Harmonic State Space (HSS) Modeling in Power Electronics

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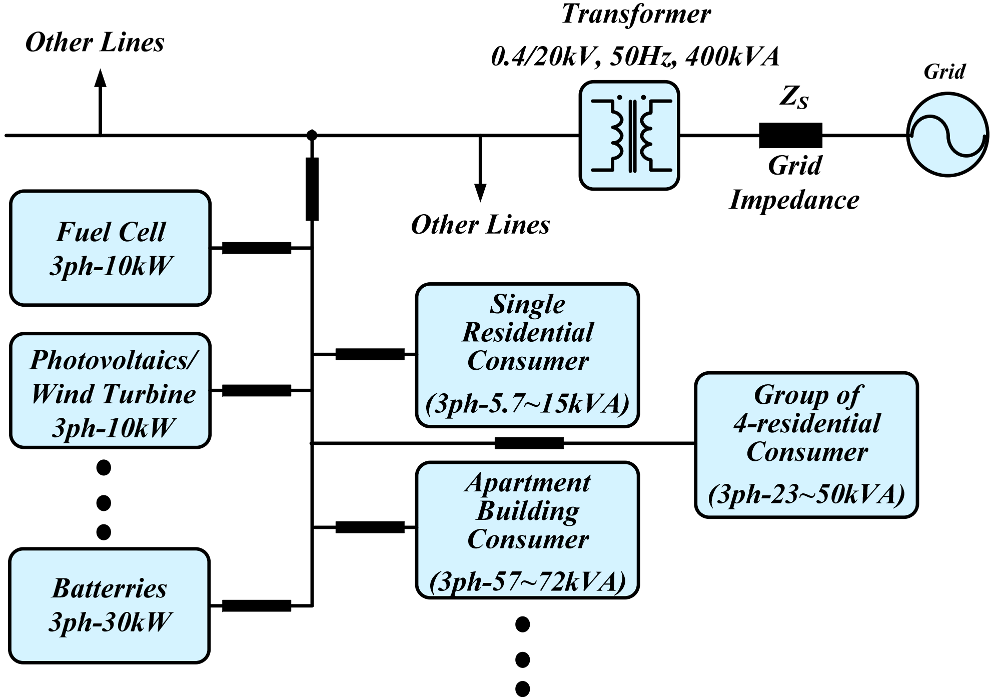
Outline

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

Background

❑ Power electronics based power system (Example)

Intermittent Operation !!

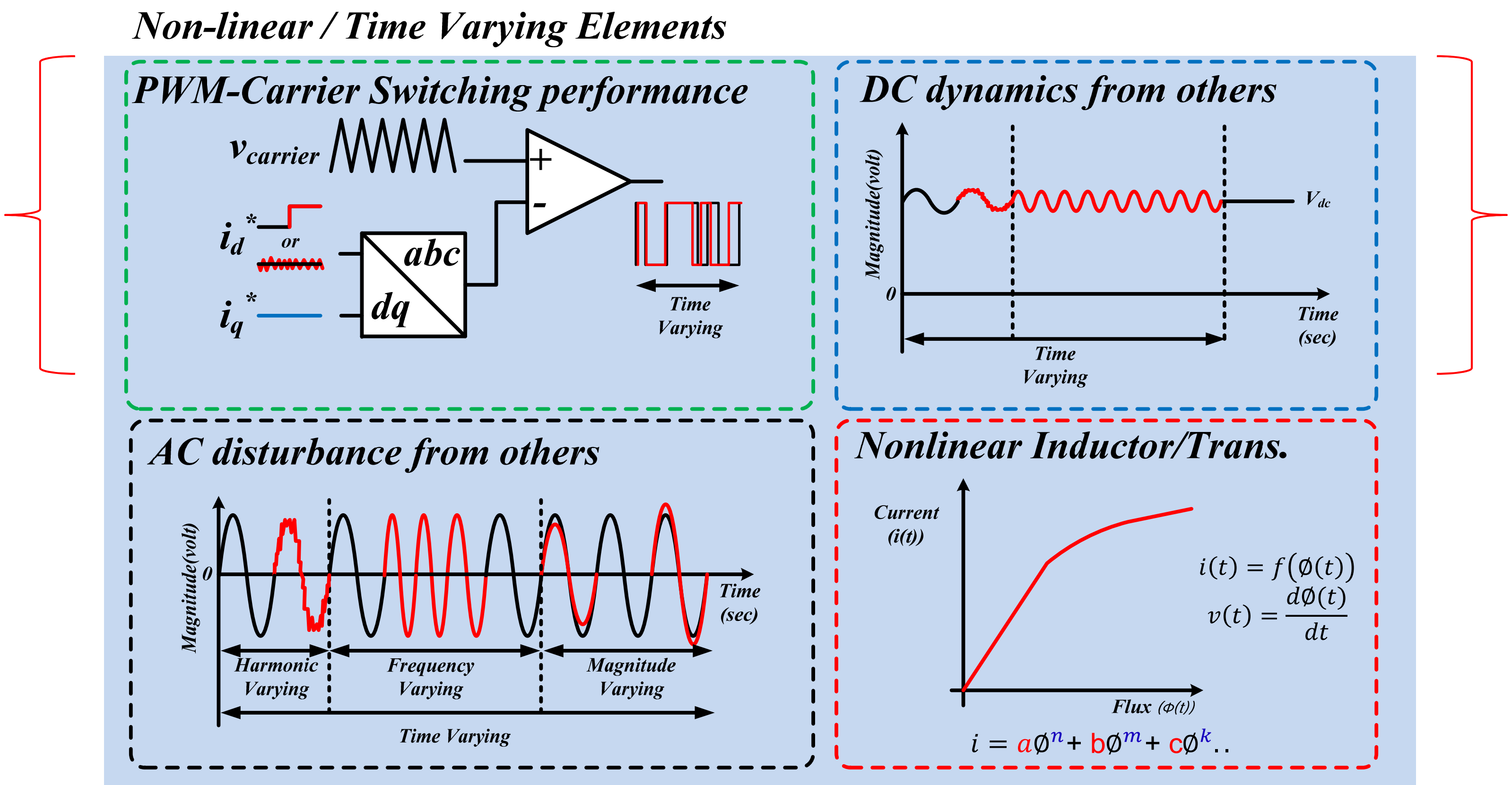


Simplified LV micro grid network (Cigre Benchmark)

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

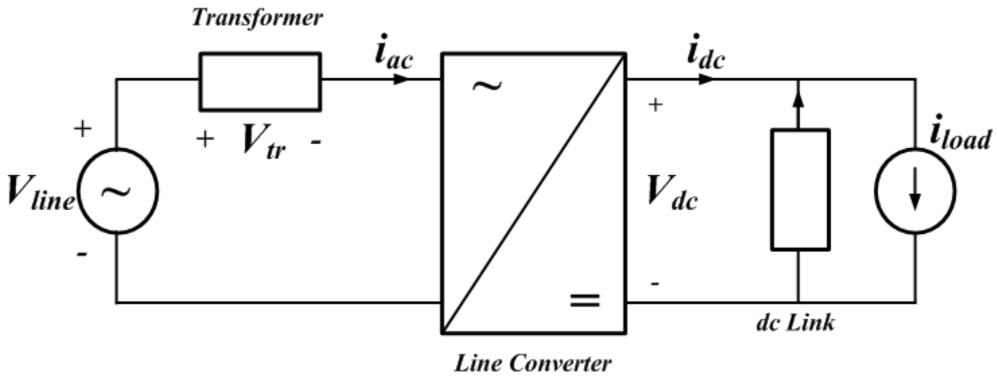
Problem & Motivation

- Time Varying Components in Power Electronics Converters



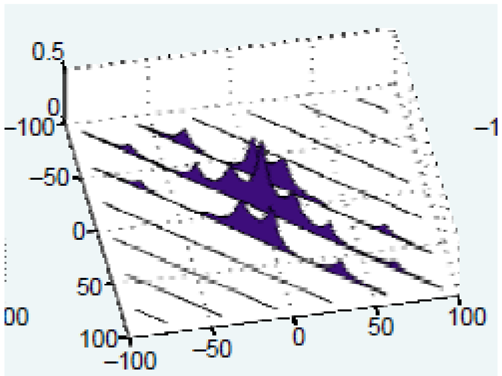
Problem & Motivation

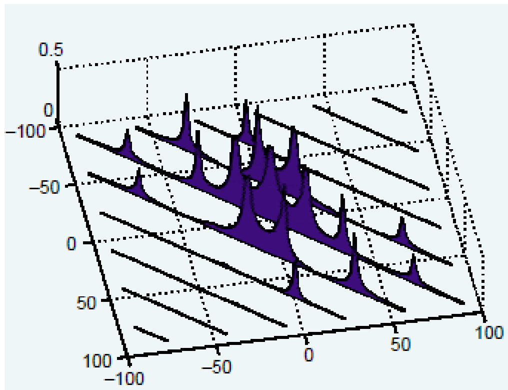
- Regional trains stopped (Example of LTP analysis)



Normal

Opeation





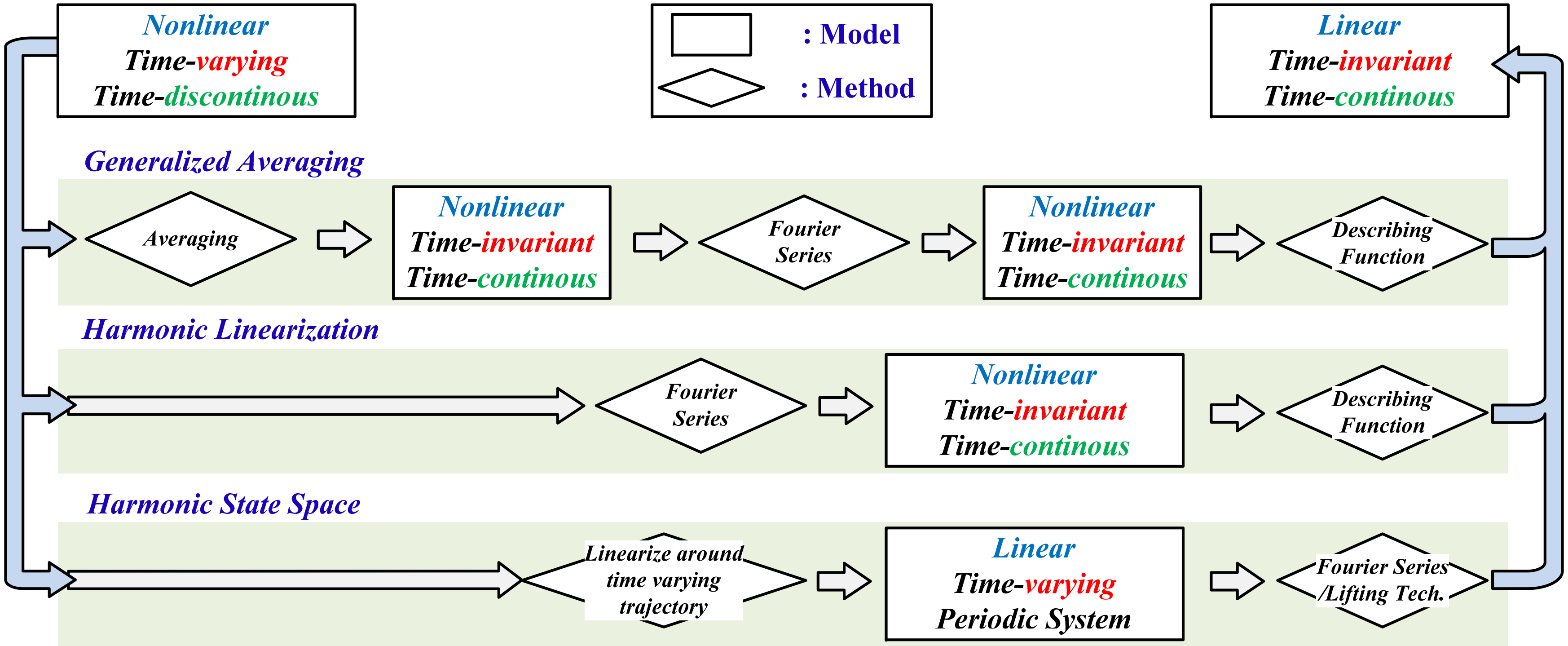
Breaking

operation

E. Mollerstedt and B. Bernhardsson, "Out of control because of harmonics-an analysis of the harmonic response of an inverter locomotive," *IEEE Trans. on Control Sys.*, vol. 20, pp. 70-81, 2000.

Problem & Motivation

- Handling a time-varying / nonlinear components



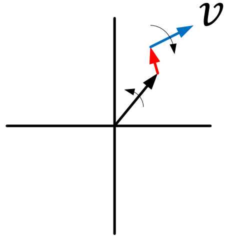
- *Conventional modeling approach didn`t consider the effect of time varying components.*
- *Including a time-varying / nonlinear components is a challenge in a modeling procedure*

HSS Modeling

- Basic Structure of LTP model

- Nonlinear State Space

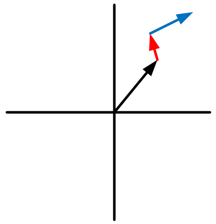
$$\dot{x} = f(x, t, u)$$
$$y = g(x, t, u)$$



- Linear Time Invariant (LTI)

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

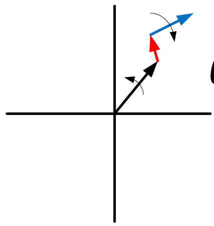
Linearize about a single state



- Linear Time Periodic (LTP)

$$\dot{x} = A(t)x + B(t)u$$
$$y = C(t)x + D(t)u$$

Linearize about a periodic state



[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

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$
$$y(t) = Cx(t) + Du(t)$$

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) \qquad (2)$$
$$y(t) = C(t)x(t) + D(t)u(t)$$

Time Varying Fourier Coefficient

$$x(t) = \Gamma(t)X \qquad (3)$$

where,

$$\Gamma(t) = \left[e^{-jh\omega_0 t} \cdots e^{-j2\omega_0 t}, e^{-j\omega_0 t}, 1, e^{j\omega_0 t}, e^{j2\omega_0 t} \cdots e^{jh\omega_0 t}\right]$$
$$X = [X_{-h}(t) \cdots X_{-1}(t) X_0(t) X_1(t) \cdots X_h(t)]^T$$

Time Varying Fourier Coefficient

$$\dot{x}(t) = \dot{\Gamma}(t)X + \Gamma(t)\dot{X} \qquad (4)$$

$$sX(\omega, t) = A(\omega) \otimes X(\omega, t) + B(\omega) \otimes U(\omega, t) \qquad (5)$$
$$Y(\omega, t) = C(\omega) \otimes X(\omega, t) + D(\omega) \otimes U(\omega, t)$$

Harmonic State Space Model

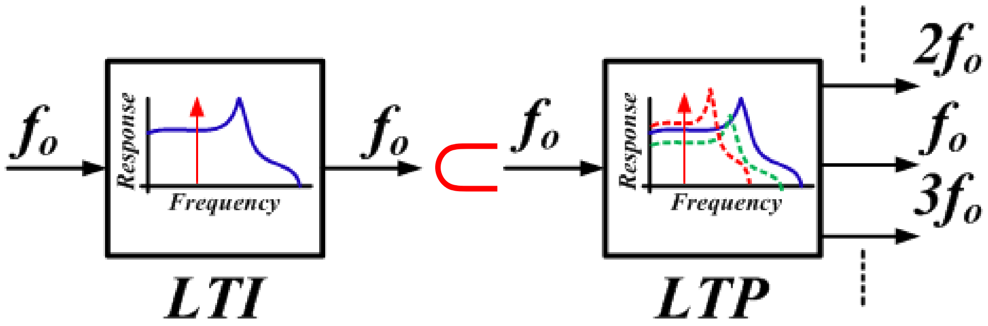
$$(s + jm\omega_0)X_n = \sum_{-\infty}^{\infty} A_{n-m}X_m + \sum_{-\infty}^{\infty} B_{n-m}U_m \qquad (6)$$
$$Y_n = \sum_{-\infty}^{\infty} C_{n-m}X_m + \sum_{-\infty}^{\infty} D_{n-m}U_m$$

$$sX = (A - N)X + BU \qquad (7)$$
$$Y = CX + DU$$

HSS Modeling

- Introduction of LTP theory

Single-frequency response



Multi-frequency response

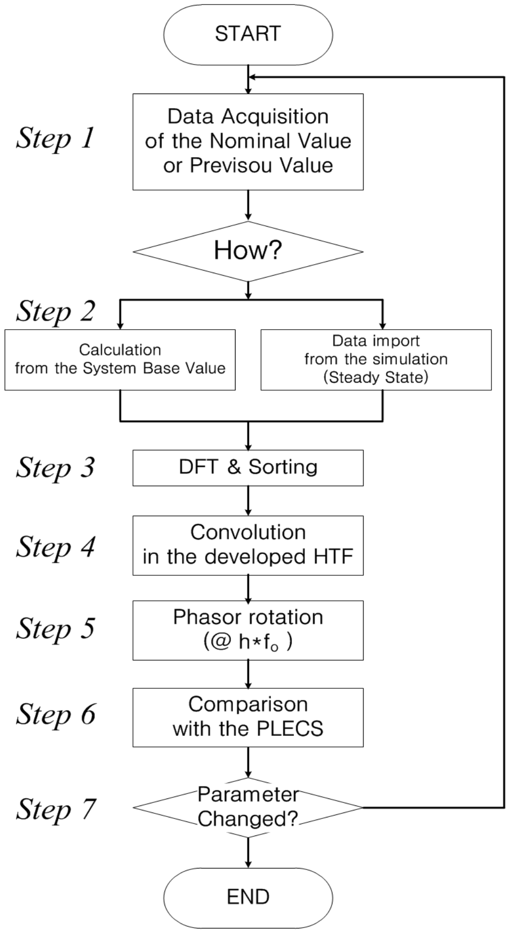
Advantages of HSS

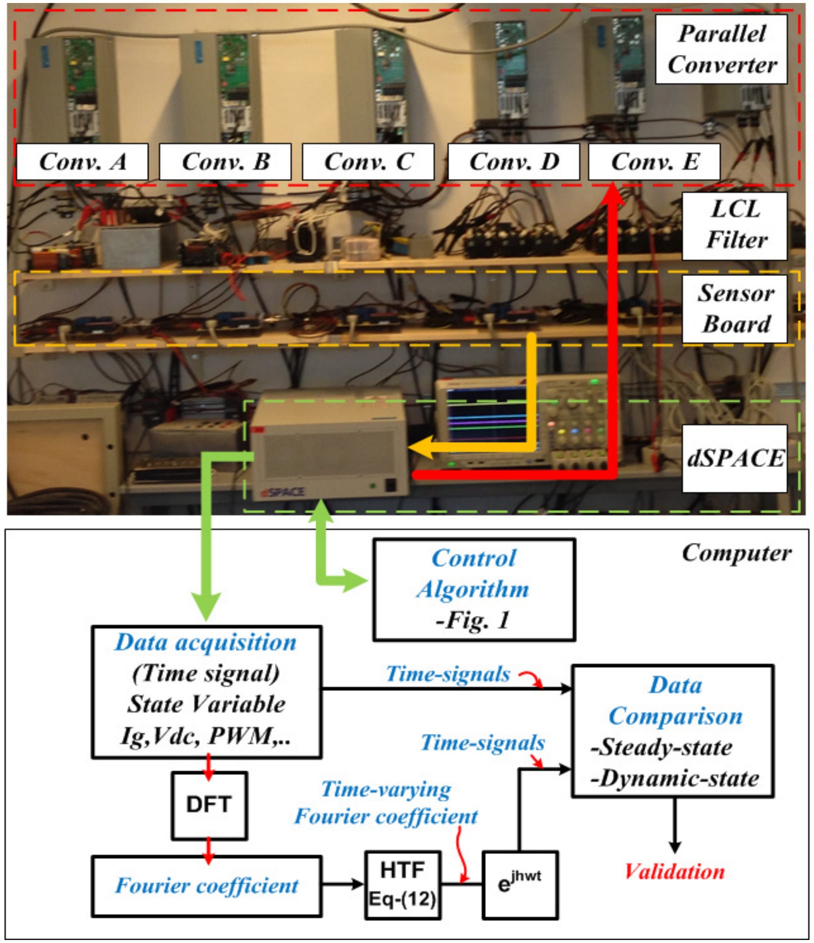
- **Dynamics of each harmonics**
- **Coupling analysis of AC-DC system.**
- **Including time - varying component**
- **Easy to be connected with other system matrix**
- **Possibility to figure out the characteristic, which can not be found in LTI model.**

N. M. Wereley and S. R. Hall, "Frequency response of linear time periodic systems," in *Proceedings of the 29th IEEE Conference on Decision and Control, 1990.*, 1990, pp. 3650-3655 vol.6.

Simulation & Experiments

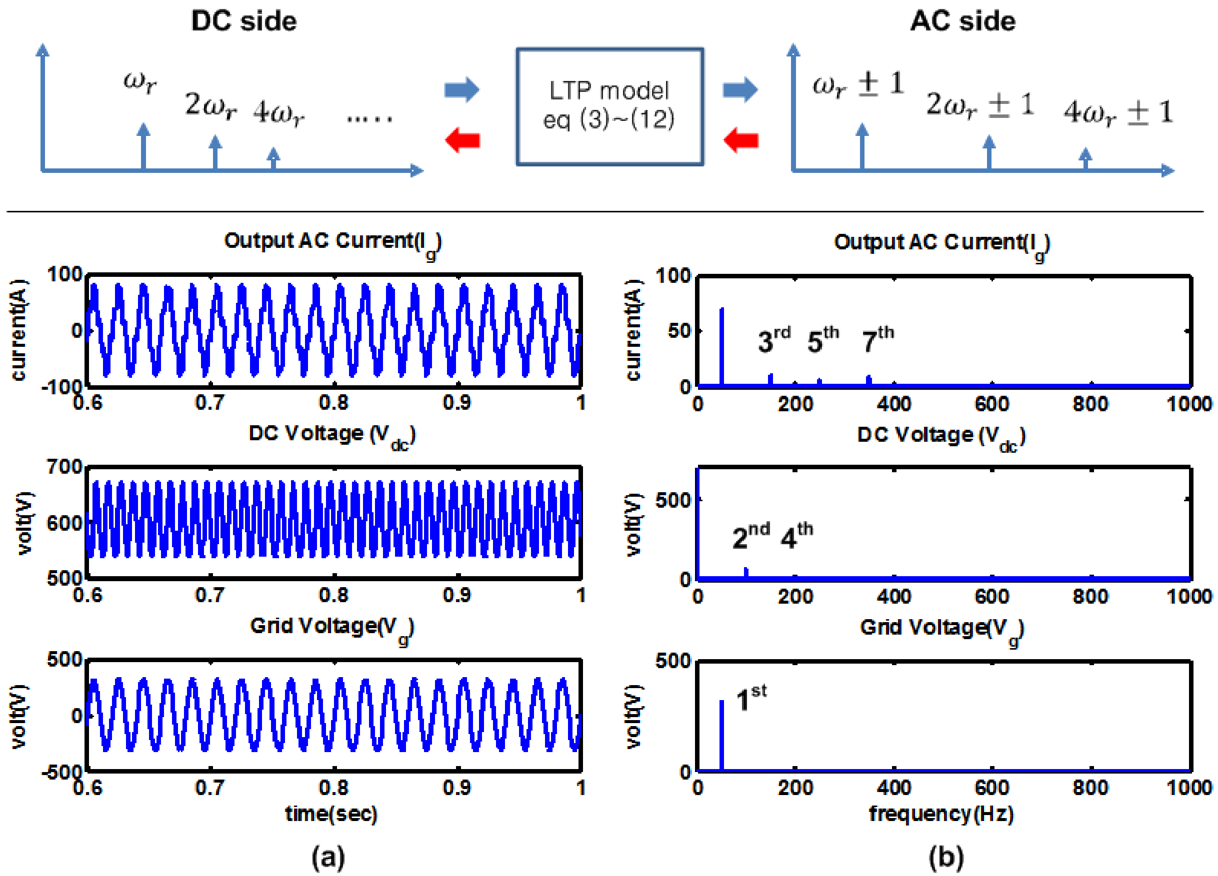
- Flow chart for the HTF simulation and Experimental Validation





Simulation & Experiments

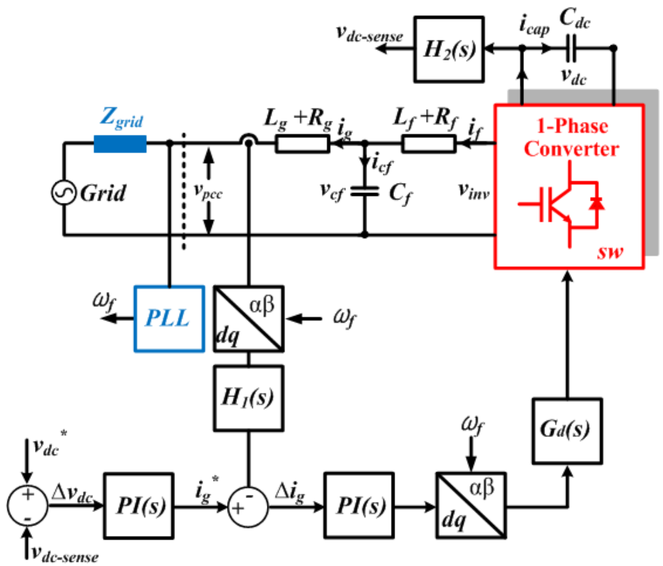
- Harmonic coupling - Single phase converter

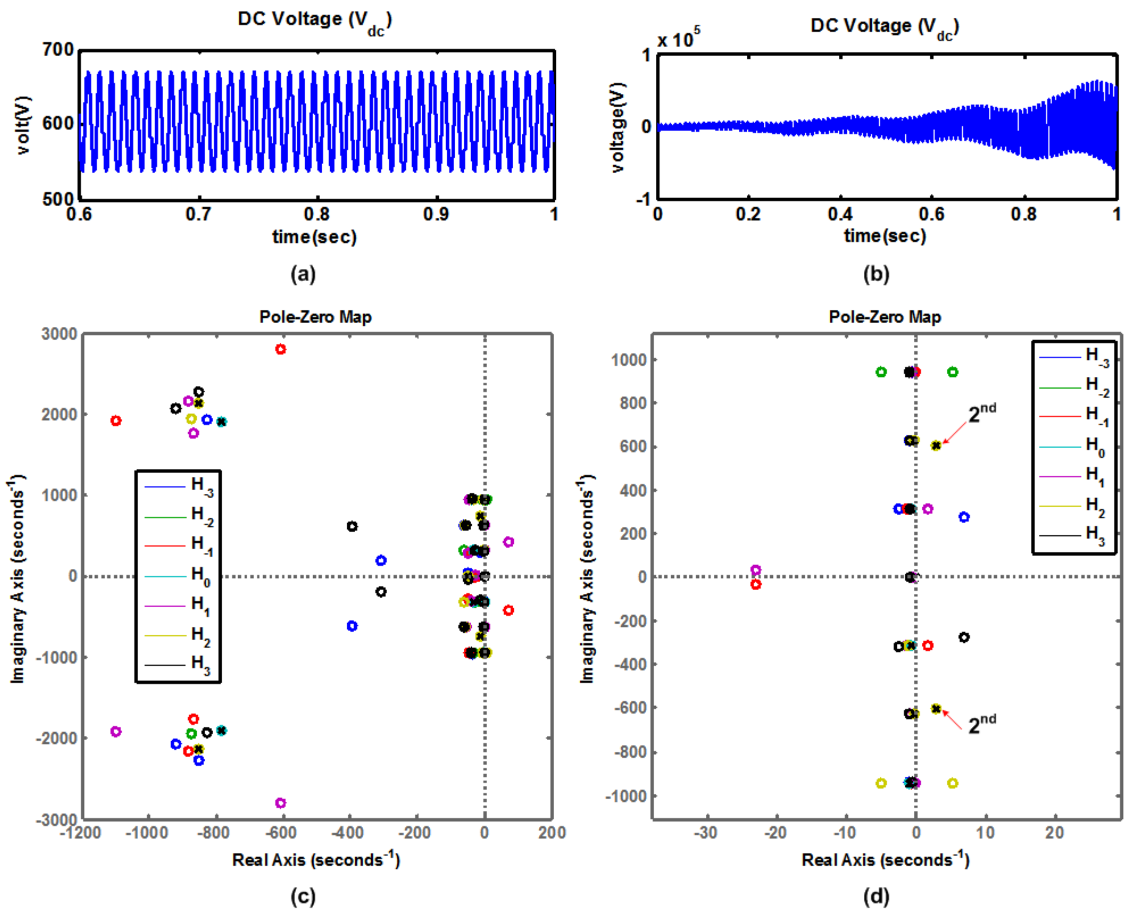


J. Kwon, X. Wang, C.L. Bak, F. Blaabjerg, “Harmonic Instability Analysis of Single Phase Grid Connected Converter using Harmonic State Space (HSS) modeling method”, in Proc. IEEE ECCE 2015.

Simulation & Experiments

- Dynamic simulation – Single phase converter





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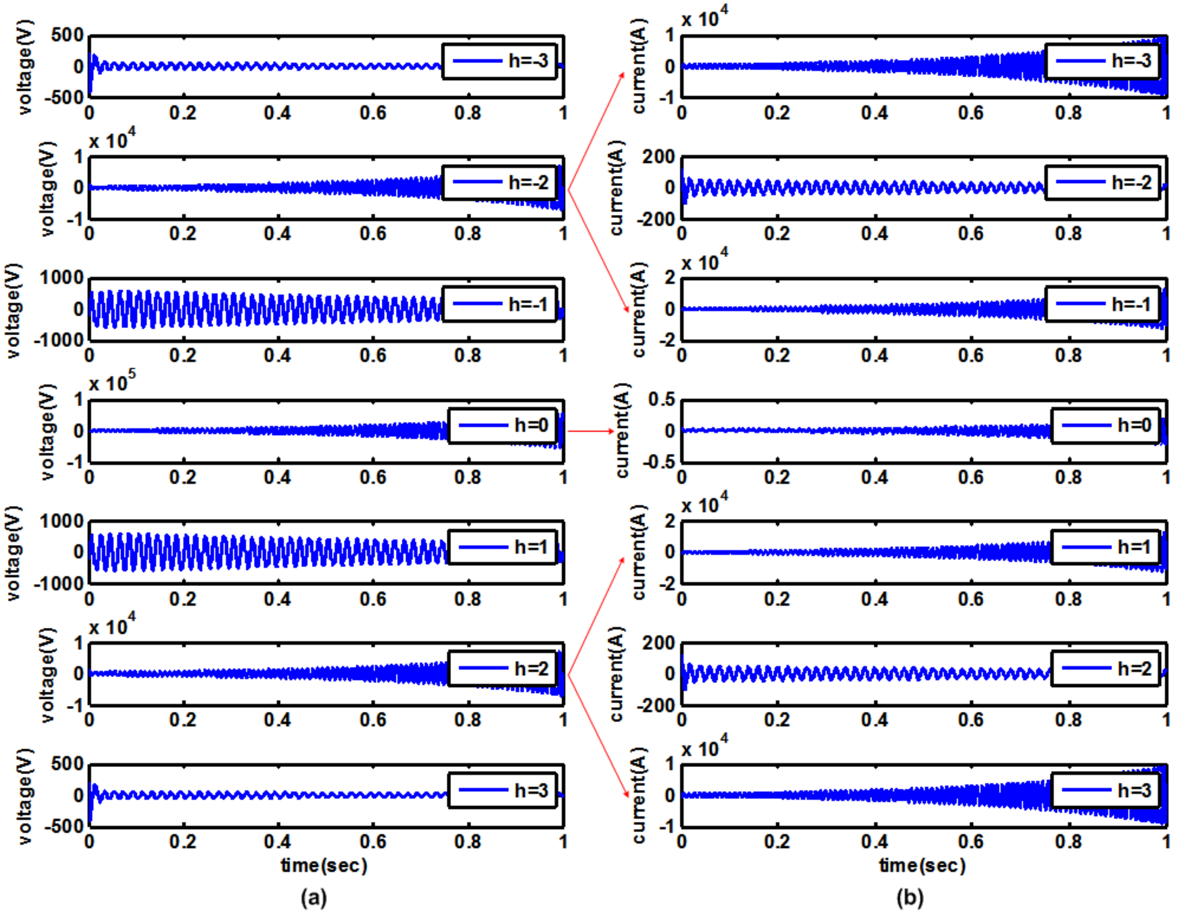
Simulation & Experiments

- Dynamic harmonic response – Single phase converter (Instability)



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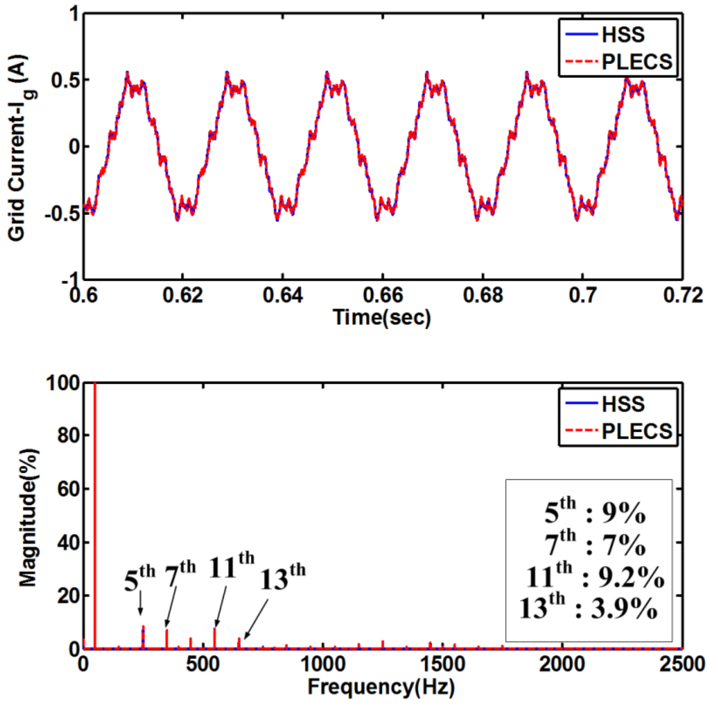
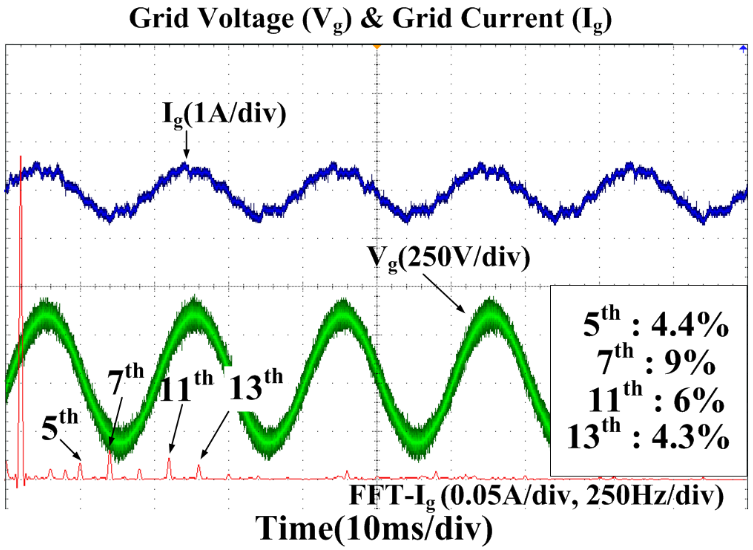
Simulation & Experiments

- Experimental Validation



(a)



(b)

J. Kwon, X. Wang, C.L. Bak, F. Blaabjerg, “Analysis of Harmonic Coupling and Stability in Back to Back Converter Systems for Wind Turbines using Harmonic State Space (HSS)”, in Proc. IEEE ECCE 2015.

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?

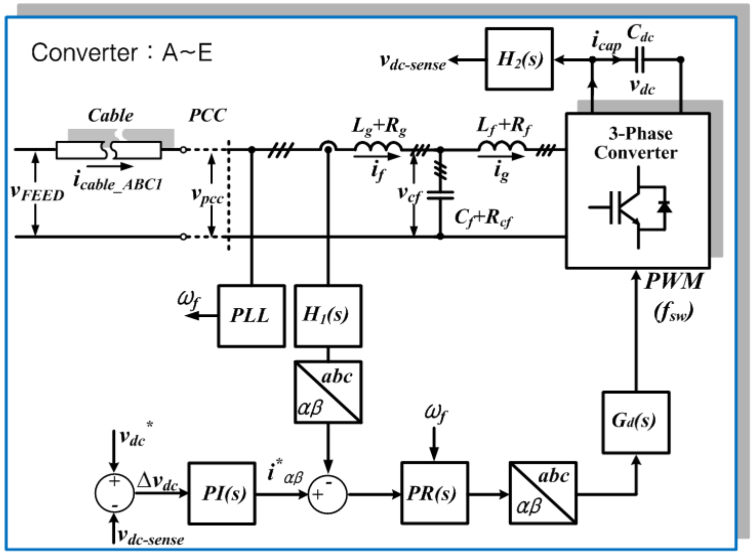
“ THE HIDDEN HARMONY IS BETTER THAN THE OBVIOUS ”

- P. PICASSO

www.harmony.et.aau.dk

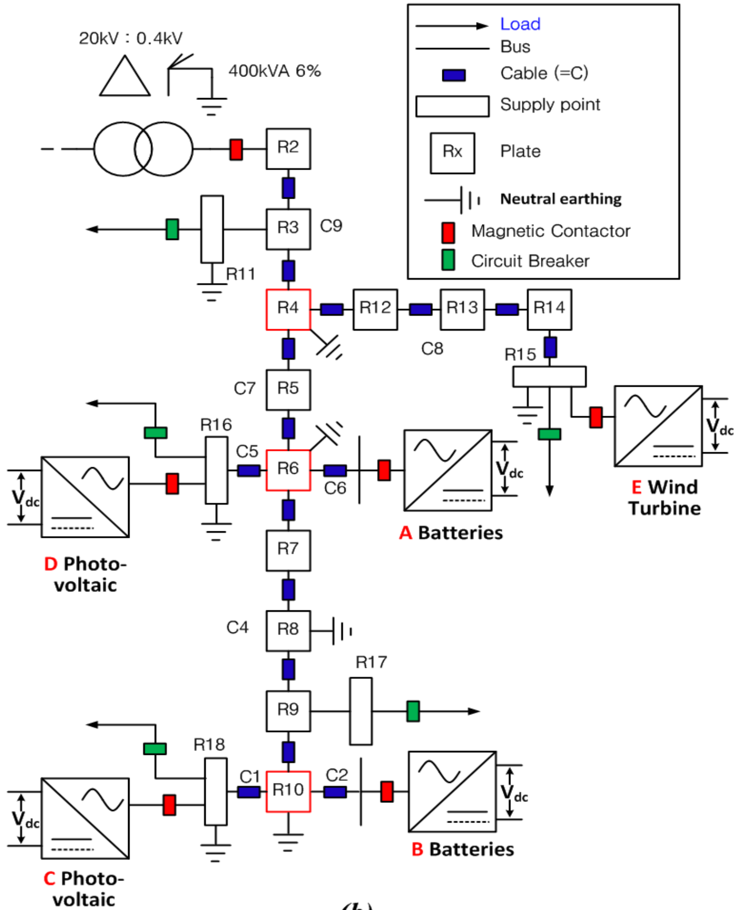
Simulation

- Multi connected grid converter



(a)

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

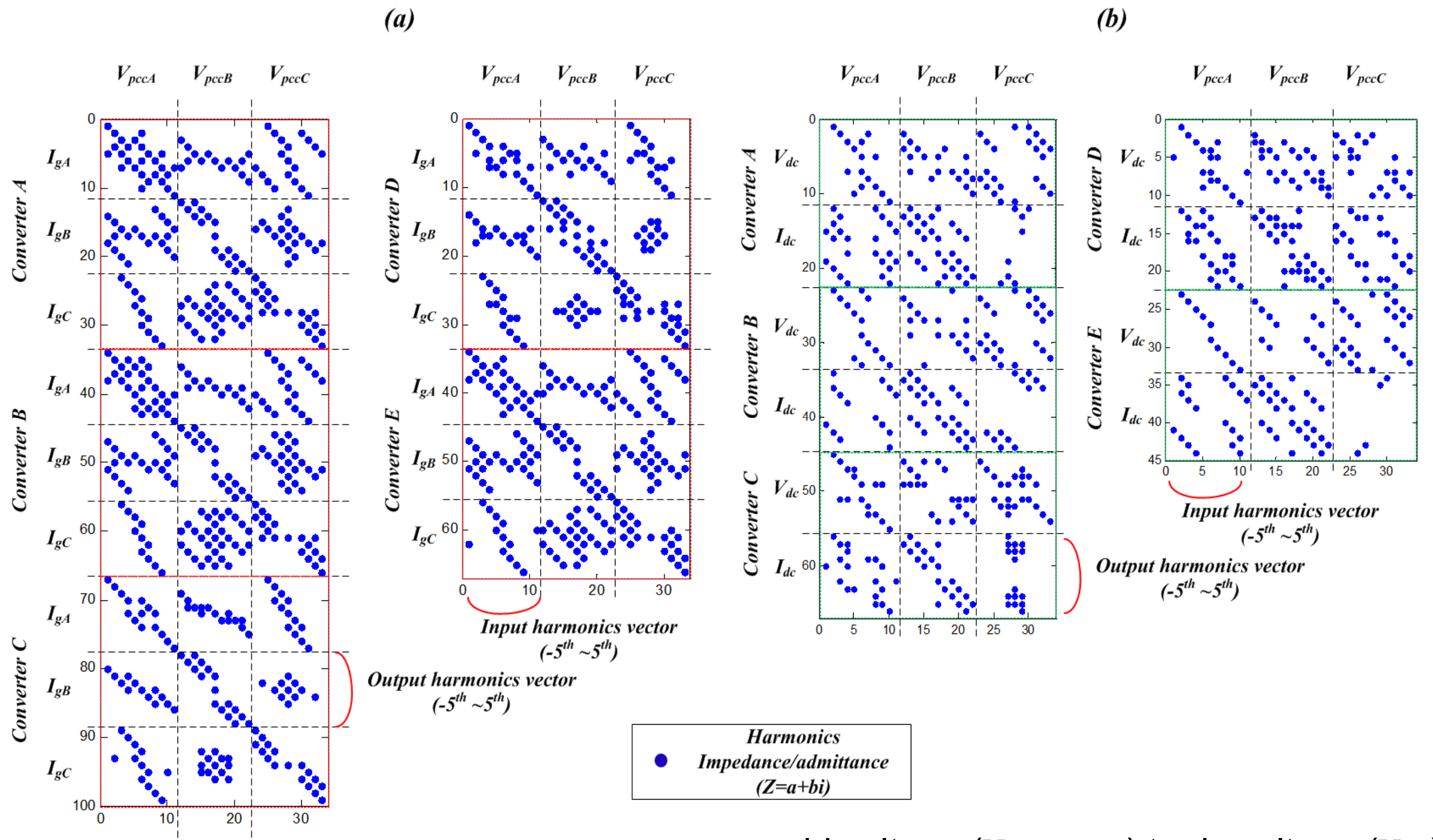


(b)

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

Simulation

- Jacobian Sparse Matrix– Multi-parallel connected converter



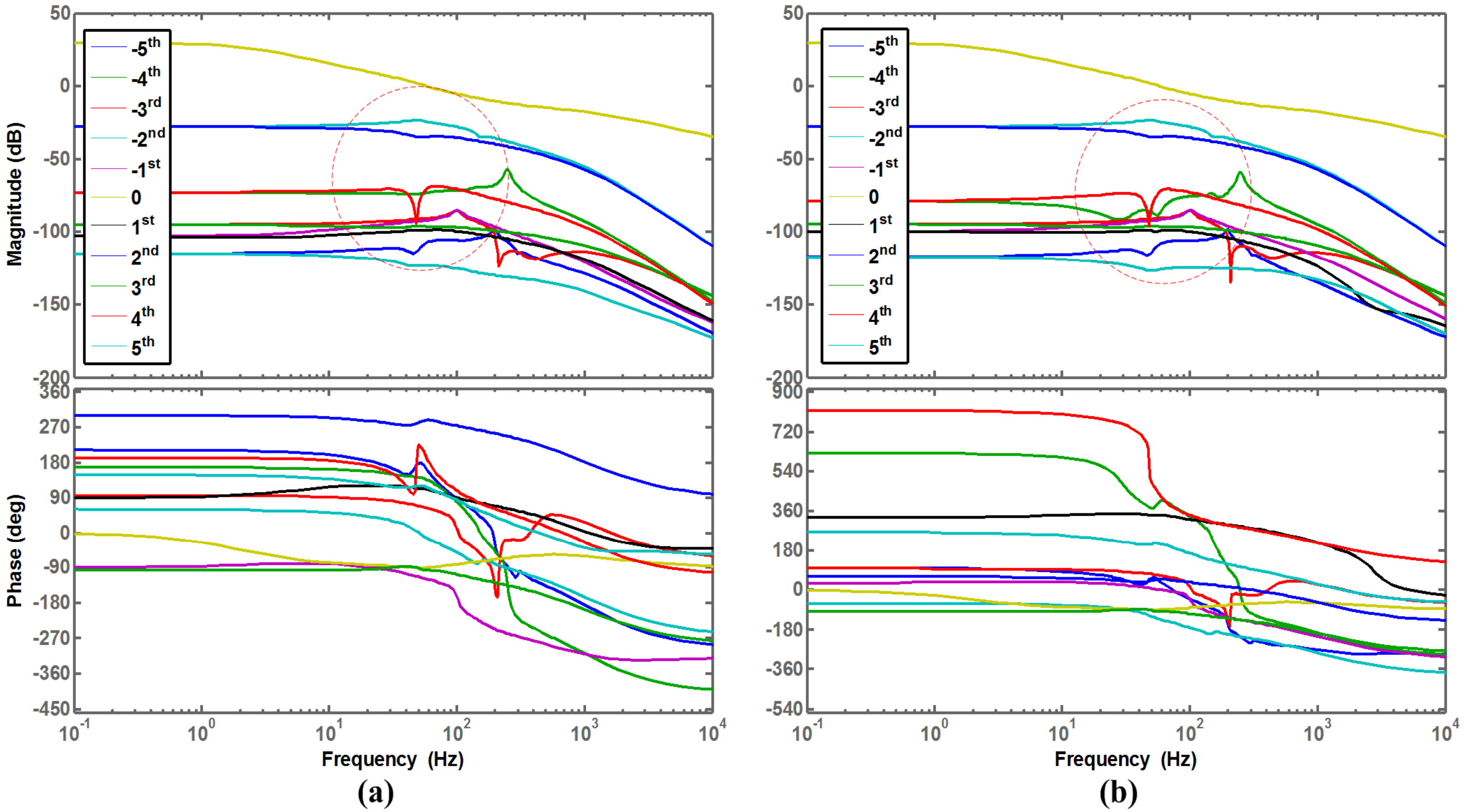
grid voltage ($V_{line-ABC}$) to grid current (I_{g-ABC})

grid voltage ($V_{line-ABC}$) to dc voltage (V_{dc}) and dc current (I_{dc})

J. Kwon, X. Wang, C.L. Bak, F. Blaabjerg, "The Modeling and Harmonic Coupling Analysis of Multiple-Parallel Connected Inverter Using Harmonic State Space (HSS)", in Proc. IEEE ECCE 2015.

Simulation

- Dynamic simulation – Multi-parallel connected converter



Converter - A (I_{g-A}/V_{pcc-A}),   Converter - A (I_{g-B}/V_{pcc-B})

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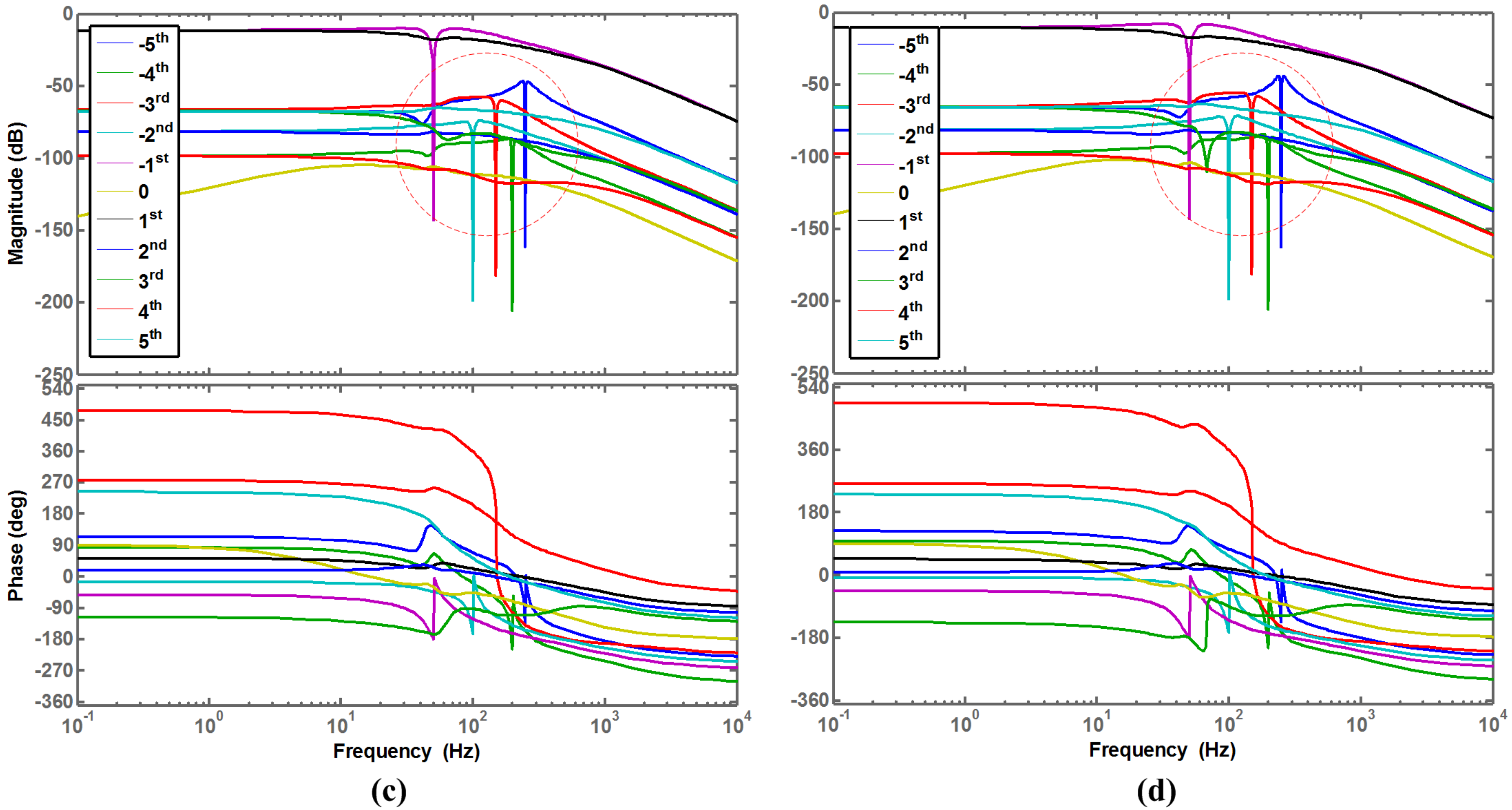
Simulation

- Dynamic simulation – Multi-parallel connected converter



Converter – A (V_{dc-A}/V_{pcc-A}), $\mathrm{I}_{\mathrm{dc-load}} = 75A_{dc}$

Converter – A (V_{dc-A}/V_{pcc-A}), $\mathrm{I}_{\mathrm{dc-load}} = 13A_{dc}$

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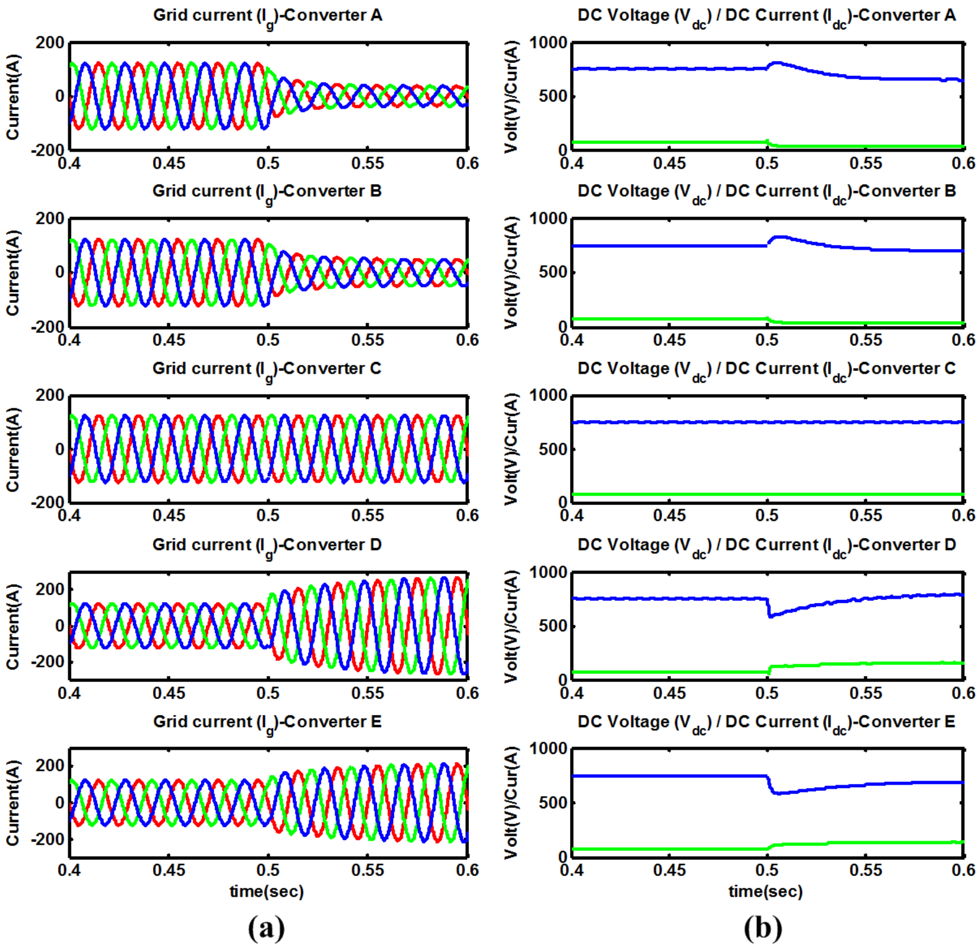
Simulation

- Dynamic simulation – Multi-parallel connected converter



	V_{dc} (v)	R_{dc} (Ohm)
Conv.A	650	50
Conv.B	700	20
Conv.C	750	10
Conv.D	800	5
Conv.E	700	5

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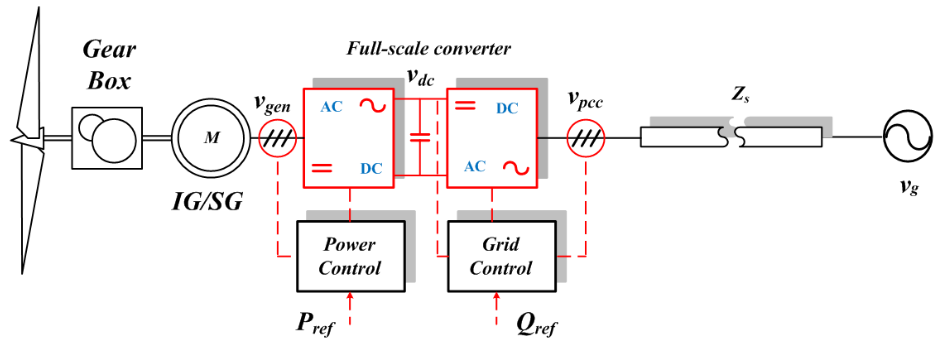
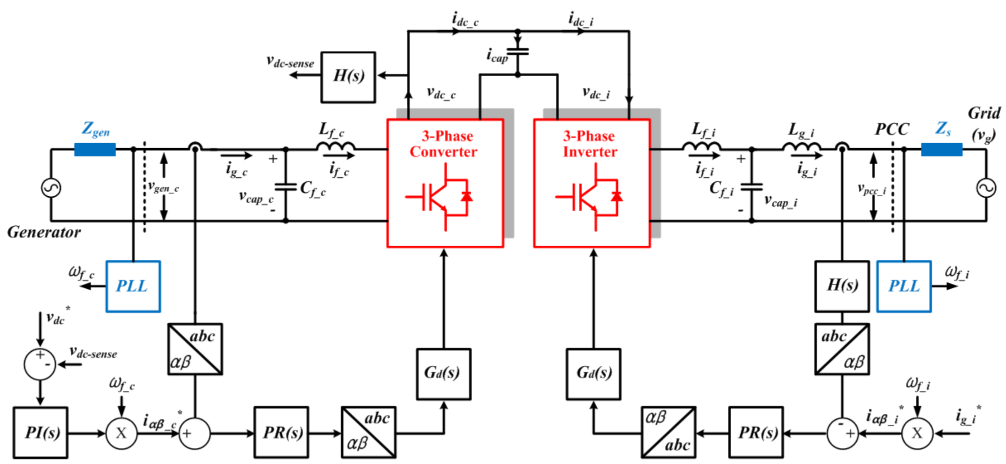
Simulation & Experiments

- Back-to-Back Converter



(a)

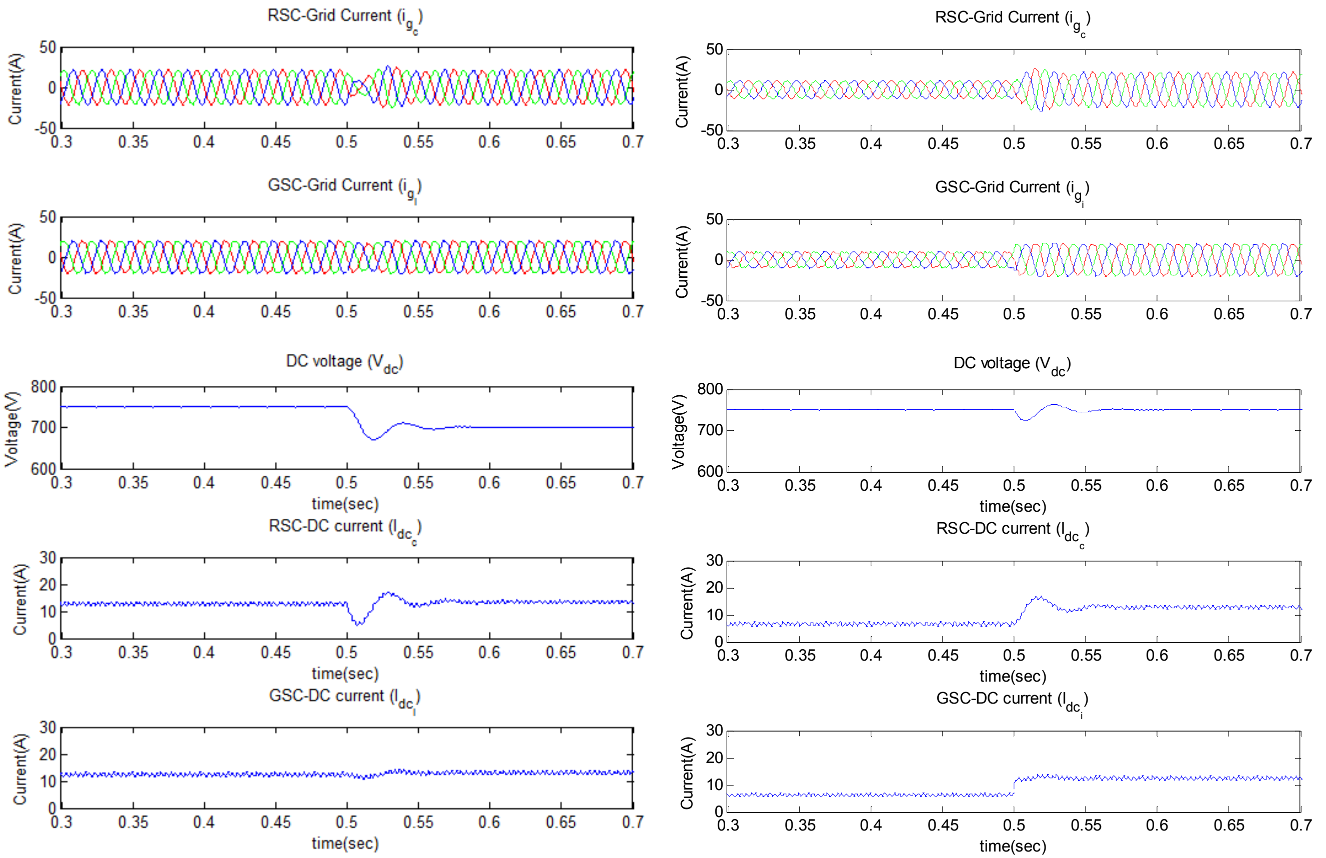


(b)

J. Kwon, X. Wang, C.L. Bak, F. Blaabjerg, "Analysis of Harmonic Coupling and Stability in Back to Back Converter Systems for Wind Turbines using Harmonic State Space (HSS)", in Proc. IEEE ECCE 2015.

Simulation & Experiments

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



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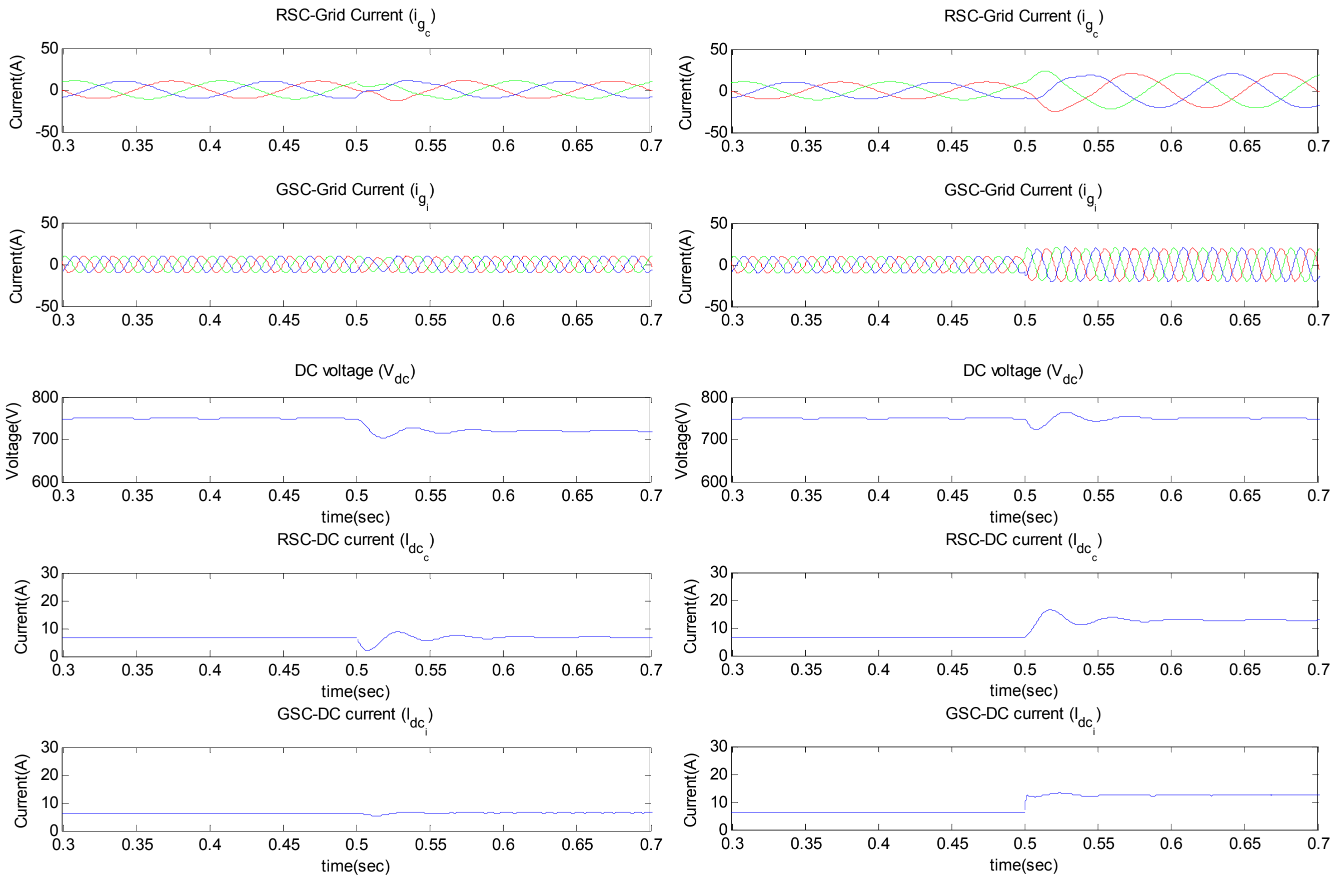
Simulation & Experiments

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



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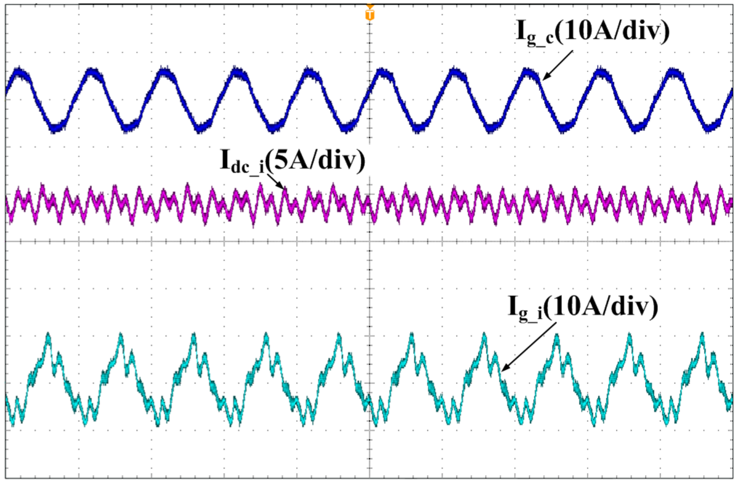
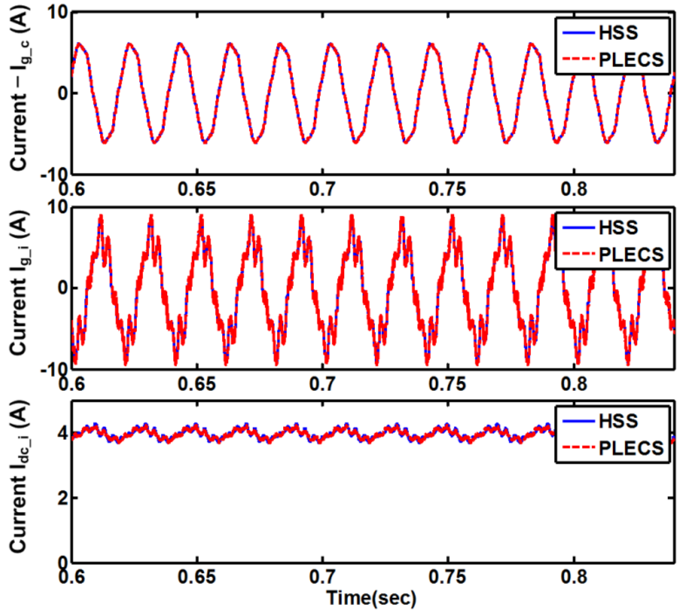
Simulation & Experiments

❑ Experimental Validation



(a)



(b)

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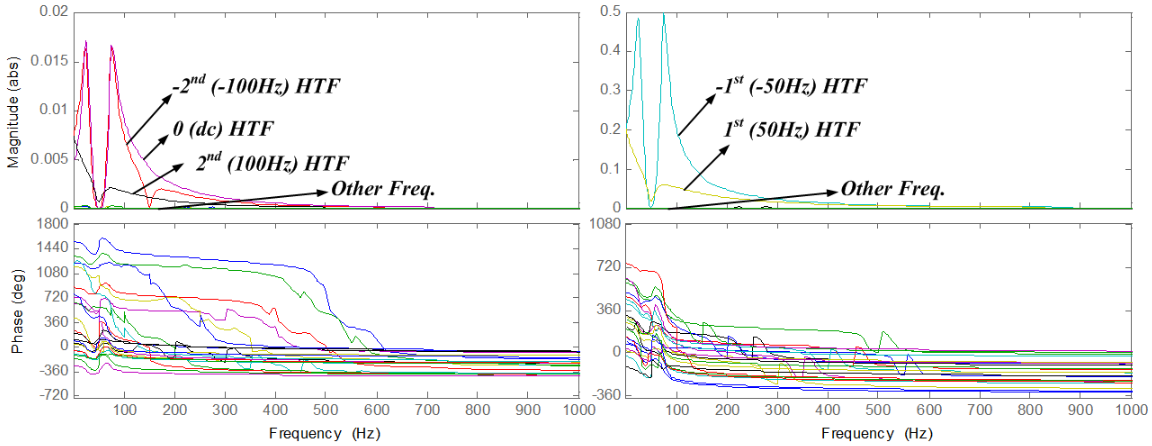
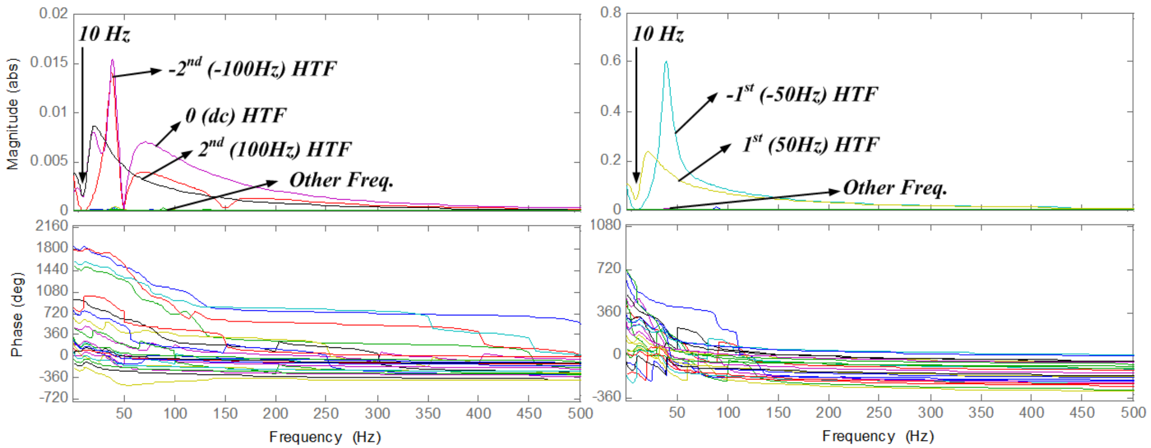
Simulation & Experiments

- Dynamic simulation – Back to Back converter



RSC=50 Hz, GSC=50Hz



RSC=10 Hz, GSC=50Hz

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