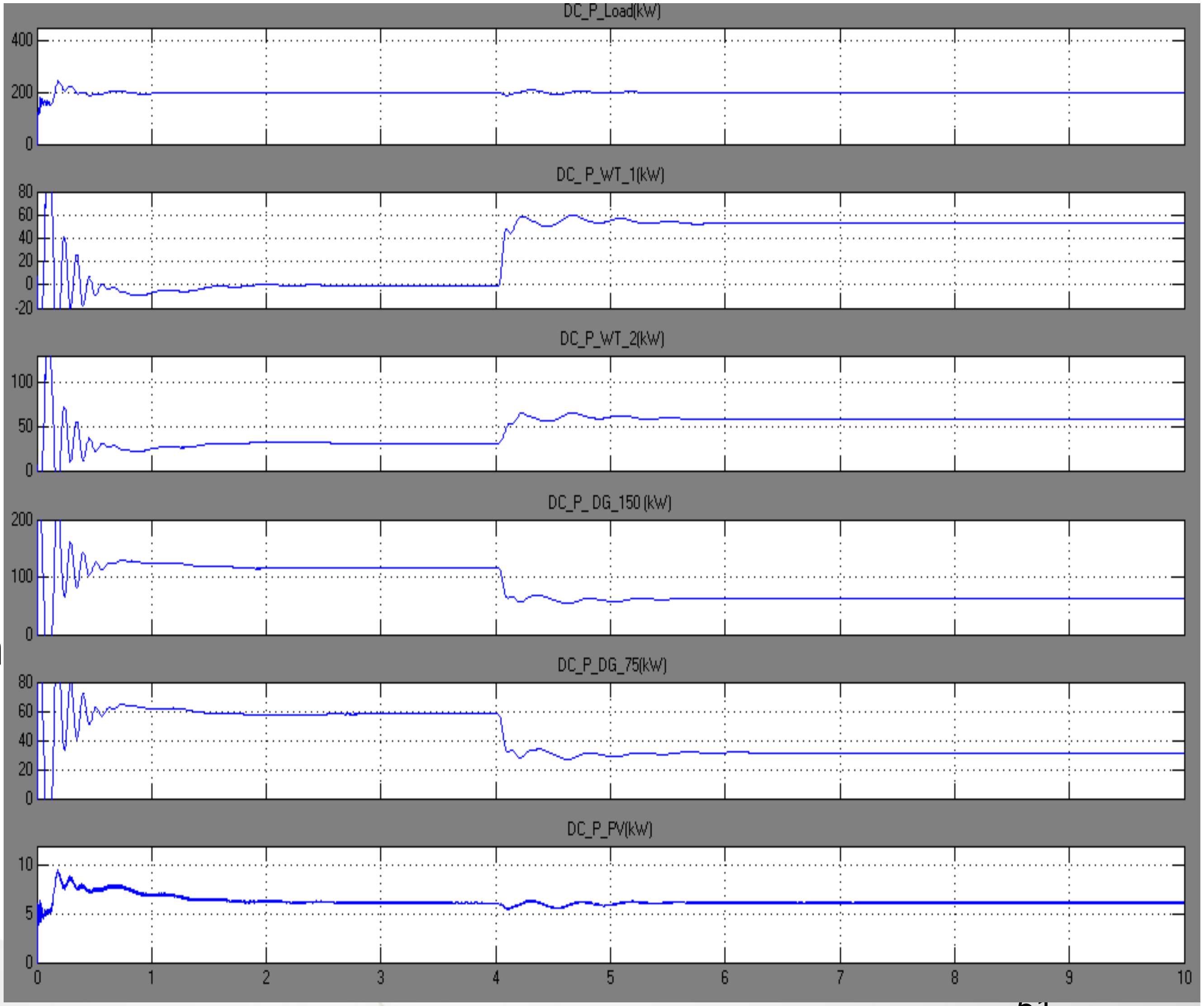
CS2: Simulation With Fixed Load Variable Wind Speed

- ❖Load 300kW
- ❖Wind Speed 15/10/14 m/s
- ❖WTs respond to wind speed change
- ❖When wind generation drop, DGs met up additional load



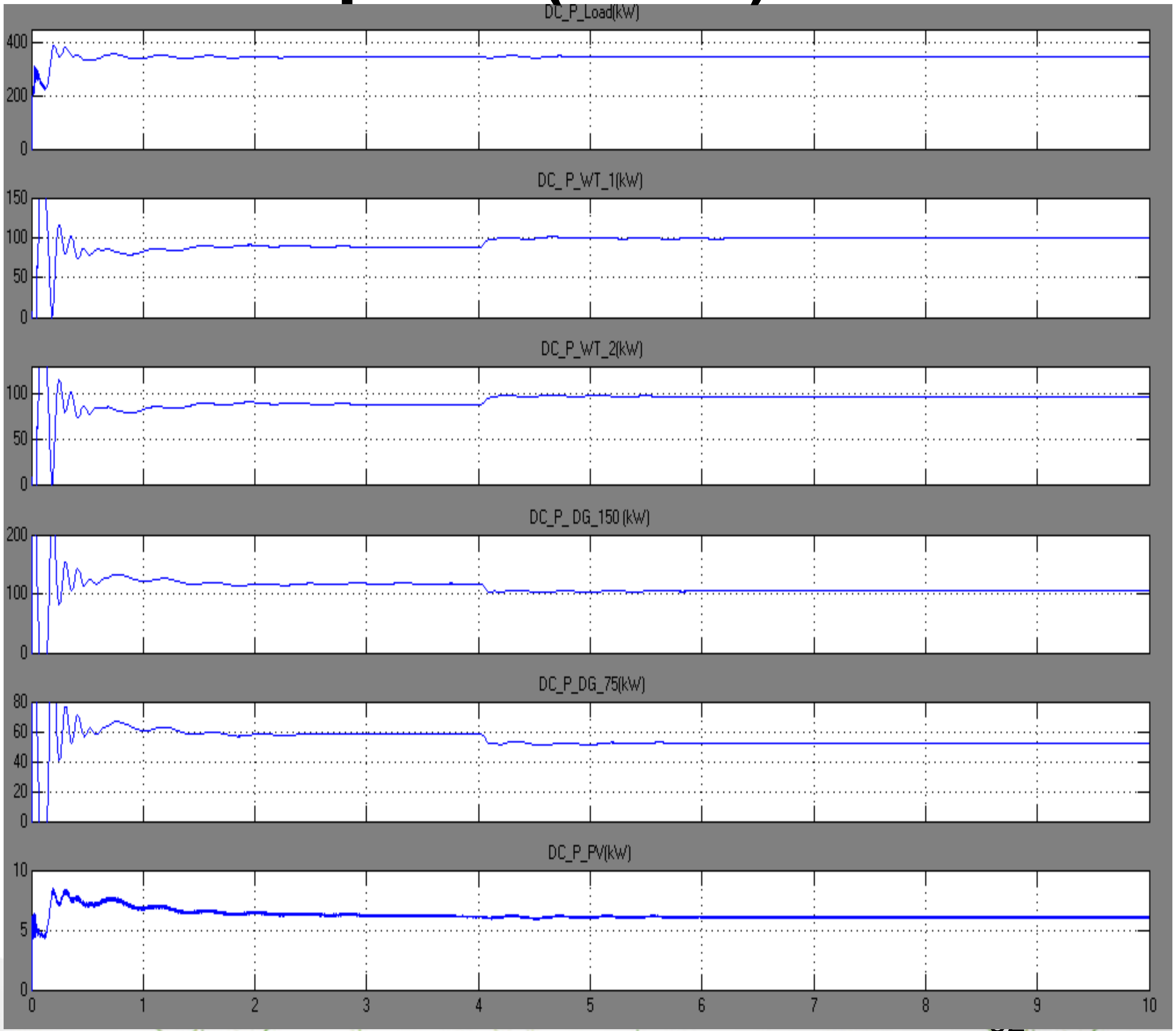
CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

- Load 200kW
- Wind Speed 7/9 m/s
- WTs respond to wind speed change
- When wind generation rises, Diesel generation drop automatically.



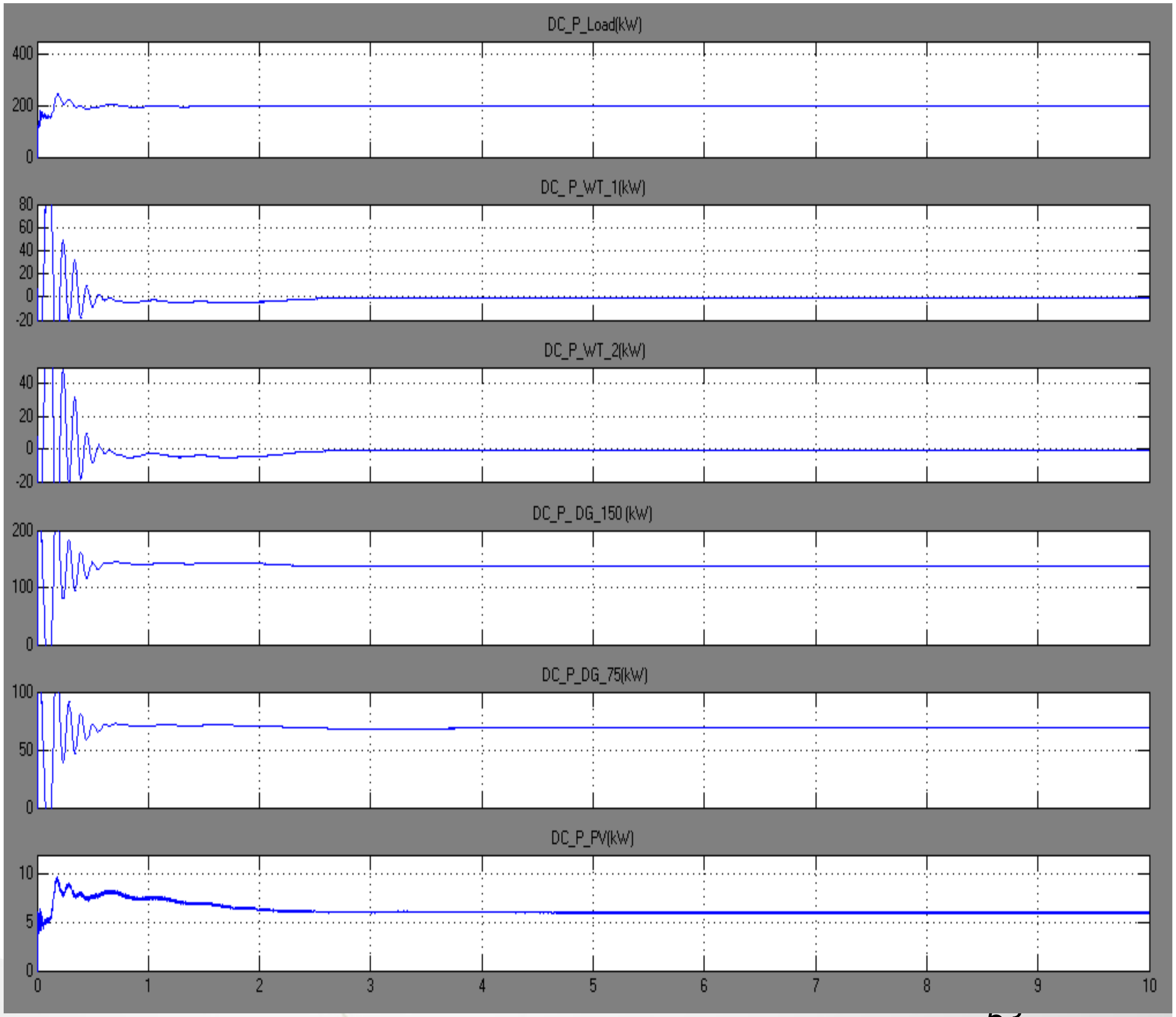
CS2: Simulation With Fixed Load Variable Wind Speed (cont.)

- Load 350kW
- Wind Speed 14/15 m/s
- WTs respond to wind speed change
- When wind generation rises, Diesel generation drop automatically.



CS3: Simulation With Diesel Generator and Photovoltaic System(cont.)

- ❖Load 200kW
- ❖ Zero Wind Speed
- ❖Load is met up by DGS and PV.

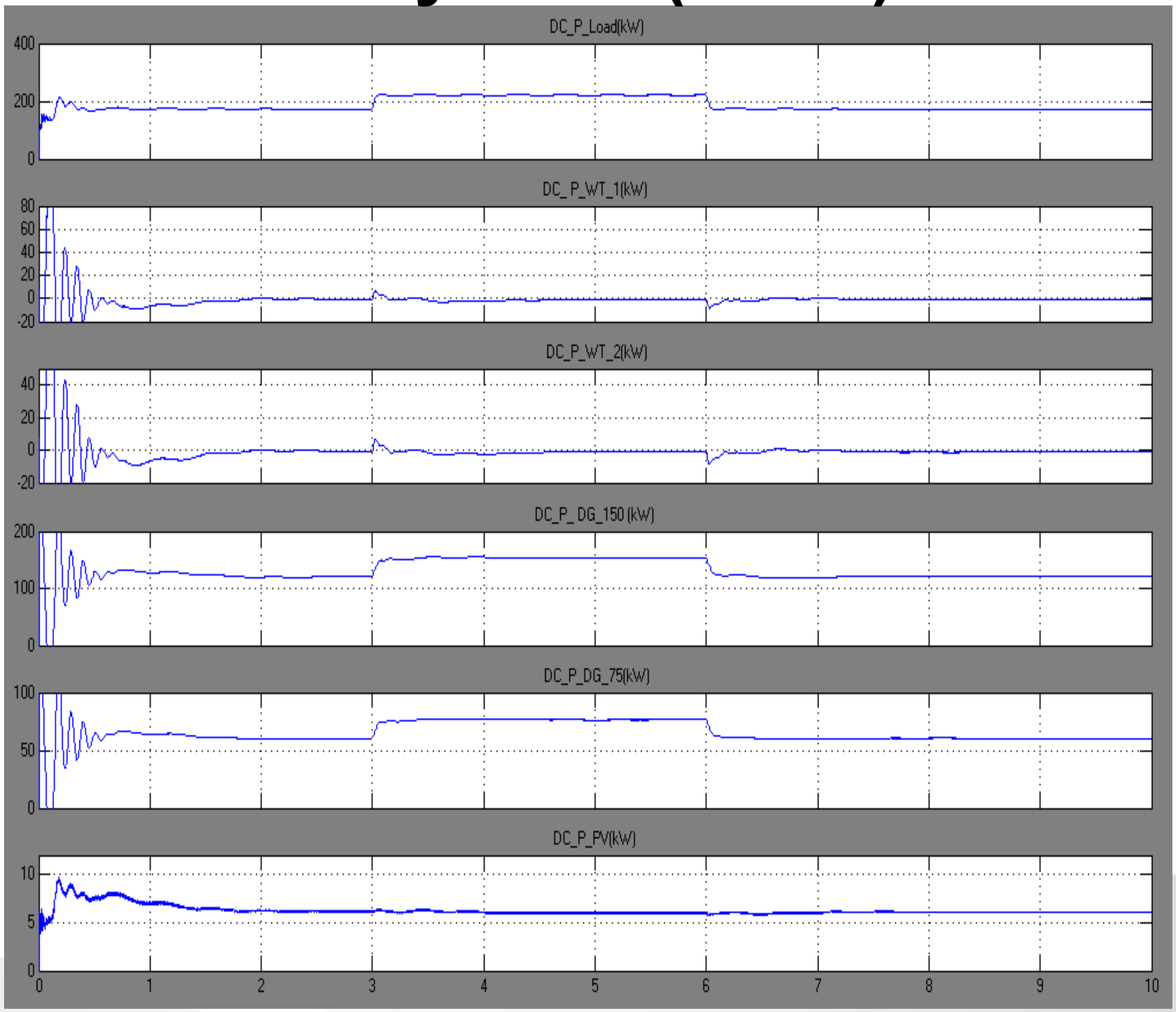


CS3: Simulation With Diesel Generator and Photovoltaic System (cont.)

❖Load 175/225/175kW

❖ Zero Wind Speed

❖Diesel generation follows the load



Conclusions

- Wind data, solar data and load data of small community of St. John's Newfoundland have been collected and studied.
- Economical and feasible components of the hybrid power system have been selected so that minimized system cost can be achieved.
- AC coupled and DC coupled hybrid systems have been designed using HOMER.
- Comparison has been made between these two system based on component required, system cost, use of renewable fraction, diesel used and corresponding emissions.

Conclusion(cont.)

- Modeling of individual component has been done by using Matlab /Simulink.
- Individual models have been combined to form the complete system.
- Three different case studies have been considered for transient analysis.
- Finally it can be said that for remote hybrid power system based on DC coupling would be a better power system option

Future Works

- Longer duration Simulation
- Introduce precise control mechanisms in each sub block.
- Selecting a location with higher solar radiation resource.
- Build AC based system and DC based systems and compares their performance
- The power distribution of DC based system would be an interesting scope of further work.

Acknowledgment

- Dr. Tariq Iqbal
- National Science and Engineering Research Council (NSERC), Wind Energy strategic Network (WESNet), School of Graduate Studies (SGS) of Memorial University

Publications

- Tanjila Haque, M. T. Iqbal, *“A Comparison of Dynamics and Control of AC and DC Coupled Hybrid Power Systems,”* presented at WESNet Workshop, February 24-25, Ryerson University, Toronto, ON, Canada 2011
- Tanjila Haque, M. T. Iqbal, “*A Comparison of AC and DC Coupled Remote Hybrid Power Systems*,” presented at 19th IEEE-NECEC Conference 2010, St. John’s, NL
- Tanjila Haque, M. T. Iqbal, “*A Comparison of AC and DC Coupled Hybrid Power Systems*,*”* presented in WESNet Poster Presentation, CanWEA, 2010, Montreal, Quebec

Thanks