SAND2012-6618P

Linear Analysis of Power Electronics for Energy Storage Systems

Exceptional service in the national interest

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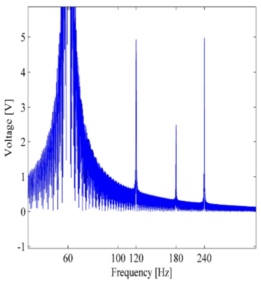

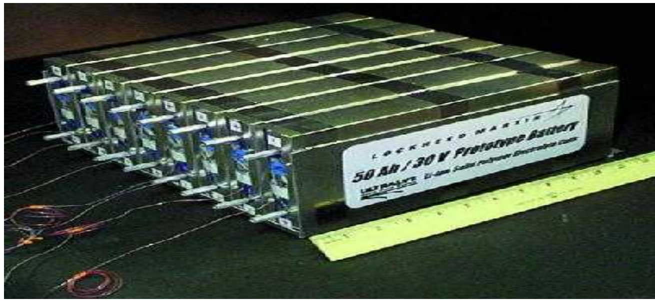

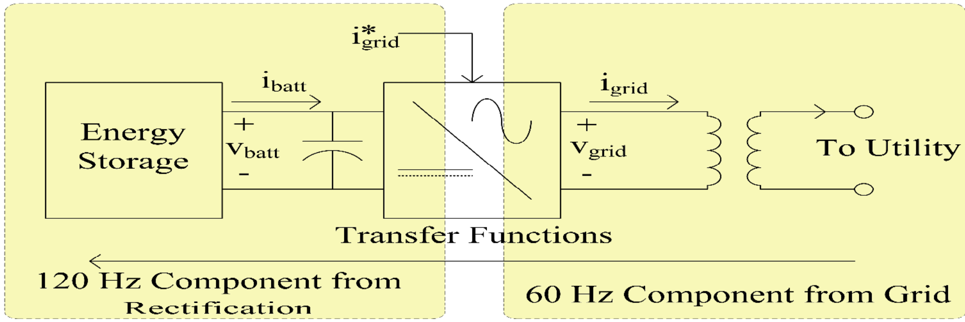

Luke Watson

Mentor: Dr. Stanley Atcitty

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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About Myself

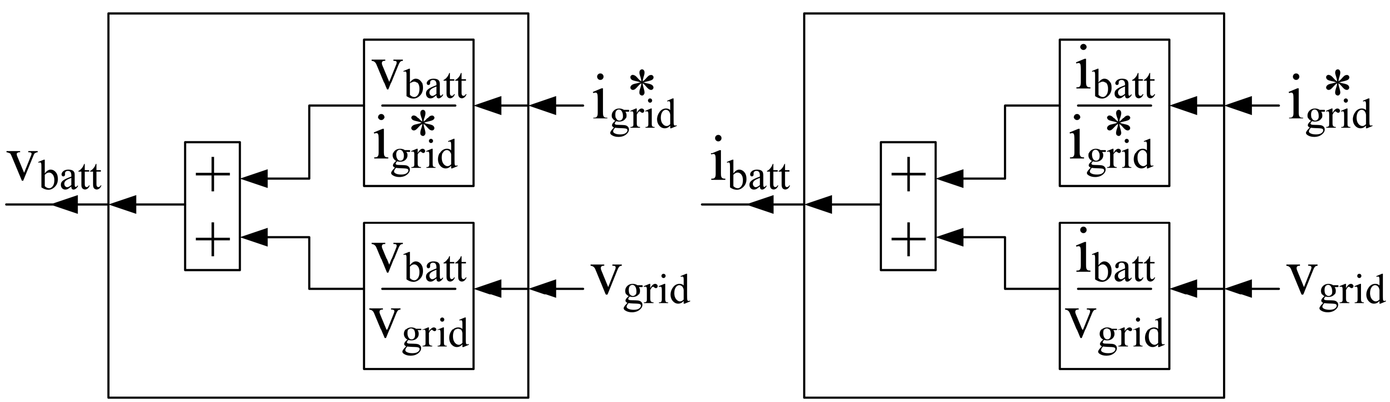
- Electrical Engineering PhD student at Missouri S&T (Formerly University of Missouri - Rolla) studying power electronics
- Expected Graduation in August 2013
- Research Interests:

    Power electronics, controls
- University advisor – Dr. Jonathan Kimball

MISSOURI S&T University of Science & Technology

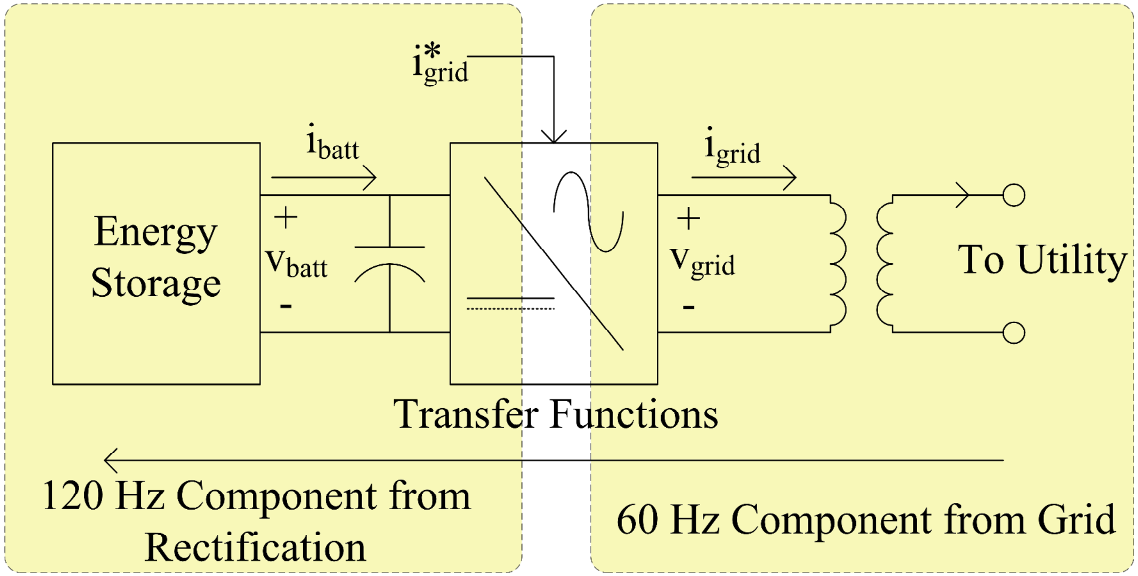
Why Model with Linear Transfer Functions?

- Battery manufacturers have limited knowledge on what harmonics their battery will see once placed in the field.
- How this frequency content effects the battery lifetime is not well understood when tied to electric utility grid during a disturbance.
- A linear inverter model will allow manufacturers to predict what these frequencies will be and design a battery specifically for grid-tied systems, which are robust to these frequencies.



Problem with Linear Analysis

- Computationally Expensive
- Transfer functions are linear approximations of a system. Real world problems are nonlinear.

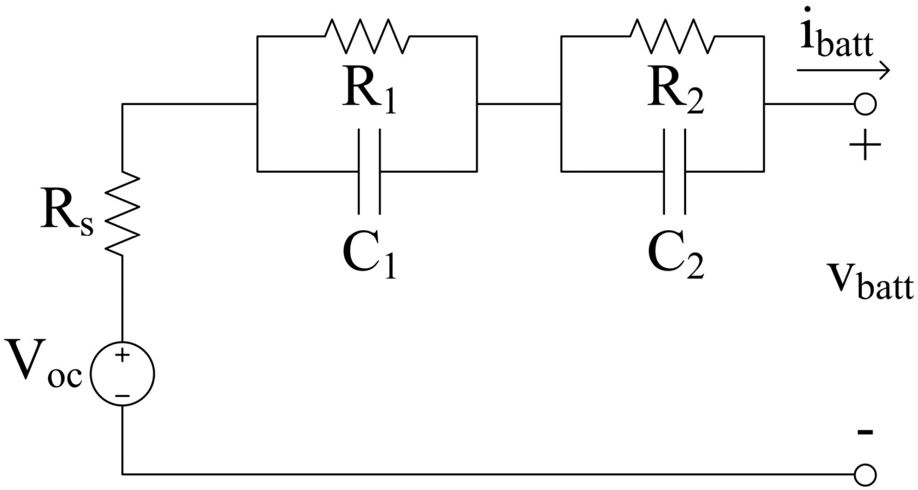


Project Goals

- Derive transfer functions for I_{batt}/V_{grid}, V_{batt}/V_{grid}, I_{batt}/I_{grid}, and V_{batt}/V_{grid}
- Verify transfer functions against switch level PLECS model
- Determine if harmonics are a significant on the battery terminals
- Optimization of inverter controls using linear transfer functions

Energy Storage Modeling

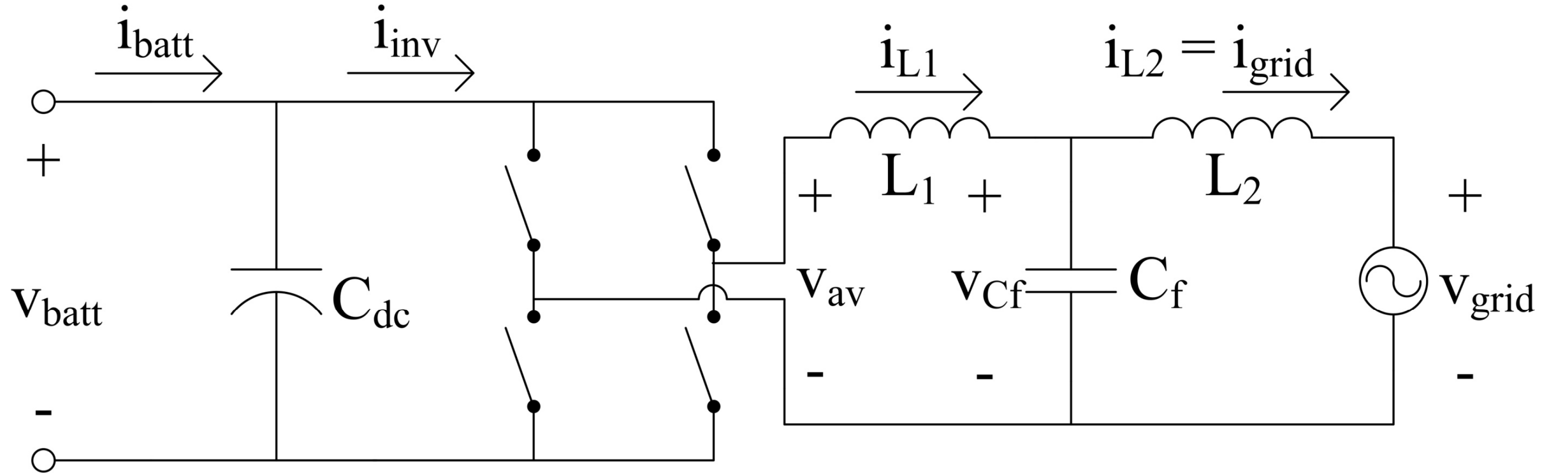
Battery model derived using spectroscopy data:



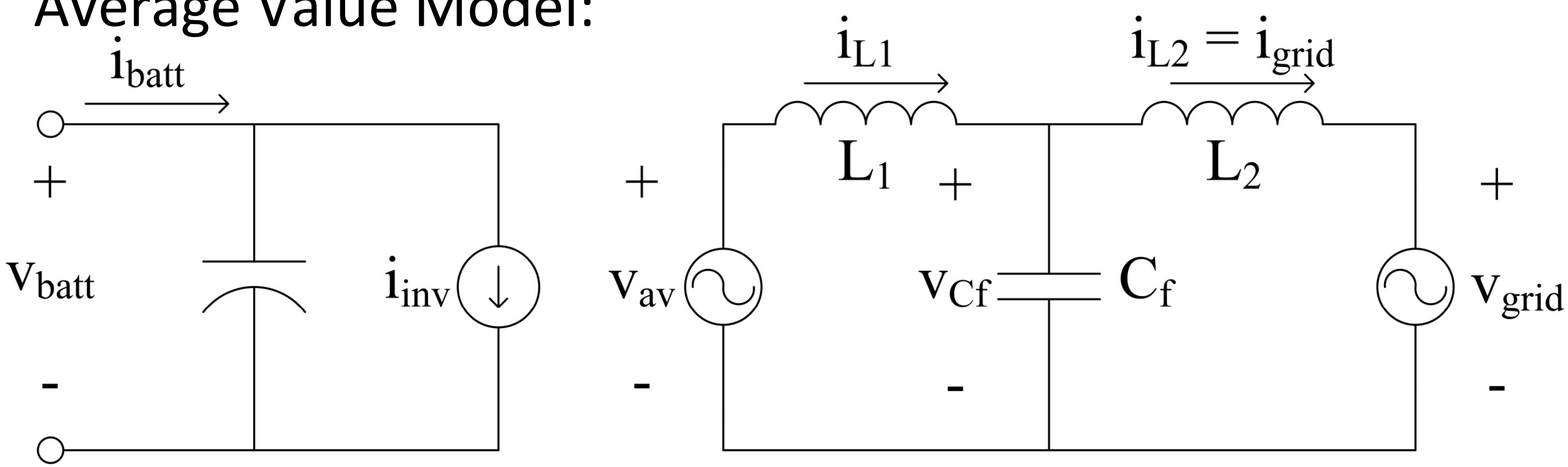
Fregosi, D.; Bhattacharya, S.; Atcitty, S.; , "Empirical battery model characterizing a utility-scale carbon-enhanced VRLA battery," *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE* , vol., no., pp.3541-3548, 17-22 Sept. 2011

Power Electronics Modeling

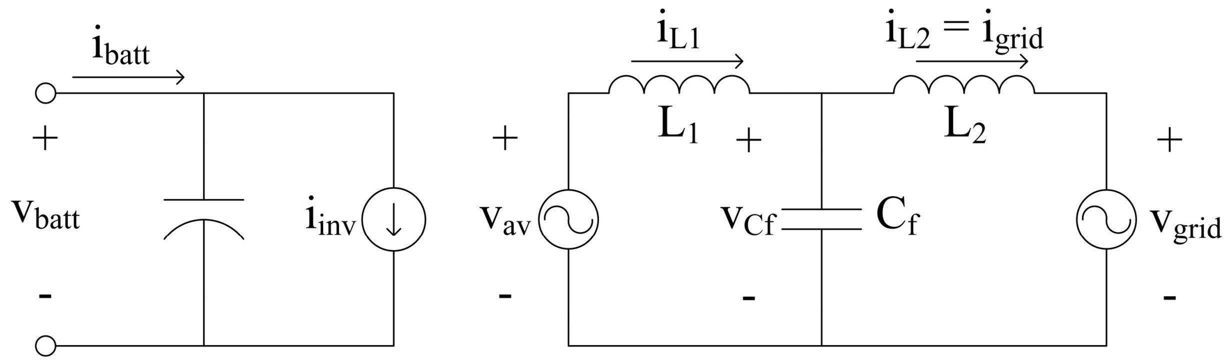
Switch Model:



Average Value Model:



Linearization Issue



$$P_{in} = P_{out}$$

$$v_{dc} i_{inv} = v_{av} i_{L1}$$

$$i_{inv} = \frac{v_{av} i_{L1}}{v_{dc}}$$

$$i_{inv} = \frac{V_{av} \sin(\omega t) I_{L1} \sin(\omega t + \phi)}{v_{dc}}$$

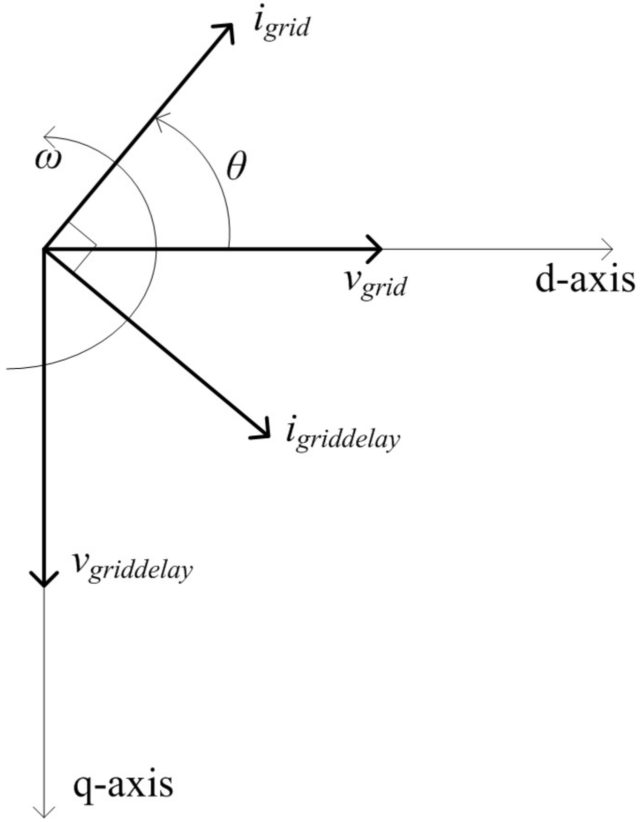
$$i_{inv} = \frac{V_{av} I_{L1}}{2 v_{dc}} [\cos(\phi) - \cos(2\omega t + \phi)]$$

120 Hz component from 60 Hz components

Rotating Reference Frames

- Any sinusoid can be broken up into a sine and cosine component

$$v = v_d \cos(\omega t) - v_q \sin(\omega t)$$



Single phase dq conversion:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} v \\ v_{delay} \end{bmatrix}$$

Linearization with DQ Components

$$i_{inv} = \frac{i_{L1,dq} v_{av,dq}}{v_{dc}}$$

$$i_{L1,dq} = i_{L1,d} \cos(\omega t) - i_{L1,q} \sin(\omega t)$$

$$v_{av,dq} = v_{av,d} \cos(\omega t) - v_{av,q} \sin(\omega t)$$

$$i_{inv} = \frac{i_{L1,d} v_{av,d} + i_{L1,q} v_{av,q}}{2v_{dc}} + \left(\frac{i_{L1,d} v_{av,d} - i_{L1,q} v_{av,q}}{2v_{dc}}\right) \cos(2\omega t) - \left(\frac{i_{L1,d} v_{av,q} + i_{L1,q} v_{av,d}}{2v_{dc}}\right) \sin(2\omega t)$$

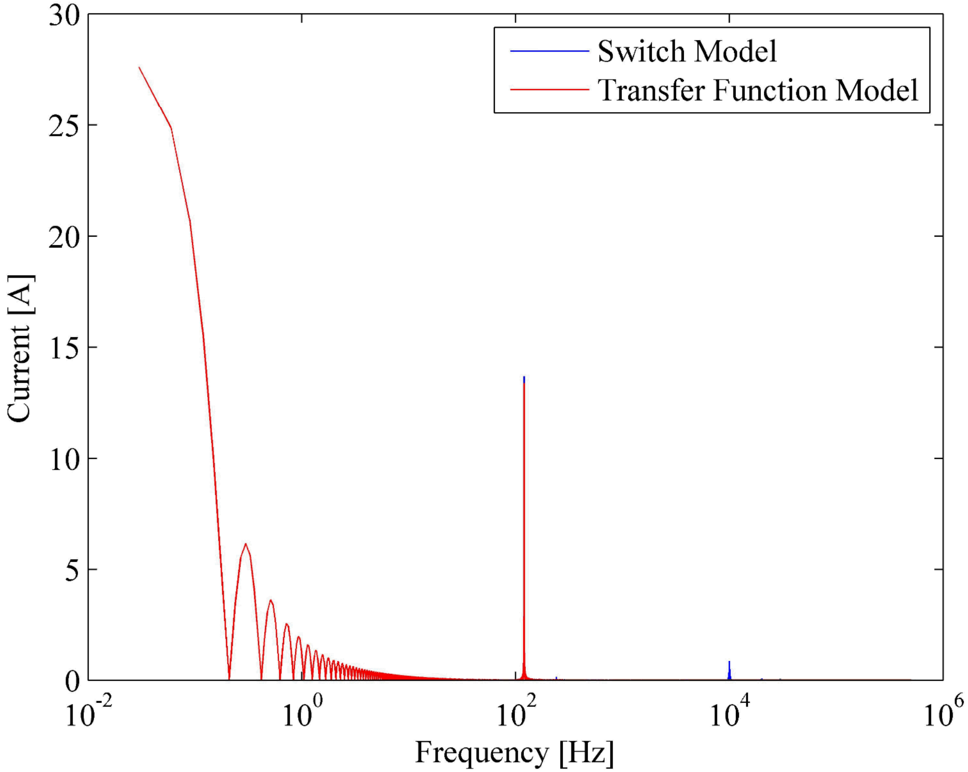
$$i_{inv,dc} = \frac{i_{L1,d} v_{av,d} + i_{L1,q} v_{av,q}}{2v_{dc}}$$

$$i_{inv,2q} = \frac{i_{L1,d} v_{av,q} + i_{L1,q} v_{av,d}}{2v_{dc}}$$

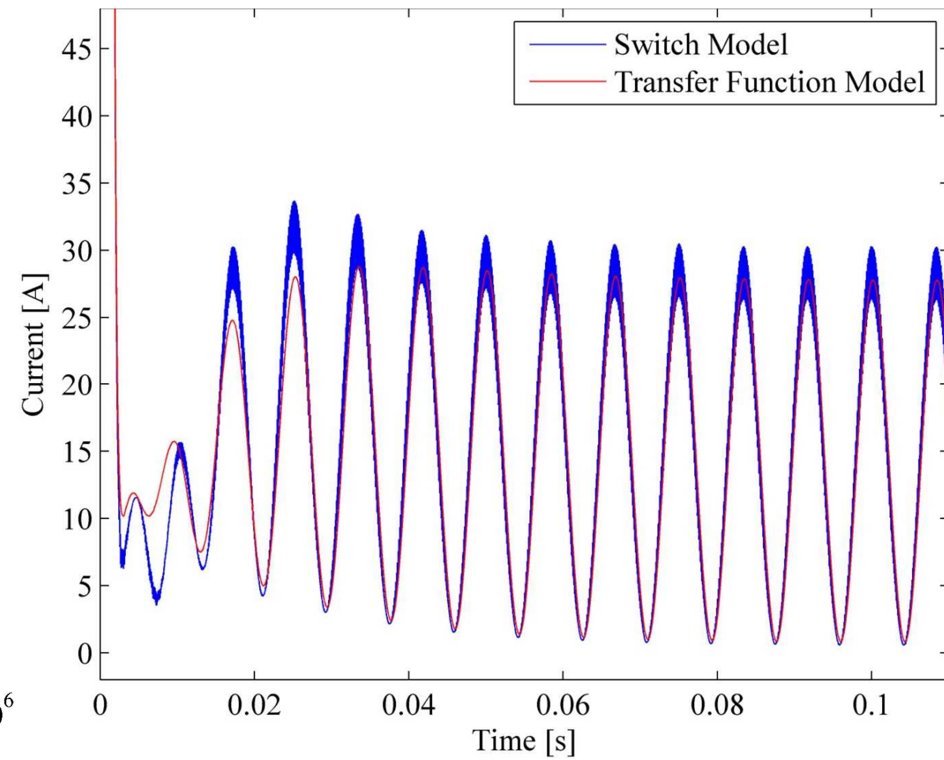
$$i_{inv,2d} = \frac{i_{L1,d} v_{av,d} - i_{L1,q} v_{av,q}}{2v_{dc}}$$

Simulation Verification of TF's

Battery Current – Switch model vs. mathematical model



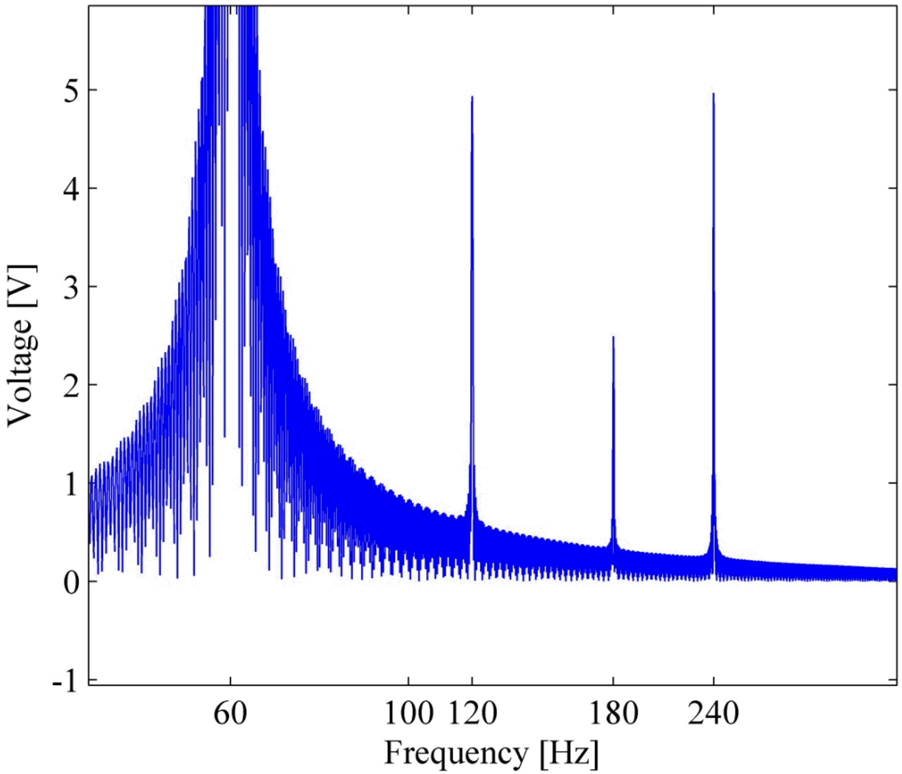
Frequency Domain



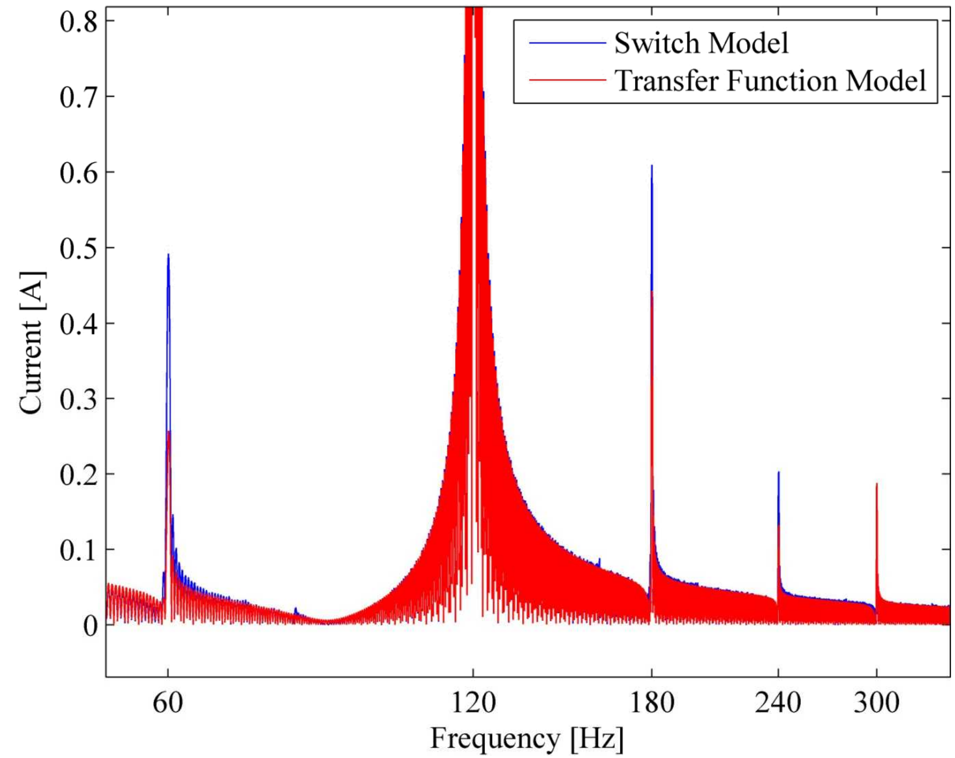
Time Domain

Watson, L.D.; Kimball, J.W.; Atcitty, S.; , "Linear single phase inverter model for Battery Energy Storage System evaluation and controller design," *Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE* , vol., no., pp.1861-1867, 5-9 Feb. 2012
doi: 10.1109/APEC.2012.6166075

Simulation Verification of TF's



Input Grid Voltage



Battery Current

Future work – Submit manuscript to IEEE journal

Thanks!

- Thanks to Dr. Imre Gyuk and the energy storage program for supporting this work.

Backup Slides

Derived Control to Output TF's

Controlling i_{grid}:

$$\frac{i_{gridd}}{v_{av}} = \frac{1}{C_f L_1 L_2 s^3 + (-C_f L_1 L_2 \omega^2 + L_1 + L_2)s}$$

Controlling i_{L1}:

$$\frac{i_{L1d}}{v_{av}} = \frac{C_f^2 L_2^2 s^4 + 2C_f L_2 (C_f L_2 \omega^2 + 1)s^2 + (C_f L_2 \omega^2 - 1)^2}{C_f^2 L_1 L_2^2 s^5 + C_f L_2 (2L_1 (C_f L_2 \omega^2 + 1) + L_2)s^3 + (L_1 (C_f L_2 \omega^2 - 1)^2 + C_f L_2^2 \omega^2 + L_2)s}$$

Harmonic Transfer Functions