PQSynergy 2014 19 May 2014

Modeling and Control of Photovoltaic Grid Connected Inverter Based on Nonlinear System Identification for Power Quality Analysis

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19 May 2014

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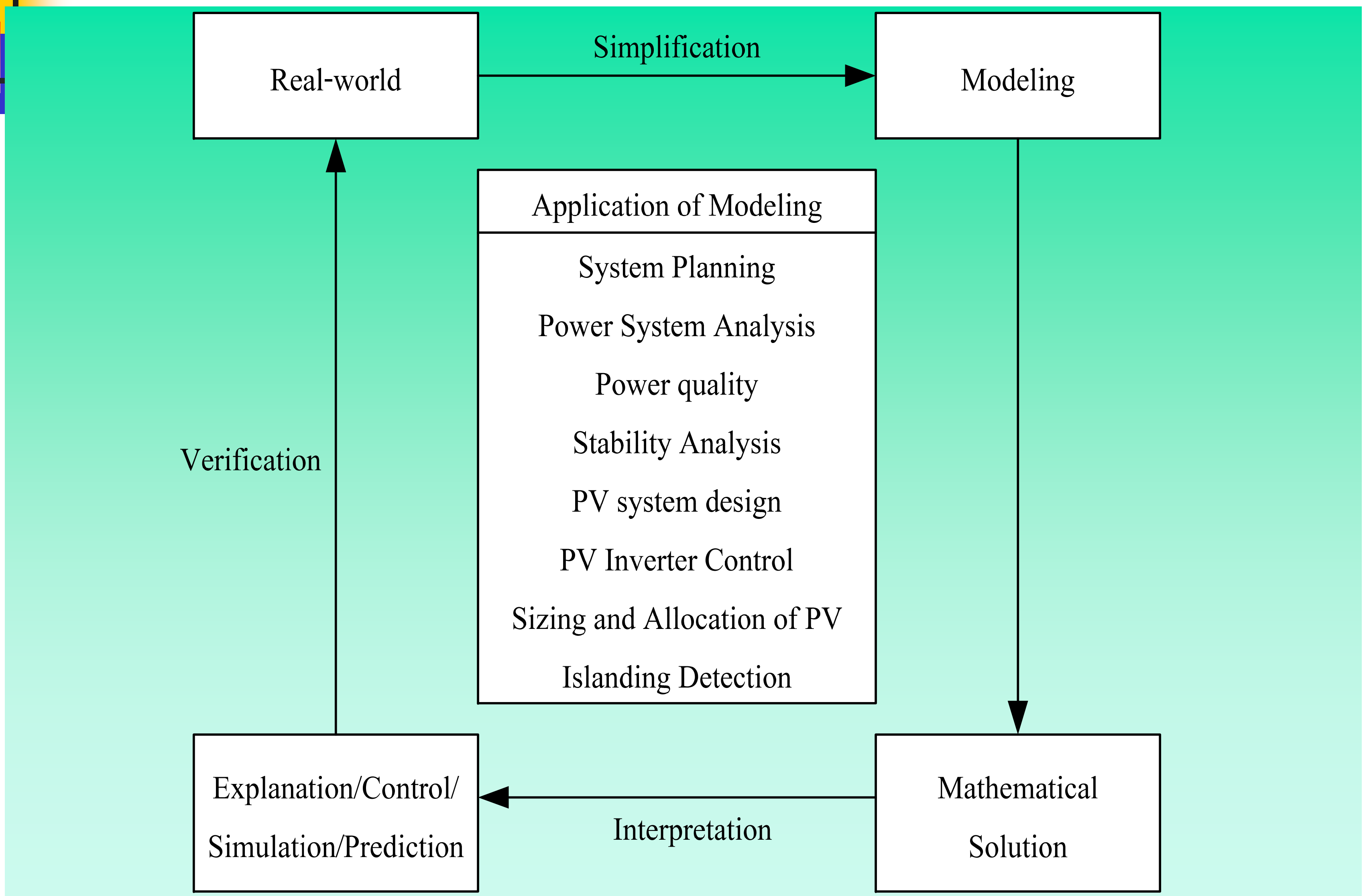
TOPIC

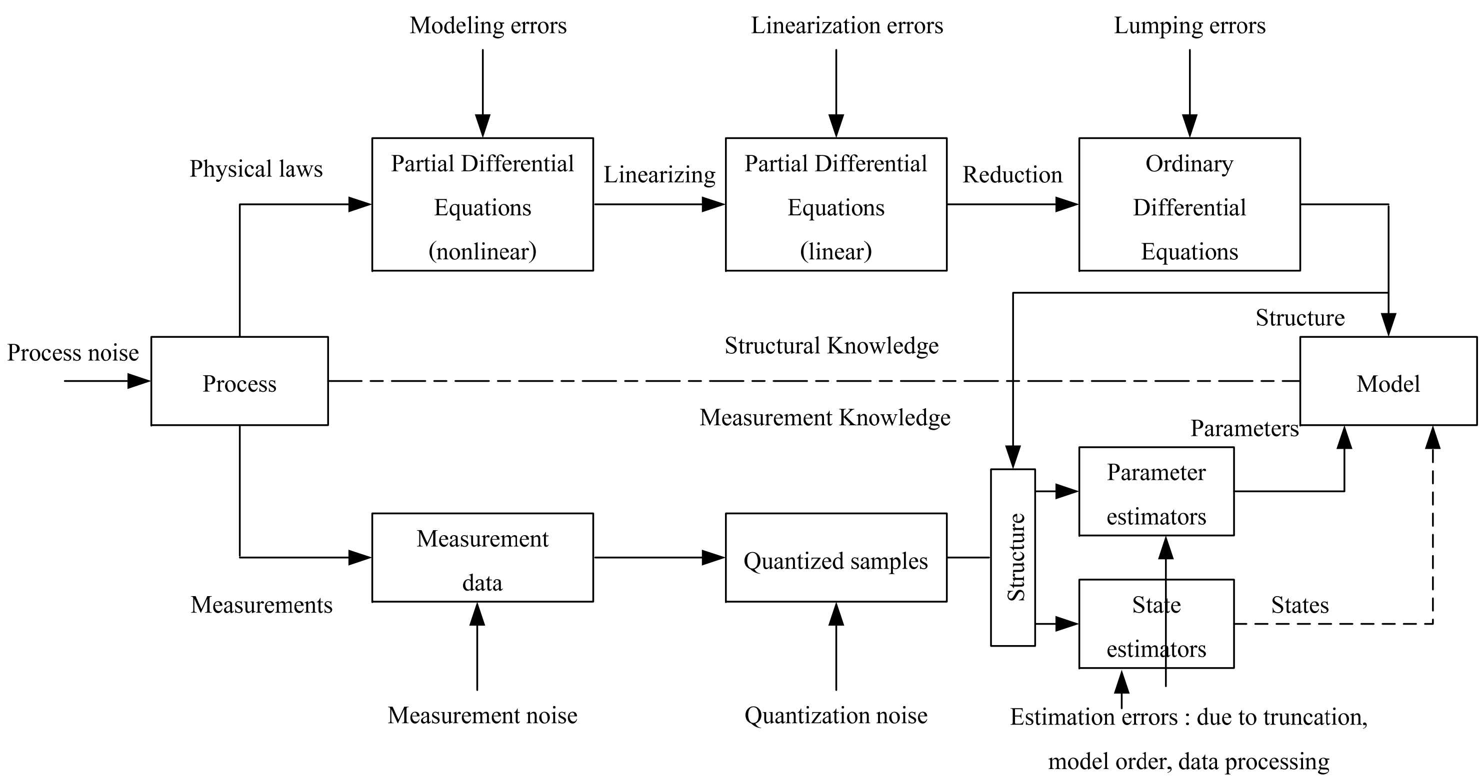
- INTRODUCTION
- MATHEMATICAL MODELING
- NONLINEAR SYSTEM IDENTIFICATION
- CASE STUDY WITH PV INVERTER
- POWER QUALITY ANALYSIS
- MODELING APPLICATION
- CONCLUSION

Mathematical Modeling of system

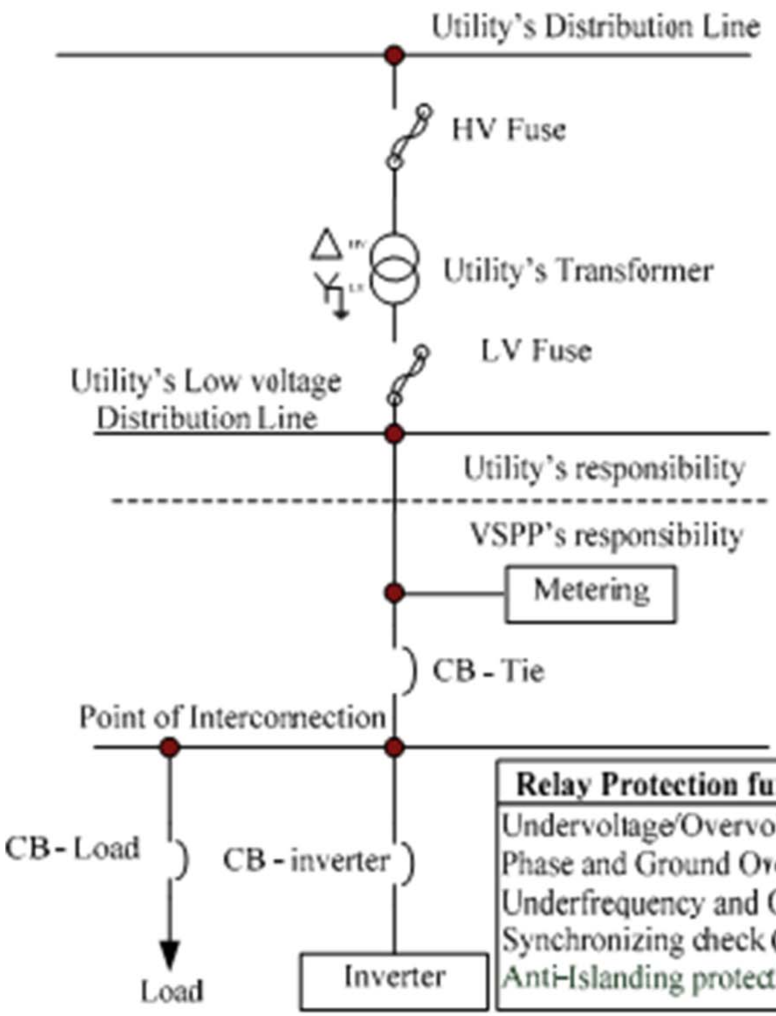


Method for system Modeling

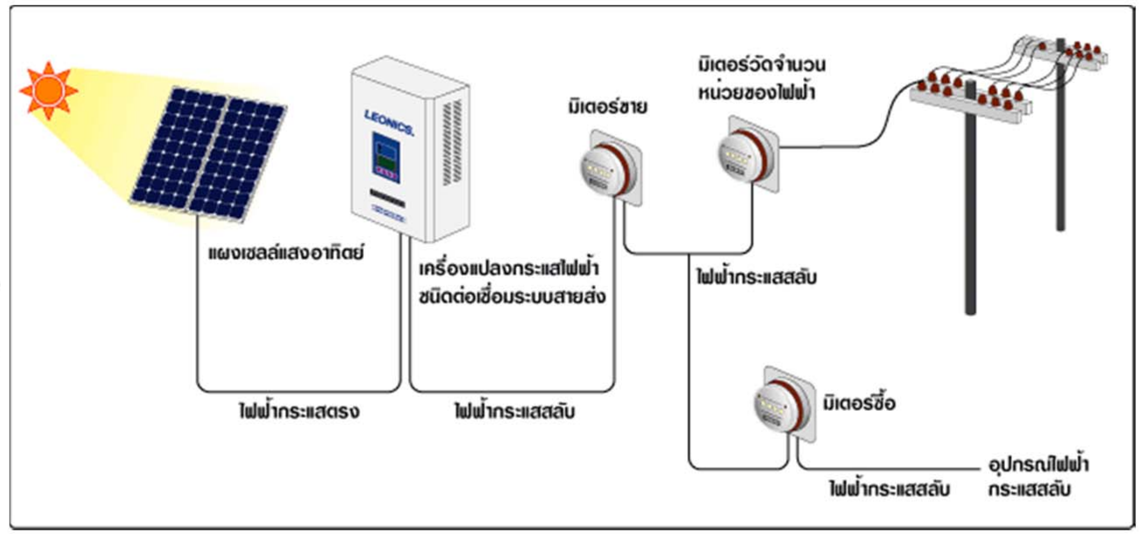
- Analytical (Theory & Circuit)
- Experimental (System Identification)



Grid connected Inverter of PV

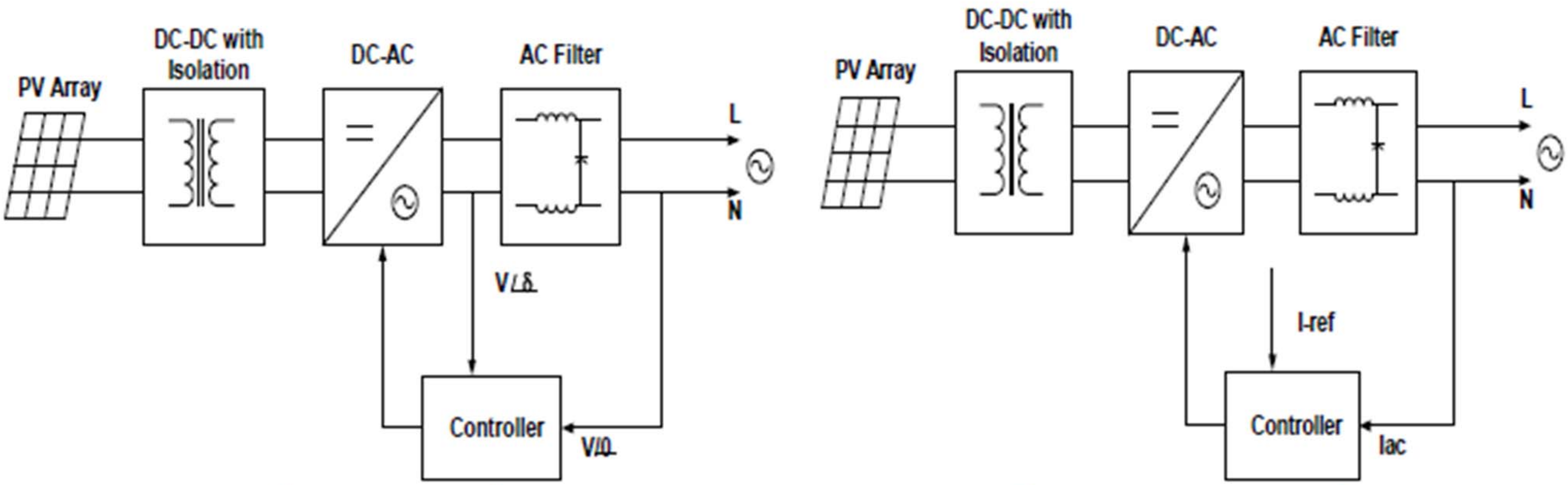


Relay Protection function of Inverter
Undervoltage/Overvoltage (27/59)
Phase and Ground Overcurrent (50/51)
Underfrequency and Overfrequency (81)
Synchronizing check (25)
Anti-Islanding protection



Inverter Configuration

- Voltage source Inverter



(a) Voltage Control Inverter (b) Current Control Inverter

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PV Inverter

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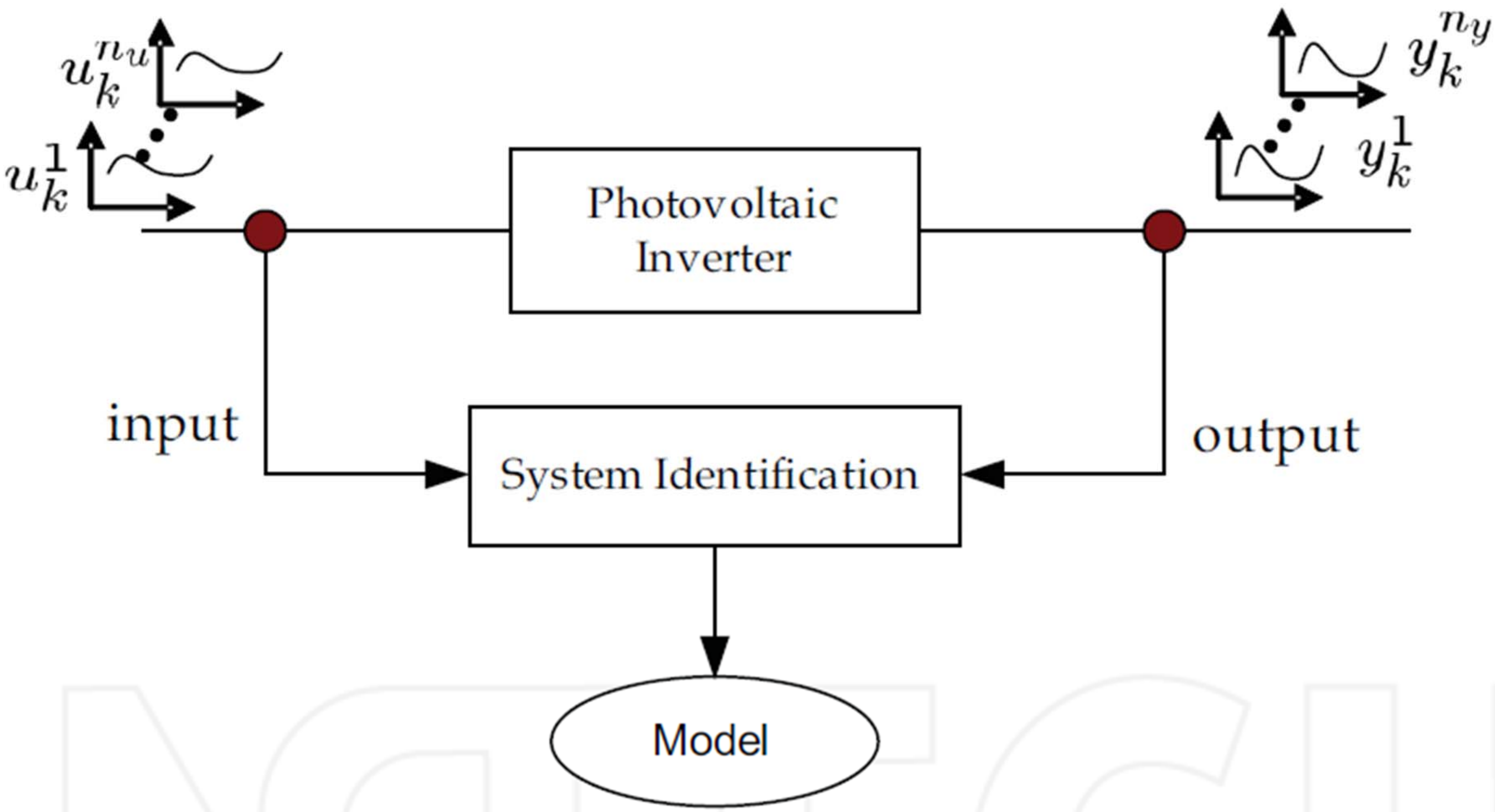
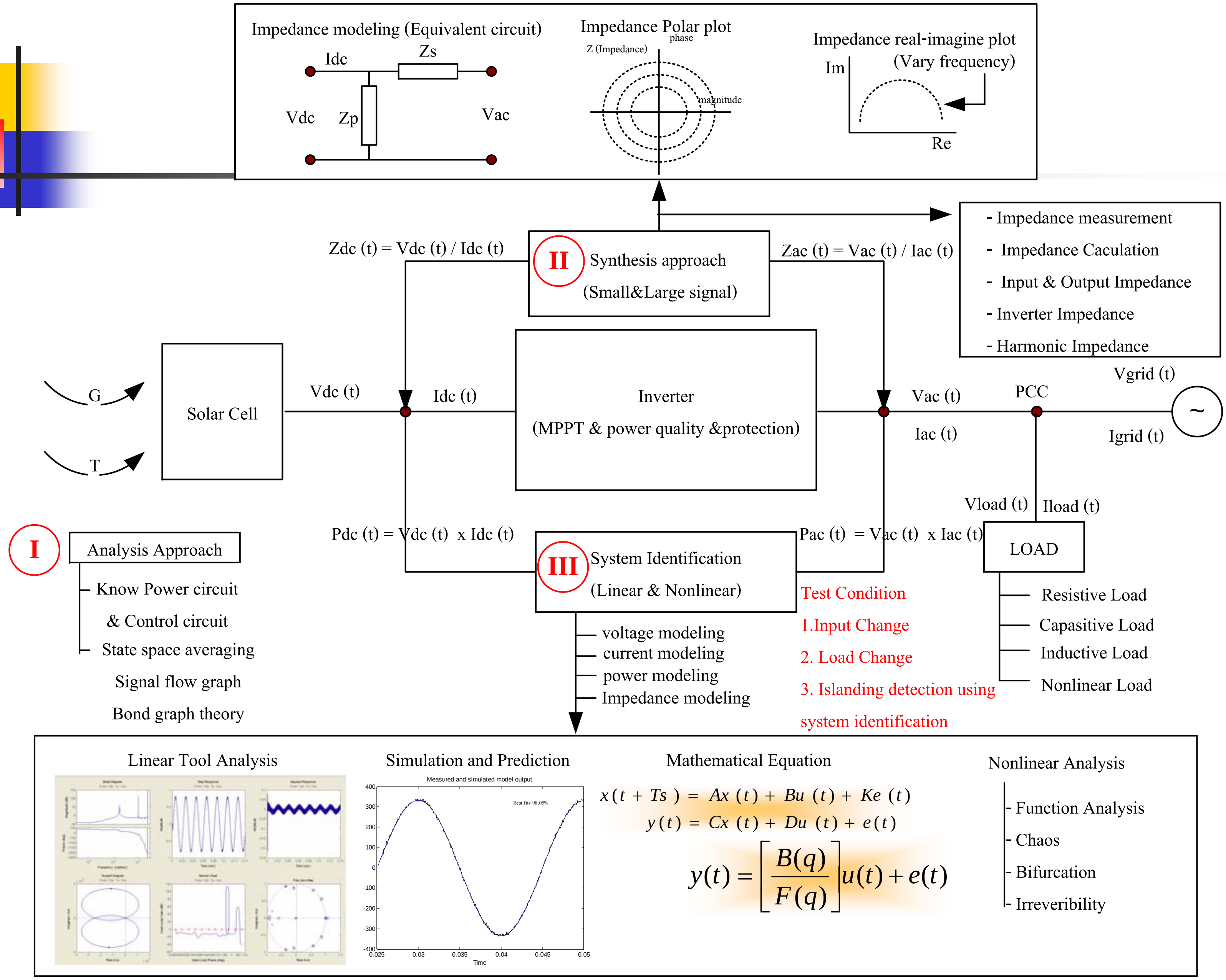
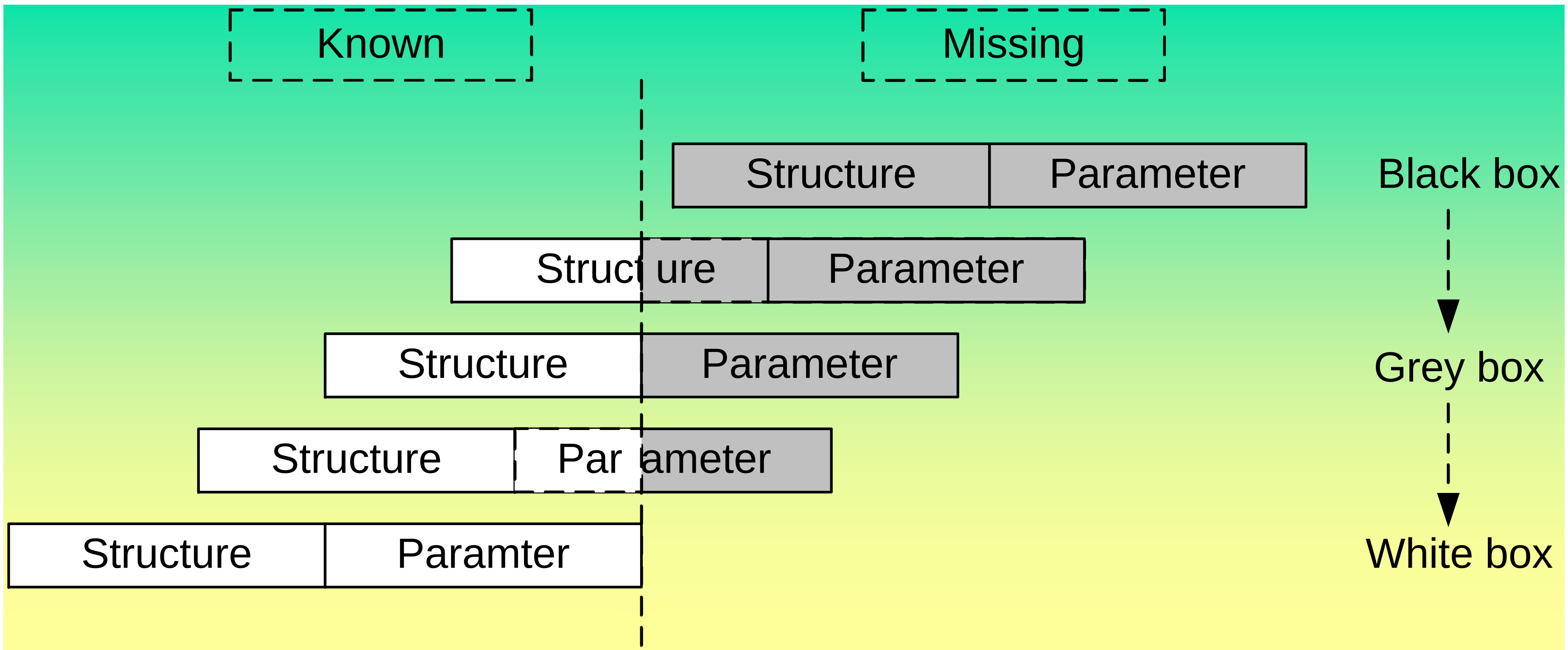


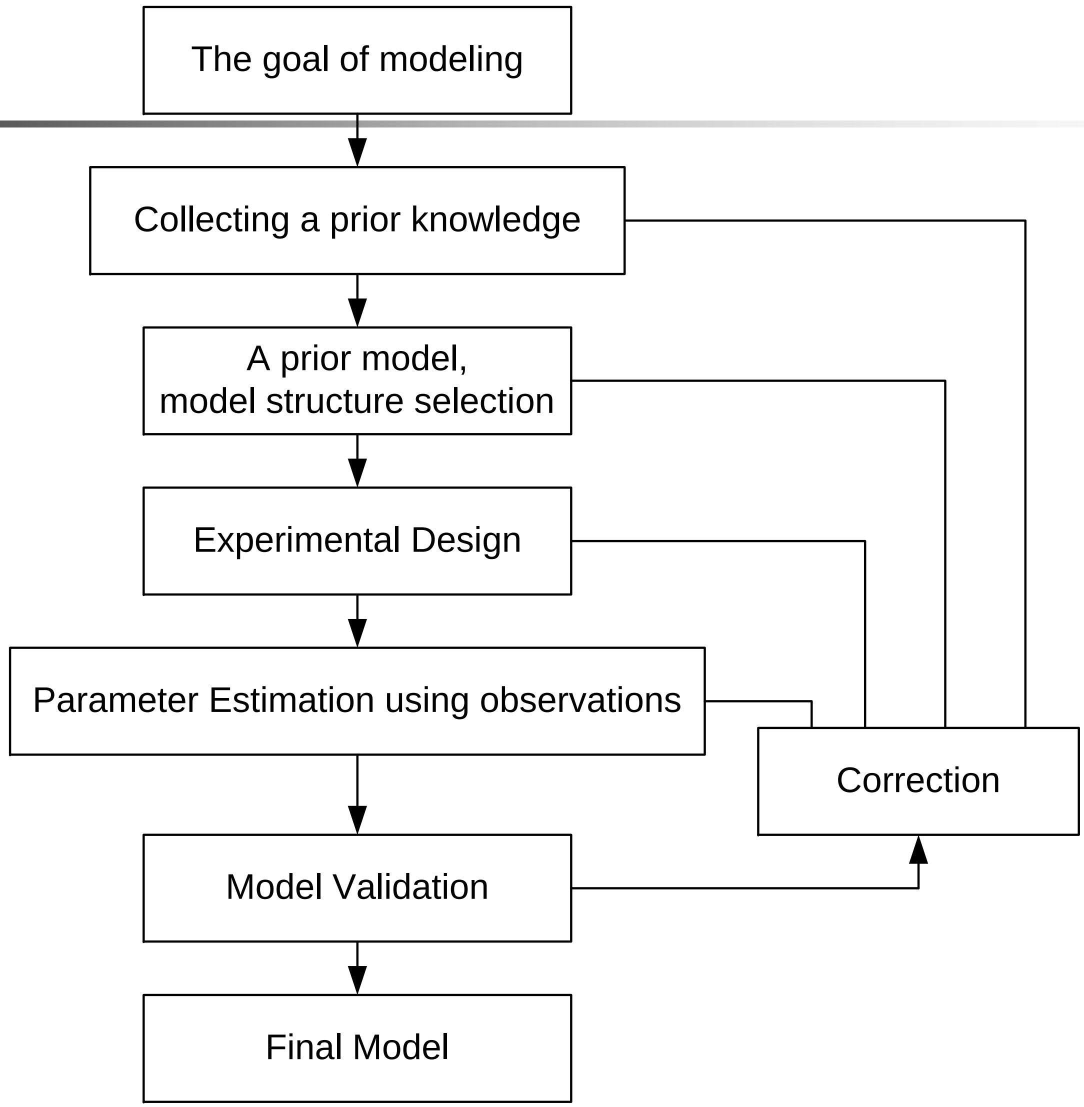
Comparison advantage/disadvantage of three approach



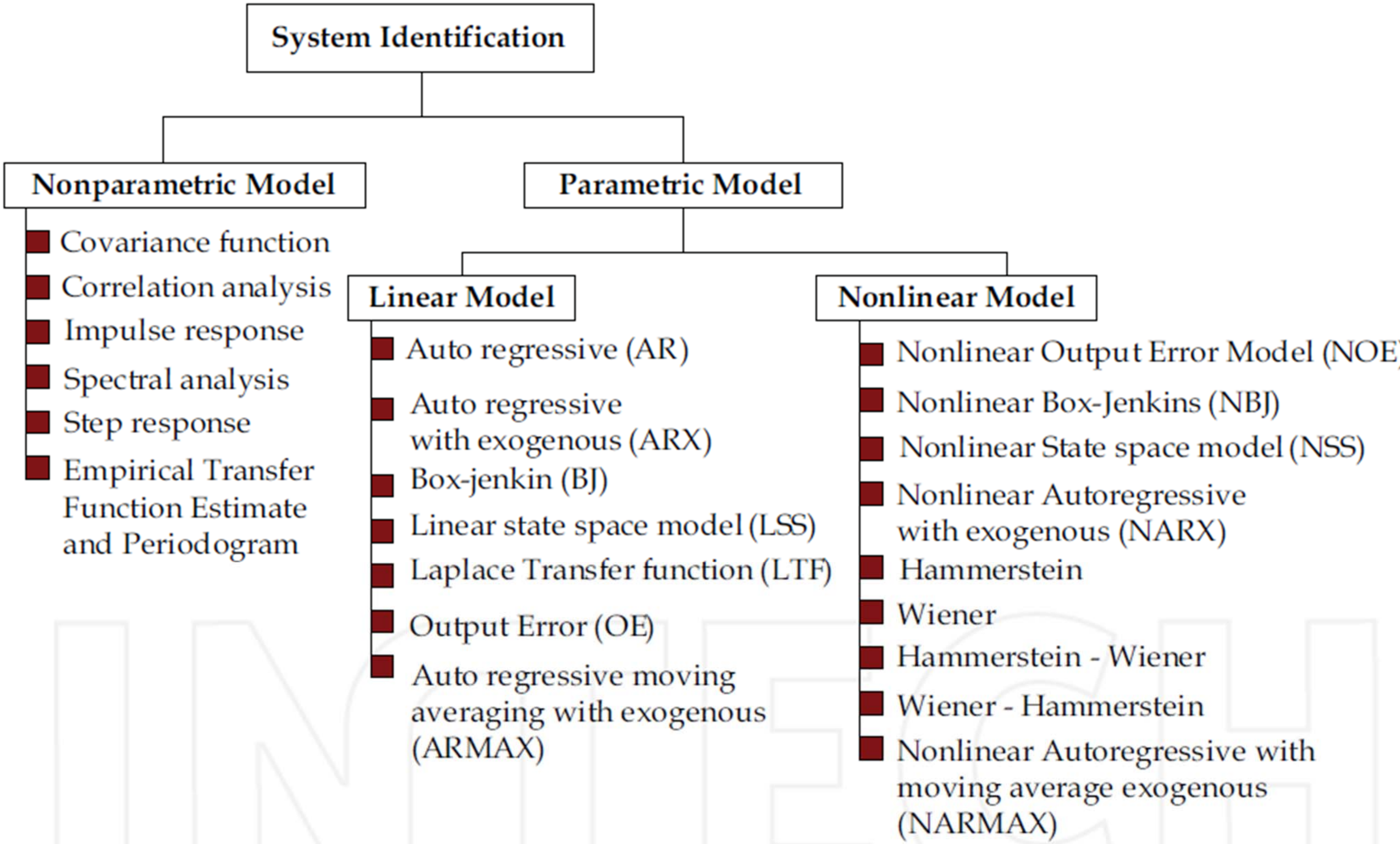
Principle of System



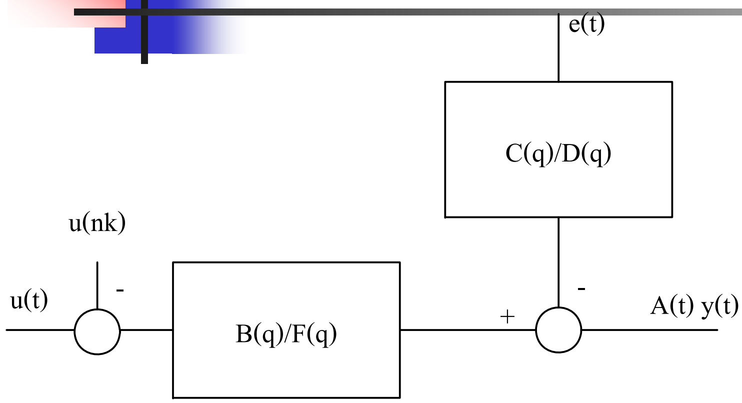
System Identification



Type of System Identification



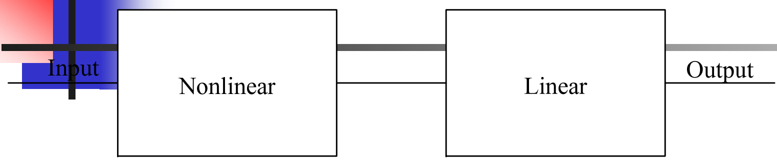
Discrete Time Linear Model



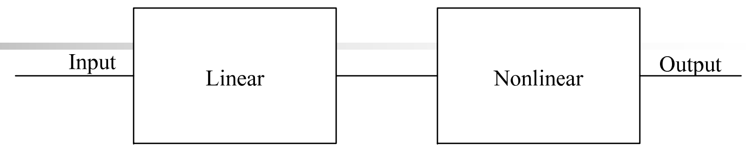
Model Structure	Discrete Time Form
ARX	$A(q)y(t) = \sum_{i=1}^{nu} B_i(q)u_i(t-nk_i) + e(t)$
ARMAX	$A(q)y(t) = \sum_{i=1}^{nu} B_i(q)u_i(t-nk_i) + C(q)e(t)$
Box-Jenkins (BJ)	$y(t) = \sum_{i=1}^{nu} \frac{B_i(q)}{F_i(q)}u_i(t-nk_i) + \frac{C(q)}{D(q)}e(t)$
Output Error (OE)	$y(t) = \sum_{i=1}^{nu} \frac{B_i(q)}{F_i(q)}u_i(t-nk_i) + e(t)$

- u(t) – input
- y(t) – output
- e(t)- error
- A(q),B(q),C(q),D(q),E(q) – Coefficient
- q –shift operator

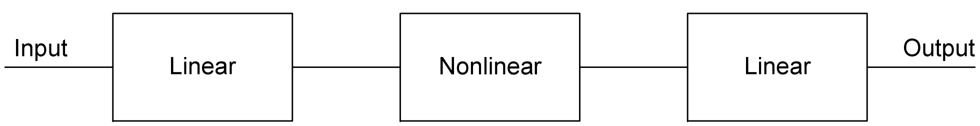
Nonlinear System Identification



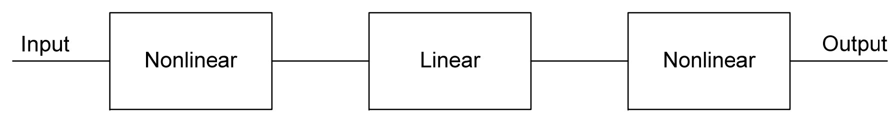
Hammerstein Model



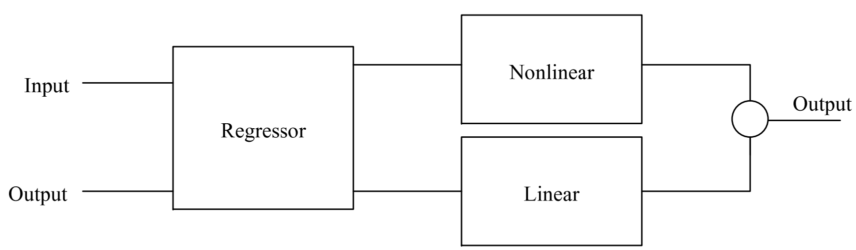
Weiner Model



Weiner-Hammerstein Model

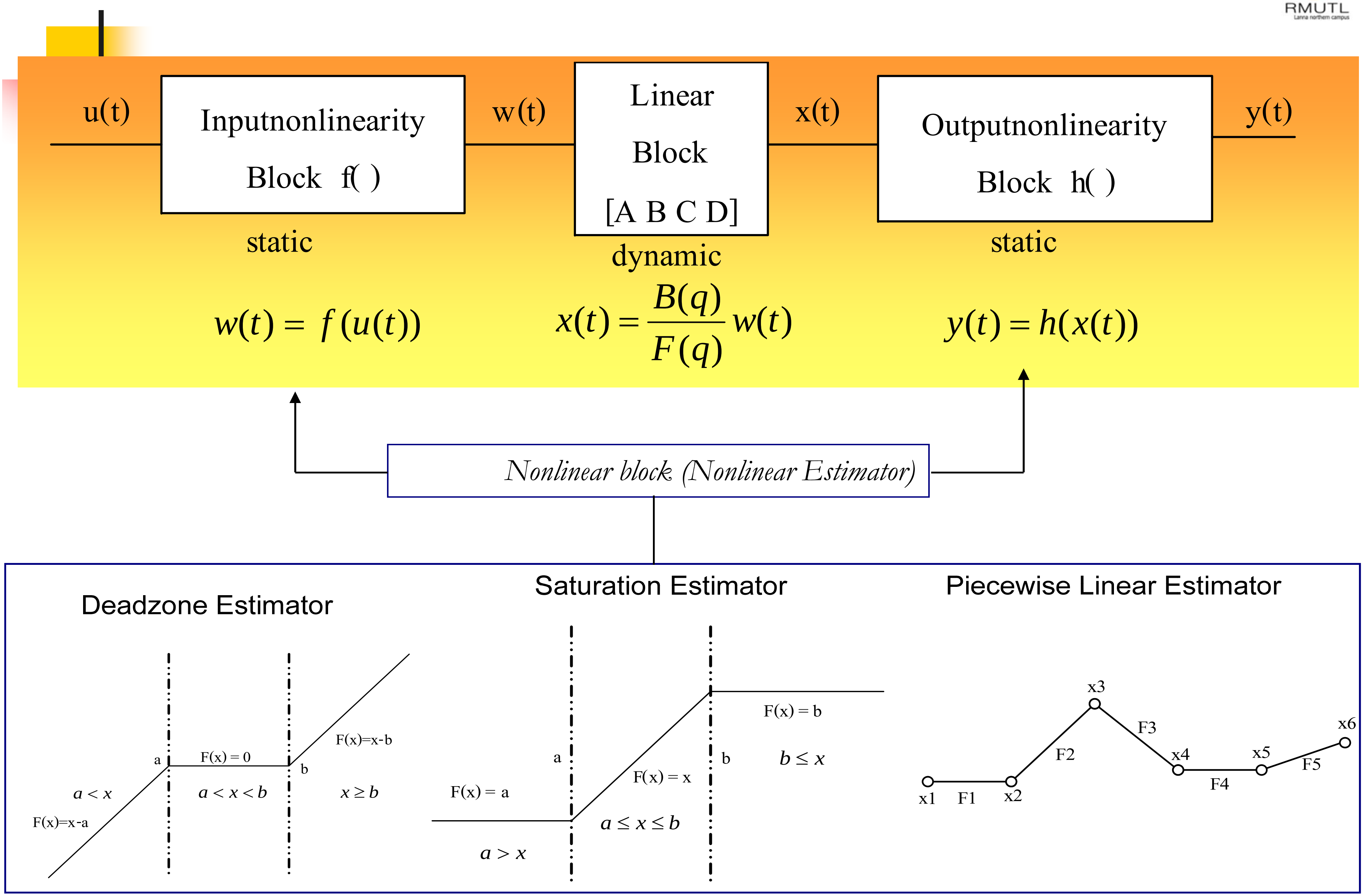


Hammerstein-Weiner Model



Nonlinear Auto Regressive with exogenous Model

Structure of Hammerstein-Weiner Model



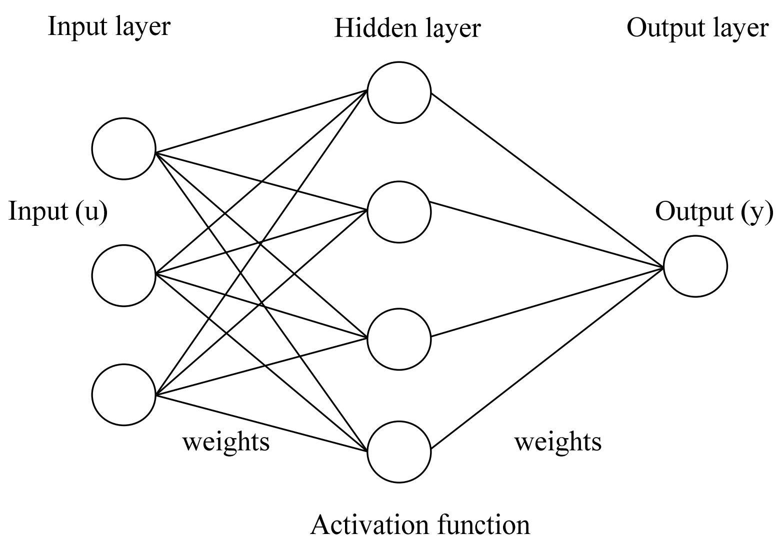
Nonlinear block (Nonlinear Estimator)

❖ *Wavelet Network (Wavenet Nonlinear Estimator : WN)*

Wavelet Transform

$$y = (u-r)PL + \sum_{i}^{n} as_i * f(bs(u-r)Q + cs) + \sum_{i}^{n} aw_i * g(bw_i(u-r)Q + cw_i) + d$$

Neural Network (Sigmoid Network : SN)



$$y(u) = (u-r)PL + \sum_{i}^{n} a_i f((u-r)Qb_i - c_i) + d$$

Criteria for Model Selection

Accuracy $$fit = 100 * (1 - norm(y^* - y) / norm(y - \bar{y}))$$ highest

Final Prediction Error $$FPE = V\left(\frac{1 + \frac{d}{N}}{1 - \frac{d}{N}}\right)$$ smallest

Loss Function $$V = \det\left(\frac{1}{N}\sum_{1}^{N} \varepsilon(t, \theta_N)(\varepsilon(t, \theta_N))^T\right)$$ highest •

Akaikae's Information Criteria $$AIC = \log V + \frac{2d}{N}$$ smallest

lowest order *number of pole (nb) plus zero (nf)* rder calculate •

Research Methodology

1. Determine condition or Experimental
2. Collect data and Processing Input-Output Waveform
3. Divide data into Estimate and Validate data
4. Select type of mathematicl model
5. Estimate output of modeling and compare with experimental data
6. Examine accuracy and property of model
7. Choose the best model and use it for application

Testing inverter

Frobius IG 1500 W

TECHNICAL DETAILS.

It goes without saying that every FRONIUS IG complies with all the obligatory guidelines and standards of each country. More in-depth information and certificates may be viewed at www.fronius.com under "downloads". Of course, all FRONIUS IG bear the CE mark.

TECHNICAL DATA FRONIUS IG	15	20	30	40	60 HV
MPP voltage range	150 - 400 V	150 - 400 V	150 - 400 V	150 - 400 V	150 - 400 V
Max. input voltage (at 1000 W/m2; -10°C)	500 V	500 V	500 V	500 V	530 V
PV array output	1300 - 2000 Wp	1800 - 2700 Wp	2500 - 3600 Wp	3500 - 5500 Wp	4600 - 6700 Wp
Nominal output	1300 W	1800 W	2500 W	3500 W	4600 W
Max. power output	1500 W	2000 W	2650 W	4100 W	5000 W
Max. efficiency	94.2 %	94.3 %	94.3 %	94.3 %	94.3 %
Euro efficiency	91.4 %	92.3 %	92.7 %	93.5 %	93.5 %
Mains voltage/frequency	230 V / 50 Hz (60 Hz)				
Size (l x w x h)	366 x 344 x 220 mm (500 x 435 x 225 mm)		610 x 344 x 220 mm (733 x 435 x 225 mm)		
Weight	9 kg (12 kg)		16 kg (20 kg)		
Cooling	controlled forced-air cooling				
Housing variations	designer internal housing; optional outer housing				
Ambient temperature range	-20 ..... 50 °C				

Leonics Apollo G300 5000 W

LEONICS

APOLLO G-300

GRID CONNECTED INVERTER

Wall mount case

- Pure sine wave power output
- Peak efficiency > 91% (include isolation transformer)
- Low Harmonic Distortion (THDi) less than 4%
- Main and solar generator are galvanically isolated
- Built-in Maximum Power Point Tracking (MPPT)
- Microprocessor control
- Advanced IGBT Technology
- Islanding protections during failure of utility grid power supply
- Fully automatic self-START in the morning and

LEONICS

APOLLO G-300 series GRID CONNECTED INVERTER

SPECIFICATIONS

MODEL	Wall Mount type / Rack Mount type*	G-303 / G-303/RM	G-304 / G-304/RM	G-304M2 / G-304M2/RM	G-306 / G-306/RM
RATED POWER	PV input	2.8 kWp	3.9 kWp	4.7 kWp	5.6 kWp
	AC output	2.5 kW	3.5 kW	4.2 kW	5 kW
SYSTEM	Controller	intelligent with microcomputer controlled			
	Technology	IGBT technology			
DC INPUT	Operating voltage range	165 - 300 V			
	Max. allowable voltage (for short period of time)	350 V			
GRID LINE	Voltage and phase	+10%, -15% for 220 Vac and 230 Vac (single phase) according to standards of IEC 61727 and IEC 62116 200 - 253 Vac or 240 Vac (single phase) according to standards of AS 4777 200 - 240 Vac or 220 Vac (single phase) according to standards of IEC 61727 and IEC 62116 (for PEA grid line) 209 - 240 Vac for 230 Vac (single phase) according to standards of IEC 61727 and IEC 62116 (for MEA grid line)			
	Frequency	50 / 60 Hz ±0.5 Hz for 220 Vac and 230 Vac 50 /60 Hz ±06 Hz for 240 Vac 48 - 51 Hz for 220 Vac and 230 Vac according to standards of IEC 61727 and IEC 62116 (for PEA and MEA grid line)			
AC OUTPUT	Power factor	more than 0.98			
	Total harmonic distortion	total less than 4% each less than 3%			
	Current limiting	110%			
ISOLATION	Galvanic isolation	yes			
EFFICIENCY	Peak efficiency	more than 91%			
CONTROL		automatic cooling fans / MPPT control /unity power factor control			
PROTECTION	Input / Ouput	over voltage / under voltage (AC & DC) frequency (AC)			
	Islanding	voltage and phase shift detection			
	Over heat	auto shutdown and auto restart			
	Surge energy dissipation	280 Joules 10 /1,000 microsec wave form			
INDICATOR	LED	Main, Operating, Alarm			
	LCD display	DC /AC voltage, Current Watt, Today kWh, Accumulated kWh, Calendar, Clock, Condition setting, Fault			
AUDIABLE ALARM	Multiple tone sound with reset for silence	mains failure, inverter fault (inhibitable)			
COMMUNICATION INTERFACE	DB-9 connector	RS-232 serial interface port			
	RS-485 Adaptor	RS-485 interface (option)			
ACOUSTIC NOISE	At 1 metre	less than 50 dBA			
ENVIRONMENT	Temperature	0 - 45°C			
	Humidity	0 - 95 % (non - condensing)			
DIMENSION (W x H x D) in cm.	Wall mount case	37.5 x 49 x 22.9	37.5 x 49 x 22.9	43.9 x 52 x 28	43.9 x 52 x 28
	Rack mount case	48.2 x 19.6 x 47	48.2 x 19.6 x 47	48.2 x 22 x 49.7	48.2 x 22 x 49.7
WEIGHT in kg. (approximate)	Wall mount case	24	24	31	31
	Rack mount case	23	23	26	26
DESIGN REGULATION	Tested according to	AS 4777, AS 3100, IEC 61727 and IEC62116			

*The rack mount case models are not included the floor standing rack mount enclosure. Continuous product development is our commitment, in that manner, the above specifications may be changed without prior notice.

Authorized Distributor

LEO ELECTRONICS CO.,LTD.

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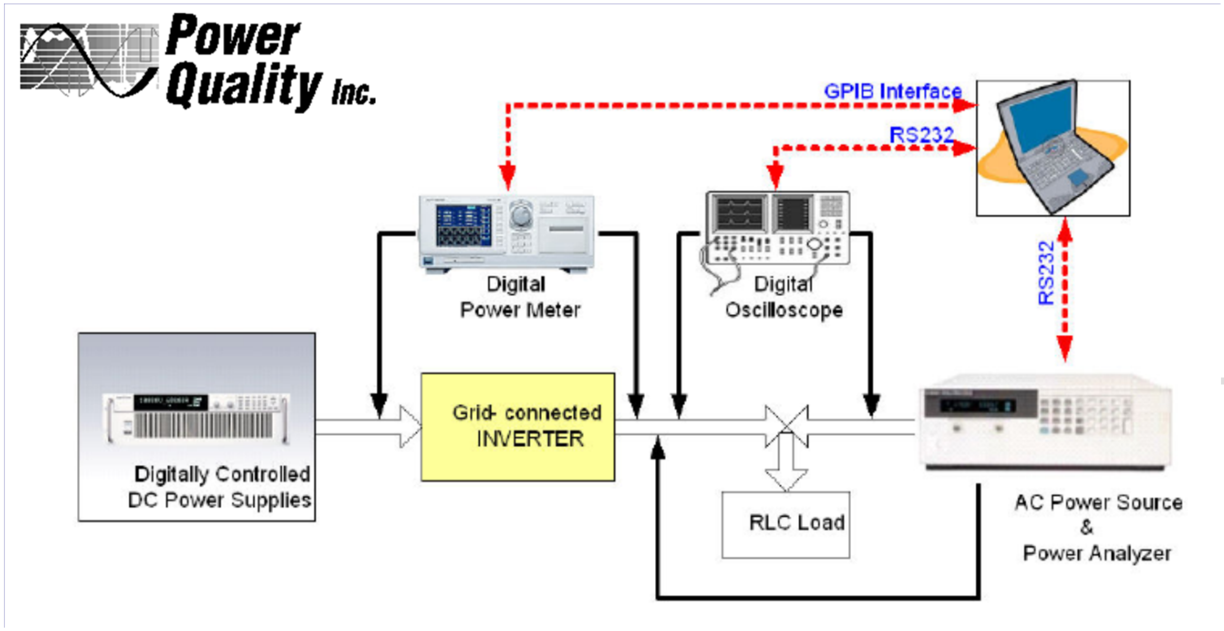
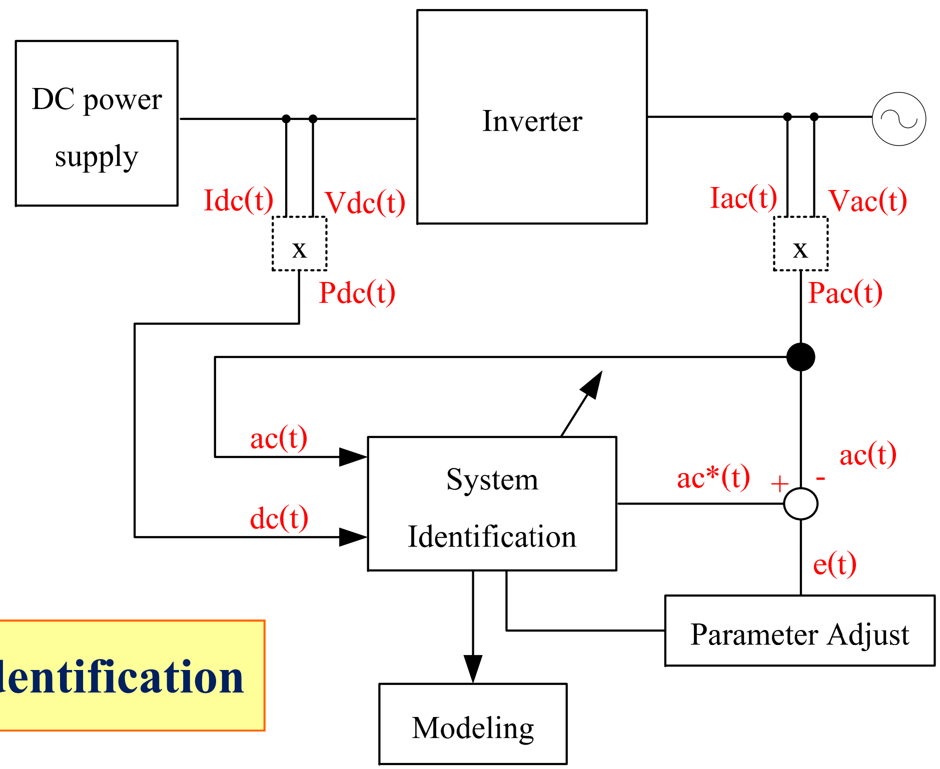
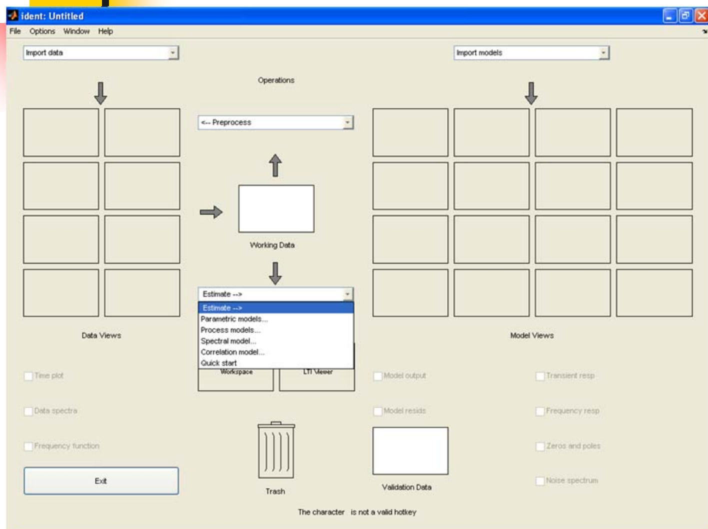


Experimental setup

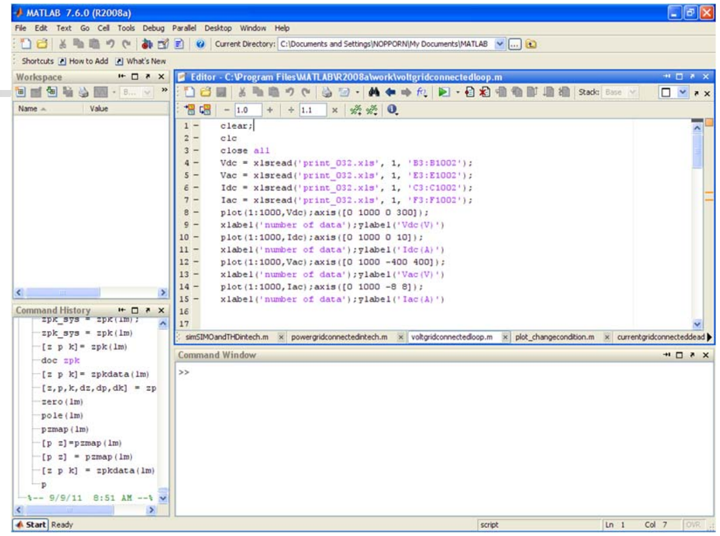


inverter modeling using system identification

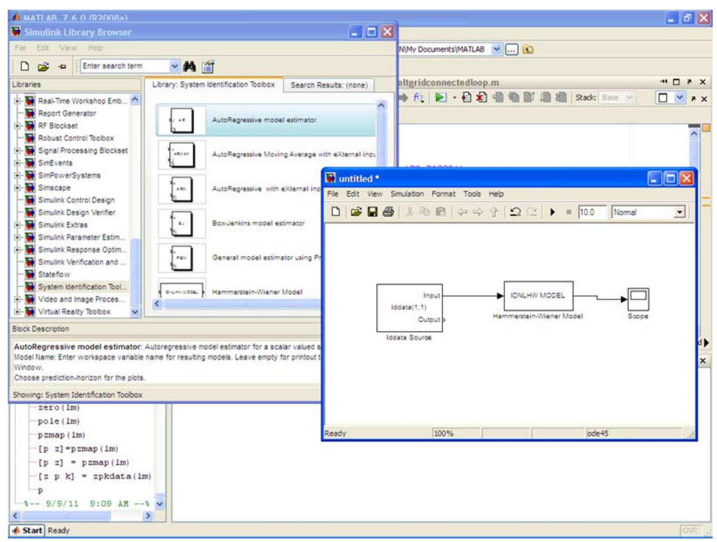
Using System Identification Toolbox in MATLAB



Toolbox



M-file



simulink

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Write M-file

Flow chart	คำสั่งที่ใช้
Import data	Xlsread (…..)
Data process	Resampling(….) IDDATA(….)
Divide data into estimate, validate	Identify (number)
Model selection	oe(….) nlhw (...)
Comparison model output and experiment data	Compare(….)
Maximize (accuracy) Minimize (error, model order)	If loop max( ), min( )
Iteration linear parameter and nonlinear function	For loop
select optimize model	

System Modeling

Modeling Analysis

Step	Commands
Initialize model condition	Findstate(…),
Simulation & prediction	sim(…..), predict(….)
Power Quality analysis	mean(….), sqrt(…) sum(…), fft(….)
Analyze nonlinear model	get(…..), idss(….), idnlhw(….)
Linearization	Findop(…) linapp(…..), linearize(...)
Analyze linear model (frequency response, state space, transfer function, zero pole gain)	sys(…),view(…) frd(…), ss(…..), tf(...), zpk(…),
Plot graphical tool	LTIview(….), bode(….), nyquist(….), nichols(…), impulse(…..), step(…..)

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Topic for Experimental and Modeling

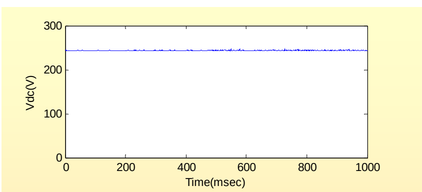
- Modeling System in Steady state
- Modeling System in Transient
- Modeling System in Islanding
- Modeling System with cross validation
- Modeling with MIMO model

Modeling and Condition from Experimental

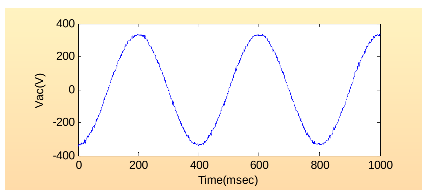
Type of Modeling	Parameter	Condition
Linear Modeling		
Auto Regressive with Exogenous,	SISO	Steady state
Auto Regressive Moving Average with Exogenous	SISO	Steady state
Box-Jenkins (BJ)	SISO	Steady state
Output error (OE)	SISO	Steady state
Nonlinear Modeling		
Nonlinear Autoregressive with Exogenous	SISO	Steady state
Hammerstein	SISO	Steady state
Wiener	SISO	Steady state
Hammerstein-Wiener	SISO	Steady state

Experimental in Steady State

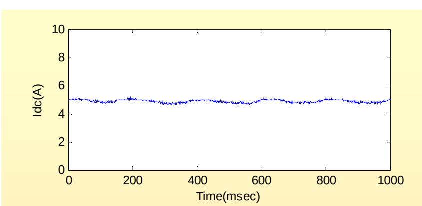
Input and Output waveform



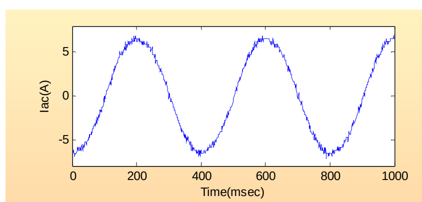
DC Voltage



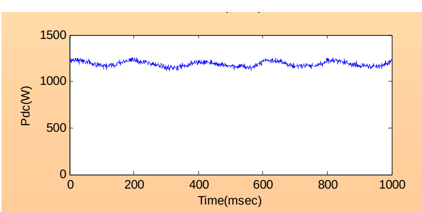
AC Voltage



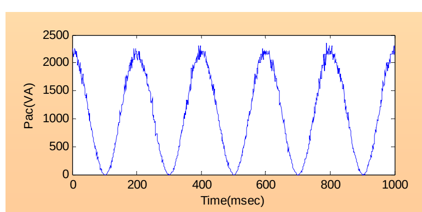
DC Current



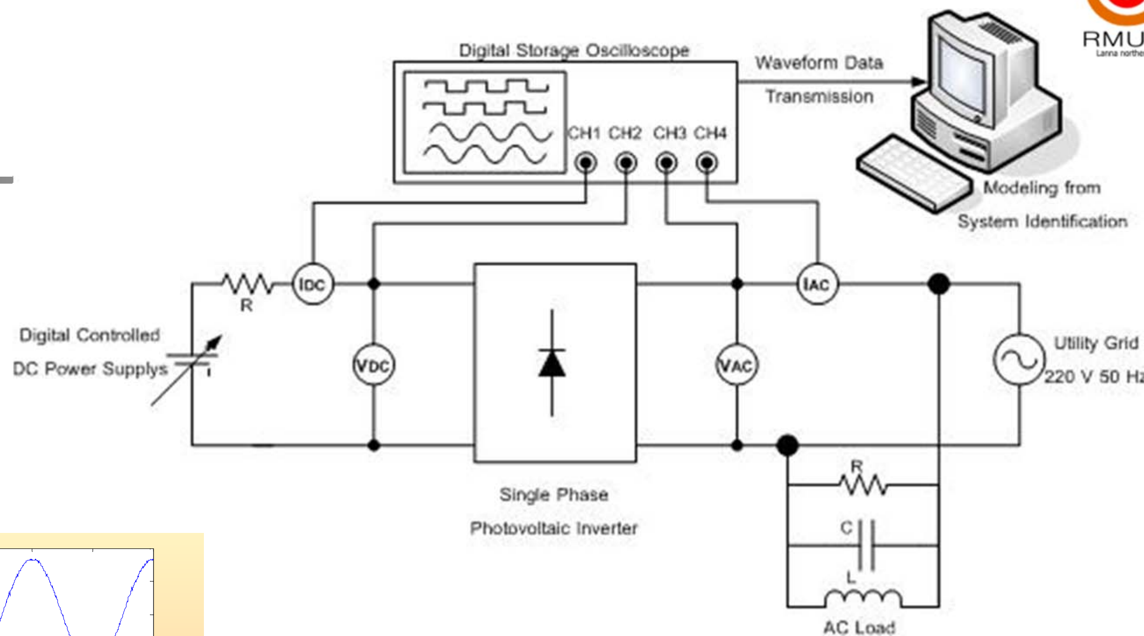
AC Current



DC Power

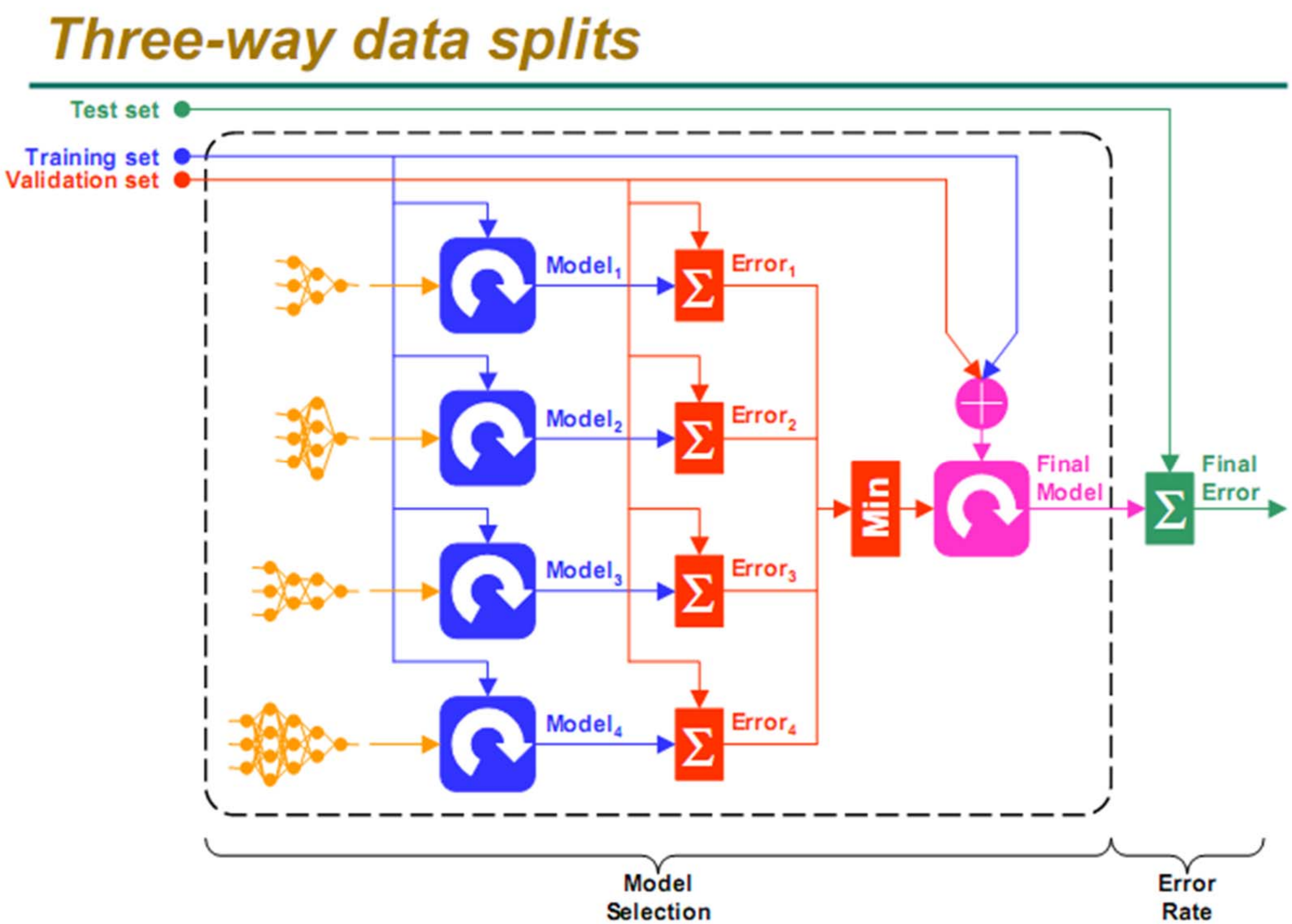


AC Power

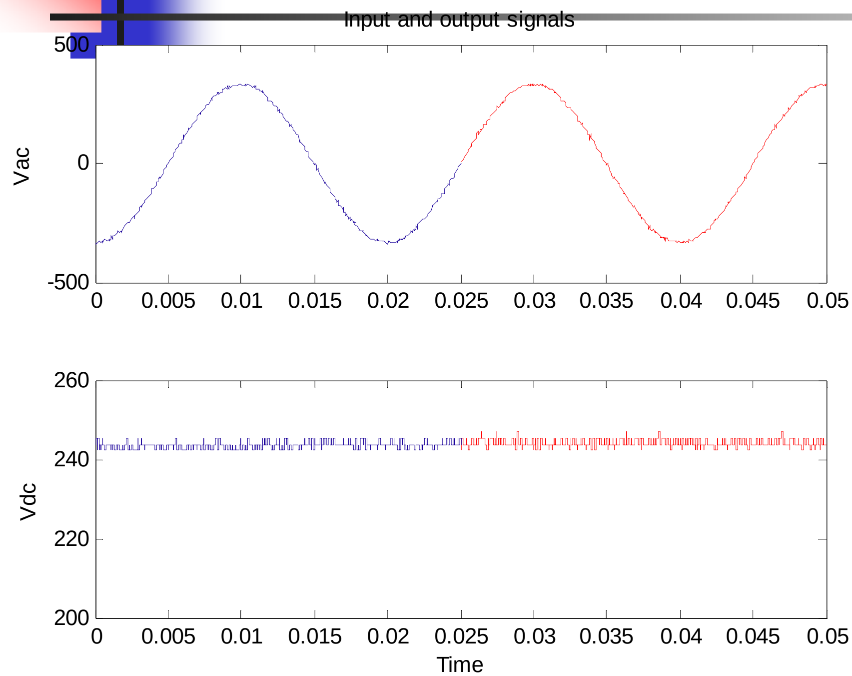


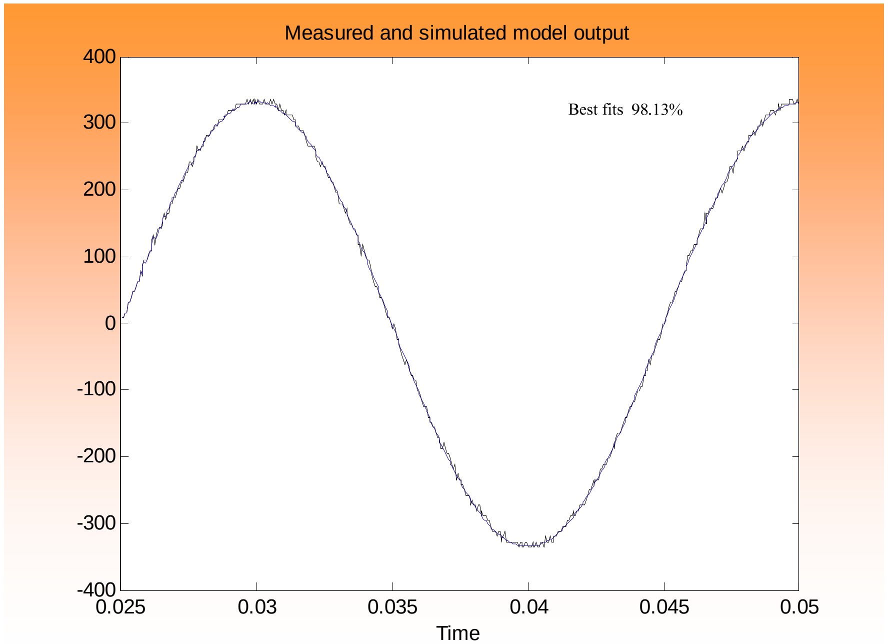
Experimental Setup

Three Way Data Splits



Modeling and Simulation in Steady State





Data divide into estimate and validate data

The experiment and simulated model output

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Result of Modeling

Model	Linear Polynomial Parameters						% fit	FPE	AIC
	a_n	b_n	c_n	d_n	f_n	k_n			
Arx	10	10	-	-	-	9	26.49	3,292	8.09
Armax	5	1	3	-	-	3	92.03	2,584	7.85
BJ	-	5	5	1	3	1	92.82	2,655	7.88
OE	-	3	-	-	3	5	93.56	2,910	7.97

Model	**Nonlinear**		**Linear**			**Model properties**		
			a_n	b_n	k_n	**% fit**	**FPE**	**AIC**
NARX	-	WN	9	1	9	81.02	5,012	8.51
	-	SN	10	7	8	81.01	4,086	8.30
Model	**Nonlinear**		**Linear**			**Model properties**		
	I/P	**O/P**	b_n	f_n	k_n	**% fit**	**FPE**	**AIC**
Hammerstein	SN	-	3	3	1	92.79	4,022	9.54
	WN	-	3	3	1	92.88	3,037	9.47
Wiener	-	SN	2	5	0	53.86	3,790	11.86
	-	WN	4	2	2	61.03	3,013	10.28
Hammerstein-Wiener	SN	SN	4	2	2	93.75	3,323	7.06
	WN	**WN**	**1**	**3**	**2**	**93.91**	**2,670**	**7.54**

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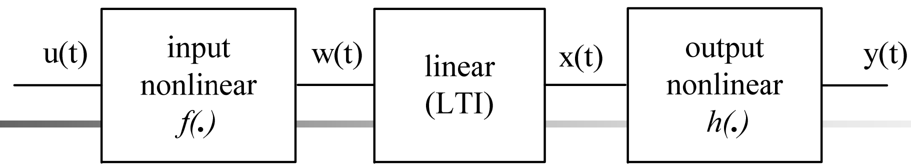
Compare Linear and Nonlinear Model

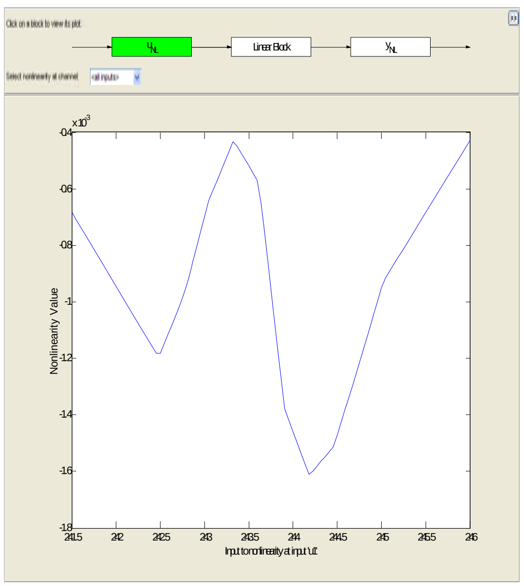
- Accuracy of Hammerstein-Wiener and Hammerstein Model more than Linear model
- Model order of Nonlinear Hammerstein-Wiener and Hammerstein Model lower than linear Model
- Accuracy of Linear system identification lower than Nonlinear model
- Model order of linear higher than nonlinear system identification

Result of Hammerstein-Wiener model

Data	Input/Output Nonlinear	Nb	nf	nk	Model order	% fit	FPE	AIC
Voltage	Deadzone	1	5	1	5	87.23	3,079.8	10.33
	Saturation	4	5	2	8	93.54	729.03	6.59
	Pwlinear	**1**	**2**	**2**	**2**	**98.05**	**26.27**	**3.26**
	Sigmoid	3	2	2	4	93.75	3,323	7.06
	Wavenet	1	3	2	3	98.01	2,670	7.54
Current	Deadzone	3	8	2	10	91.76	0.07	2.57
	Saturation	3	4	2	6	95.02	0.23	2.99
	Pwlinear	4	6	7	9	94.31	0.05	1.53
	Wavenet	9	17	2	25	93.22	19.08	15.19
	Sigmoidnet	5	8	3	12	91.68	25.61	18.14
Power	Deadzone	3	7	5	9	91.05	8,688.3	9.06
	Saturation	6	4	1	9	92.28	1,262.7	9.44
	Pwlinear	8	6	2	13	92.32	3,263	8.08
	Sigmoidnet	4	9	3	12	92.82	8,480	6,010
	Wavenet	**5**	**7**	**2**	**11**	**93.62**	**2008**	**1429**

System Analysis

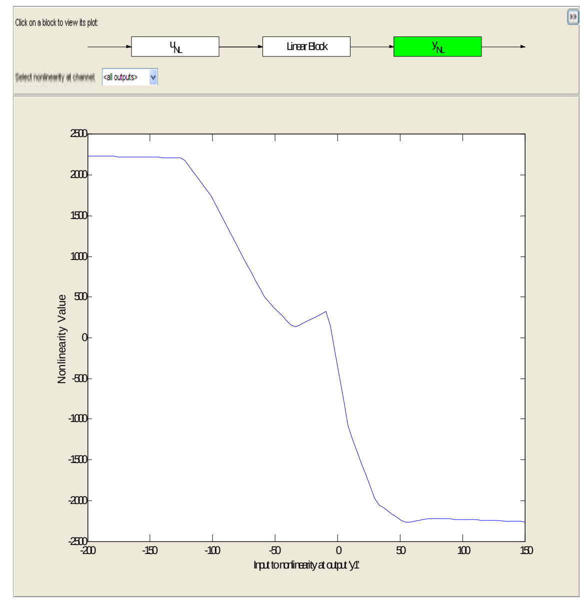




$$y(t) = \left[\frac{B(q)}{F(q)}\right] u(t) + e(t)$$

$$B(q) = q^{2}$$

$$F(q) = 1 - 1.99q^{-1} + q^{-2}$$

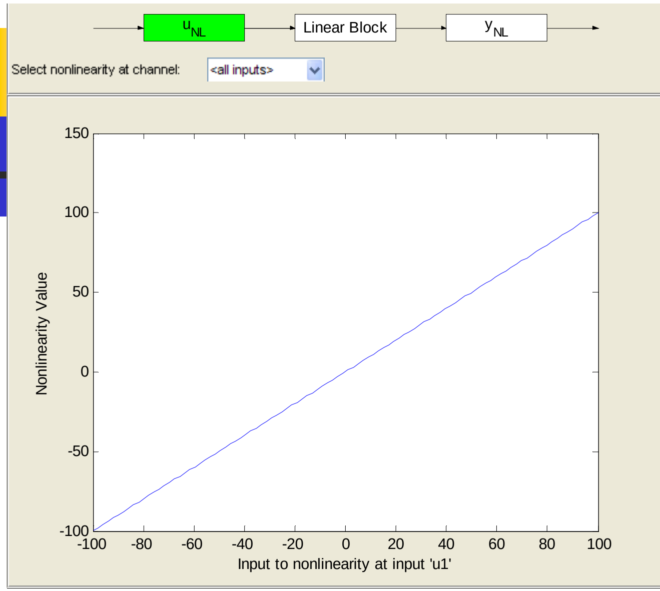


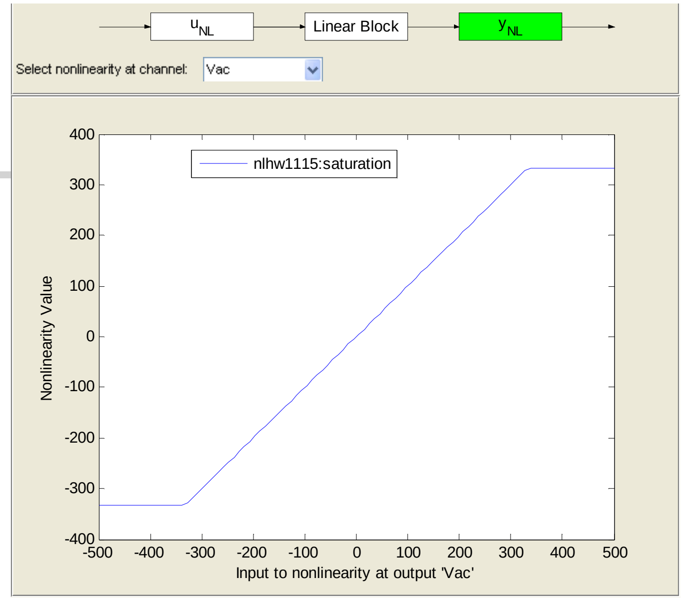
Input nonlinear

Discrete polynomial model

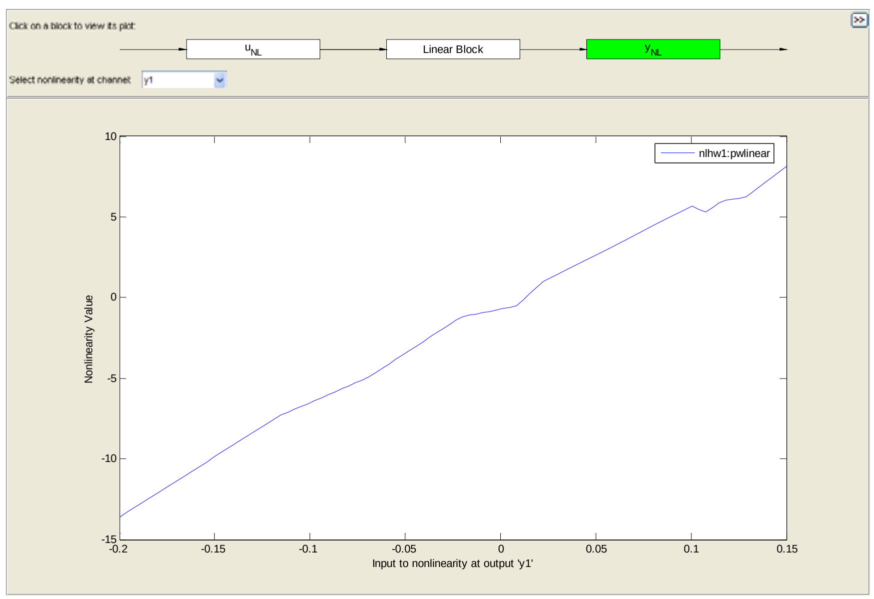
Output nonlinear

Nonlinear Estimator





Deadzone

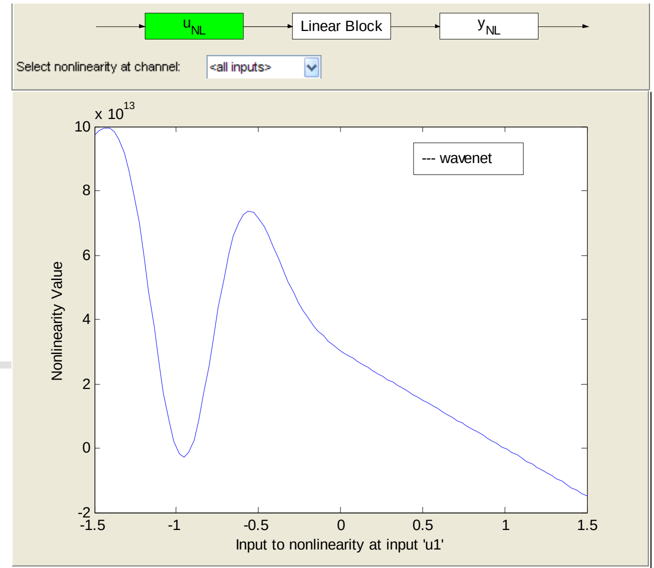


Saturation

piecwiselinear

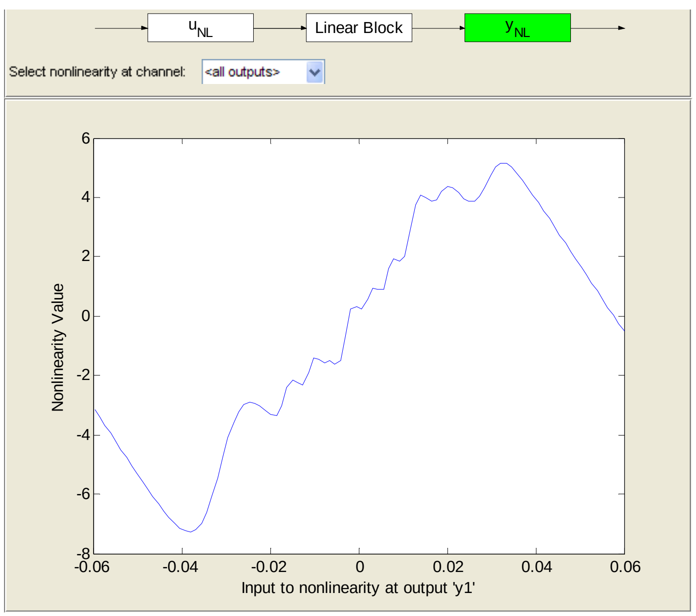
Properties	Input Nonlinear	Output Nonlinear
Regressor Mean	0.0052	-9.61×10^{-17}
NonLinear Subspace	1	1
Linear Subspace	1	1
Linear Coef	-0.1387	-6.1046
Dilation	[1x10 double*]	[1x10 double]
Translation	[1x10 double]	[1x10 double]
Output Coef	[10x1 double]	[10x1 double]
Output Offset	-0.0527	1.1208

wavenet



Properties	Input Nonlinear	Output Nonlinear
Number of Unit	6	11
Regressor Mean	- 8.5126	-98.55
Nonlinear Subspace	0.0056	4.58e-4
Linear Subspace	0.0056	4.58e-4
Output Offset	-7.0973	-0.4855
Linear Coef	176.51	3.1140
Scaling Coef	[0x1 double*]	[3x1 double]
Wavelet Coef	[6x1 double]	[8x1 double]
Scaling Dilation	[0x1 double]	[3x1 double]
Wavelet Dilation	[6x1 double]	[8x1 double]
Scaling Translation	[0x1 double]	[3x1 double]
Wavelet Translation	[6x1 double]	[8x1 double]

Sigmoidnet



Linear System analysis

Nonlinear System → Linearization → Linear System

State space equation

$$x(t+Ts) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

$$A = \begin{bmatrix} 1.99 & 1 & -1.486e-5 \\ -0.99 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$
$$D = \begin{bmatrix} 0 & 12.99 \end{bmatrix}$$

Transfer function

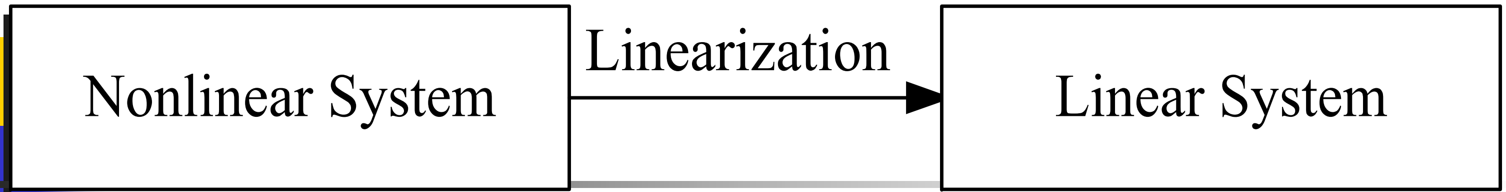
$$G(z) = \frac{-1.486e-5}{z^2 - 1.999z + 0.996}$$

Gain = -1.486e-5 *zero = 0* *pole = 0.997-0.0159i*

= 0.997+0.0159i

= 0

Linear System analysis

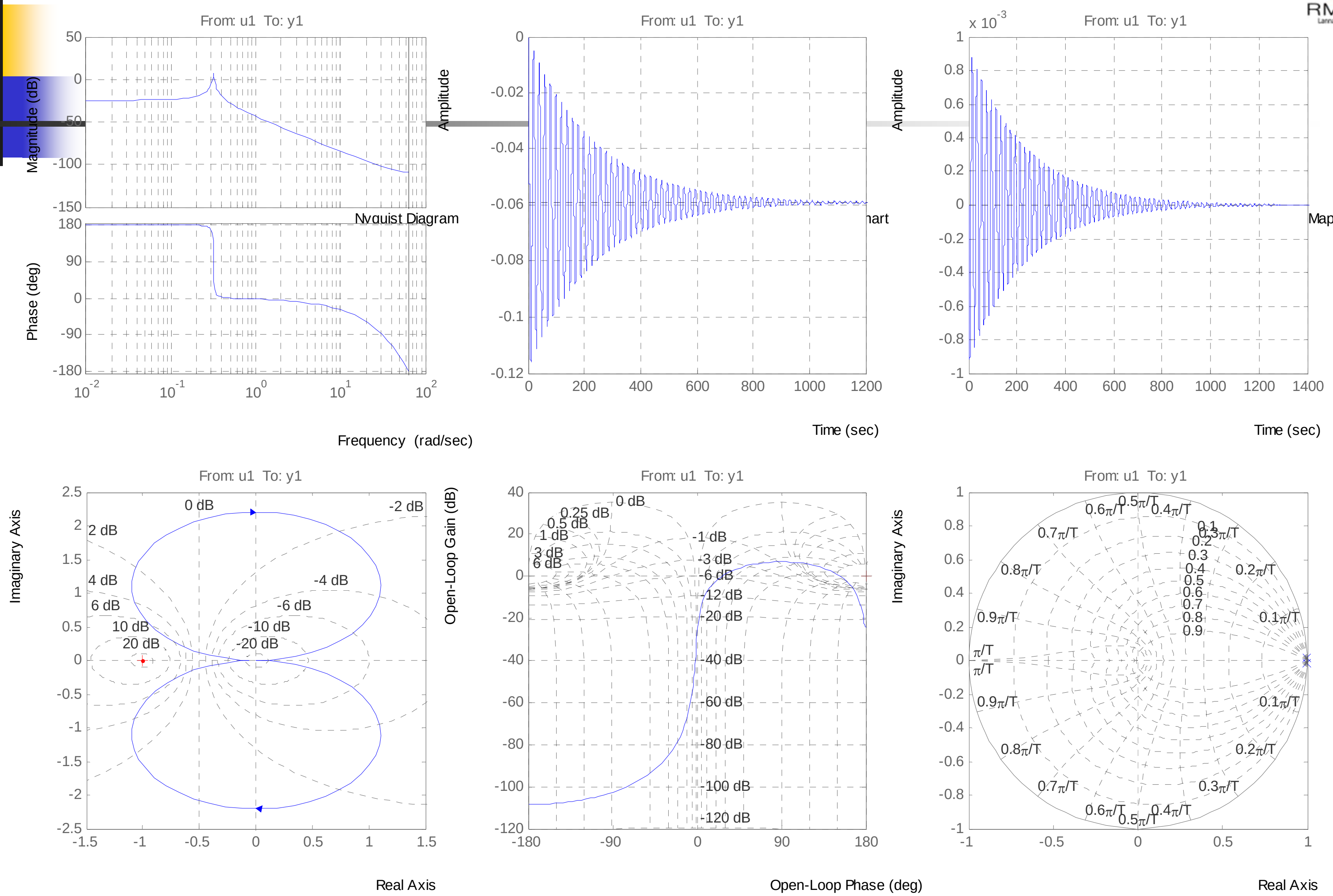


$$B(q) = 1.025q^{-5} - 1.635q^{-6} + 0.1838\,q^{-7} + 0.4257q^{-8}$$

$$F(q) = 1 - 2.396q^{-1} + 1.794q^{-2} - 0.3979\,q^{-3}$$

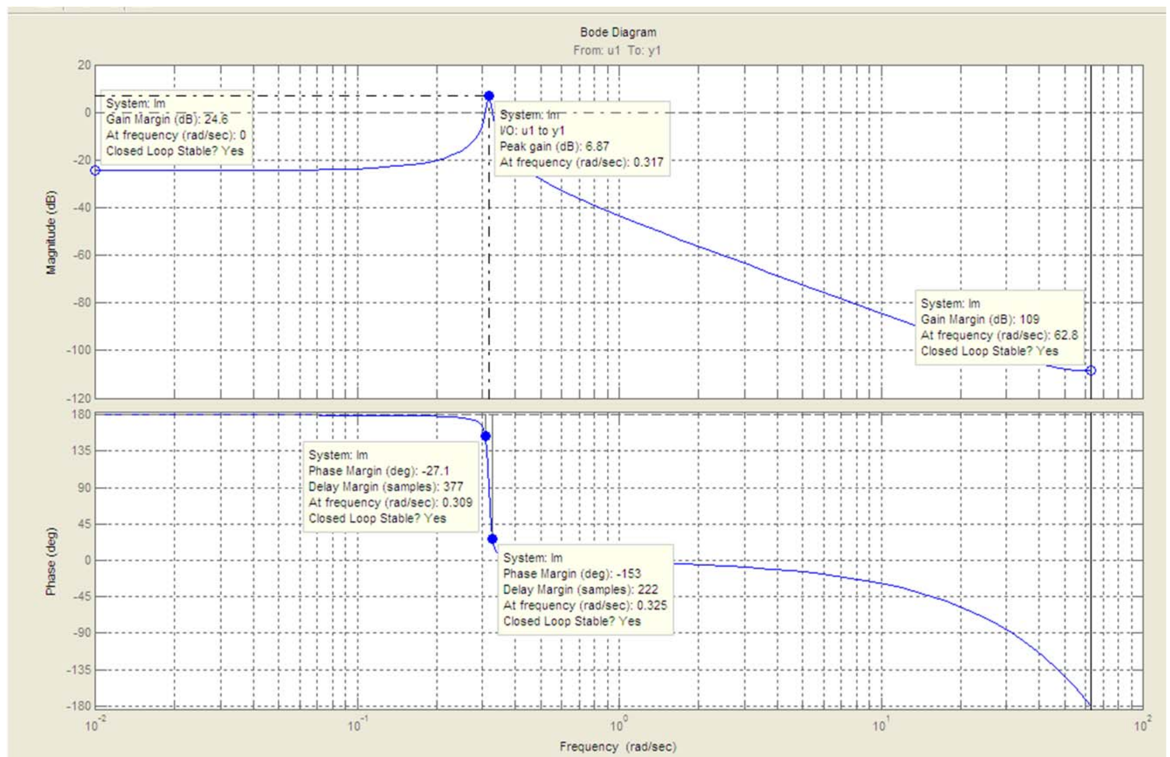
$$G(z) = \frac{1.025z^{3} - 1.635z^{2} + 0.183z + 0.425}{z^{8} - 2.395z^{7} + 1.794z^{6} - 0.397z^{5}}$$

Graphical Tool for analysis

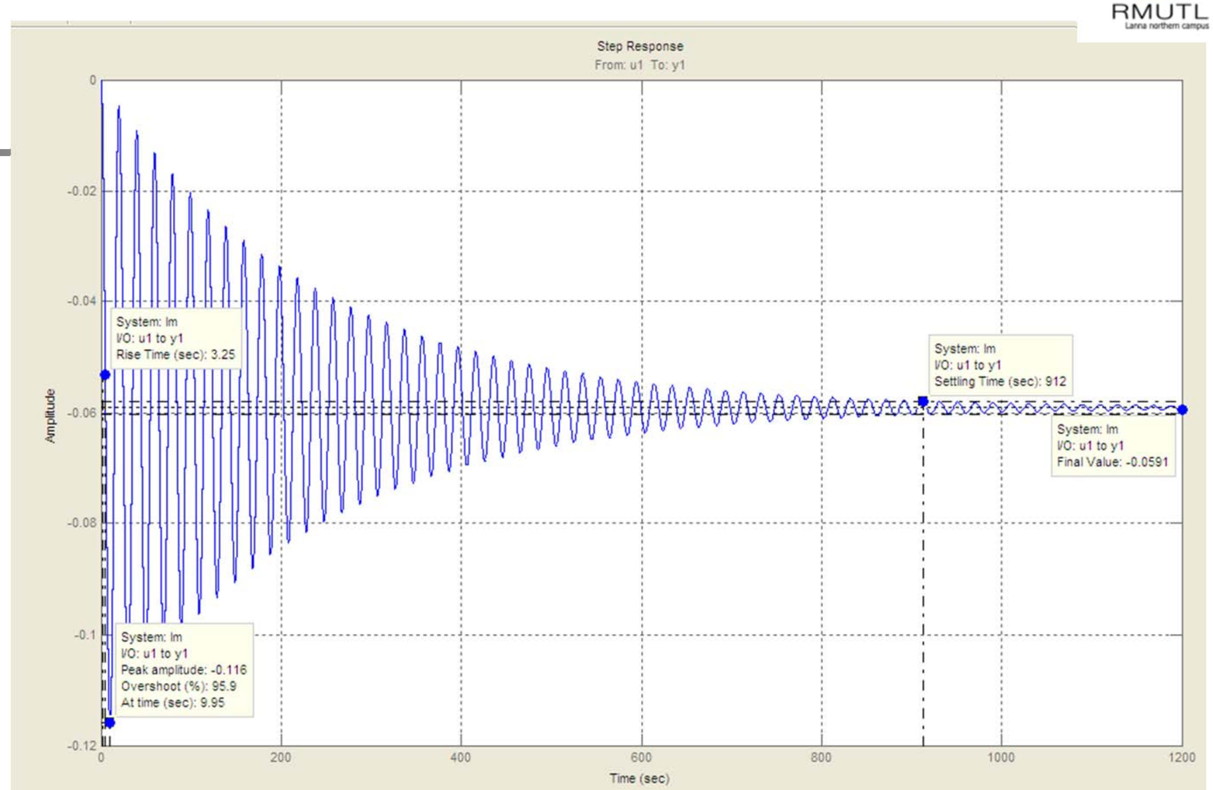


Bode plot

- Peak gain Value 6.87 dB at frequency 0.317 rad/sec
- Gain Margin 2 value 24.6 dB at frequency 0 rad/sec and 109 dB at frequency 62.8 rad/sec
- Phase Margin -27.1 at frequency 0.309 rad/sec

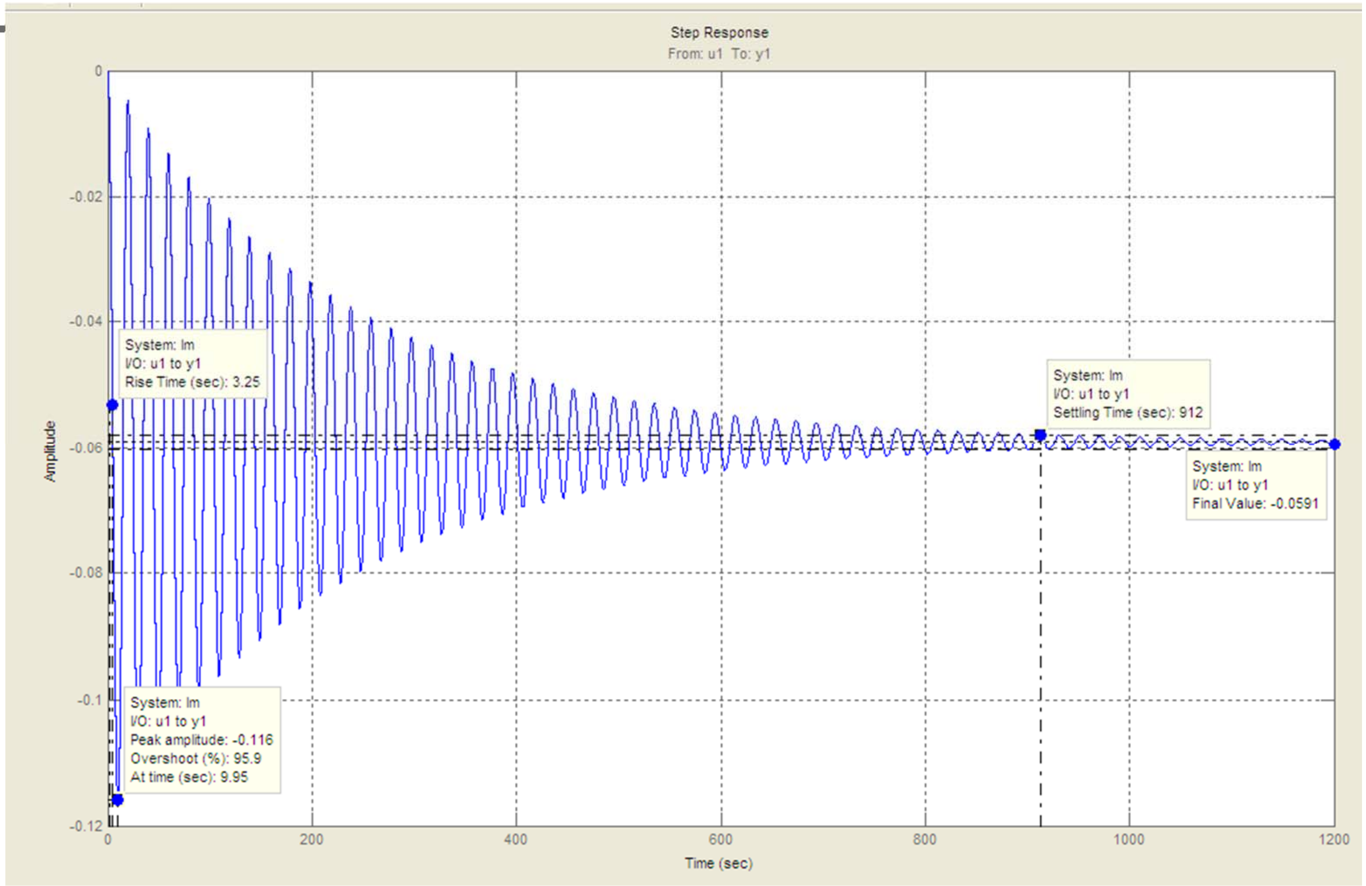


Step response



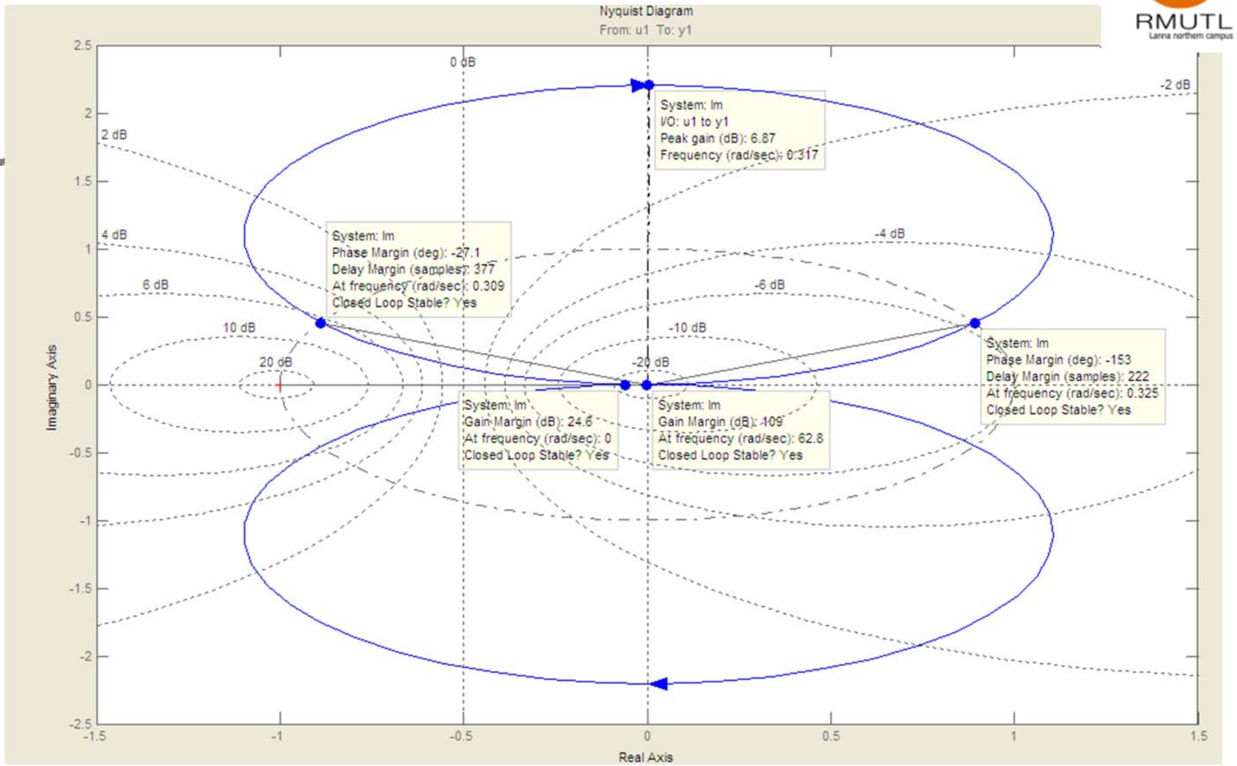
- When we feed unit step input
- rise time, tr 3.25 Second
- peak time, tp 9.95 Second Maximum - 0.116
- maximum overshoot 95.9%
- settling time, ts 912 Second and final magnitude 0.059

Impulse response



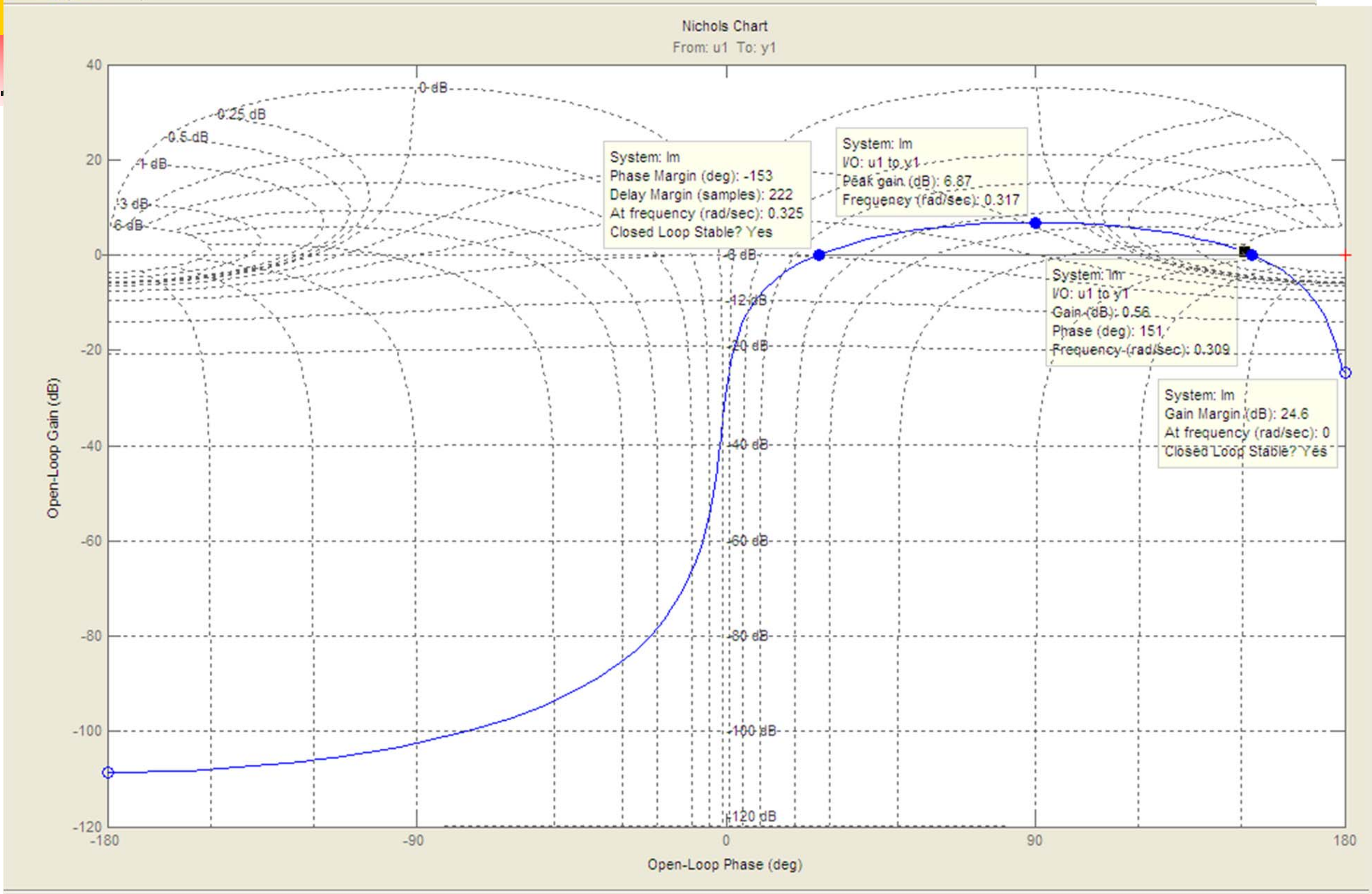
- Amplitude -0.000915 at time 4.95 and steady state time 917 second

Nyquist Analysis



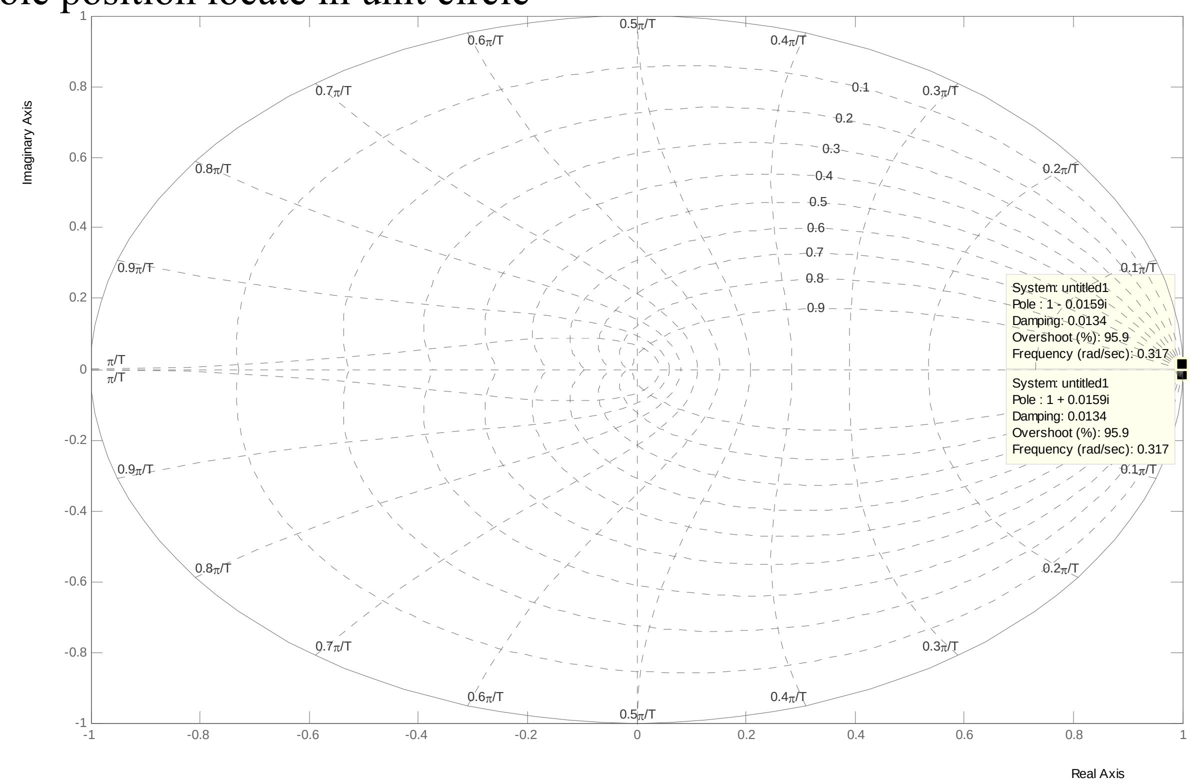
- Peak gain = 6.87 dB at frequency 0.317 rad/s
- Gain margin 2 values are 24.6 dB at frequency 0 rad/sec and 109 dB at frequency 62.8 rad/sec
- Phase margin 2 values are -27.1 degree at frequency 0.309 rad/sec and -153 degree at frequency 0.325 rad/sec

Nichols plot



Pole zero map

- Pole Position at 1-0.0159i and Zero Position at 1+0.0159i
- damping 0.0134 ,   overshoot 95.9%   at frequency 0.317 rad/sec
- Stability Analysis found that pole position locate in unit circle



Power Quality Inc.

Linear system Stability analysis

RMUTL

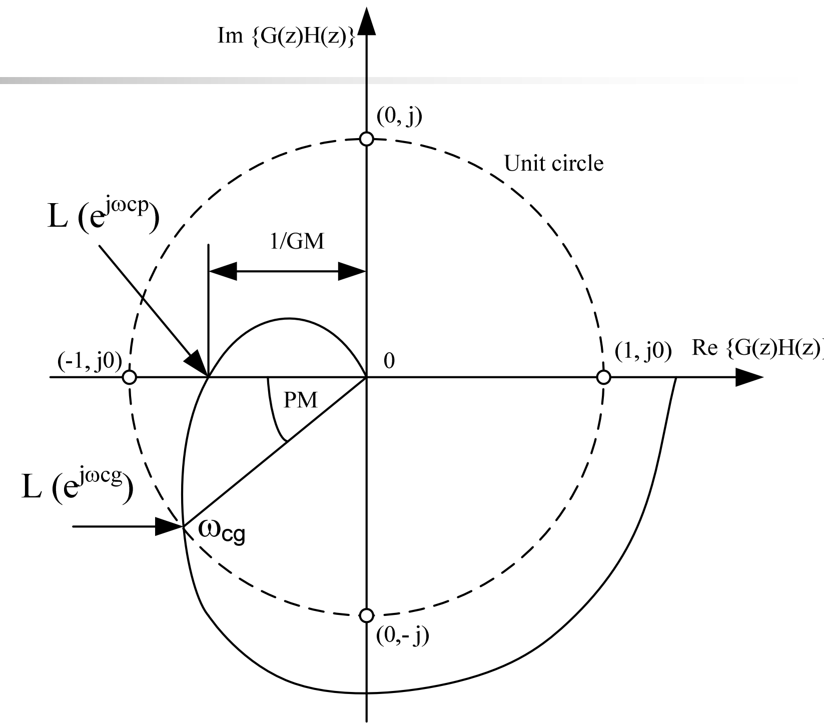
- Nonlinear → Linear
- Linearization around operating point
- Steady State condition
- Stability analysis

Linear system Stability analysis

- Right hand plane (RHP)
- Root locus, Routh – Hurwitz criterion
- Z plane and Unit circle
- Eigenvalue of Jacobian matrix
- Lyapunov
- Bode-Nyquist stability criterion

Bode-Nyquist stability criterion

- gain margin (GM)
- phase margin (PM)
- gain crossover frequencies
- phase crossover frequencies



SISO Stability Criterion

1 ≈ 0 dB < GM < 4 ≈ 12 dB and 30 < PM < 60

$$Pm = 180 + \arg\ L(e^{j\omega}$$

$$Gm = \frac{1}{|L(e^{j\omega cp})|} = \frac{1}{|Re(e^{j\omega}}$$

Topic for Experimental and Modeling

- Modeling System in Steady state
- Modeling System in Transient
- Modeling System in Islanding
- Modeling System with cross validation
- Modeling with MIMO model

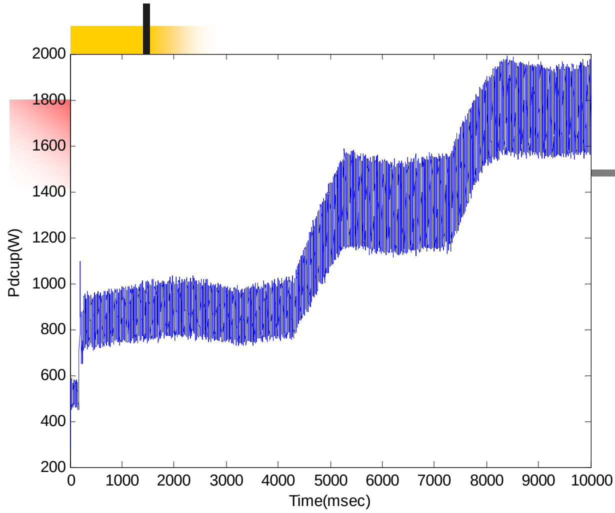
Power Quality Inc.

Experimental for Transient Condition

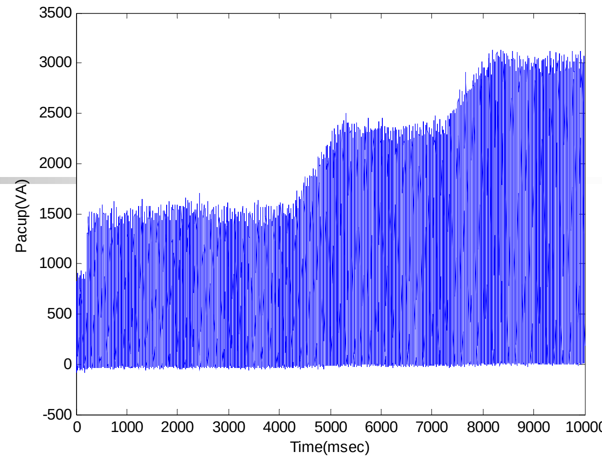
RMUTL

Electrical parameter	Step Up		Step Down	
AC Voltage output (V)	220	220	220	220
AC Current output (A)	7	2	2	7
AC Power output (W)	1540	440	440	1540

Step up condition

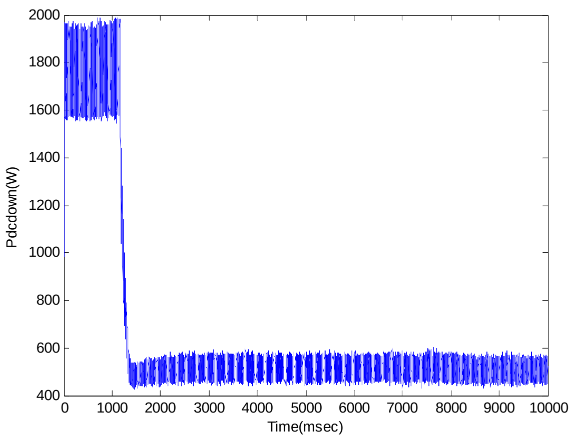


Power dc input

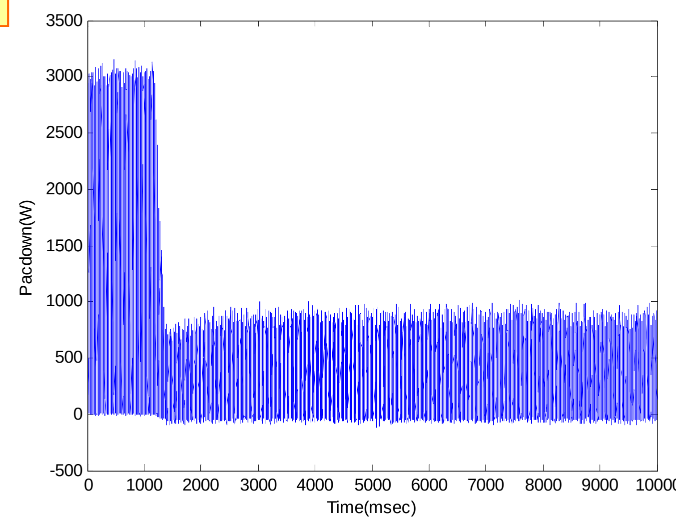


Power ac output

Step down condition



Power dc input



Power ac output

Model properties and comparison of waveform

Step Up Condition

Nonlinear	Linear Parameters			Model Properties			
I/P & O/P	**nb**	**nf**	**nk**	**model**	**% fit**	**FPE**	**AIC**
Deadzone	3	4	2	6	91.75	3,230	7.40
Saturation	4	3	2	6	83.46	3256	11.34
Pwlinear	4	4	5	7	87.20	4720	8.38
Sigmoidnet	3	5	5	7	83.85	4238	8.43
Wavenet	4	5	2	8	84.57	2980	9.52

Power Quality Inc.

RMUTL

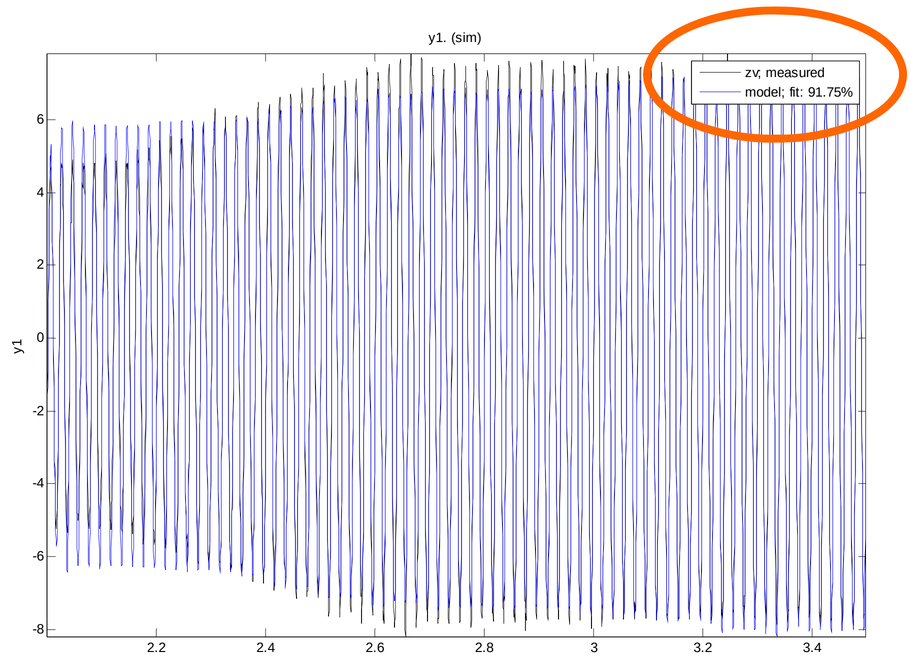
Model properties and comparison of waveform

Step Down Condition

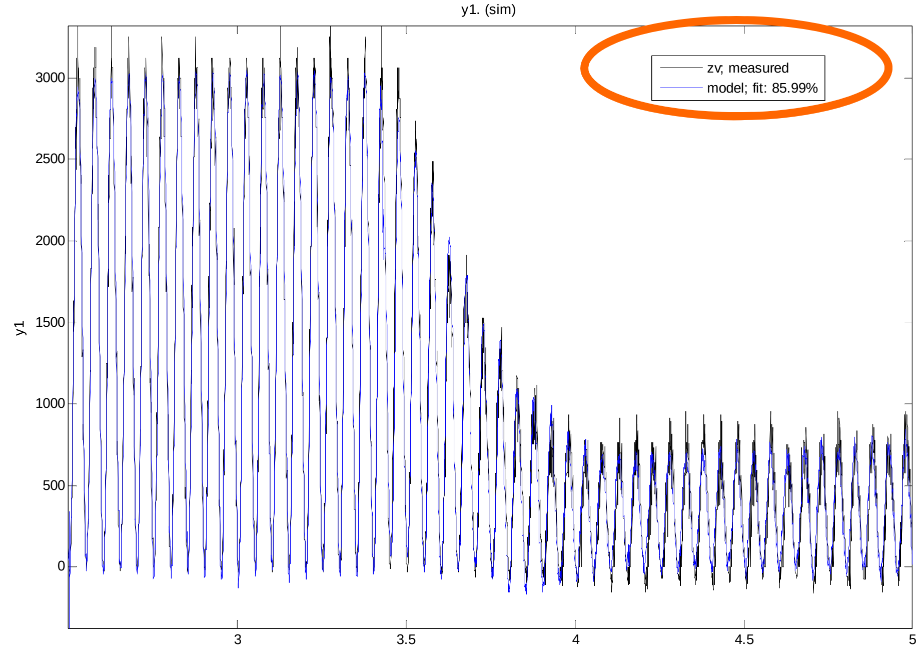
Nonlinear	Linear Parameters			Model Properties			
I/P & O/P	nb	nf	nk	model	% fit	FPE	AIC
Deadzone	4	5	5	8	85.12	9,718	9.18
Saturation	3	5	5	7	81.29	3049	11.23
Pwlinear	3	4	3	6	85.99	3233	10.0
Sigmoidnet	4	4	1	7	81.17	4426	8.28
Wavenet	4	5	4	8	82.45	3325	9.25

Simulation Result for Transient

Step up condition

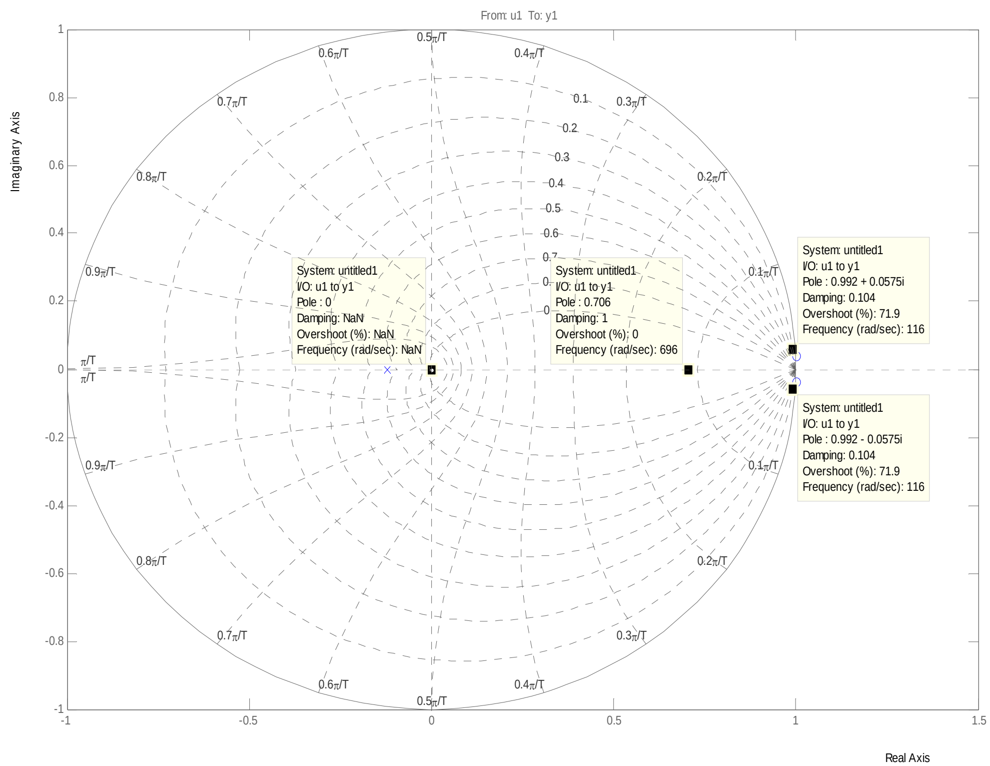


Step down condition



Stability Analysis

- Stability : consider from pole position, magnitude of pole and unit cirle
  - Pole 4 position follow as
  - 0.9923 + 0.0575i, 0.9923 - 0.0575i, 0.7060 and -0.1213
- Magnitude are 0.9940, 0.9940, 0.7060 and 0.1213

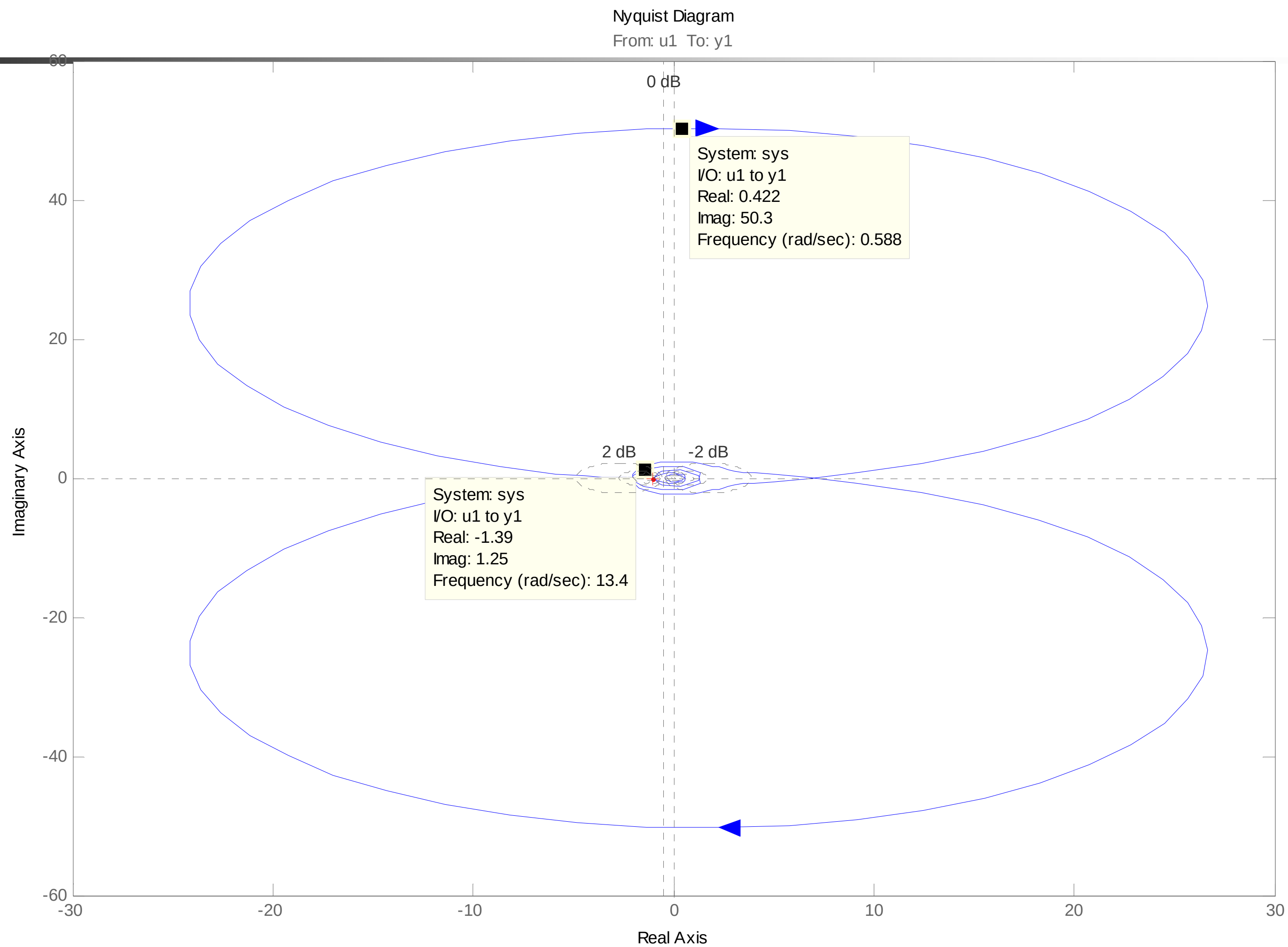


Magnitude of pole < 1

All Pole locate in unit circle

: System is stable

Linear Stability analysis

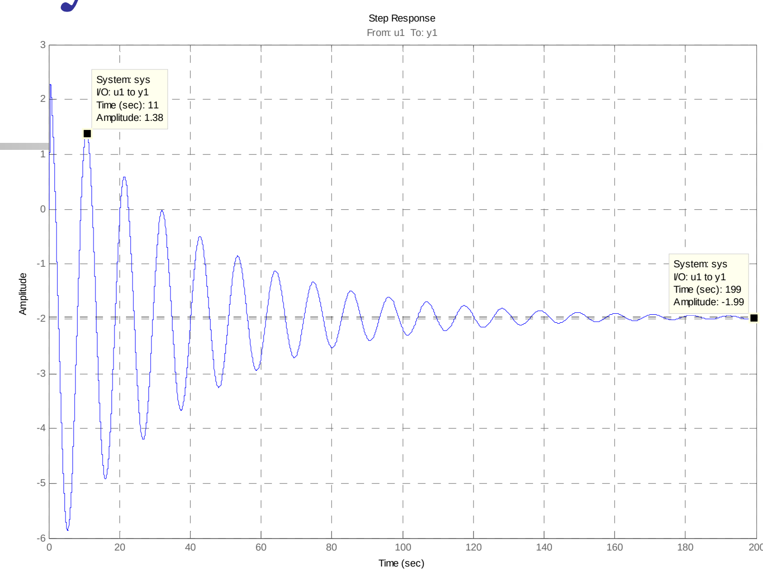


Linear Stability analysis

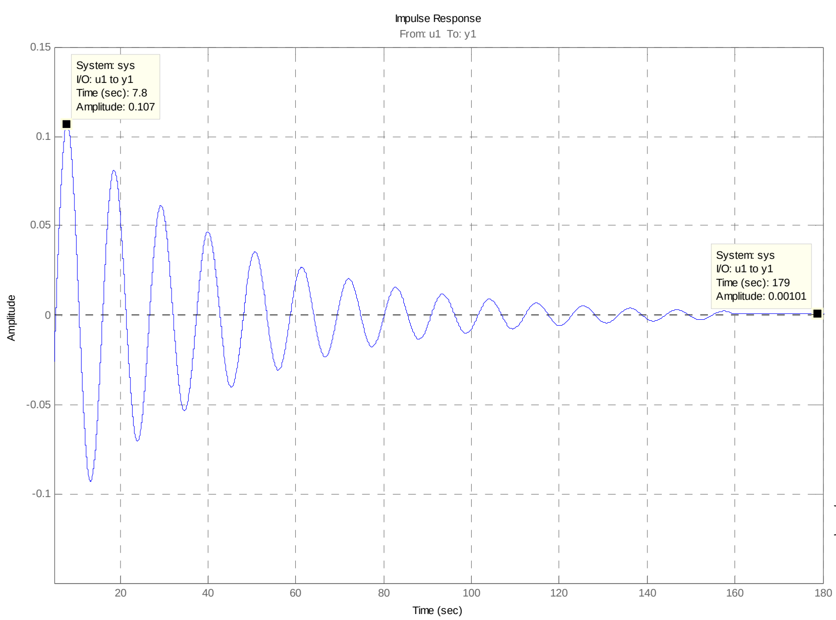
Criteria	Condition	Result	Stability
Gain Margin (GM)	0 < GM < 4	0.679 dB	Stable
Phase Margin (PM)	30 < PM < 60	31.8	Stable

Absolute stability analysis

Criteria	Result
Rise Time	5.2 sec
Settling Time	206 sec
Overshoot	95.9%



Step Response

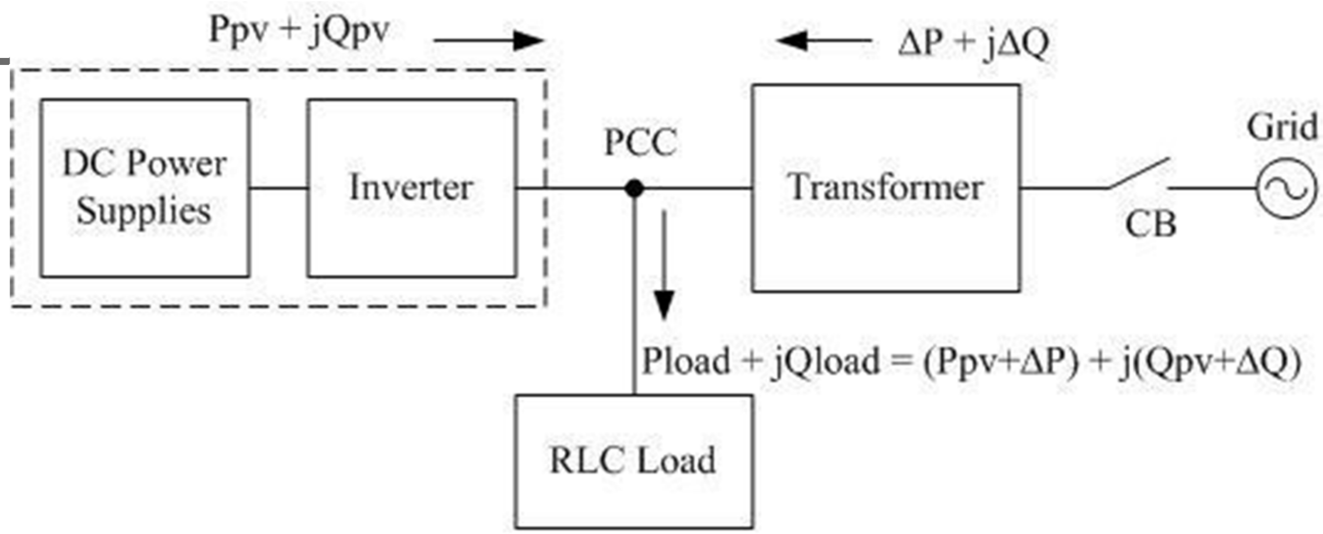


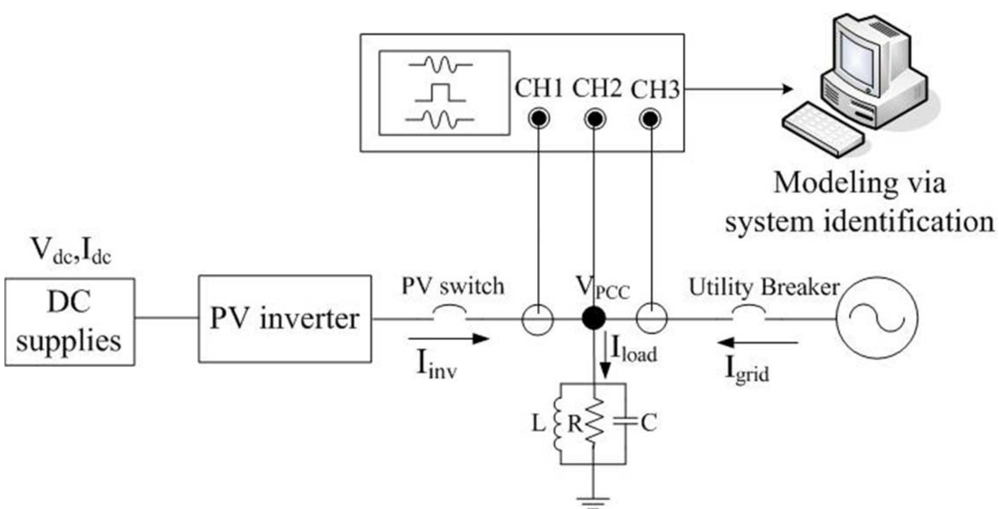
Impulse Response

Topic for Experimental and Modeling

- Modeling System in Steady state
- Modeling System in Transient
- Modeling System in Islanding
- Modeling with MIMO model

Modeling of Islanding condition





Power Quality Inc.

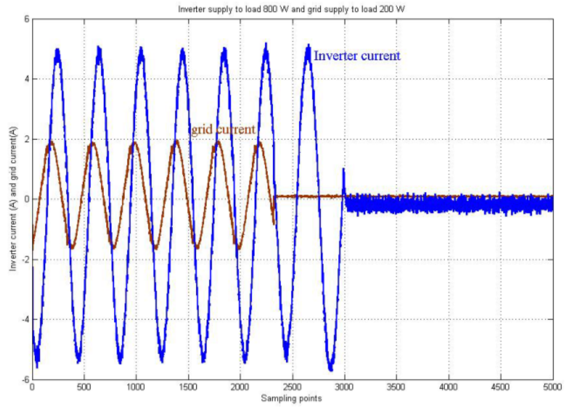
Design Simulation in Six Condition of Islanding

No	Model input	$P_{inverter}$ (W)	P_{load} (W)	P_{grid} (W)	Load
I	Grid current	1,000	800	-200*	R
II	Grid current	1,200	1,000	200	R
III	Grid current	1,000	1,000	-	RLC
IV	PCC voltage	1,000	800	-200	R
V	PCC voltage	1,200	1,000	200	R
VI	PCC voltage	1,000	1,000	-	RLC

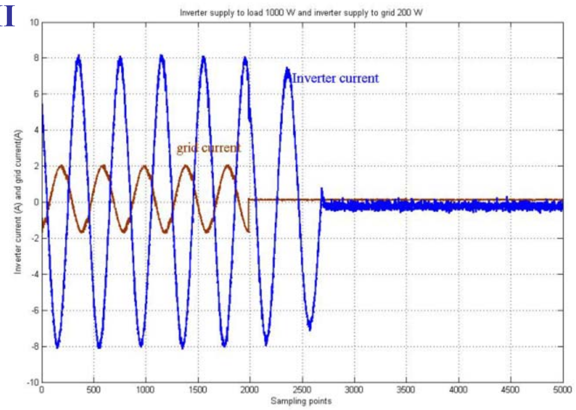
* sign (–) mean grid current energize power into the load

RMUTL

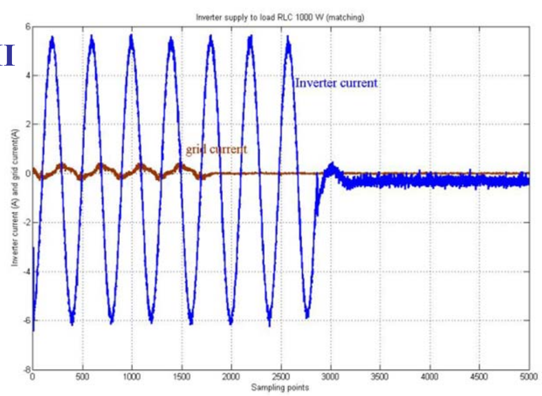
Scenario I



Scenario II

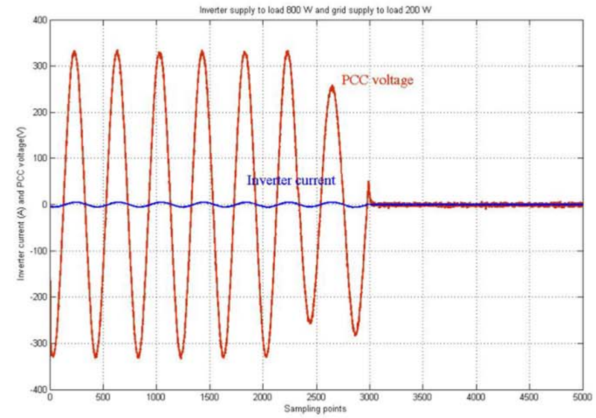


Scenario III

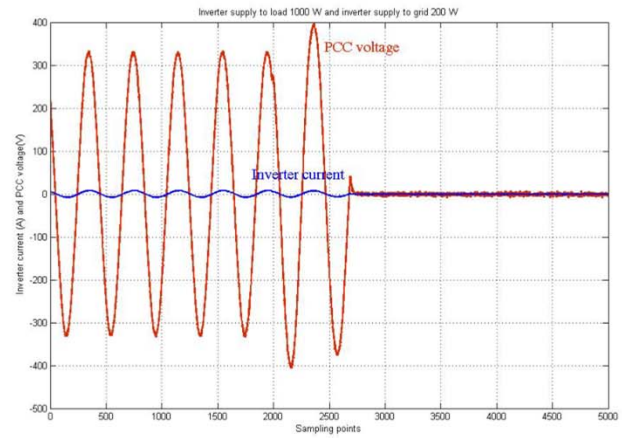


Grid current input

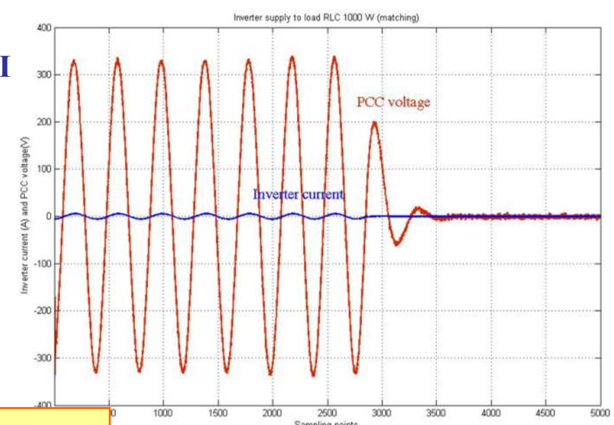
Scenario IV



Scenario V



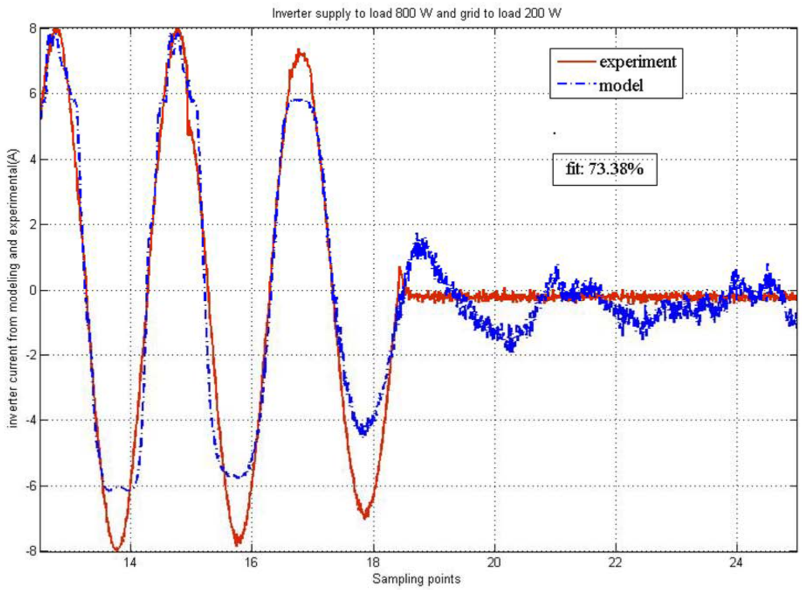
Scenario VI



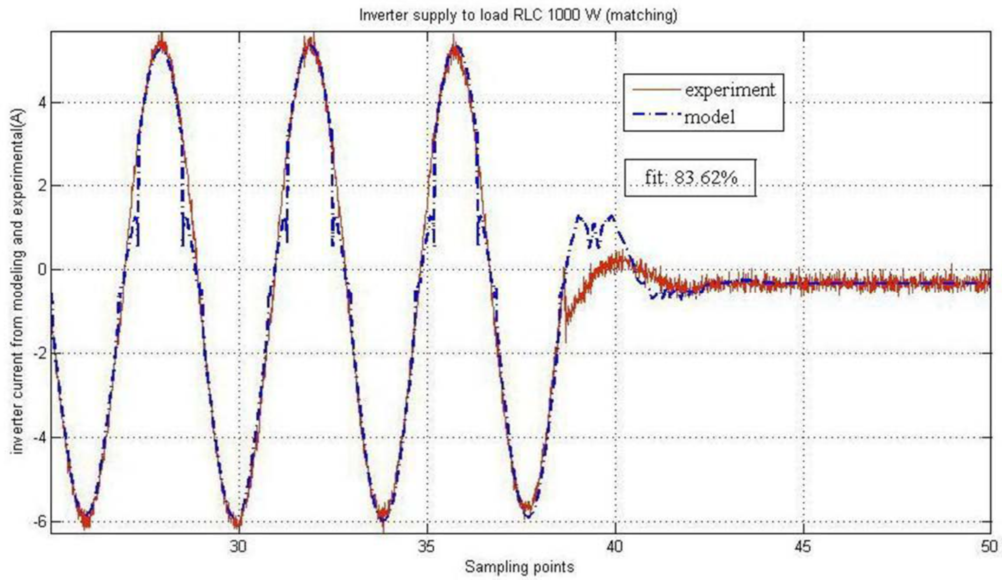
PCC voltage

The Input and output of model

Simulation Result in condition 1 and 6



scenario I

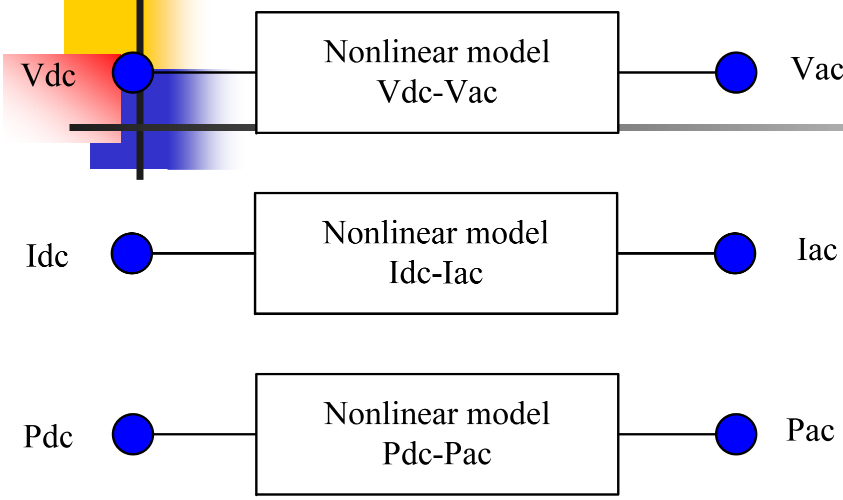


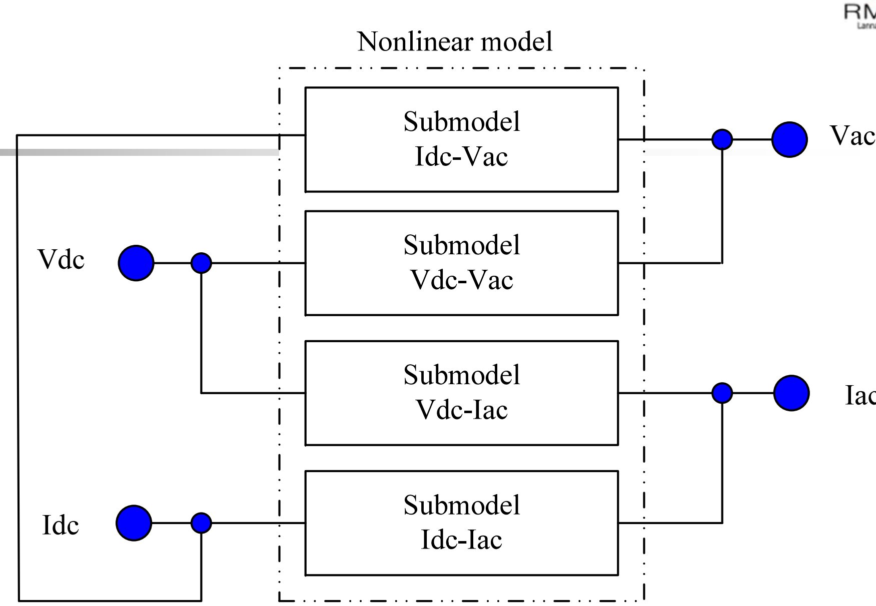
scenario VI

Topic for Experimental and Modeling

- Modeling System in Steady state
- Modeling System in Transient
- Modeling System in Islanding
- Modeling with MIMO model

MIMO (Multi Input Multi Output) Model





$$\left.\begin{aligned} v_{ac}(t) &= h\left(\frac{B_v(q)}{F_v(q)} f(v_{dc}(t)) + e(t)\right) \\ i_{ac}(t) &= h\left(\frac{B_i(q)}{F_i(q)} f(i_{dc}(t)) + e(t)\right) \\ p_{ac}(t) &= h\left(\frac{B_p(q)}{F_p(q)} f(p_{dc}(t)) + e(t)\right) \end{aligned}\right\}$$

Single input single output (SISO) model

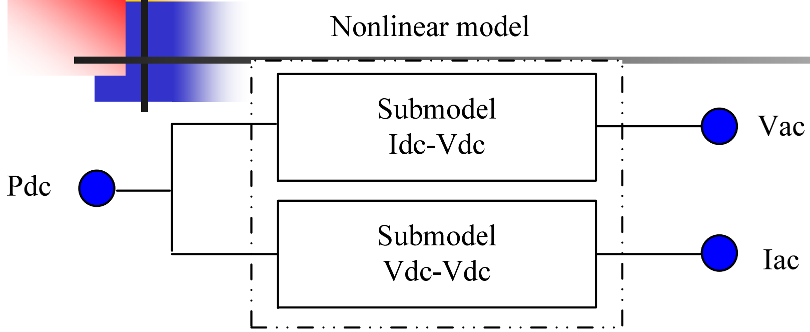
= 3x n = 3x 1 = 3

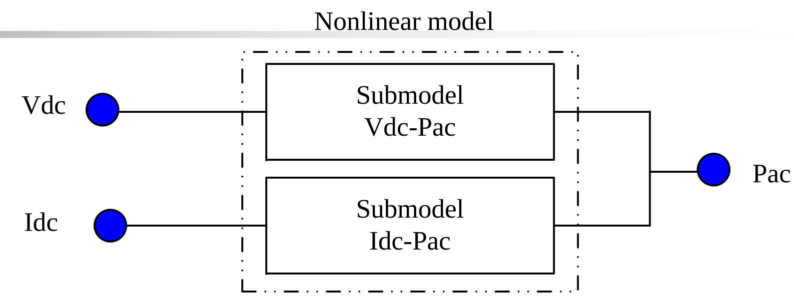
$$\left.\begin{aligned} V_{ac}(t) &= h\left(\frac{B_{vv}(q)}{F_{vv}(q)} f(v_{dc}(t)) + e(t)\right) \otimes h\left(\frac{B_{ii}(q)}{F_{ii}(q)} f(i_{dc}(t)) + e(t)\right) \\ I_{ac}(t) &= h\left(\frac{B_{iv}(q)}{F_{iv}(q)} f(v_{dc}(t)) + e(t)\right) \otimes h\left(\frac{B_{ii}(q)}{F_{ii}(q)} f(i_{dc}(t)) + e(t)\right) \end{aligned}\right\}$$

Multiple input multiple output (MIMO) model

= 3x n = 3x4 = 12

Structure of Model





$$\left.\begin{aligned} V_{ac}(t) &= h\left(\frac{B_v(q)}{F_v(q)} f(P_{dc}(t)) + e(t)\right) \\ I_{ac}(t) &= h\left(\frac{B_i(q)}{F_i(q)} f(P_{dc}(t)) + e(t)\right) \end{aligned}\right\}$$

$$p_{ac}(t) = h\left(\frac{B_v(q)}{F_v(q)} f(v_{dc}(t)) + e(t)\right) \otimes h\left(\frac{B_i(q)}{F_i(q)} f(i_{dc}(t)) + e(t)\right)$$

Single input multiple output (SIMO) model

= 3 x n = 3 x 2 = 6

Multiple input single output (MISO) model

= 3 x n = 3 x 2 = 6

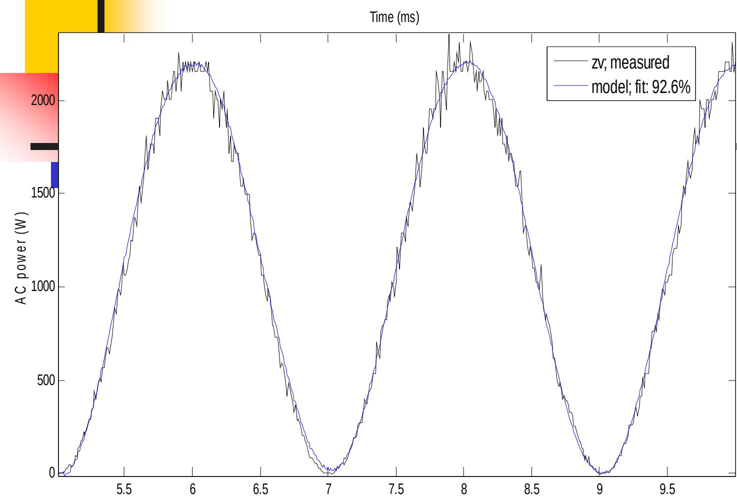
Number of linear parameter (nb nf nk)

= 3x n ; n = submodel

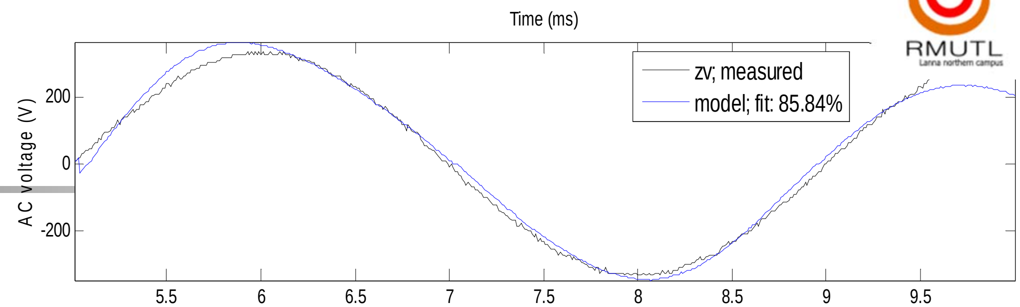
Result of MIMO Model

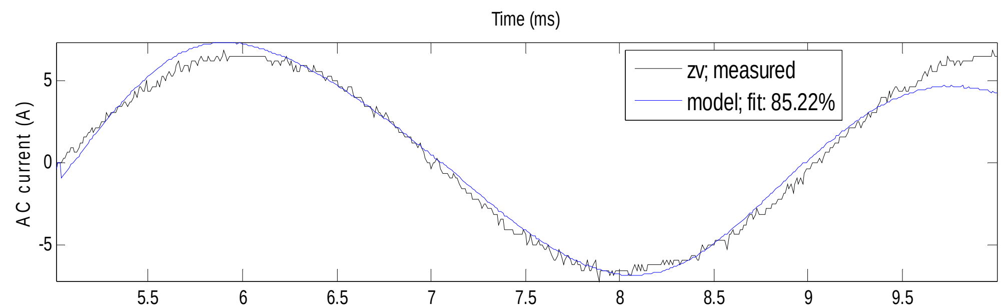
Type	I/P	O/P	Linear [nb];[nf] [nk];	%fit	FPE	AIC
MISO	DZ	DZ	[2 4]; [6 3]; [4 4]	92.60	63,034	11.35
	ST	ST	[2 2]; [2 3]; [3 3]	89.06	31,559	10.35
SIMO	DZ	DZ	[4 4]; [3 2]; [3 2]	85.84 85.22	155.45	5.04
	ST	ST	[3 4]; [5 2]; [2 2]	95.12 91.23	27.71	3.32
MIMO	DZ	DZ	[4 4 3 5]; [5 5 3 6]; [3 4 4 2]	87.34 84.15	254.45	7.89
	ST	ST	[3 5 4 5]; [4 5 4 3]; [4 4 4 2]	97.03 91.70	175.43	6.35

The experiment and simulated model output

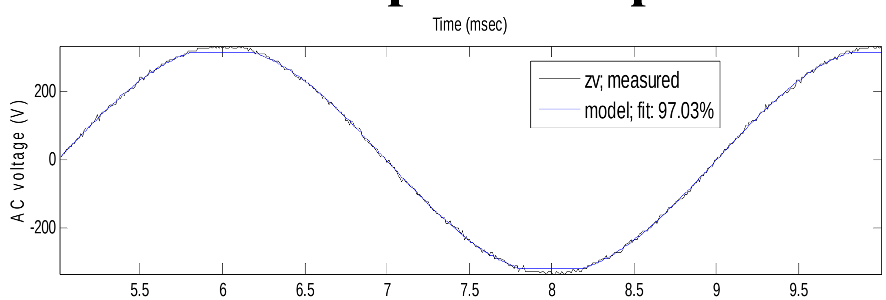


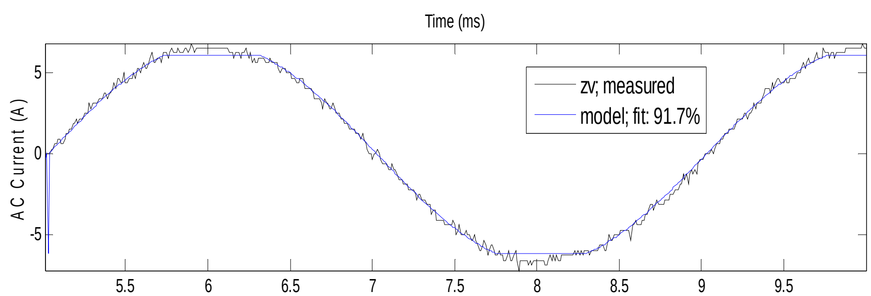
MISO power output





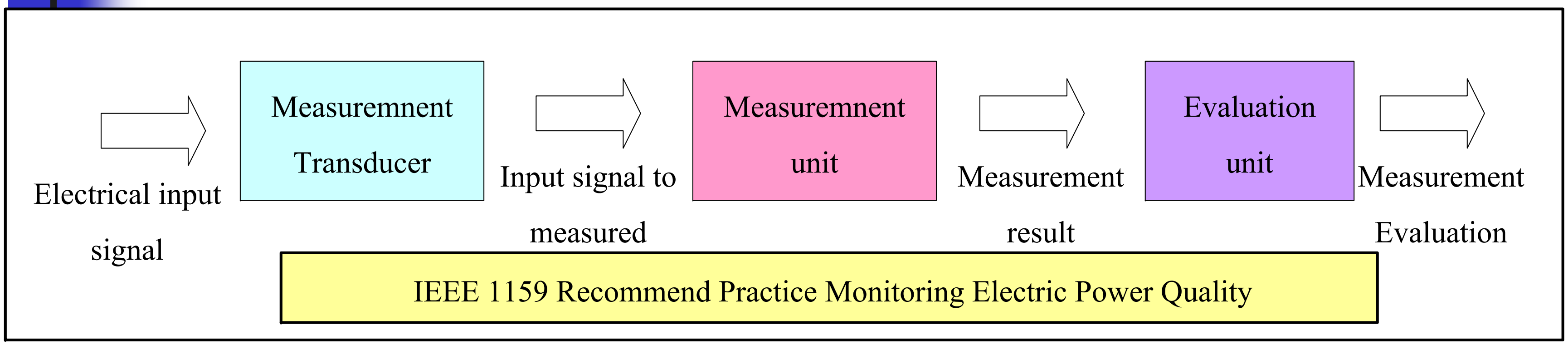
SIMO voltage and current output

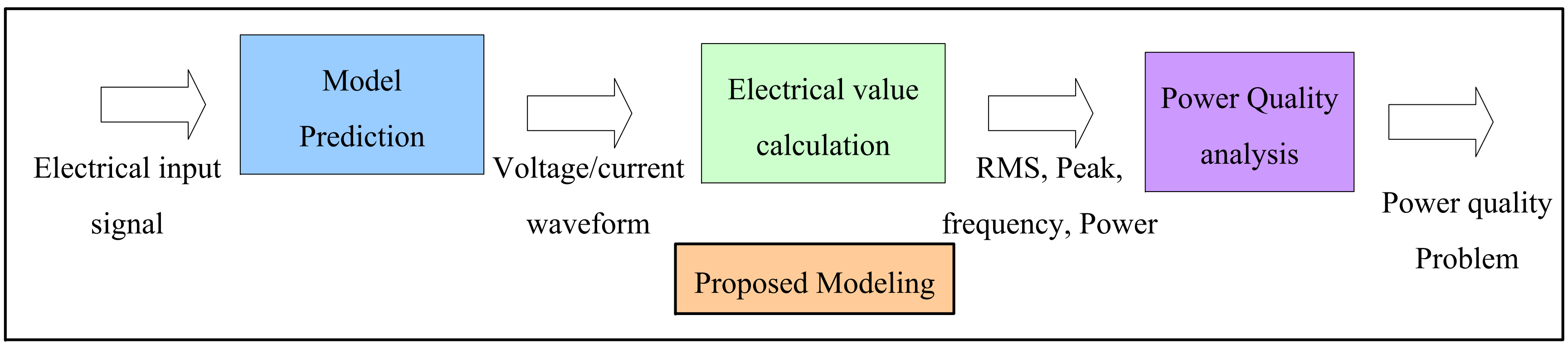




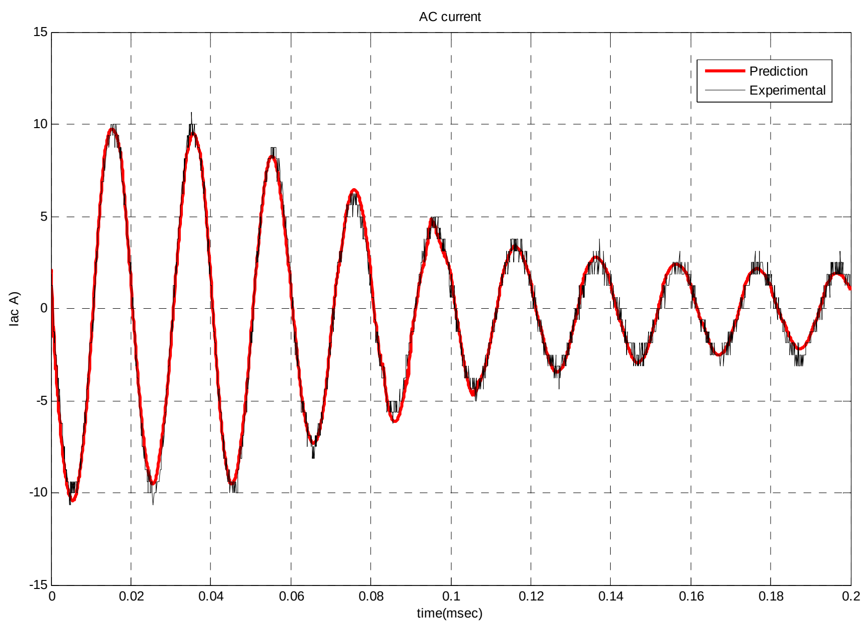
MIMO voltage and current output

Method for Power Quality Analysis from measurement and Modeling

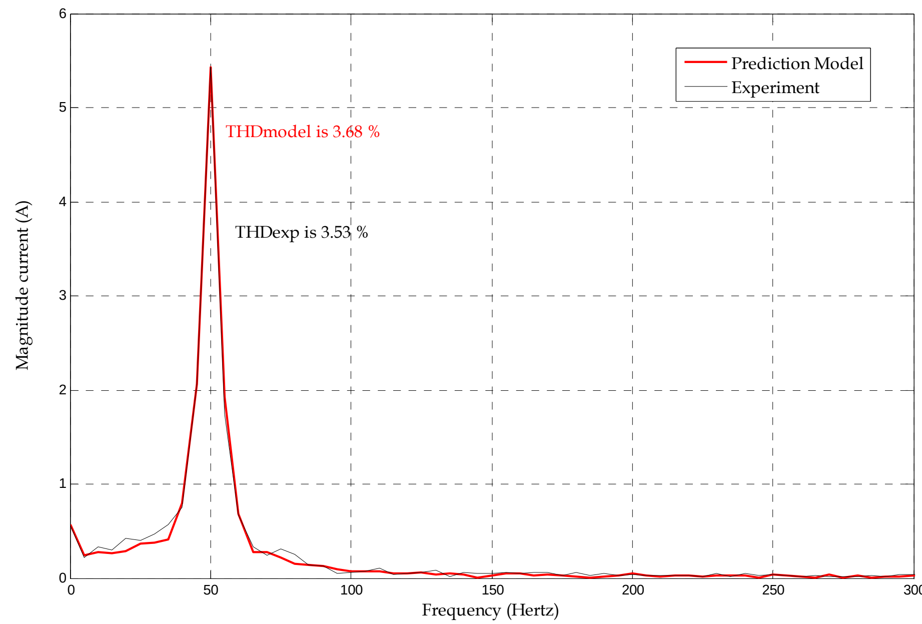




Simulation and Experimental for Power Quality Analysis



Model output



Total Harmonic Distortion output

Power Quality Analysis in Steady State and Transient Condition

Parameter	Steady state FVHC condition			Transient step down condition		
	Experimental	Modeling	% Error	Experimental	Modeling	% Error
Vrms (V)	218.31	218.04	0.12	217.64	218.20	-0.26
Irms (A)	23.10	23.21	-0.48	4.47	4.45	0.45
Frequency (Hz)	50	50	0.00	50.00	50.00	0.00
Power Factor	0.99	0.99	0.00	0.99	0.99	0.00
THDv (%)	1.15	1.2	-4.35	1.18	1.24	-5.08
THDi (%)	3.25	3.12	4.00	3.53	3.68	-4.25
S (VA)	5044.38	5060.7	-0.32	972.85	970.99	0.19
P (W)	4993.94	5010.1	-0.32	963.12	961.28	0.19
Q (Var)	711.59	713.85	-0.32	137.24	136.97	0.19
V p.u.	0.99	0.99	0.00	0.98	0.99	-1.02

Model Application and Future Research

- Gray box system identification
- Recursive system identification – Kalman filtering

Increase accuracy and Real time modeling

- Model predictive control
- Model order reduction – Robust control

Control base on Modeling

- Power Quality Analysis from Modeling
- Voltage Stability Analysis from Modeling
- Load flow and penetration analysis from Modeling

Power Quality Issue from Modeling

Conclusion

- A model of a PV inverter has been experimentally obtained from the Nonlinear Hammerstein-Wiener method.
- The model consists of three parts, static input and output parts, and dynamic middle part.
- The obtained model is validated and compared with the experimental results.
- The dynamic stability behavior of the system has been analyzed through the linearized version of the system using a frequency response analysis.
- Power Quality Analysis of output system can be done by using modeling and standard

PQ Synergy 2014 19 May 2012

Thank you for you attention