Estimation of Grid Harmonics in the Presence of Renewable Energy Sources

Prof. S. N. Singh

Department of Electrical Engineering

Indian Institute Of Technology Kanpur

snsingh@iitk.ac.in

Talk Outline

- Introduction
- RES Grid integration and major issues
- Harmonics effect, standards and measurement
- Advanced estimation techniques
- Case studies
- Conclusion
- Future scope & challenges

Introduction

- Current Policies/Action Plans/Thrust/Key issues

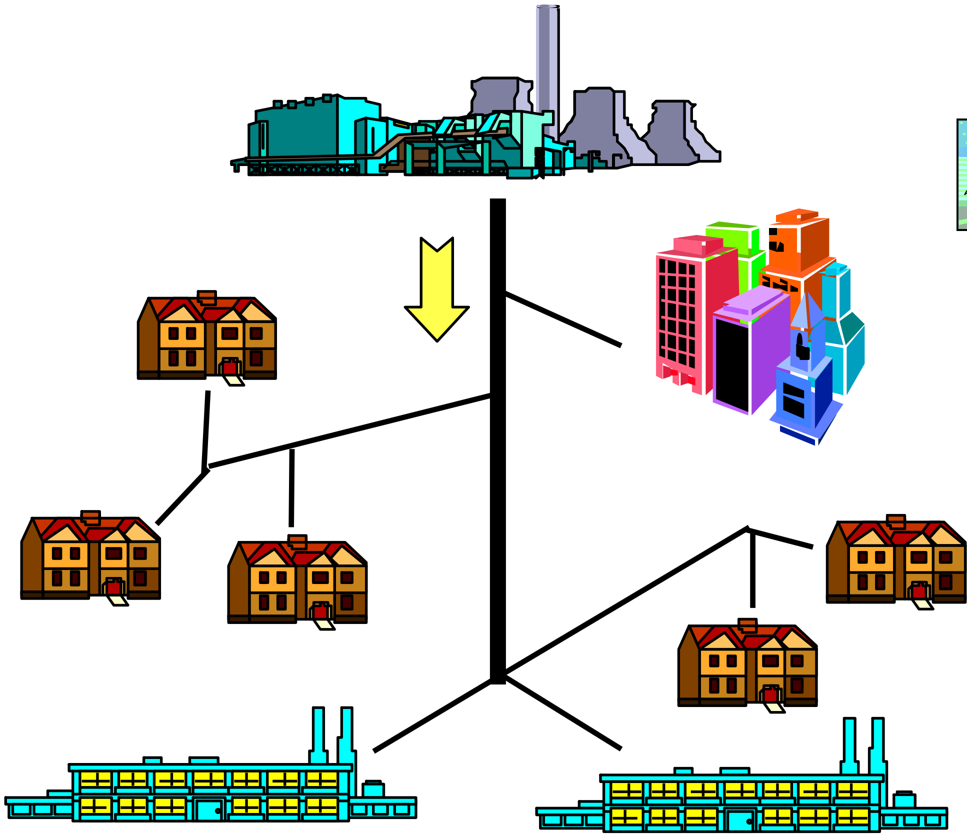
  - A cleaner electricity system
  - Phase out coal-fired generation by 20xx
  - Increase RES mix ratio to xx%
  - Power to all by 20xx
  - Smart grid initiatives:
    - Use of distributed energy resources
    - More participation of customers

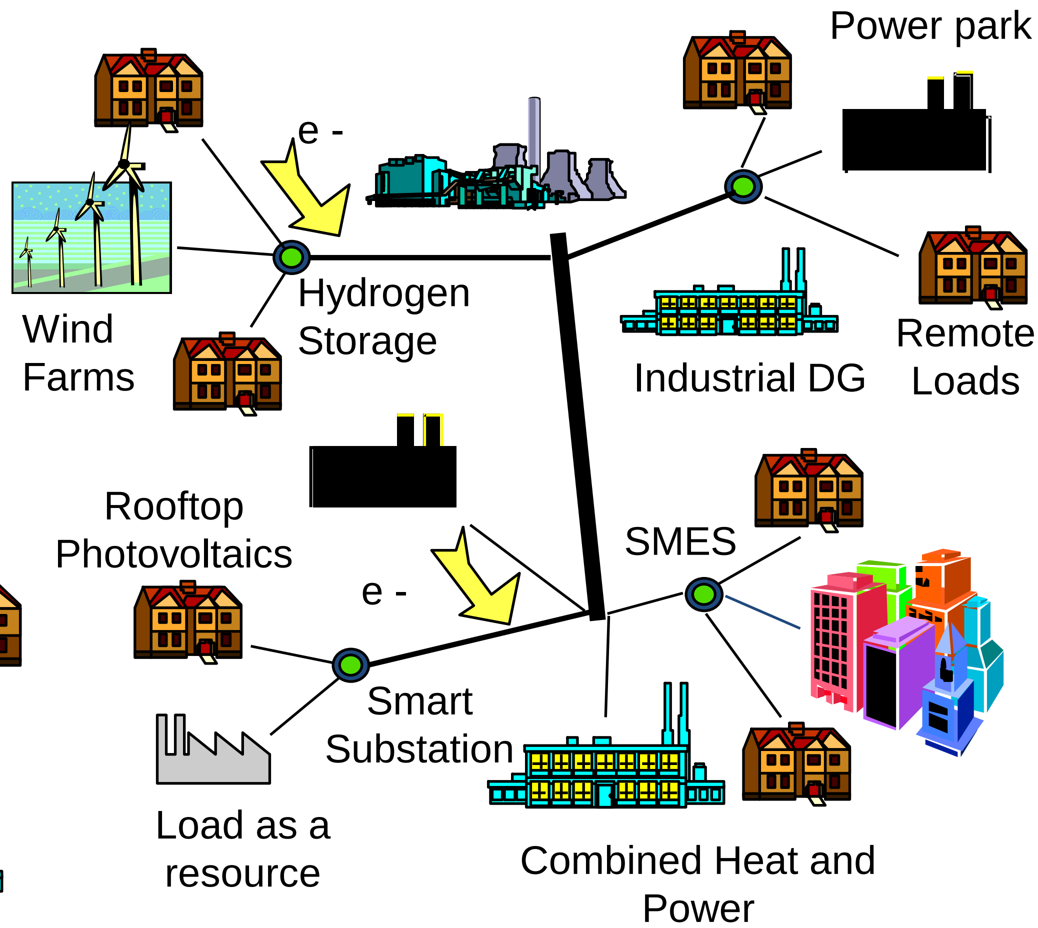
Present and Future Power System

Present Power System
- Heavily Relying on Fossil Fuels
- Generation follows load
- Limited ICT use

Future Power System
- More use of RES, clean coal, nuclear power
- Load follows Generation
- More ICT & Smart meter use

Today's Electricity … *Tomorrow's Choices …*





Features of a Smart Grid

Ref: DOE document at http://www.oe.energy.gov/smartgrid

Self-Healing to correct problems early

Interactive with consumers and markets

Optimized to make best use of resources

Predictive to prevent emergencies

Distributed assets and information

Integrated to merge all critical information

More Secure from threats from all hazards


Introduction

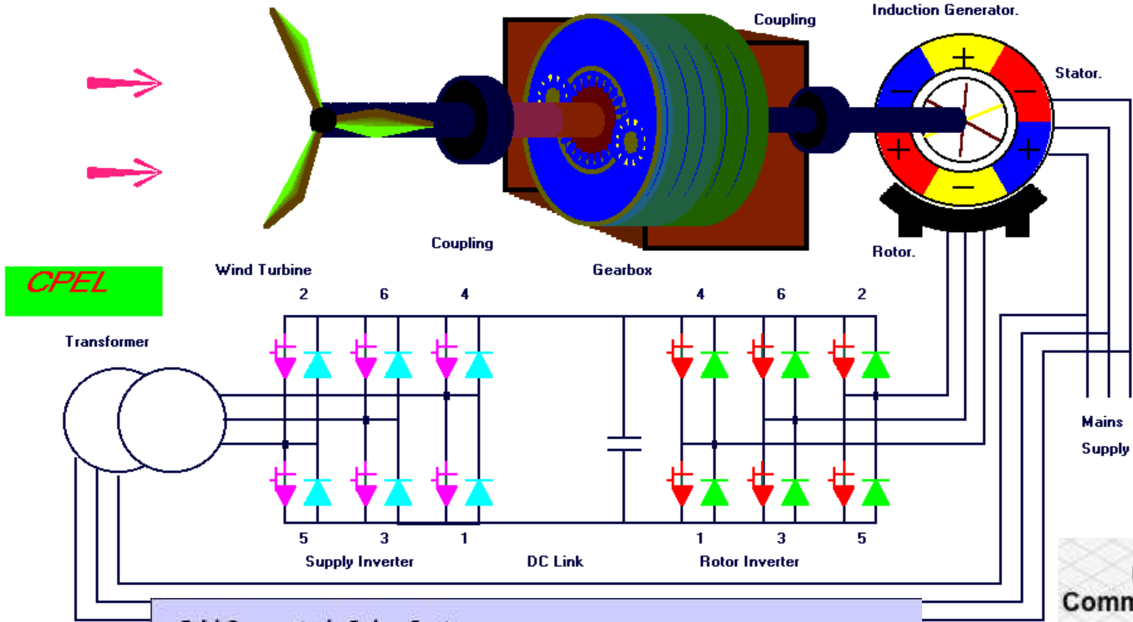
❑ Renewable Energy Sources (RES)

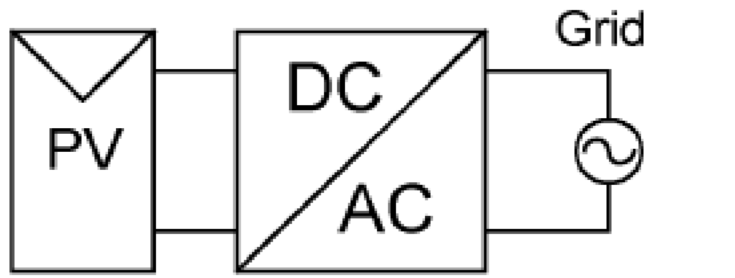
- ✓ Excellent natural energy sources, available in abundance.
- ✓ Environment friendly, low operating cost and so on.

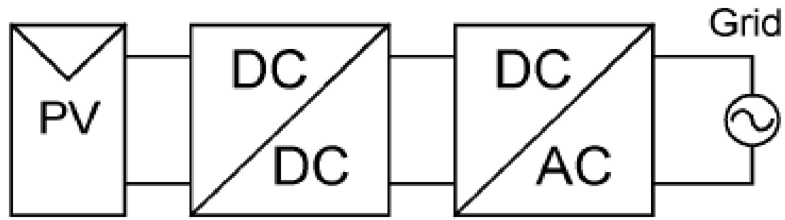
- ✗ Intermittent and obviously uncontrolled on its own.

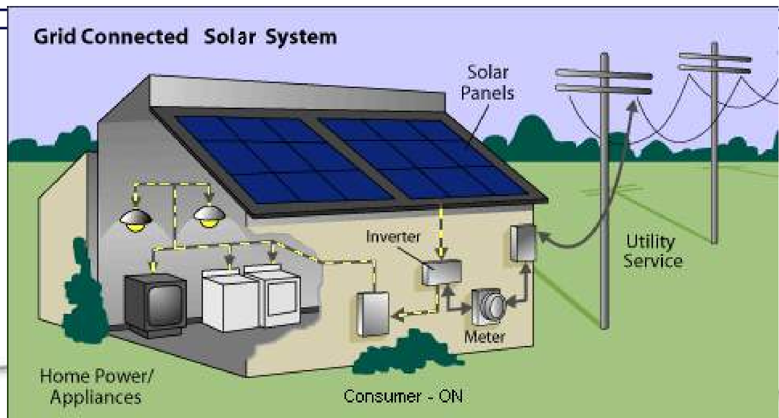
- ► Proper control, storage and interconnection.
- ► Power electronics do that job exceptionally well and became an interface between RES and end user.

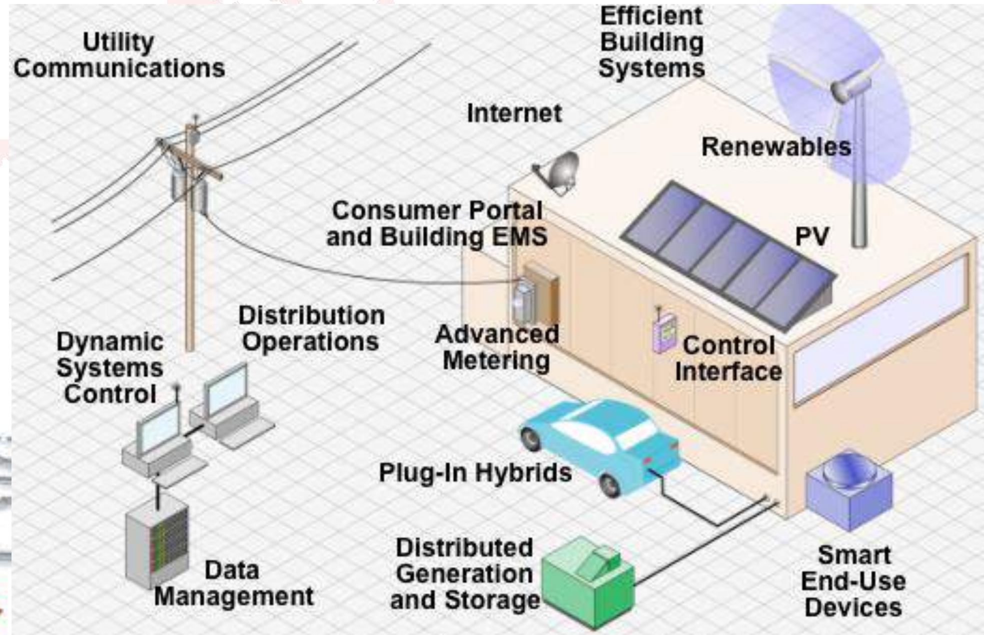
RES Grid Integration











Major Issues and Challenges

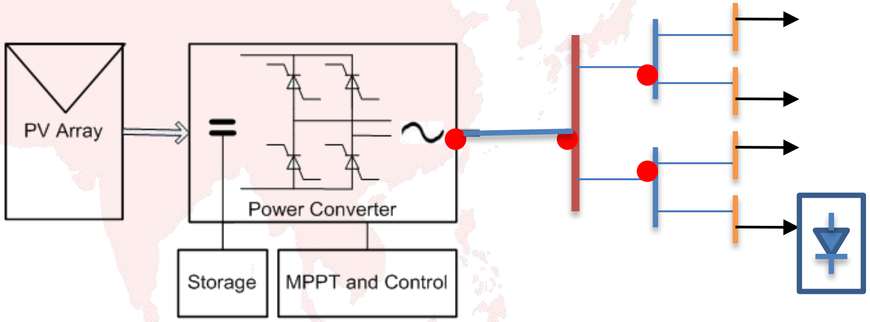
- Interconnection (topology/voltage level)
- Handling uncertainties for load-generation matching (Frequency or active power control)
- Reactive power Control (Voltage control)
- Stability (Angle control)
- Transmission constraints
- Protection and system reliability
- Power Quality

Role of Power Electronic in GI

- Provide the necessary voltage and frequency compatibility between the renewable source output and the utility grid
- Optimally control renewable sources for maximized energy yield among other objectives
- Provide active and reactive power control during normal operation or disturbance events

Role of Power Electronic in GI

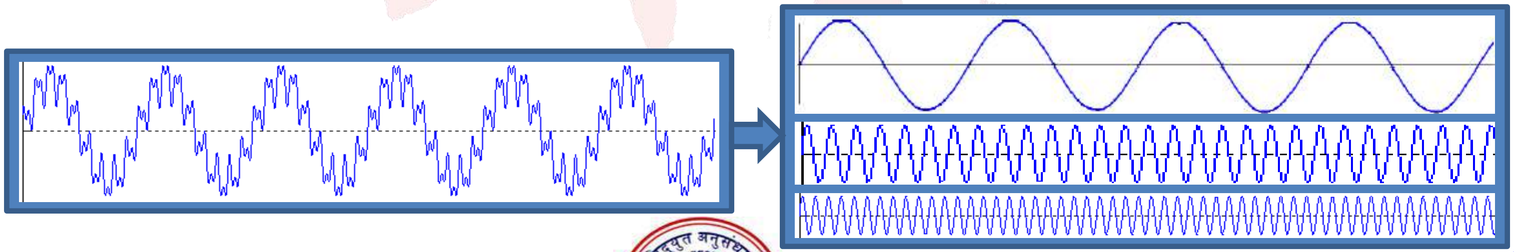
- Injects harmonics and interharmonics into the system and adversely affects power quality
- Custom power devices like STATCOM/DVR/ UPQC help to restore/maintain PQ within limiting values



Harmonics generation due to RES

Why harmonics are of concerns ?

- Increased losses and audible noise.
- Torsional oscillations in T-G/motor-load pair.
- Mal-operation of protection & control circuits.
- Aging and Failure of equipments
- Resonance problem.
- Interference with communication lines.



Standards

- IEC 61000-3-2/4/6 [Harmonics Limit]
- IEC 61000-4-7 [Harmonics Measurement/Estimation]
- IEC 61000-4-30 [Power quality measurement]
- IEC 61727 [The utility interface for PV systems]
- IEC 61400-21 [PQ measurement of grid connected Wind Turbine]
- IEEE 1547 [Interconnection of DER with Electric Grid]
- IEEE 519 [Harmonics Limit and Measurement/Estimation]

Available Measuring Instruments

YOKOGAWA: WT3000 PRECISION POWER ANALYZER

http://tmi.yokogawa.com/products/digital-power-analyzers/digital-power-analyzers/wt3000-precision-power-analyzer/

HIOKI: POWER QUALITY ANALYZER 3197

http://www.hioki.com/newproduct/3197/3197_e.html

Fluke: 430 Series Three-phase Power Quality Analyzers

http://www.fluke.com/fluke/inen/Power-Quality-Tools/Three-Phase/Fluke-430-Series.htm?PID=56078

Available Measuring Instruments

❑ Key points:

- Mainly for visual, easy monitoring of PQ parameters
- Low tolerance for fundamental frequency deviation (0.03% in case of WT3000)
- Low tolerance for sampling rate deviation
- Low resolution (Interharmonics measurement not possible)
- Low accuracy (grouping/subgrouping provides cumulative effect)
- Practical signals may not be stationary

Ideal Estimator/Measuring Device

- All features estimation (Frequency, Amplitude and Phase)
- Accuracy (Interharmonics, amplitude, phase)
- Instantaneous (Fast with less input samples)
- Robust (Against noise and fundamental frequency deviation)
- Least computational burden
- Easy and simple to implement
- System independent and adaptive (Not specific to any model or system)

Estimation Methods

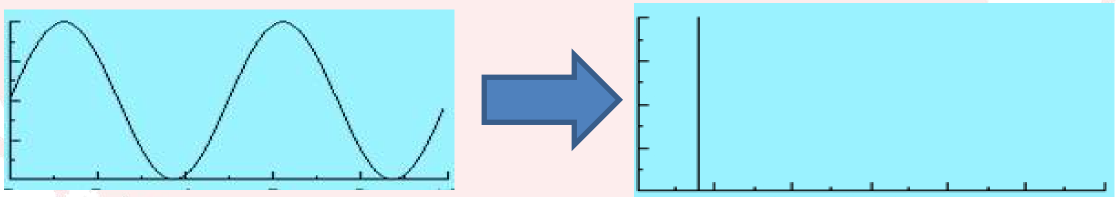
Harmonics Estimation Techniques

- **Non-parametric Method**
  - **Frequency Domain Analysis**
    - Discrete Fourier transform
      - Windowing
      - Synchronization
  - **Time-Frequency Domain Analysis**
    - Wavelet transform
    - Hilbert-Huang transform
    - Chirp z-transform
- **Parametric Method**
  - **Sinusoidal Models**
    - ESPRIT
    - MUSIC
    - KF
    - ANN(BPN)
    - ANN(RBFNN)
    - ADALINE
  - **Stochastic Models**
    - Autoregressive Model (AR)
    - ARMA
    - Prony's
    - SVD

Fast Fourier Transform

Fourier Transform converts a function from the time domain to the frequency domain

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} \, dt$$



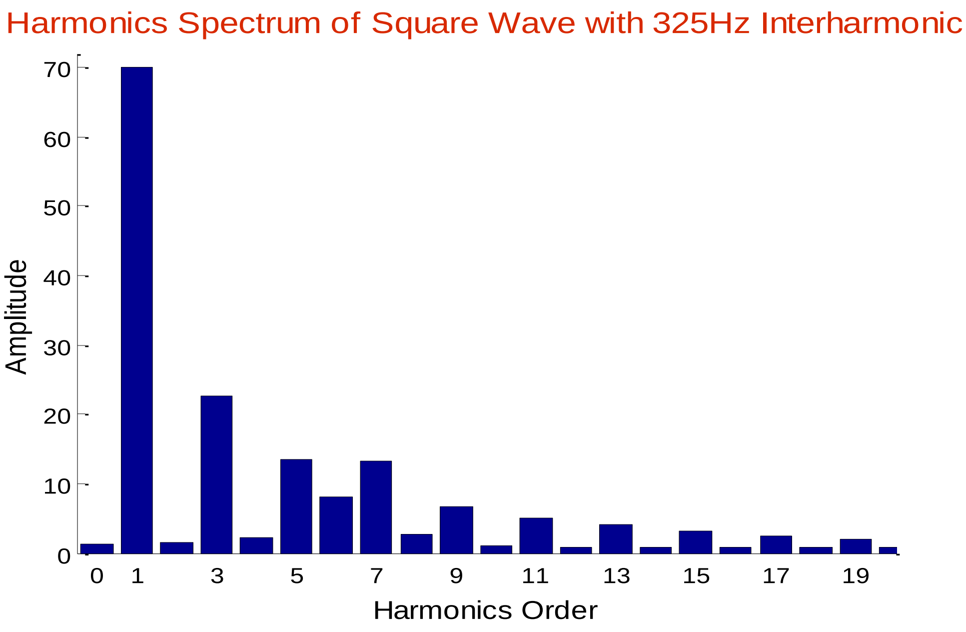
❑Strengths

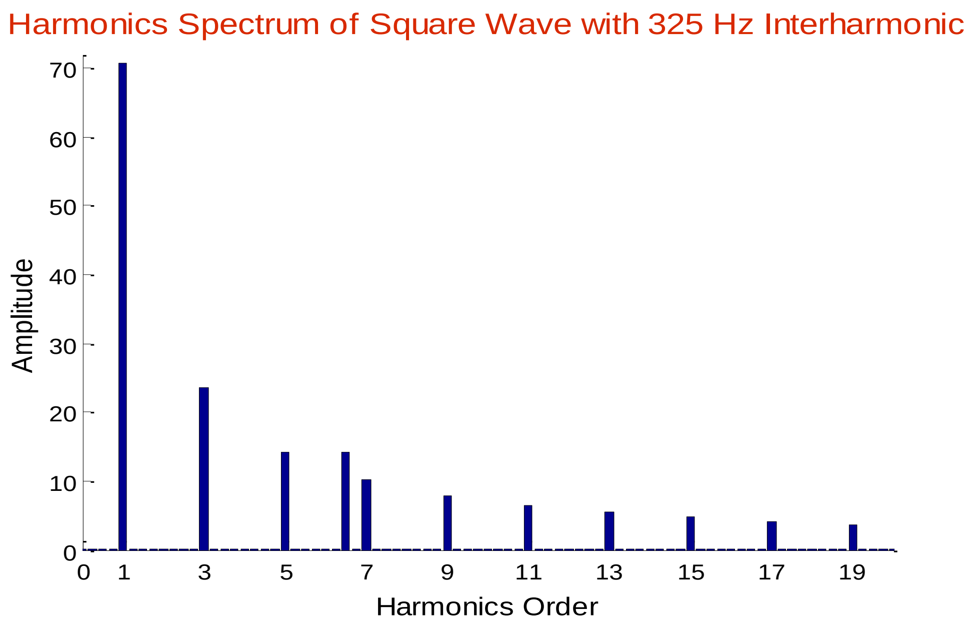
- ✓ Low computational burden.
- ✓ Simple.
- ✓ Most reliable for stationary signal.

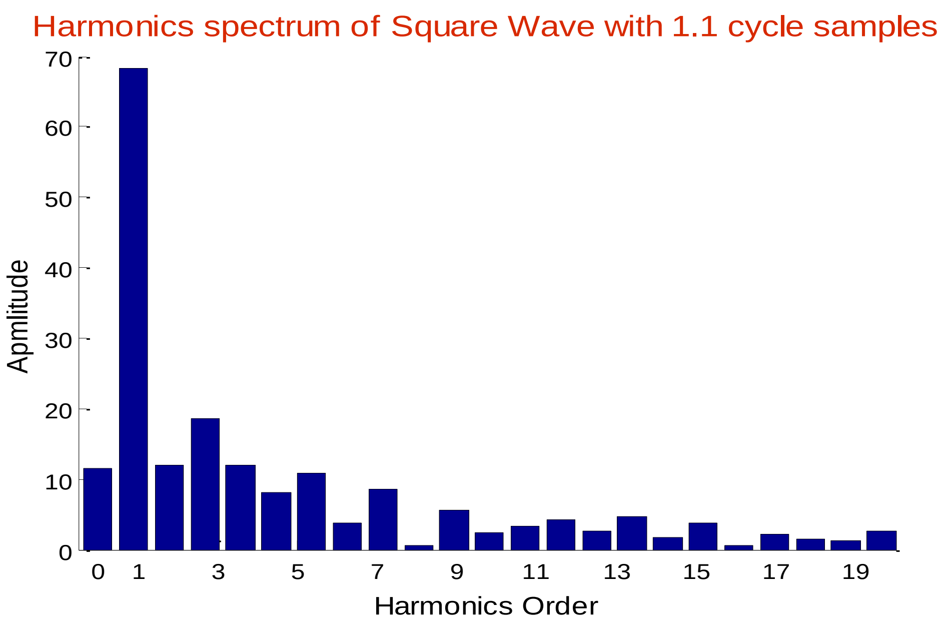
Fast Fourier Transform

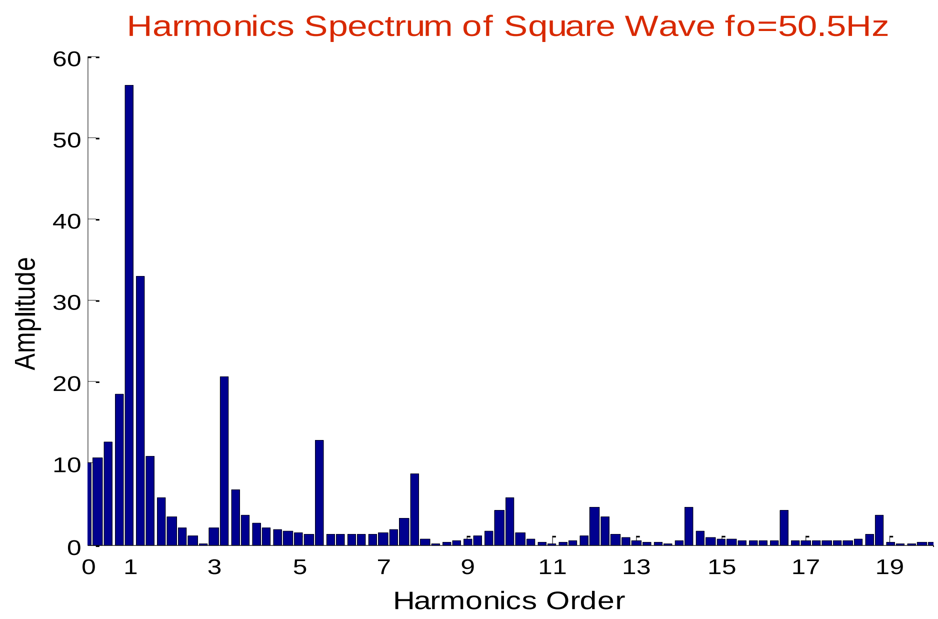
❑Major Shortcomings

- Poor resolution makes it difficult to detect interharmonics.
- It requires analysis window to be exactly integer multiple of fundamental period.
- Frequency deviation leads to leakage and picket-fence effect.
- Not able to detect local transients as time information is completely lost.

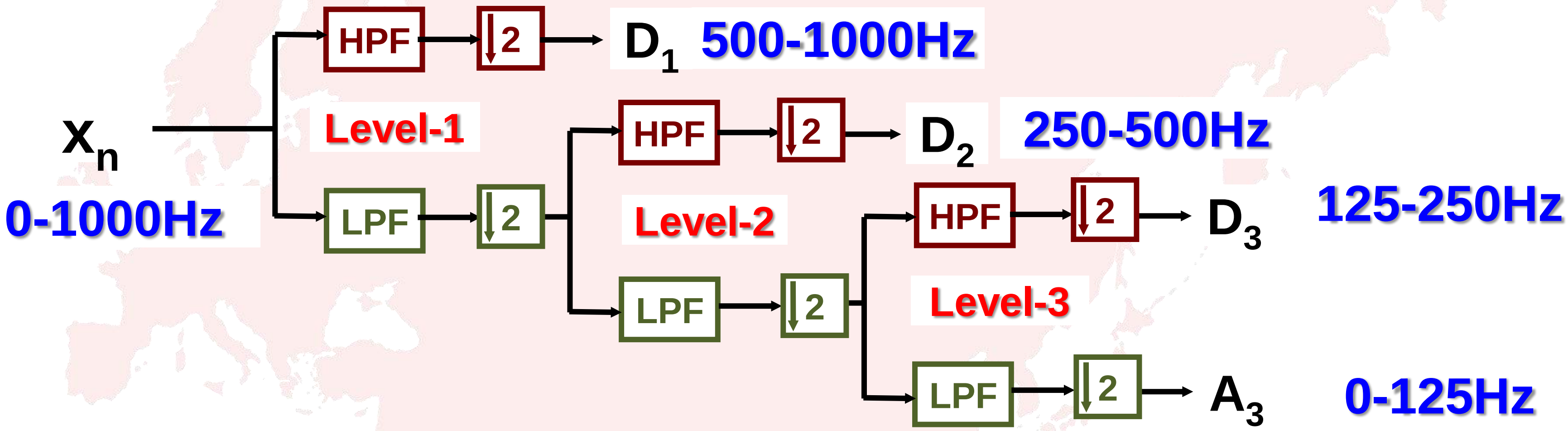

Harmonics Spectrum of Square Wave with 325Hz Interharmonic
Amplitude
0
10
20
30
40
50
60
70
0 1 3 5 7 9 11 13 15 17 19
Harmonics Order

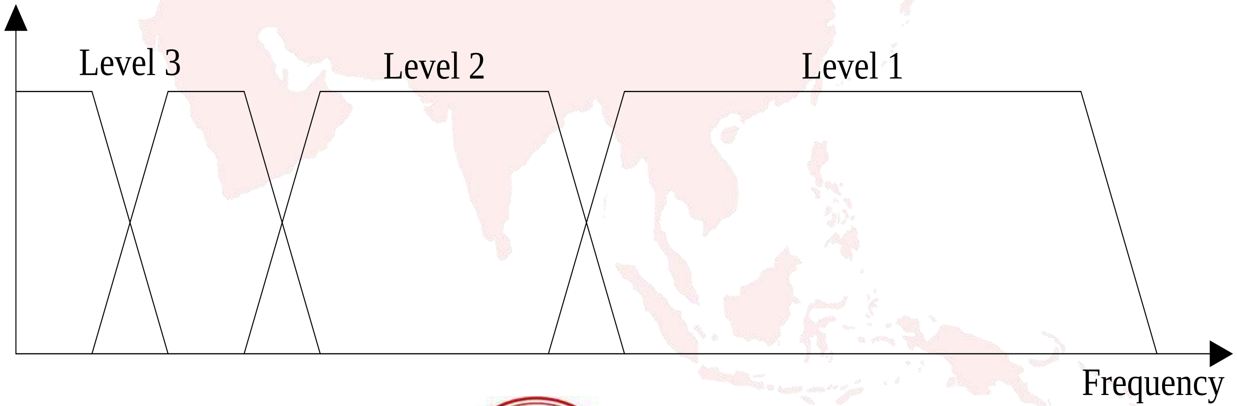

Harmonics Spectrum of Square Wave with 325 Hz Interharmonic
Amplitude
0
10
20
30
40
50
60
70
0 1 3 5 7 9 11 13 15 17 19
Harmonics Order


Harmonics spectrum of Square Wave with 1.1 cycle samples
Apmlitude
0
10
20
30
40
50
60
70
0 1 3 5 7 9 11 13 15 17 19
Harmonics Order

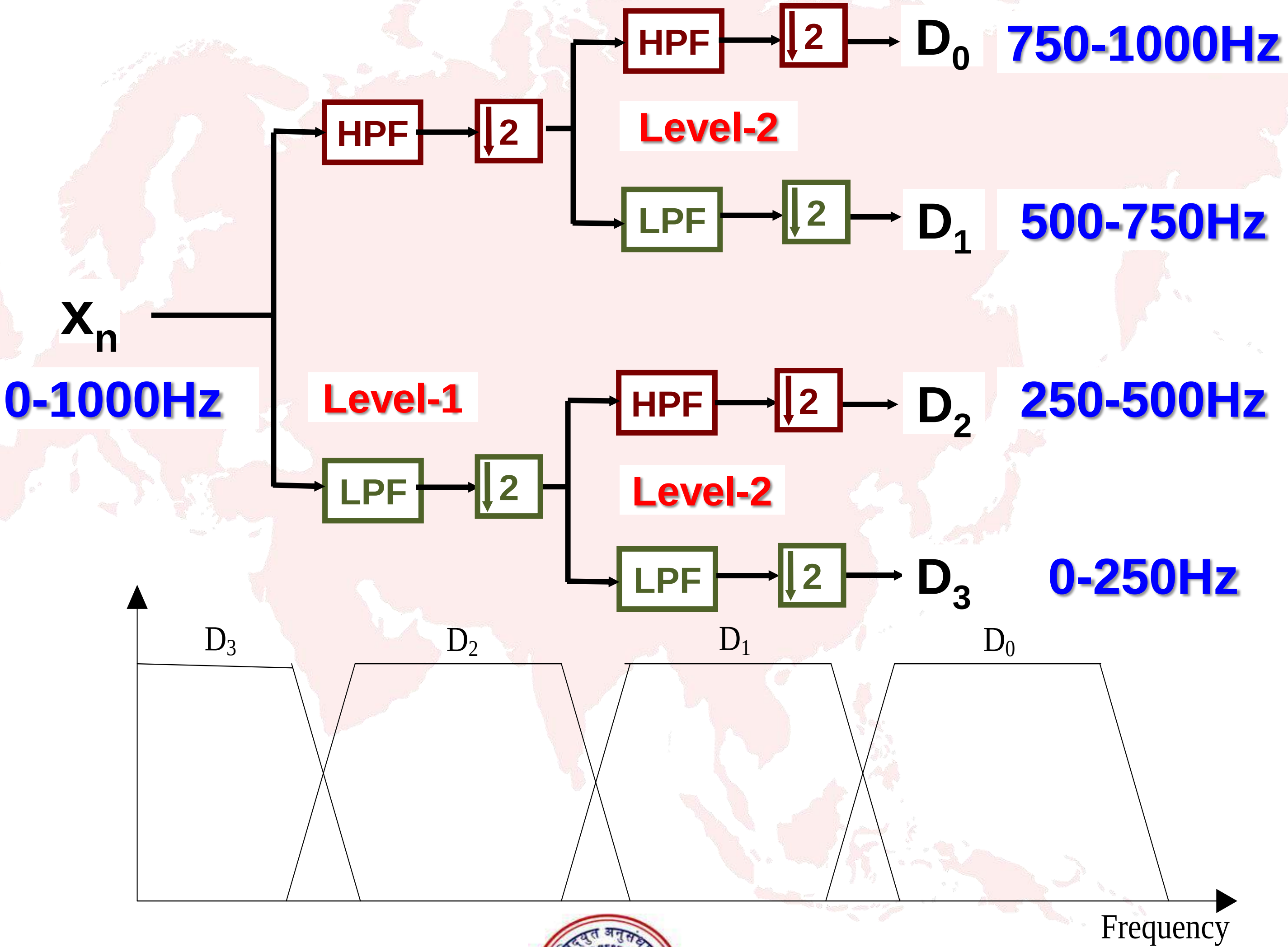

Harmonics Spectrum of Square Wave fo=50.5Hz
Amplitude
0
10
20
30
40
50
60
0 1 3 5 7 9 11 13 15 17 19
Harmonics Order

Wavelet Transform





Wavelet Packet Transform



Wavelet Transform

❑Strengths

- ✓ Provide frequency and time information simultaneously.
- ✓ Multi-resolution capabilities.
- ✓ More suitable for transients detection.
- ✓ Convenient for IEC standard regime.

❑Shortcomings

- ✗ High computational burden
- ✗ It provides harmonics in terms of frequency bands.
- ✗ Additional tools needed for interpretation of the transformed parameters.

Prony Method

Prony method is based on the representation of a signal as a linear combination of exponential functions.

$$x_n = \sum_{m=1}^{M} a_m e^{((\alpha_m + j2\pi f_m)(n-1)T + j\theta_m)}$$ **for n=1, 2, …, N**

where,

M=model order,

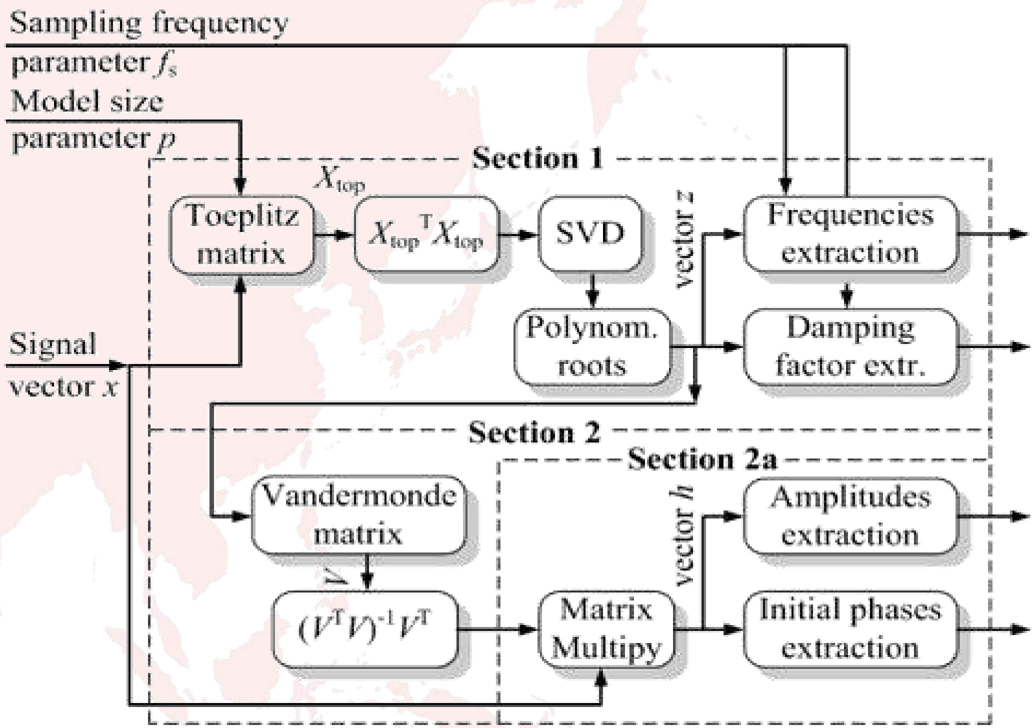
a_m=amplitude of m[th] complex exponential,

α_m=damping factor,

f_m=sinusoidal frequency,

θ_m=initial phase angle, and

T=sample interval



Prony Method

❑Strengths

- ✓ Able to identify damped components and damping factor.
- ✓ High resolution without leakage effects.

❑Shortcomings

- ✗ High computational burden
- ✗ Highly sensitive to noise present in the signal.
- ✗ Model order selection is difficult. Inaccurate model order lead to very high inaccuracy.

Kalman Filter

According to Fourier series, any periodic signal can be represented as:

$$x_n = \sum_{k=1}^{K} a_k \cos(2n\pi f_k + \theta_k) + \omega_n$$

If, amplitude and phase angles are considered as states, it can be equivalently written as:

$$x_n = h_n y_n + \omega_n$$

Kalman Filter

State equation will be:

$$y_n = \phi_{n-1} y_{n-1} + \eta_{n-1}$$

where, ϕ represents state transition matrix, relating old state to new state.

The estimated value of the states can be obtained from:

$$y_n = y_n^0 + K_n (x_n - h_n y_n^0)$$

Kalman Filter

❑Strengths

- ✓ Information is processed immediately unlike batch processing methods.
- ✓ On-line tracking of variation is possible.
- ✓ This is highly robust against measurement noise and model errors.

❑Shortcomings

- ✗ Convergence is relatively poor.
- ✗ Suffers from filter divergence problem.
- ✗ Optimal filter tuning (error covariance matrix) is difficult. It results in poor performance.

AI Applications…

❑Artificial Neural Network

A series of time-series samples can be applied to a trained model to get amplitude and/or phase angles of pre-defined frequency components:

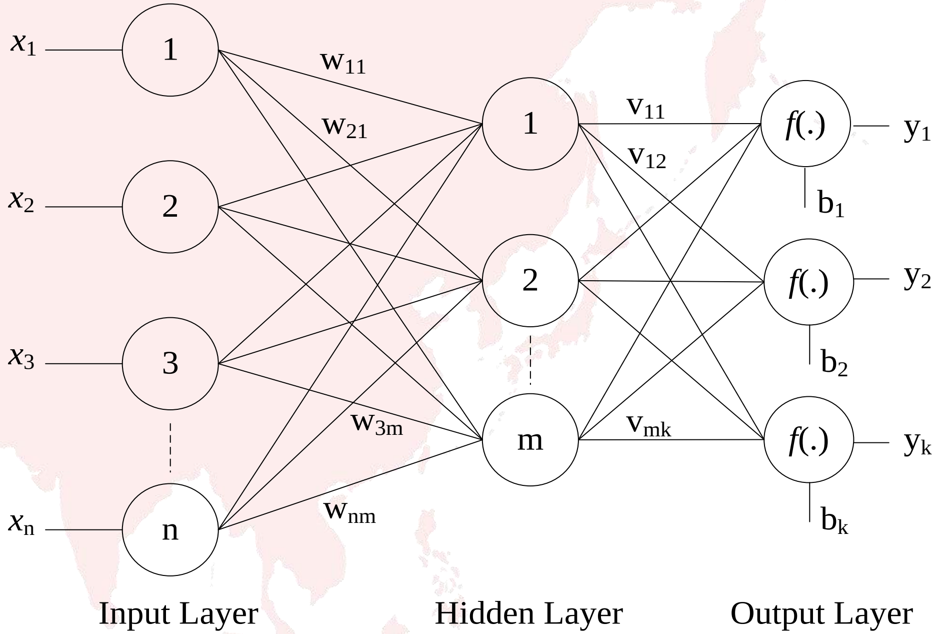
$$x_n = \sum_{k=1}^{K} a_k \cos(2n\pi f_k + \theta_k) + \omega_n$$

$$x_n \rightarrow \boxed{\text{Mapping}} \rightarrow \overline{a}, \overline{\theta}$$

International Copper Promotion Council (India)

AI Applications…

❑Artificial Neural Network



Artificial Neural Network

❑Strengths

- ✓ Well trained network needs just half cycle data to provide fast estimates for real time applications.
- ✓ Adaptive in nature.
- ✓ Enough robust against noise, if trained properly.

Artificial Neural Network

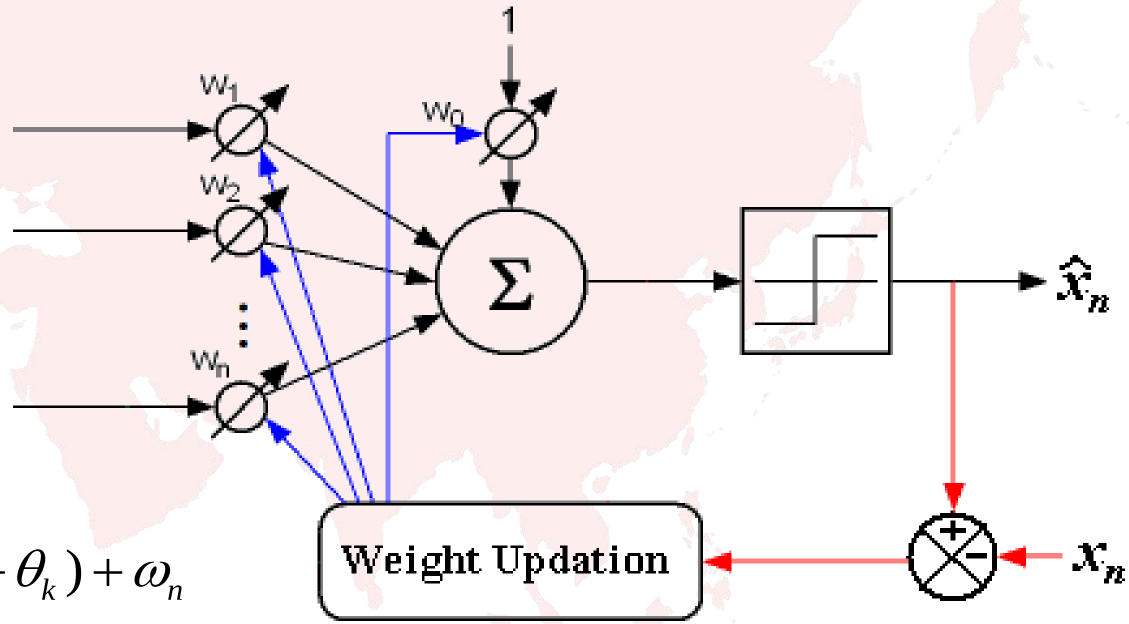
❑Major Shortcomings

- Only predefined frequency components can be obtained.
- Can be trapped in local minima.
- Multilayered complex structure, difficult to implement.
- Any new data pattern or transients results in more error.
- Difficult to obtain efficient and suitable training data.

ADALINE

❑Adaptive Linear Combiner

- Weights provide the desired amplitude and phase angles



$$x_n = \sum_{k=1}^{K} a_k \cos(2n\pi f_k + \theta_k) + \omega_n$$

ADALINE

❑Strengths

- ✓ Recursive in nature hence more robust against noise.
- ✓ Immediately process the available data sample and capable of tracking variations.
- ✓ No need of training data unlike ANN.

❑Shortcomings

- ✗ Only predefined frequency components can be obtained and results in high inaccuracies if same is present.
- ✗ Unable to detect interharmonics.
- ✗ Frequency deviations also results in erroneous results.
- ✗ Convergence is slow hence more response time.

ESPRIT

- Estimation of Signal Parameters via Rotational Invariance Technique

ESPRIT is a parametric method that represents the distorted signal as a sum of sinusoids and then use sequence of observations to obtain the parameters of the model by dividing them into signal and noise subspace.

$$x(n) = \sum_{k=1}^{K} a_k \cos(2n\pi f_k + \phi_k) + w(n)$$

$$\boldsymbol{X} = \begin{bmatrix} x(0) & x(1) & \dots & x(M-1) \\ x(1) & x(2) & \dots & x(M) \\ . & . & \dots & . \\ . & . & \dots & . \\ x(N-M) & x(N-M+1) & \dots & x(N-1) \end{bmatrix}$$

Applying shift invariance property & least squares estimation

Eigen decomposition

Signal & noise subspace separation

ESPRIT

❑Strengths

- ✓ **High resolution therefore precise frequencies estimation.**
- ✓ **Fairly robust against noise.**
- ✓ **Accurate amplitude and phase estimation.**
- ✓ **No need of training data or prior system knowledge for modeling.**

❑Shortcomings

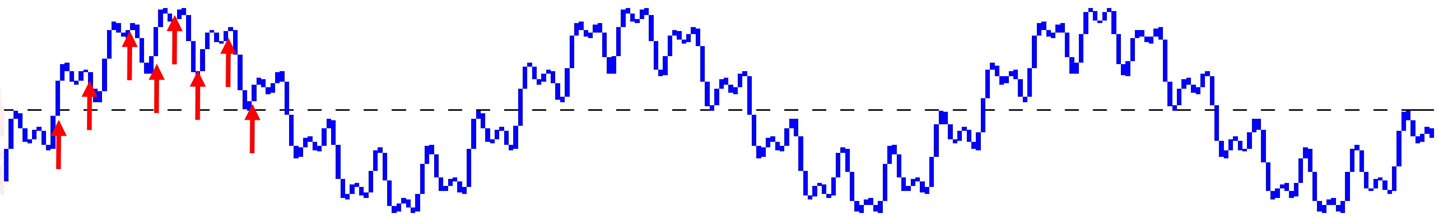
- ✗ High computational requirements.
- ✗ Low accuracy for non-stationary signals.

Case Study-1

AWNN Based Harmonics Estimation of Wind and PV Systems

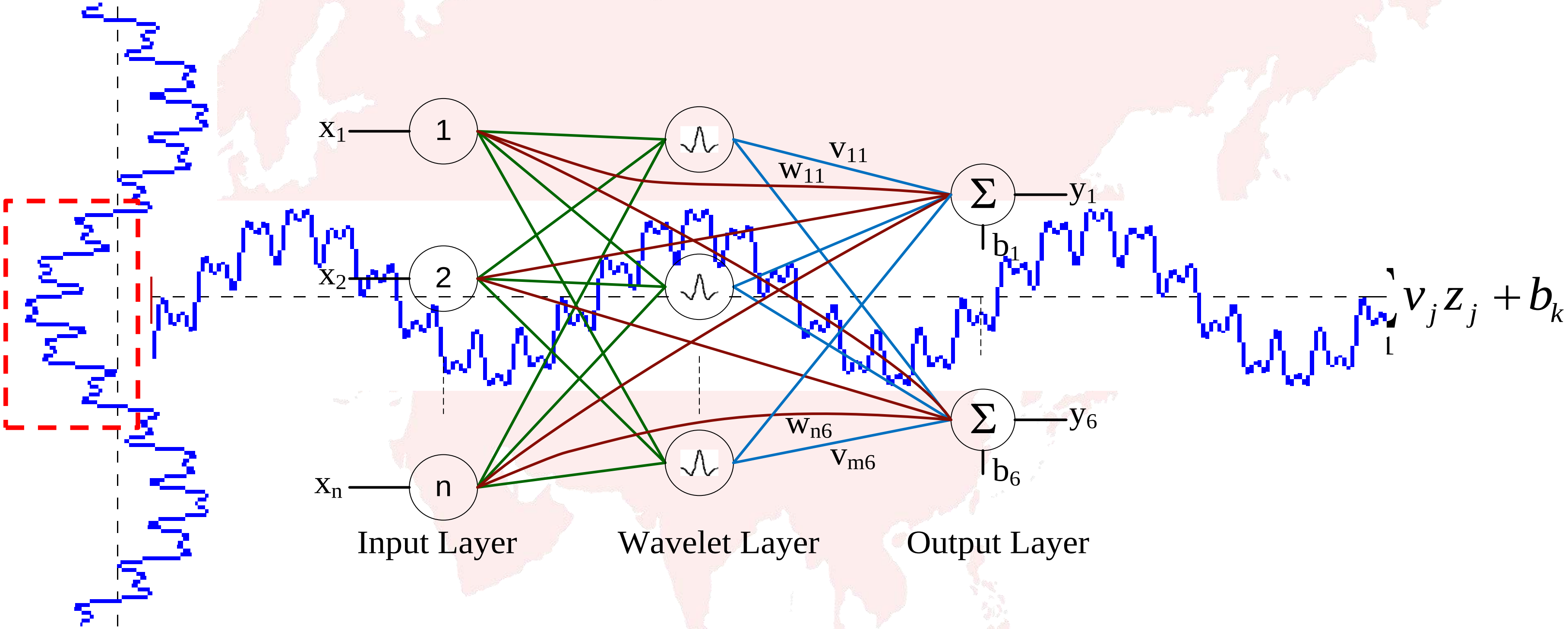
AWNN Based Harmonics Estimation

❑Problem Formulation



$$X(s,\sigma)=\sum_{h=1}^{H}A_h(s,\sigma)\sin(hs\omega T_s+\theta_h(\sigma))$$

AWNN Based Harmonics Estimation



AWNN Based Harmonics Estimation

Network Parameters		Training Parameters	
Number of inputs	32	Learning rate η	0.012
Number of hidden layers	1	Momentum α	0.01
Number of wavelons	8	Max no of iterations	500
Type of wavelon	Mexican hat	Number of training patterns	500
Number of outputs	4	Validation patterns	500

AWNN Based Harmonics Estimation

❑Important Expressions

- **Wavelon Function** $$\psi(x) = (n - \chi^2)e^{-0.5\chi^2}$$ ......(1)

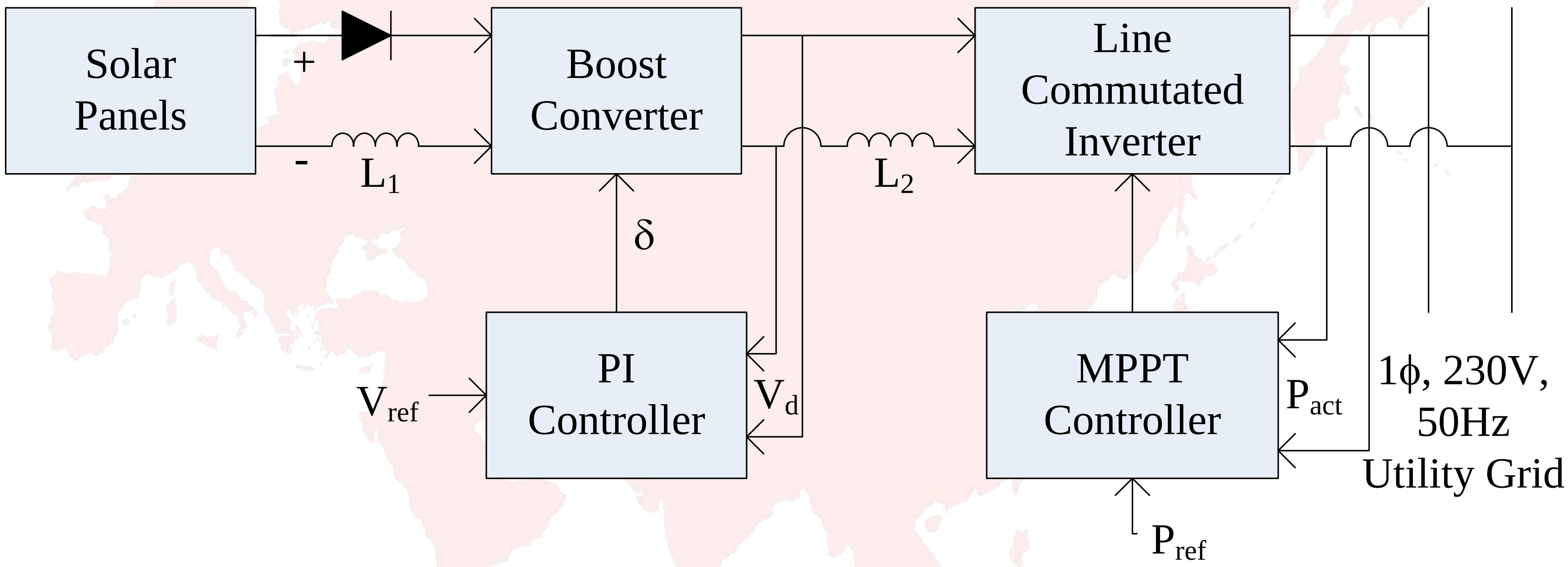
- **Wavelon Output** $$z_j = \left(n - \sum_{i=1}^{n} \left(\frac{x_i - t_{ji}}{\lambda_j} \right)^2 \right) e^{-0.5\sum_{i=1}^{n}\left(\frac{x_i - t_{ji}}{\lambda_j}\right)^2}$$ ......(2)

- **Objective Function** $$E = \frac{1}{2}\sum_{p=1}^{P}\sum_{k=1}^{K}(y_{pk}^{d} - y_{pk})^2$$ ......(3)

- **Parameter Updation** $$\beta(\kappa+1) = \beta(\kappa) + \eta\Delta\beta(\kappa) + \alpha\Delta\beta(\kappa-1)$$ ......(4)

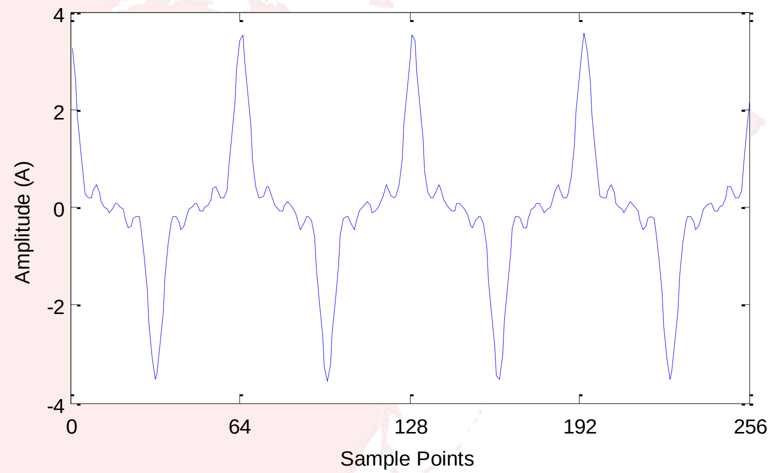
AWNN Based Harmonics Estimation

Case-A: **Current Waveform of PV Solar Energy Conversion Scheme [26]**

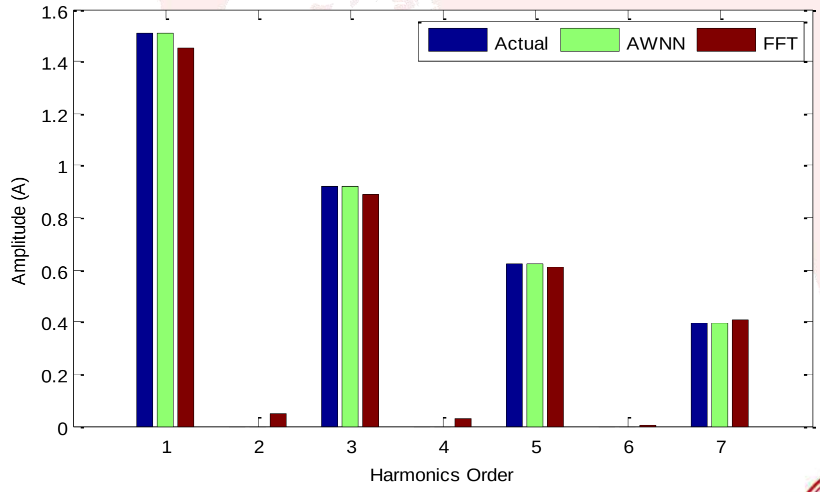


AWNN Based Harmonics Estimation

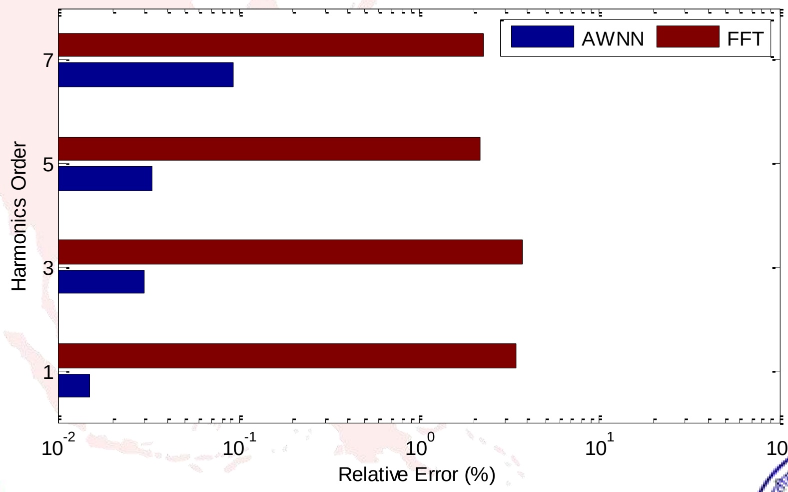
Simulated grid current waveform of PV energy conversion scheme.



Harmonics spectrum of grid current

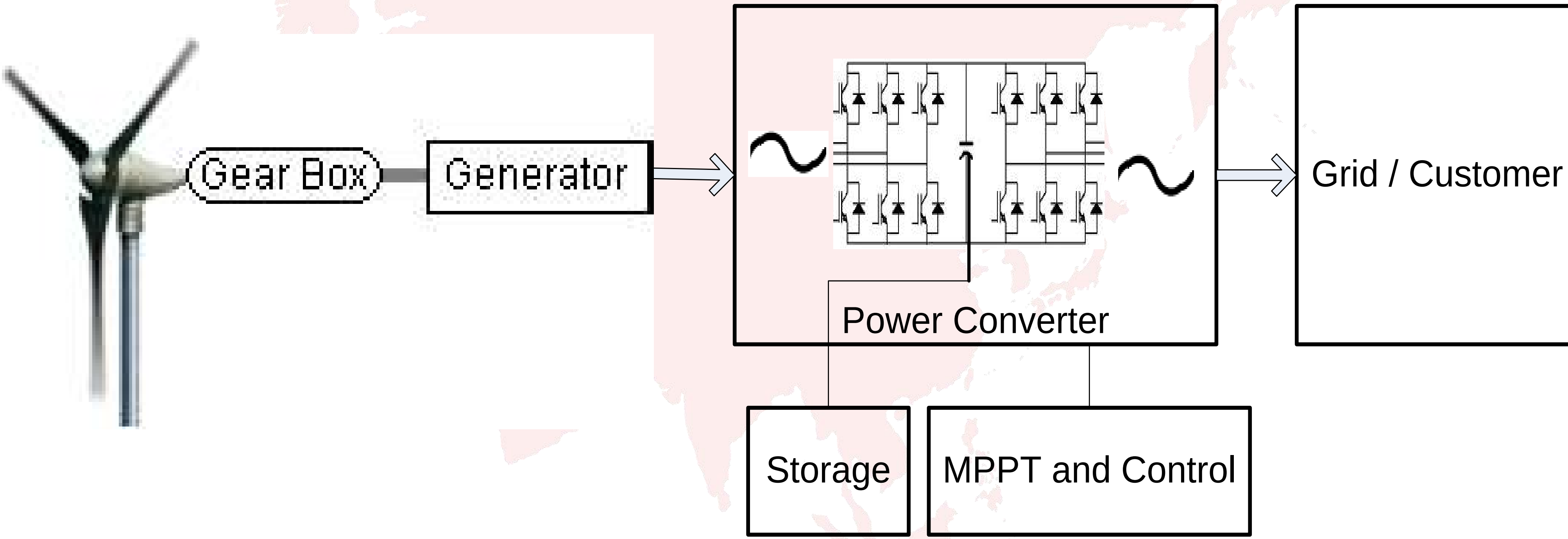


Relative error



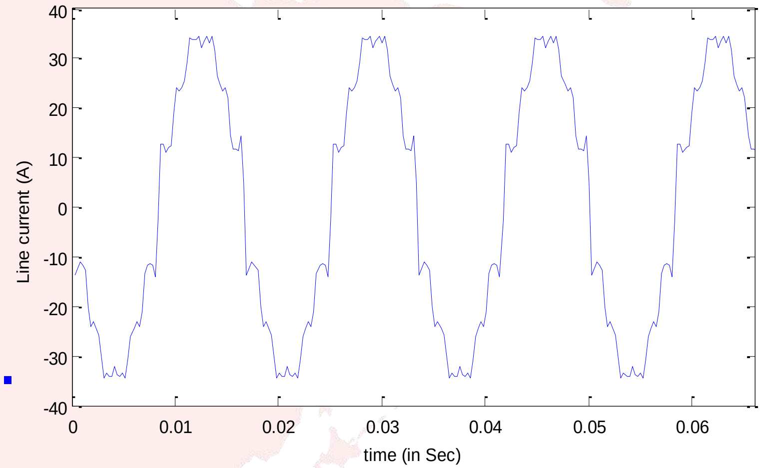
AWNN Based Harmonics Estimation

Case-B: Grid Current Waveform of Current Source Converter based Wind Energy System

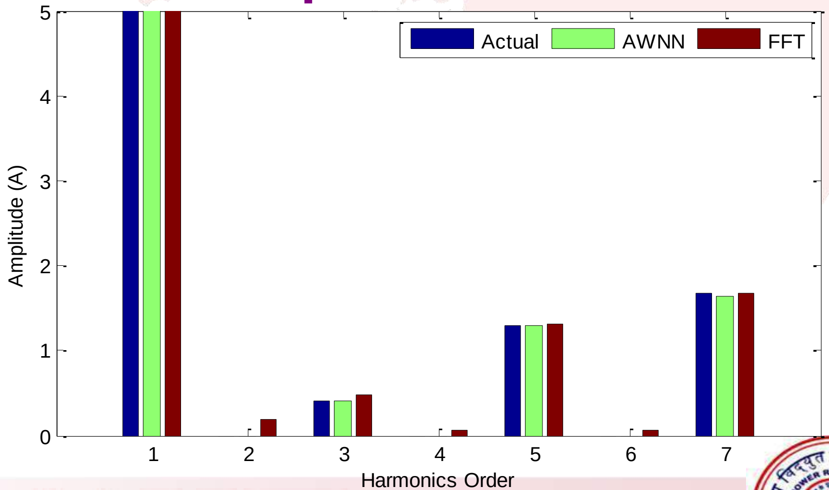


AWNN Based Harmonics Estimation

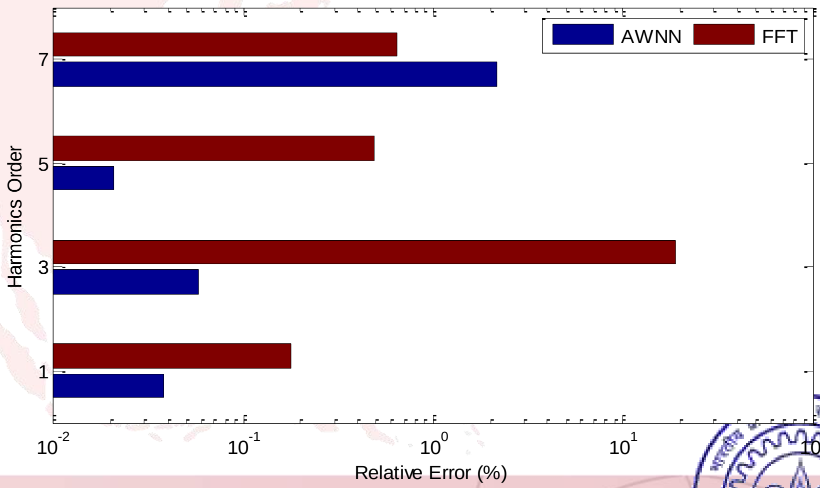
Simulated mains line current wave-form of wind energy system.



Harmonics spectrum of mains current



Relative error



Case Study-2

ESPRIT based Harmonics/Interharmonics Estimation of Non-linear Load Currents/Voltage

ESPRIT Based Harmonics Estimation

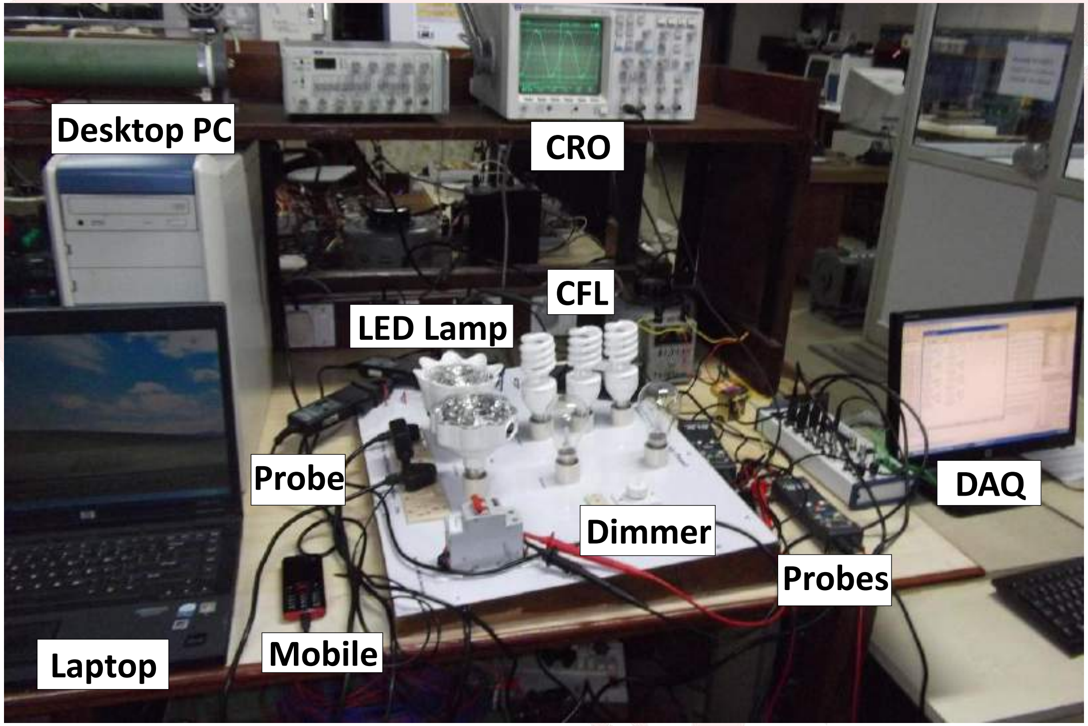
Case-A: Simulated Signal

$$x(n) = \sum_{k=1,2,3,4,5,7} a_k \cdot \cos(2\pi nkf_1T_s + \phi_k) + \sum_{l=1,2} a_l \cdot \cos(2\pi nf_lT_s + \phi_l) + w(n)$$

Method \ Harmonics Order		1	IH-1	2	3	IH-2	4	5	7	Comp. Time (s)	Recnst. Error ε_r
True Values	Freq. (Hz)	50	82	100	150	182	200	250	350	-	-
	Amp. (A)	25.0	3.0	0.5	3.0	5.0	1.0	4.0	2.5		
	Phase (deg)	30	-100	0	0	10	0	-30	65		
IEC – Subgroup	Freq. (Hz)	50	75	100	150	175	200	250	350	0.0066	1.173
	Amp. (A)	25.144	2.929	0.558	3.044	4.842	1.218	4.0456	2.464		
	Phase (deg)	29.75	-25.910	31.391	4.828	82.034	-23.538	-31.405	64.647		
Prony –based	Freq. (Hz)	49.999	81.989	99.902	149.986	181.990	200.072	250.0018	350.001	0.1287	0.147
	Amp. (A)	24.994	2.995	0.493	2.986	4.975	1.012	4.020	2.4866		
	Phase (deg)	30.024	-99.459	4.253	0.489	10.237	-2.561	-30.068	65.125		
Sliding-ESPRIT	Freq. (Hz)	Filtered Out	81.139	106.981	150.204	182.104	202.267	250.227	350.331	0.0802	0.341
	Amp. (A)		2.198	0.4302	2.798	4.669	1.251	3.833	2.142		
	Phase (deg)		-41.2511	-1.922	2.610	9.930	-1.031	151.760	65.837		
Exact Model Order ESPRIT	Freq. (Hz)	49.999	81.991	99.976	149.995	182.003	200.010	249.995	349.993	0.0618	0.0117
	Amp. (A)	24.998	3.000	0.499	3.003	4.991	1.004	3.998	2.501		
	Phase (deg)	30.023	-99.549	1.522	0.208	9.839	-0.417	150.157	65.398		

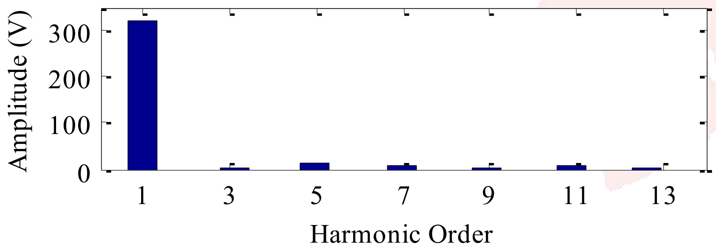
ESPRIT Based Harmonics Estimation

❑Laboratory setup for acquiring actual signal

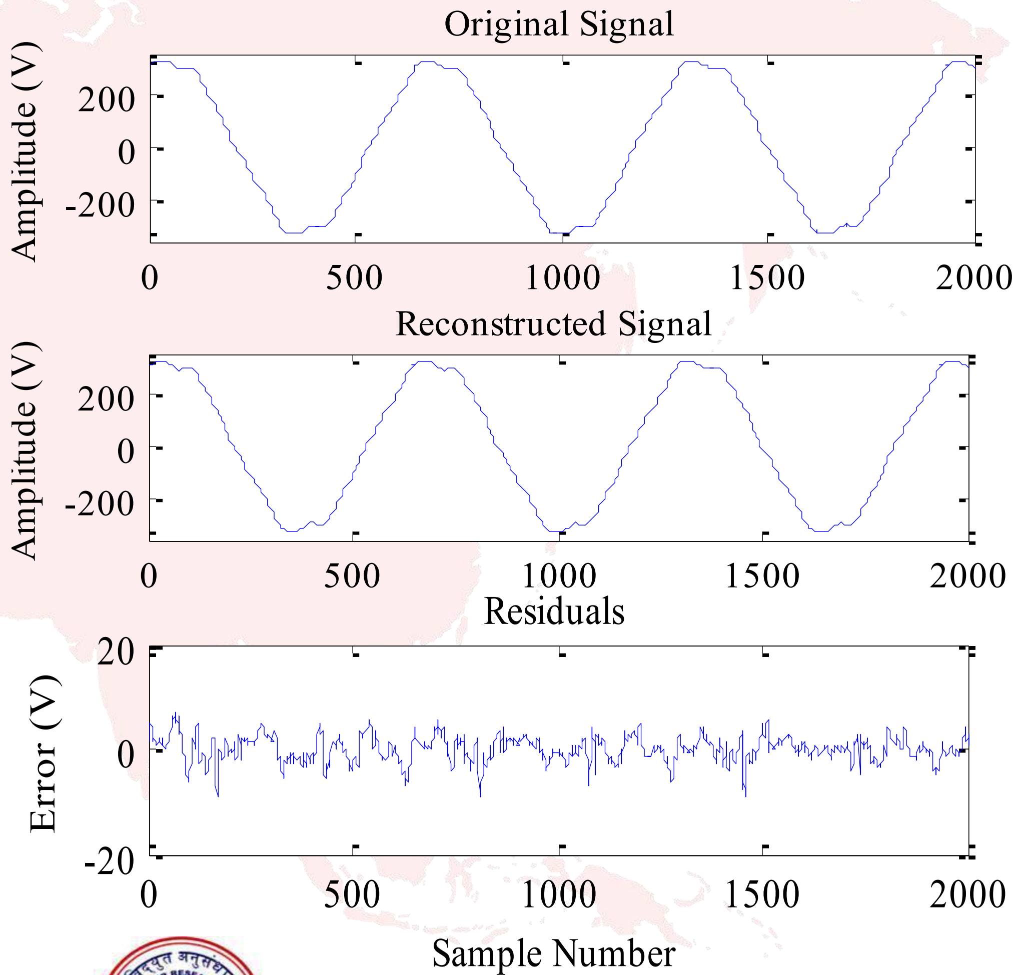


ESPRIT Based Harmonics Estimation

Case-B: Supply voltage



Harmonics spectrum



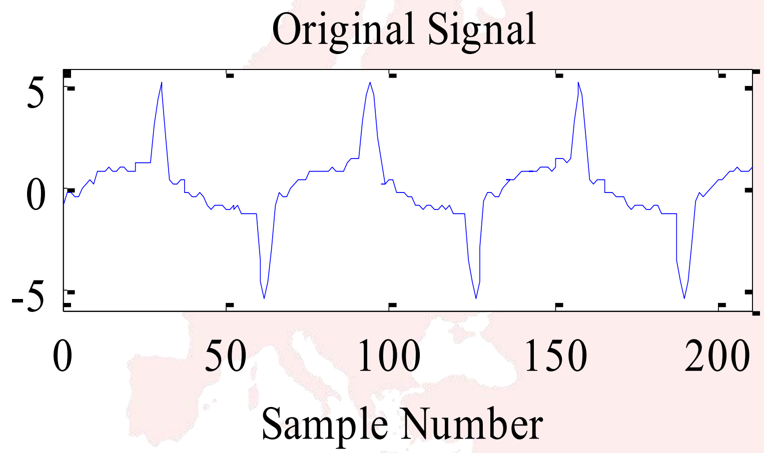
ESPRIT Based Harmonics Estimation

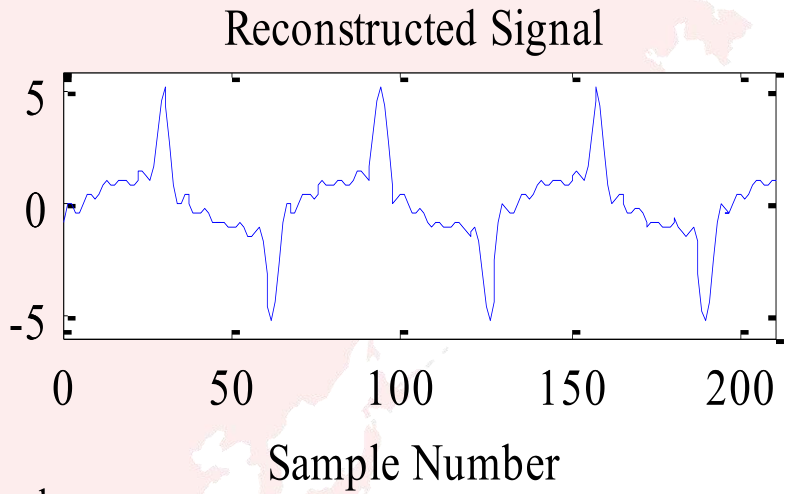
Case-B: Supply voltage

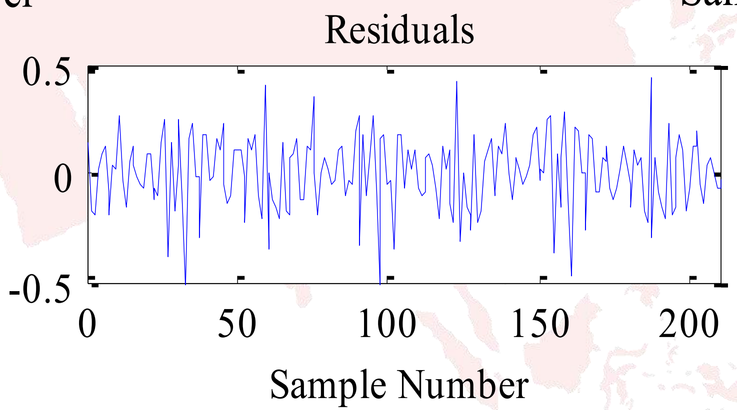
Method		IEC-Subgroup	Prony-based	Sliding-ESPRIT	Exact Model Order ESPRIT
Reconst. Error ε_r	Max	2.11	1.67	2.90	0.97
	Mean	2.10	0.81	2.03	0.83
	SD	0.0075	0.30	0.48	0.06
Comp. Time (s)	Max	0.011	20.7	49.4	19.90
	Mean	0.005	19.36	46.6	18.79
	SD	0.0013	0.67	1.31	0.57

ESPRIT Based Harmonics Estimation

Case-C: Current Signal of miscellaneous non-linear loads







ESPRIT Based Harmonics Estimation

Case-C: Current Signal of miscellaneous non-linear loads

Method	Parameter	Current Signal of misc. non-linear loads						
		Harmonics					Time	ε_r
IEC – Subgroup	Freq. (*Hz*)	50	150	250	350	450	0.005	0.065
	Amp. (A)	2.06	1.05	0.786	0.633	0.514		
	Phase (deg)	10.8	-37.9	-55.4	-89.7	-114		
Prony –based	Freq. (*Hz*)	49.96	150.6	250.2	350.2	450.4	0.101	0.220
	Amp. (A)	2.10	1.05	0.707	0.744	0.488		
	Phase (deg)	10.8	-57.7	-62.6	-97.8	-131		
Sliding-ESPRIT	Freq. (*Hz*)	Fund. N/A	150.2	250.2	350.2	450.3	0.155	0.236
	Amp. (A)		1.05	0.782	0.651	0.506		
	Phase (deg)		-45.2	-61.2	-96.8	-123		
Exact Model Order ESPRIT	Freq. (*Hz*)	50.04	150.1	250.1	350.2	450.3	0.082	0.123
	Amp. (A)	2.05	1.05	0.787	0.633	0.475		
	Phase (deg)	9.25	-43.2	-59.7	-97.4	-128		

Conclusions

- Due to increased penetration of renewable energy sources and usage of power electronics devices, PQ is going to be major concern in recent future.
- Apart from harmonics, inter-harmonics are also to be estimated accurately.
- Better estimation and measuring tools are required for efficient mitigation of PQ problems.
- It can be concluded that every method has some pros and cons and depending upon the application requirement (accuracy/speed/signal noise level etc.) suitable method should be selected.

Future Scope & Challenges

- Intermittent nature of RES produce time varying harmonics, which are difficult to estimate/track. Even standards (IEC, IEEE) consider signal to be stationary, which is invalid in upcoming scenario.
- Estimation accuracy is also suffered in the presence of other PQ problems such as voltage sag/swell or transients.
- Consideration of CT/PT effects on actual vs. measured signal is still an open field for high/medium voltage applications.

Thankyou!