Harmonic State Space (HSS) Modeling in Power Electronics

JunBum Kwon, PhD Student
Department of Energy Technology
jbk@et.aau.dk
Outline

- Background
- Problem & Motivation
- HSS Modeling
- Simulation & Experiment
- Conclusion & Future Work
Background

- Power electronics based power system (Example)

Simplified LV micro grid network (Cigre Benchmark)

- Power electronics technology is being widely used for power generation, generation and Bidirectional power flow is changing grid impedance continuously.
Problem & Motivation

- Time Varying Components in Power Electronics Converters

Non-linear / Time Varying Elements

**PWM-Carrier Switching performance**

- $v_{carrier}$
- $i_d$ or $i_d^*$
- $i_q$ or $i_q^*$

**DC dynamics from others**

- Magnitude (VDC)
- Time (sec)
- $V_{ac}$

**AC disturbance from others**

- Magnitude (V)
- Time (sec)
- Harmonic Varying
- Frequency Varying
- Magnitude Varying

**Nonlinear Inductor/Transformer**

- $i(t) = f(\phi(t))$
- $v(t) = \frac{d\phi(t)}{dt}$
- $i = a\phi^n + b\phi^m + c\phi^k$
Problem & Motivation

- Regional trains stopped (Example of LTP analysis)

Problem & Motivation

- Handling a time-varying / nonlinear components

- Conventional modeling approach didn’t consider the effect of time varying components.

- Including a time-varying / nonlinear components is a challenge in a modeling procedure.
HSS Modeling

Basic Structure of LTP model

- Nonlinear State Space
  \[ \dot{x} = f(x, t, u) \]
  \[ y = g(x, t, u) \]

- Linear Time Invariant (LTI)
  \[ \dot{x} = Ax + Bu \]
  \[ y = Cx + Du \]
  \( v = constant \)

- Linear Time Periodic (LTP)
  \[ \dot{x} = A(t)x + B(t)u \]
  \[ y = C(t)x + D(t)u \]
  \( v = v(\theta) \)
  \( \theta = \omega t \)

[1] Frequency-Domain System Identification for linear time periodic systems with application to wind turbine dynamics and CSLDV, University of Wisconsin Madison, by Dr Matthew S. Allen
HSS Modeling

- **Modeling Procedure**

  LTI to LTP

  \[
  \begin{align*}
  \dot{x}(t) &= Ax(t) + Bu(t) \quad (1) \\
  y(t) &= Cx(t) + Du(t)
  \end{align*}
  \]

  \[
  \begin{align*}
  \dot{x}(t) &= A(t)x(t) + B(t)u(t) \quad (2) \\
  y(t) &= C(t)x(t) + D(t)u(t)
  \end{align*}
  \]

- **Time Varying Fourier Coefficient**

  \[
  x(t) = \Gamma(t)X
  \]

  where,

  \[
  \Gamma(t) = \begin{bmatrix}
  e^{-j\omega_0 t} & e^{-j2\omega_0 t} & \ldots & e^{-jm\omega_0 t} \\
  e^{j\omega_0 t} & e^{j2\omega_0 t} & \ldots & e^{jm\omega_0 t}
  \end{bmatrix}
  \]

  \[
  X = \begin{bmatrix}
  X_{-h}(t) \\
  X_{-1}(t)X_0(t)X_1(t) \ldots X_h(t)
  \end{bmatrix}^T
  \]

- **Time Varying Fourier Coefficient**

  \[
  \begin{align*}
  \dot{x}(t) &= \dot{\Gamma}(t)X + \Gamma(t)\dot{X} \\
  sX(\omega, t) &= A(\omega)\otimes X(\omega, t) + B(\omega)\otimes U(\omega, t) \\
  Y(\omega, t) &= C(\omega)\otimes X(\omega, t) + D(\omega)\otimes U(\omega, t)
  \end{align*}
  \]

- **Harmonic State Space Model**

  \[
  (s + jm\omega_0)X_n = \sum_{m=-\infty}^{\infty} A_{n-m}X_m + \sum_{m=-\infty}^{\infty} B_{n-m}U_m
  \]

  \[
  Y_n = \sum_{m=-\infty}^{\infty} C_{n-m}X_m + \sum_{m=-\infty}^{\infty} D_{n-m}U_m
  \]

  \[
  sX = (A - N)X + BU
  \]

  \[
  Y = CX + DU
  \]
HSS Modeling

- Introduction of LTP theory

Advantages of HSS

- Dynamics of each harmonics
- Coupling analysis of AC-DC system.
- Including time-varying component
- Easy to be connected with other system matrix
- Possibility to figure out the characteristic, which can not be found in LTI model.

Simulation & Experiments

- Flow chart for the HTF simulation and Experimental Validation
Simulation & Experiments

Harmonic coupling - Single phase converter

\[ \omega_r, 2\omega_r, 4\omega_r, \ldots \quad \text{LTP model eq (3)~(12)} \]

\[ \omega_r \pm 1, 2\omega_r \pm 1, 4\omega_r \pm 1 \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{
(a) Output AC Current \( I_f \) vs. DC Voltage \( V_{dc} \).
(b) Output AC Current \( I_f \) vs. Grid Voltage \( V_g \).
}
\end{figure}

Simulation & Experiments

- Dynamic simulation – Single phase converter

Simulation & Experiments

- Dynamic harmonic response – Single phase converter (Instability)

Simulation & Experiments

- Experimental Validation

Conclusion & Future Work

- Grid connected inverter model using HSS modeling is developed.

- By means of HSS modeling, the time varying elements of converters can be considered and analyzed together in one domain.

- This model shows intuitively the harmonic coupling points of the models.

- The developed model will be combined with other converters for the analysis of harmonics in a large network.

- The non-linear passive components will be included in the model to analyze the harmonics generated in the saturation.
Thank You! Questions?

“THE HIDDEN HARMONY IS BETTER THAN THE OBVIOUS”

- P. PICASSO

www.harmony.et.aau.dk
Simulation

- Multi connected grid converter

(a) Block diagram for the grid connected converter model (Converter A~E)

(b) Single line diagram of LV micro-grid network model
Simulation

- Jacobian Sparse Matrix– Multi-parallel connected converter


Grid voltage ($V_{\text{line–ABC}}$) to grid current ($I_{g–ABC}$) 

Grid voltage ($V_{\text{line–ABC}}$) to dc voltage ($V_{dc}$) 

and dc current ($I_{dc}$)
Simulation

- Dynamic simulation – Multi-parallel connected converter

Dynamic simulation – Multi-parallel connected converter

Converter – A \( \left( \frac{V_{dc-A}}{V_{pcc-A}} \right) \), \( I_{dc\text{-load}} = 75A_{dc} \)

Converter – A \( \left( \frac{V_{dc-A}}{V_{pcc-A}} \right) \), \( I_{dc\text{-load}} = 13A_{dc} \)

Simulation

- Dynamic simulation – Multi-parallel connected converter

<table>
<thead>
<tr>
<th></th>
<th>$V_{dc}$ (V)</th>
<th>$R_{dc}$ (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv.A</td>
<td>650</td>
<td>50</td>
</tr>
<tr>
<td>Conv.B</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td>Conv.C</td>
<td>750</td>
<td>10</td>
</tr>
<tr>
<td>Conv.D</td>
<td>800</td>
<td>5</td>
</tr>
<tr>
<td>Conv.E</td>
<td>700</td>
<td>5</td>
</tr>
</tbody>
</table>

Simulation & Experiments

- Back-to-Back Converter

Simulation & Experiments

- Dynamic simulation – Back to Back converter (RSC=GSC=50Hz)

Simulation & Experiments

- Dynamic simulation – Back to Back converter (RSC=10 Hz, GSC=50Hz)

Simulation & Experiments

- Experimental Validation

## Simulation & Experiments

**Dynamic simulation – Back to Back converter**