TSDOS
TRANSMISSION & SUBSTATION DESIGN & OPERATION SYMPOSIUM

THE UNIVERSITY OF TEXAS AT ARLINGTON

Adaptive and Robust Harmonic Estimation

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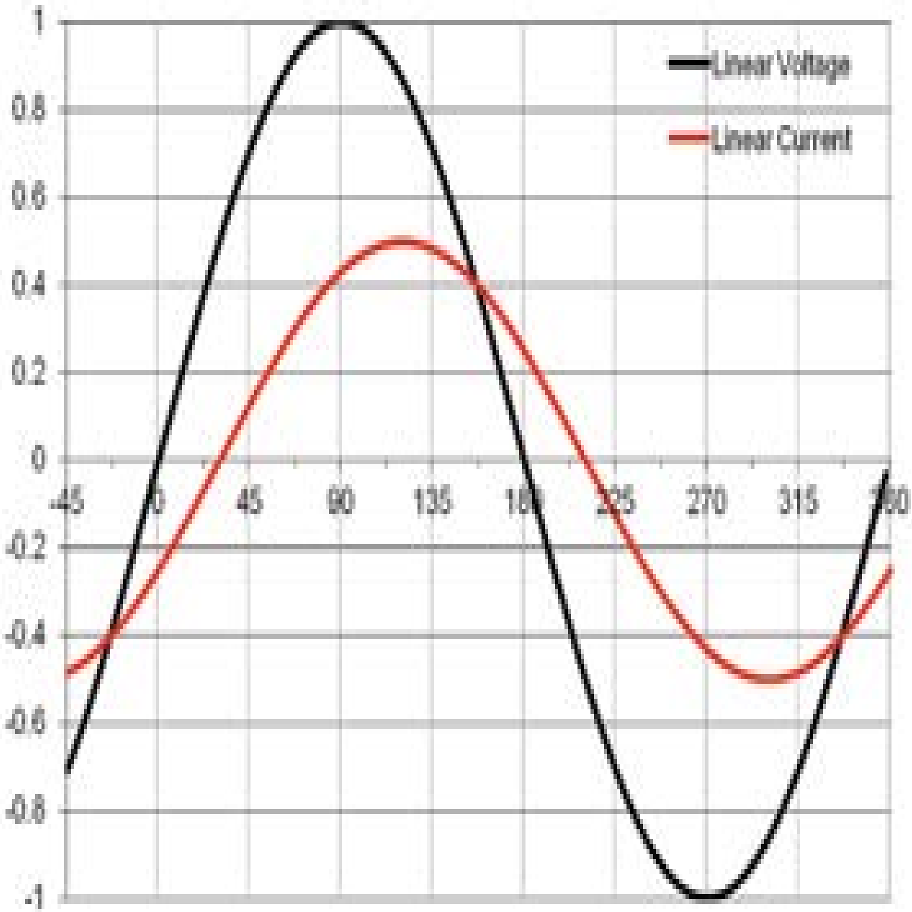
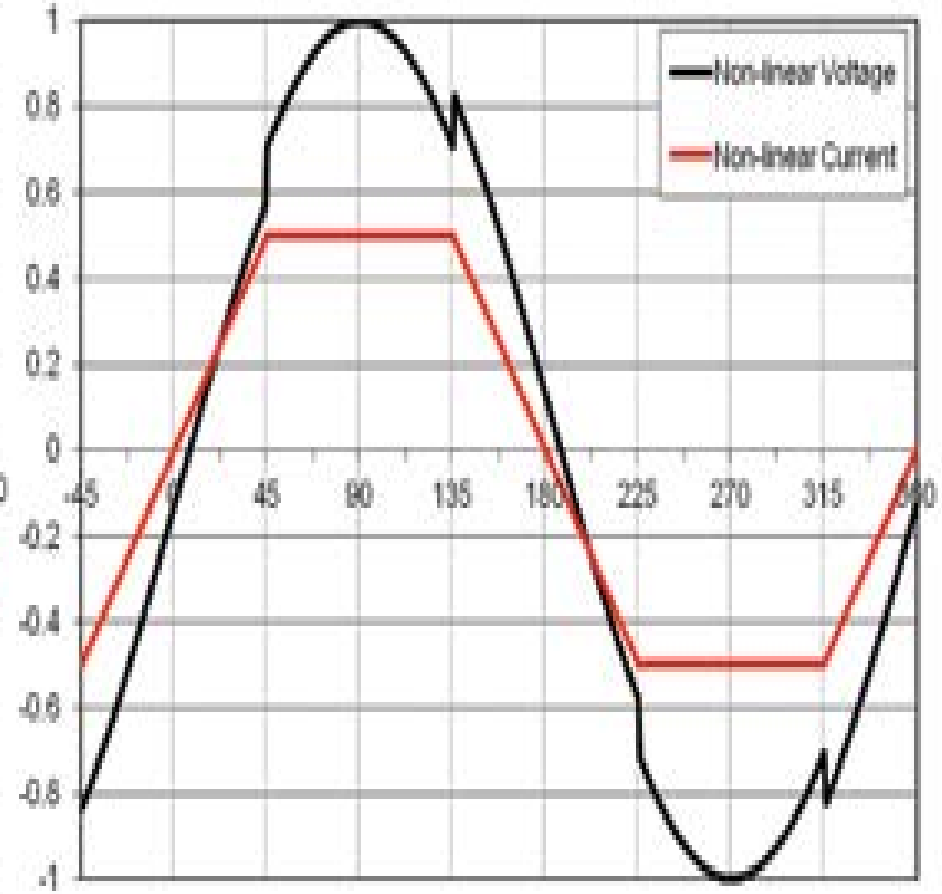
What are Harmonics

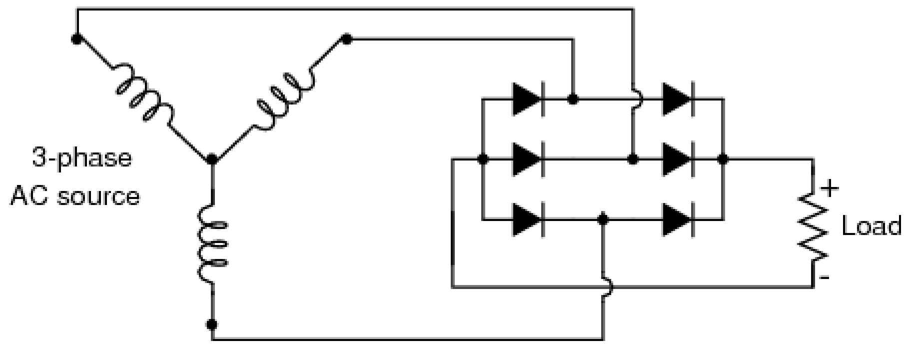
- Signal components contained in integer multiples of the fundamental frequency
- Caused by nonlinear loads that create a nonproportional relationship between voltage and current
- Examples of nonlinear loads include
  - Power electronic devices such as inverters and DC converters
  - Florescent lights
  - Variable frequency drives

Linear VS Nonlinear



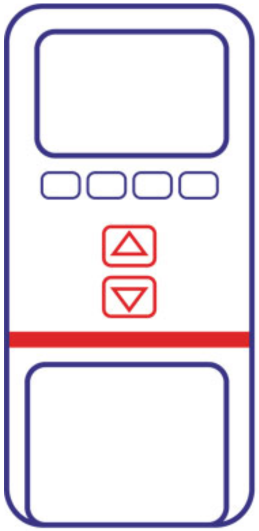


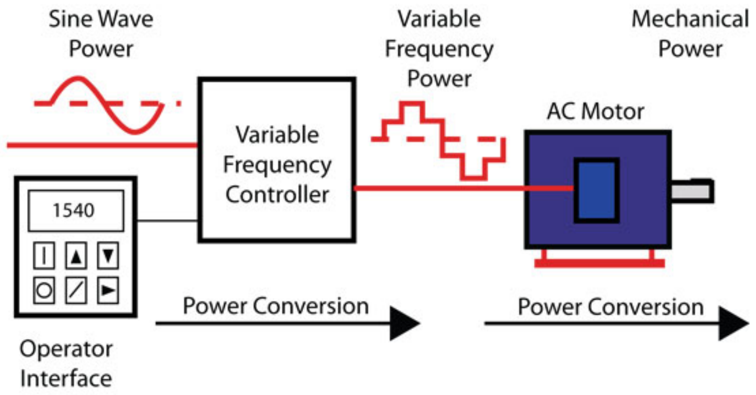
Nonlinear Devices



Three-phase Rectifier

Variable Frequency Drive





VFD System

Problems Caused by Harmonics

- Overloading the neutral
- Reduced efficiency and lifetime on connected loads
- Damaged equipment
- Low voltage
- System Losses
- Odd harmonics (3^{rd}, 5^{th}, 7^{th}, ect.) are the main cause of issues in three-phase systems

Importance of Harmonic Estimation

- Difficult to identify when conducting system analysis
- Devices such as Fluke power quality meters are needed to identify harmonics, but are expensive
- Allows for simple and accurate estimates of the harmonic components, without the need of a meter or scope
- This will help with determining and designing harmonic mitigation filters

Gradient Algorithm

- First we define how to represent the harmonics

$$i(t) = a_0 + \sum_{j=1}^{n} a_j \sin(j\omega t + \phi_j) + v(t)$$

$$i(t) = a_0 + v(t) + \sum_{j=1}^{n} a_j \cos(\phi_j) \sin(j\omega t) + a_j \sin(\phi_j) \cos(j\omega t)$$

- The current expression will have to be reformatted into parameter estimate format

$$i(t) = \varphi^T \theta$$

- Where

$\varphi = [1; \sin(\omega t); \cos(\omega t); \ldots; \sin(n\omega t); \cos(n\omega t)]$ and

$\theta = [a_0; a_1 \cos(\phi_1); a_1 \sin(\phi_1); \ldots; a_n \cos(\phi_n); a_n \sin(\phi_n)]$

Gradient Algorithm

- Next define $\epsilon = \hat{\theta} - \theta$ as the error signal where $\hat{\theta}$ represents the parameters being estimated. Similarly the error of the reconstructed signal can be represented as

$$e = \hat{\imath}(t) - i(t) = \varphi^T(\hat{\theta} - \theta)$$

- Finally, to minimize the performance index we define

$$\dot{\hat{\theta}} = -\gamma \frac{\partial e^2}{\partial \hat{\theta}^2} = -2\gamma e \frac{\partial e}{\partial \hat{\theta}} = -\gamma e \varphi$$

- γ must be a constant and >0. The above expression is known as the updating law for the gradient algorithm
- The gradient algorithm is an iterative process that drives the estimation error to zero

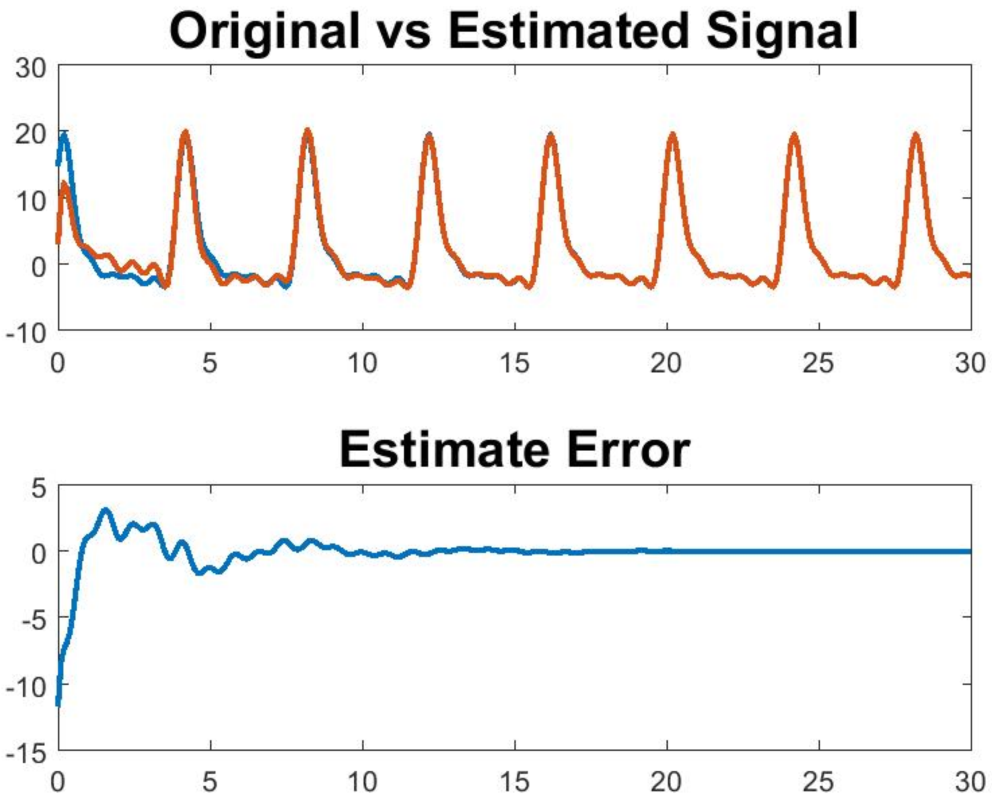
Gradient Algorithm Results

- In order to reconstruct the true values of the parameters the following equations are used $a_j = \sqrt{\theta_{2j}^2 + \theta_{2j+1}^2}$ and $\phi_j = \arctan(\frac{\theta_{2j}}{\theta_{2j+1}})$
- The gradient algorithm was tested with a sample signal of $s(t) = 2 + 7\sin\left(\omega t + \frac{\pi}{3}\right) + 5\sin\left(2\omega t + \frac{\pi}{4}\right) + 3\sin\left(3\omega t + \frac{\pi}{5}\right) + 2\sin\left(4\omega t + \frac{\pi}{6}\right) + \sin\left(5\omega t + \frac{\pi}{7}\right)$

  with the fundamental frequency set to $\frac{\pi}{2}$

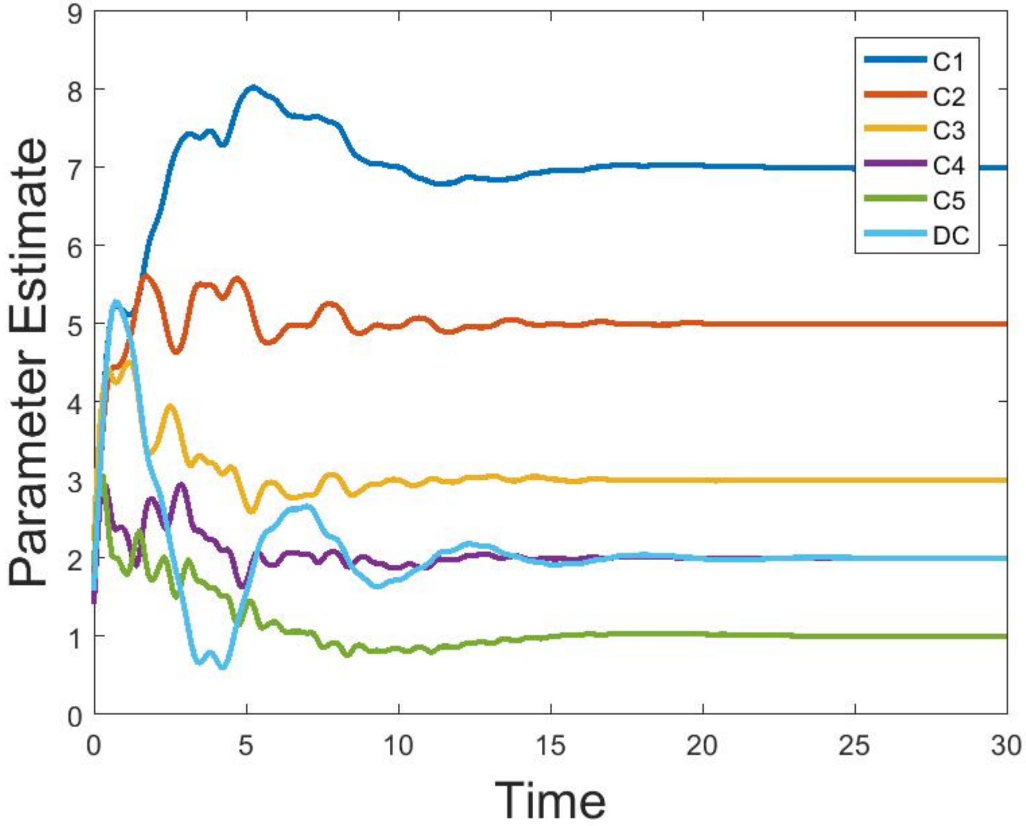
Gradient Signal Estimate and Error

- Estimate catches signal within 2 cycles
- Error goes to 0 after 15 seconds



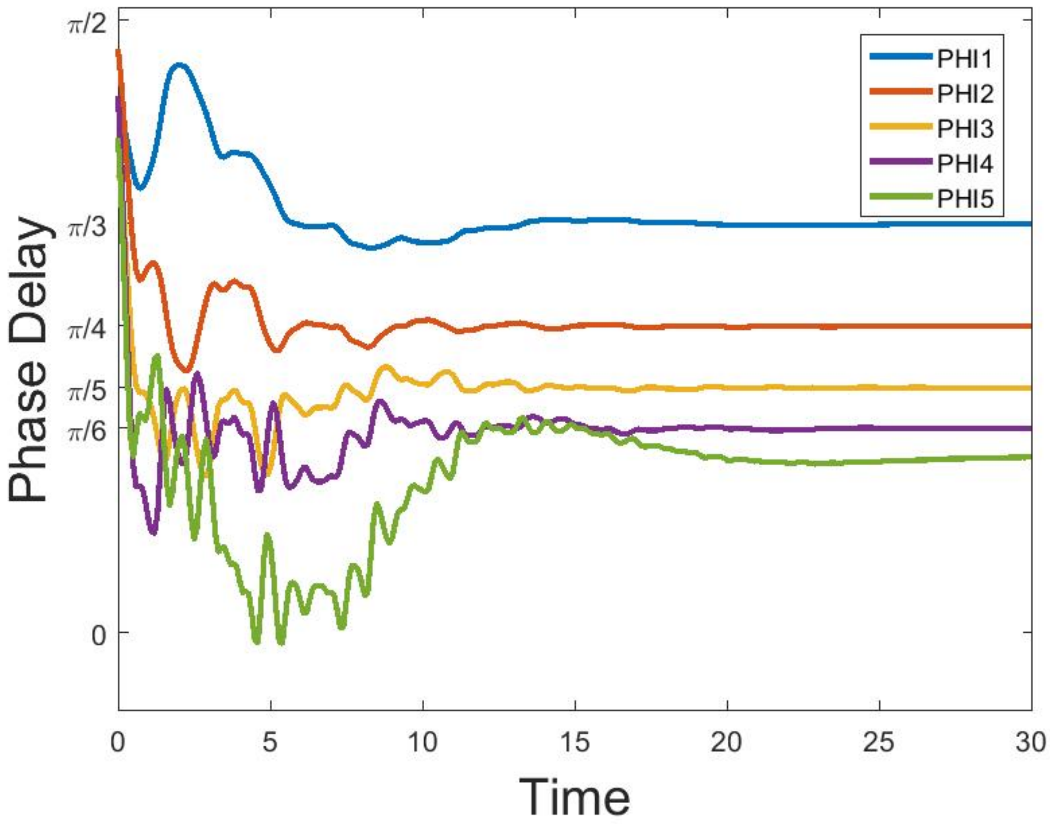
Gradient Parameter Estimation

- All parameter estimates converge to their true values including the DC bias



Gradient Phase Estimation

- All phase shifts converge to true values around 20 seconds



Robust Model Based Learning

- The system will be defined as $\dot{x} = -x + \delta_0(t) + u$
- Where $\delta_0(t)$ is the unknown function and u is the controller that will estimate it
- The only requirement is that the unknown function and its derivatives must be bounded $|\delta_0(t)| \leq \overline{\delta_0}, \left|\frac{d\delta_0(t)}{dt}\right| \leq \overline{\delta_0}', and\ \left|\frac{d^2\delta_0(t)}{dt^2}\right| \leq \overline{\delta_0}''$
- Next differentiate the previously defined system
- $\ddot{x} + k_3\dot{x} + k_1 x + k_2(\dot{x} + k_3 x) = \left[\dot{\delta}_0(t) + (k_3 + k_2 -\right.$

Robust Model Based Learning

- Define the functions $\eta(t)$ which contains the factors of the unknown function and v which contains u and $\dot{u}$
  $v = \dot{u} + (k_3 + k_2 - 1)u + (k_1 + k_2 k_3)x - (k_3 + k_2 - 1)x$
- The robust control is defined as $v(t) = -sign[x]\rho$, leading to
- Where

$$\rho \triangleq \overline{\delta_0}' + |k_3 + k_2 - 1|\overline{\delta_0} + \frac{1}{k_3}\left[\overline{\delta_0}'' + |k_3 + k_2 - 1|\overline{\delta_0}'\right]$$

Robust Control Stability and Performance

- The stability and performance of the robust control will be analyzed using a Lyapunov approach
- First the Lyapunov function will be considered as $V(x, \dot{x}, t) = \frac{1}{2}|\dot{x} + k_3 x|^2$
- Since the function is positive definite, it follows that $\dot{V} = (\dot{x} + k_3 x)[\eta(t) + v] - k_2|\dot{x} + k_3 x|^2 - k_1 k_3 |x|^2$
- Then integrate both sides leading to

$$V(t) \leq V(t_0) + \xi(t) - k_2 \int_{t_0}^{t} |\dot{x} + k_3|^2 d\tau$$

Robust Control Stability and Performance

- The function $\xi(t)$ can be defined by the following

$$\xi(t) = \int_{t_0}^{t} (\dot{x} + k_3 x)[\eta(t) + v]d\tau$$

$$= \int_{t_0}^{t} k_3 x[\eta(t) + v]d\tau + \int_{t_0}^{t} \eta(t)dx + \int_{t_0}^{t} vdx$$

$$= \int_{t_0}^{t} x[k_3\eta(t) - \dot{\eta}(t) + k_3 v]d\tau + \eta(t)v(t) - \eta(t_0)v(t_0) - \rho|x(t)| + \rho|x(t_0)|$$

$$\leq \int_{t_0}^{t} \left[|k_3\eta(t) - \eta(\dot{t})|\right.$$

Robust Control Stability and Performance

$$\leq -\eta(t_0)x(t_0) + \rho|x(t_0)|$$

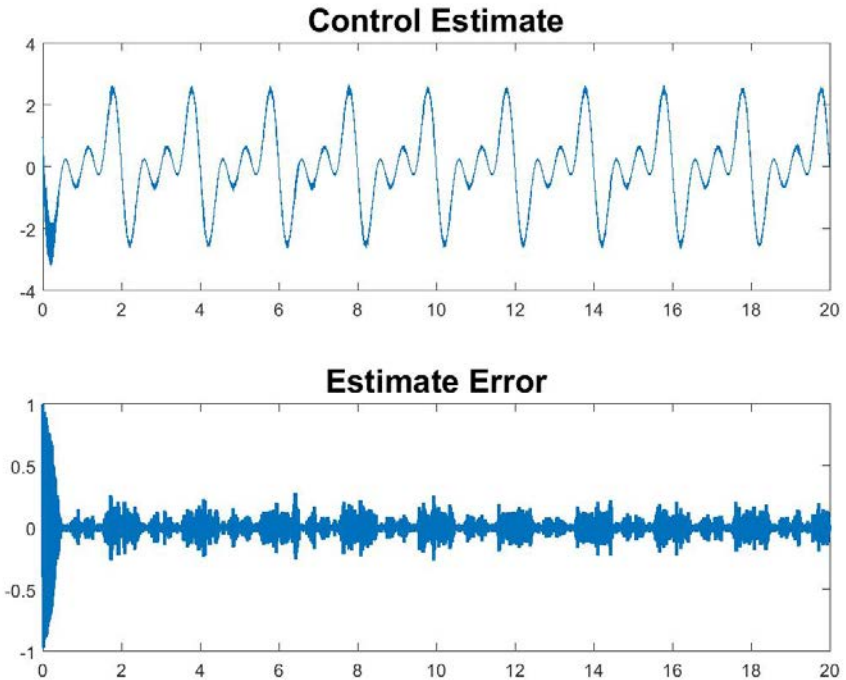
- The final expression will be

$$V(t) + k_2 \int_{t_0}^{t} |\dot{x} + k_3 x|^2 d\tau + k_1 k_3 \int_{t_0}^{t} |x|^2 d\tau$$
$$\leq V(t_0) - \eta(t_0)x(t_0) + \rho|x(t_0)|$$

- The following conclusions can be made from the above expression
  - $|x|$ and $|\dot{x}|$ are uniformly bounded
  - u and $\dot{u}$ are uniformly bounded
  - if $\ddot{x}$ is uniformly bounded then $\dot{x}$ and x are uniformly continuous

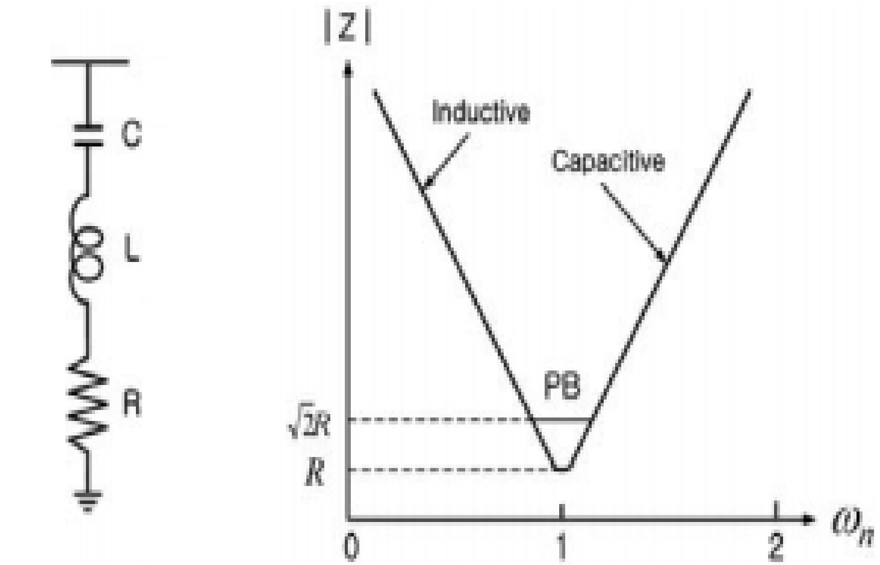
Robust Control Unknown Signal Estimate

- The unknown test signal given was $\delta_0(t) = \sin(\pi t) + \sin(2\pi t) + \sin(3\pi t)$
- Unknown signal is learned quickly in less than 6 seconds and that the error approaches zero and remains small



Passive Harmonic Filters

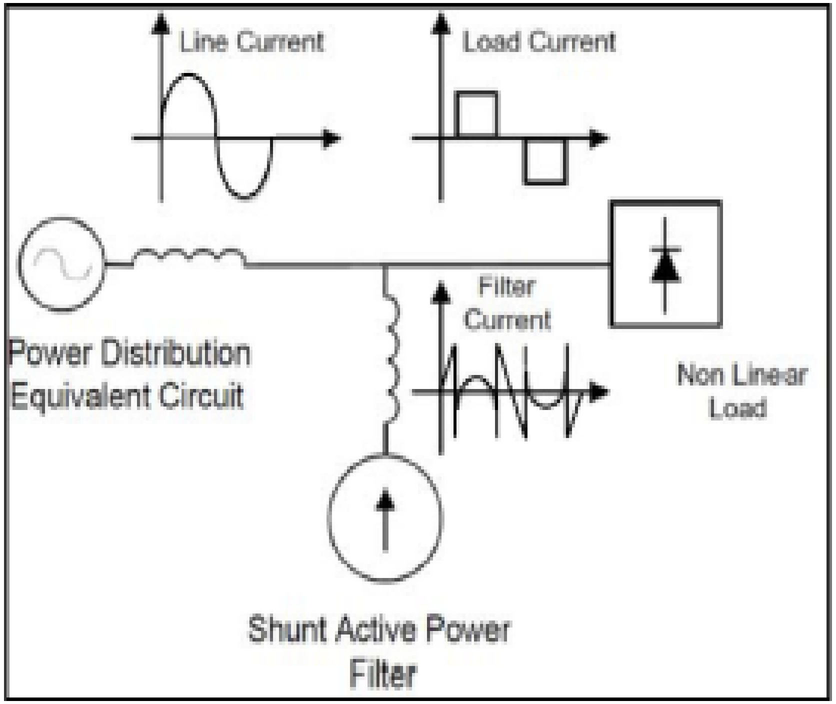
- Made up of inductors, capacitors, and resistors which are connected in parallel or series
- Designed to mitigate one specific harmonic component
- Multiple can be used to mitigate multiple harmonic components
- Gradient Algorithm can be used to identify individual harmonic components and aid in the design of the passive filter



(a) Circuit (b) Impedance characteristic

Active Harmonic Filters

- Active Harmonic filters use a controller and a switching scheme to create an equal and opposite current signal to cancel out harmonic content
- Placed in parallel or series, usually at the site of the nonlinear load
- Robust control can be used to estimate the complete signal
- Generate equal and opposite current based on estimation



Conclusion

- Harmonics are caused by nonlinear devices
- Harmonics cause problems such as equipment damage, high neutral loading, low voltage, and system losses
- Estimation techniques can be used to identify harmonics and help with filter design and mitigation

Questions