

GRID EMT

SIMULATION INITIATIVE

EMT Analysis in the Frequency Domain

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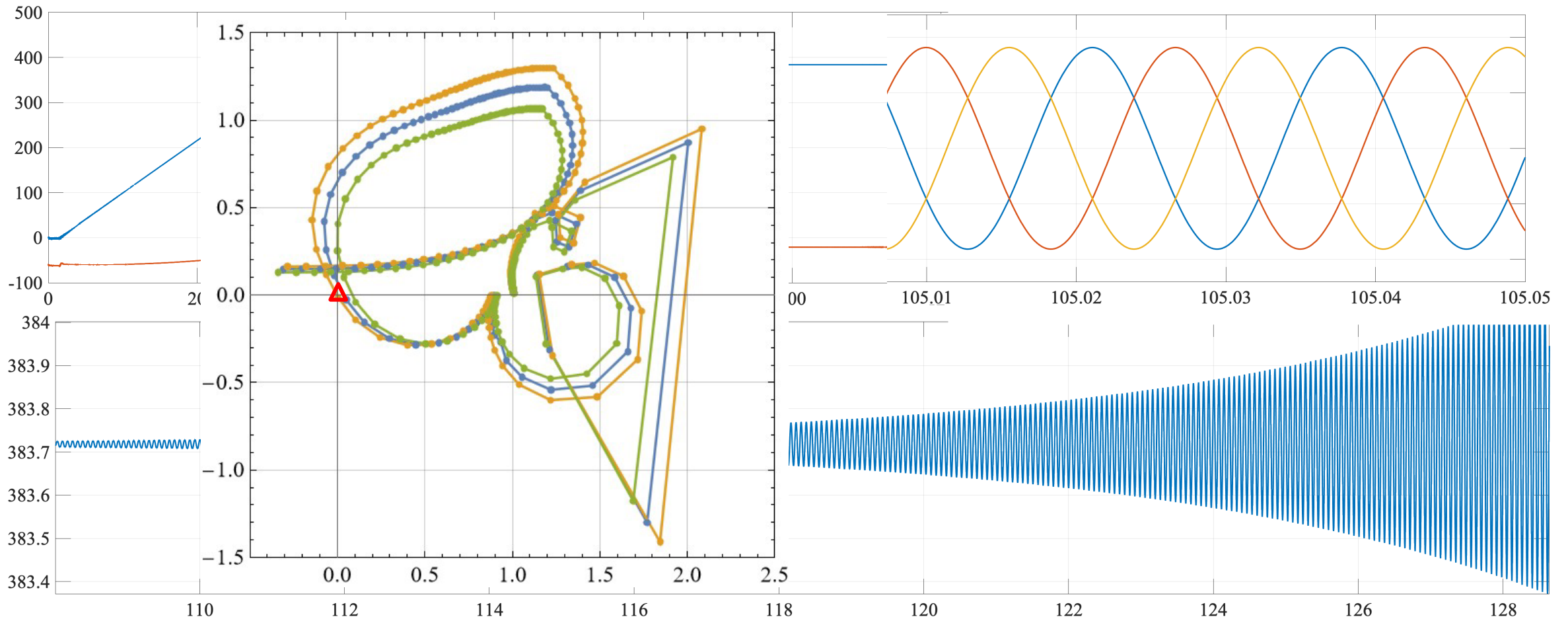
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EMT and Frequency-Domain Analysis

- Frequency-Domain Analysis Offers Several Advantages
 - Very Efficient, Easily Scalable
 - Predict Stability and Stability Margin
- Additional Advantages of Impedance-Based Frequency-Domain Methods
 - Input/Output Models Protect Internal Design IP
 - Leverages Linear Network Theory in System Modeling
 - Easy Model Reduction by Aggregation and Equivalent Circuits
- Limited to Small-Signal Stability



Simulation vs. Frequency-Domain Analysis of Stability

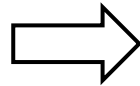
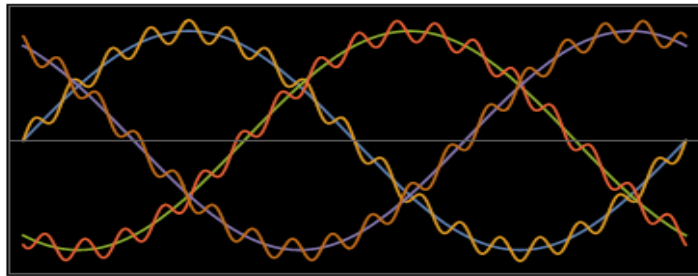


Linearization of EMT Models

- EMT Models are Nonlinear in General
- Direct Linearization Leads to Linear Time-Periodic (LTP) Models

$$[x(\omega_1 t) + \Delta x] \cdot [y(\omega_1 t) + \Delta y] \rightarrow x(\omega_1 t)y(\omega_1 t) + y(\omega_1 t) \cdot \Delta x + x(\omega_1 t) \cdot \Delta y$$

- Solution: Harmonic Linearization
 - Same Principle for Analytical Modeling, Measurement and Numerical Scan

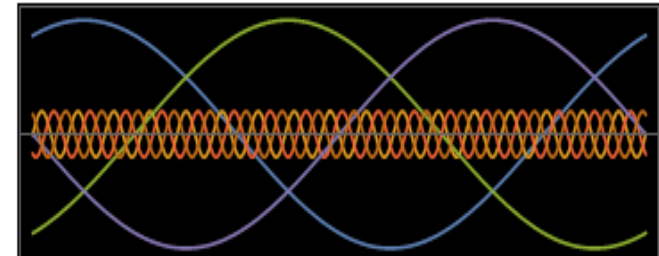


Converter to
be Modeled

f_1

f_p

Other f



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Definition of Converter Models

Impedance + Admittance → Immittance

Voltage Perturbation	Self Admittance	Transfer Admittance	
AC Port, Positive Sequence $\hat{v}_p(s)$	$Y_{pp}(s) = \frac{\hat{i}_a(s)}{\hat{v}_p(s)}$	$Y_{pd}(s) = \frac{\hat{i}_{dc}(s - j\omega_1)}{\hat{v}_p(s)}$	$Y_{pn}(s) = \frac{\hat{i}_a(s - j2\omega_1)}{\hat{v}_p(s)}$
AC Port, Negative Sequence $\hat{v}_n(s)$	$Y_{nn}(s) = \frac{\hat{i}_a(s)}{\hat{v}_n(s)}$	$Y_{nd}(s) = \frac{\hat{i}_{dc}(s + j\omega_1)}{\hat{v}_n(s)}$	$Y_{np}(s) = \frac{\hat{i}_a(s + j2\omega_1)}{\hat{v}_n(s)}$
DC Port $\hat{v}_{dc}(s)$	$Y_{dd}(s) = \frac{\hat{i}_{dc}(s)}{\hat{v}_{dc}(s)}$	$Y_{dp}(s) = \frac{\hat{i}_a(s + j\omega_1)}{\hat{v}_{dc}(s)}$	$Y_{dn}(s) = \frac{\hat{i}_a(s - j\omega_1)}{\hat{v}_{dc}(s)}$

- Traditional **Frequency Scanning** Considers Only Positive-Sequence Perturbation and Responses at the Same Frequency



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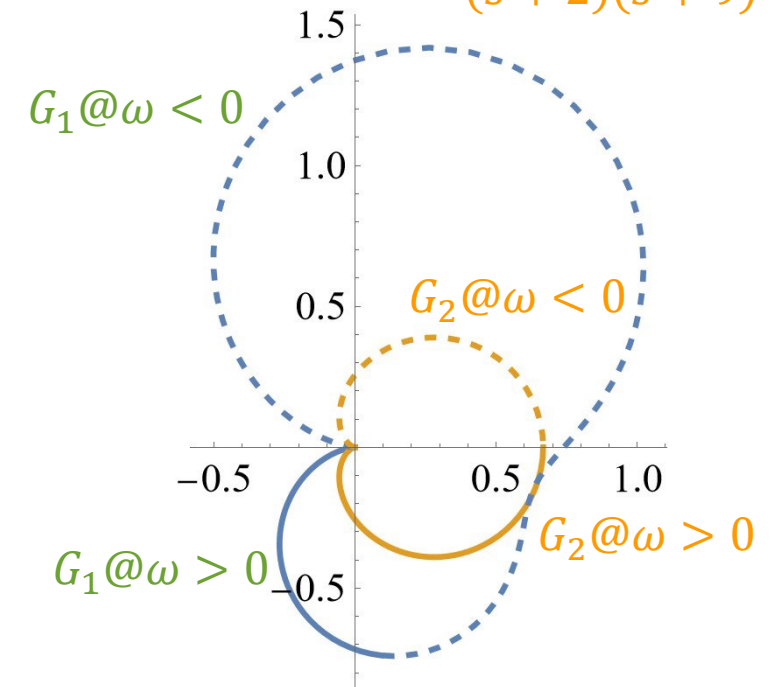
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Why Positive AND Negative Sequence Modeling?

- Instability May Occur in Either Sequence
- Immittance Models have Complex Coefficients
 - Frequency Response May not be Complex-Conjugate Symmetric about $\omega = 0$
 - Nyquist Analysis Must Cover Positive & Negative ω
 - Response at Negative Frequency cannot be Scanned
 - (PS Model at $-\omega$)* = NS Model at $-\omega$
 - PS Response at $-\omega = (\text{NS Response at } +\omega)^*$
- **System Stability = Stability in PS & NS for $\omega > 0$**

$$G_1(s) = \frac{12}{(s+2)(s+1+j8)}$$

$$G_2(s) = \frac{12}{(s+2)(s+9)}$$

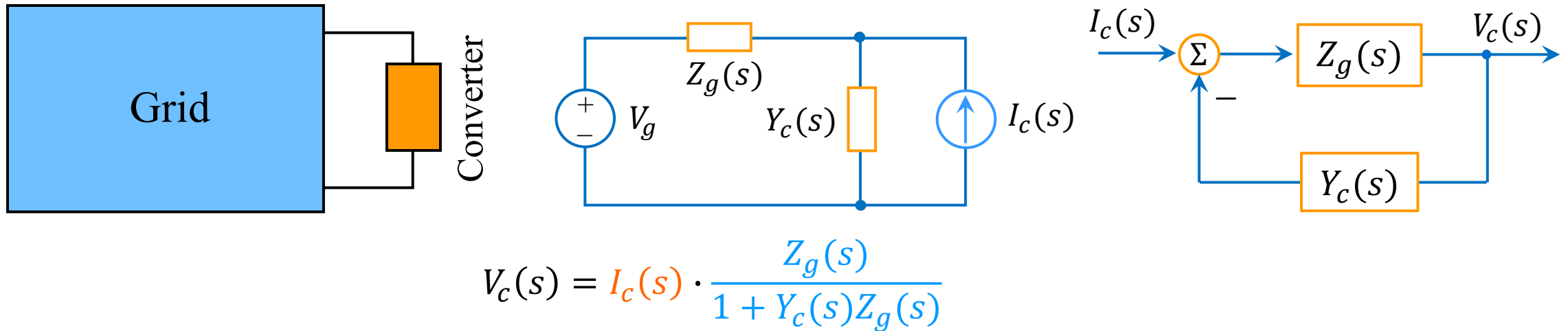


Theoretical Framework

- Characterize Individual Components by Immittances
 - Operated with Ideal External Conditions
 - Used as Input-Output Transfer Function Models
- Build System Models by Network (Nodal) Analysis
- Reformulate System Models in Feedback Loop with Open-Loop Stability
- Determine System Stability by Nyquist-Like Criteria
- Find Root Causes of Instability Based on Analytical Models and Modal Analysis
- Shape Immittance by Control to Improve System Stability



Stability at Individual Plant-Grid Interface

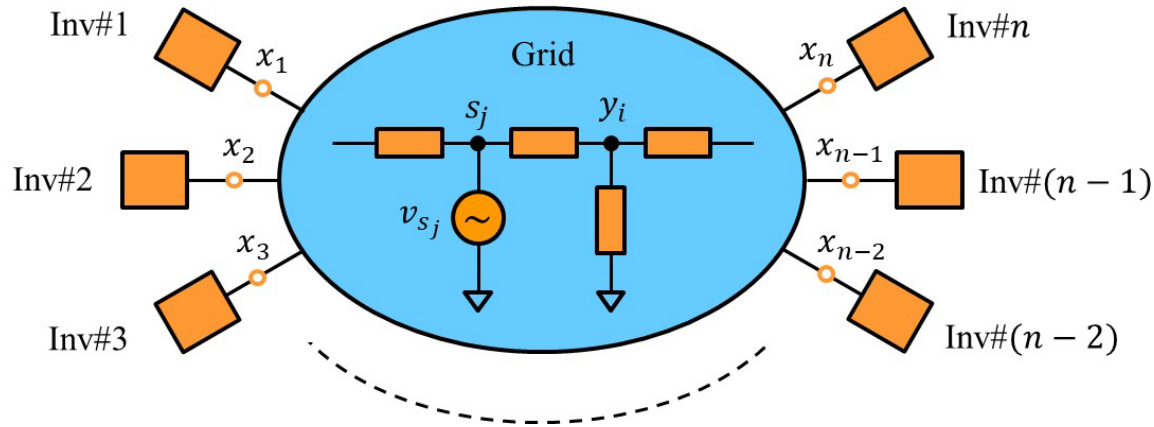


- Converter-Grid System Stability = Stability of a SISO Feedback Loop
- Practical Considerations Guarantee Stability of Open-Loop Gain
- Application at Plant Level by Scaling or Aggregation

J. Sun, "Frequency-domain stability criteria for converter-Based power systems," in *IEEE Open J. Power Electronics*, vol. 3, pp. 222-254, 2022.



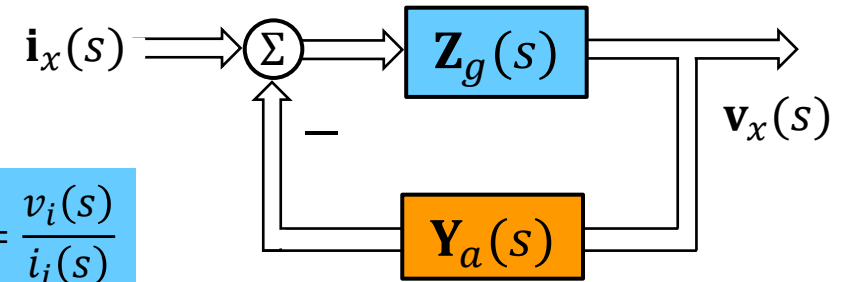
Grid System Stability



$$\mathbf{v}_x(s) = \{\mathbf{I} + \mathbf{Z}_g(s)[\mathbf{Y}_{ap}(s) + \mathbf{Y}_{ep}(s)]\}^{-1} \mathbf{Z}_g(s) \mathbf{i}_x(s)$$

$$\mathbf{Y}_{ep}(s) = -\mathbf{Y}_{cn}(s_{-2})[\mathbf{Y}_{an}(s_{-2}) + \mathbf{Y}_{gn}(s_{-2})]^{-1} \mathbf{Y}_{cp}(s)$$

$$Z_{ij}(s) = \frac{v_i(s)}{i_j(s)}$$



$$\mathbf{Z}_g(s) = \begin{bmatrix} Z_{11}(s) & Z_{12}(s) & \cdots & Z_{1n}(s) \\ Z_{21}(s) & Z_{22}(s) & \cdots & Z_{2n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1}(s) & Z_{n2}(s) & \cdots & Z_{nn}(s) \end{bmatrix}$$

- System Stability = $\mathbf{Z}_g(s)\mathbf{Y}_a(s)$ Satisfies Generalized Nyquist Criterion
- Intra- and Inter-Plant Stability; AC, DC and Hybrid AC-DC Systems

J. Sun, "Frequency-domain stability criteria for converter-Based power systems," in *IEEE Open J. Power Electronics*, vol. 3, pp. 222-254, 2022.



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Practical Experiences

Knall auf hoher See

Ökostrom Elektrotechniker rätseln: Die Konverterstation eines Offshore-Windparks schmore durch. Sind alle im Bau befindlichen Anlagen davon betroffen?

Der riesige Kasten steht auf gelbem Stahl, mitten in der Nordsee. Die Luft in seinem Hauptraum ist rein wie in einer Chlophabrik. Es herrscht Überdruck, und das auf einer Plattform rund hundert Kilometer vor Borkum.

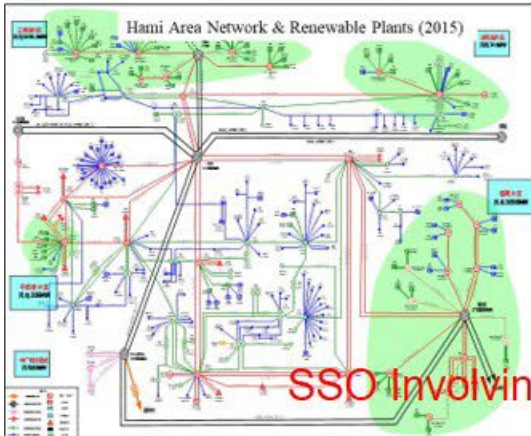
Doch am 23. März dieses Jahres, gegen 22 Uhr abends, macht sich heftiger Geräusch breit. Der Kunststoff von Isolatoren beginnt zu schmelzen. Dann knallt es. Jetzt wissen die Ingenieure: Der Traum vom sauberen Strom von hoher See ist für eine ganze Weile ausgetrennt.

Zwei Filter der Konverterstation Borwin Alpha sind durchgebrannt, zerstört wohl durch den wilden Fluss von elektrischen Schwingungen, die aus dem Windpark Band 1 in die Konverterstation strömen. Dabei waren die Techniker die Tage zuvor noch frohen Mutes gewesen. Endlich hatten sie alle 10 Windräder des Parks zusammenschalten können. Die Dreiflügler drehten sich im kräftigen Westwind und produzierten bis zu 400 Megawatt Wechselstrom, der in der Anlage zu Gleichstrom umgewandelt wurde. Zum ersten Mal soll-

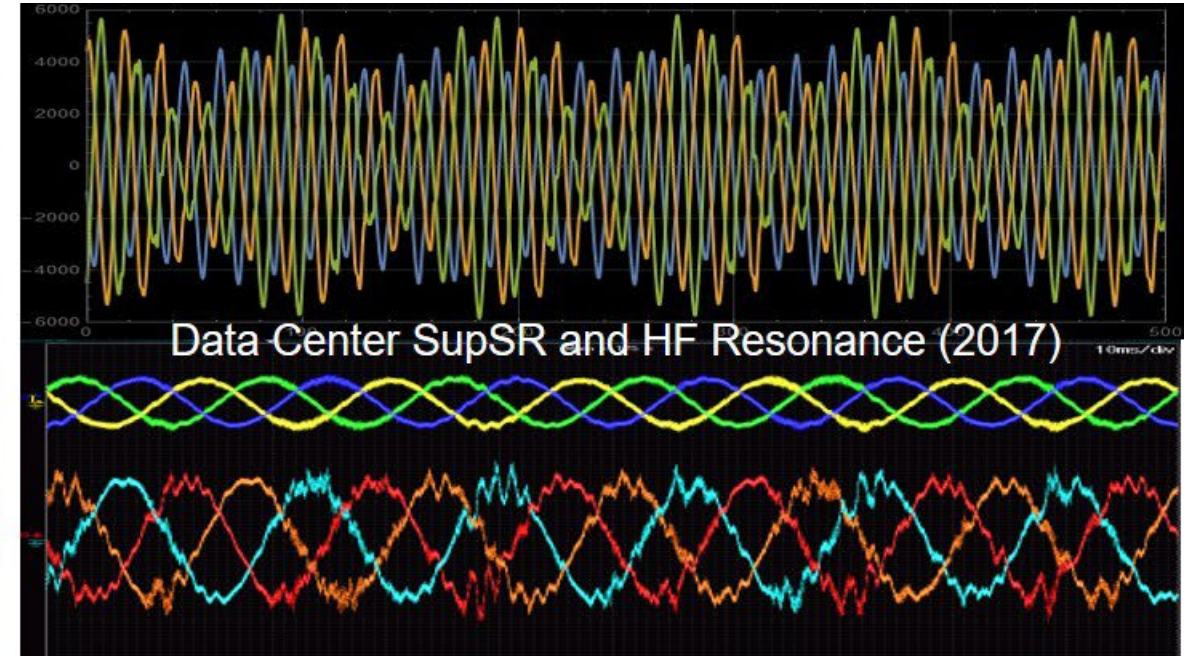


Harmonic Resonance in Offshore System (2014)

C. Buchhagen, M. Greve, A. Menze, and J. Jung, "Harmonic stability - practical experience of a TSO," in *Proc. Wind Integration Workshop*, pp. 1-6, Vienna, Nov. 2016.



SSO Involving IBRs and Generators (2015)



Data Center SupSR and HF Resonance (2017)

- Root Cause Analysis and Mitigation
- Prevention by System Studies
- Product Specifications to Guarantee Stability



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Analytical Insights

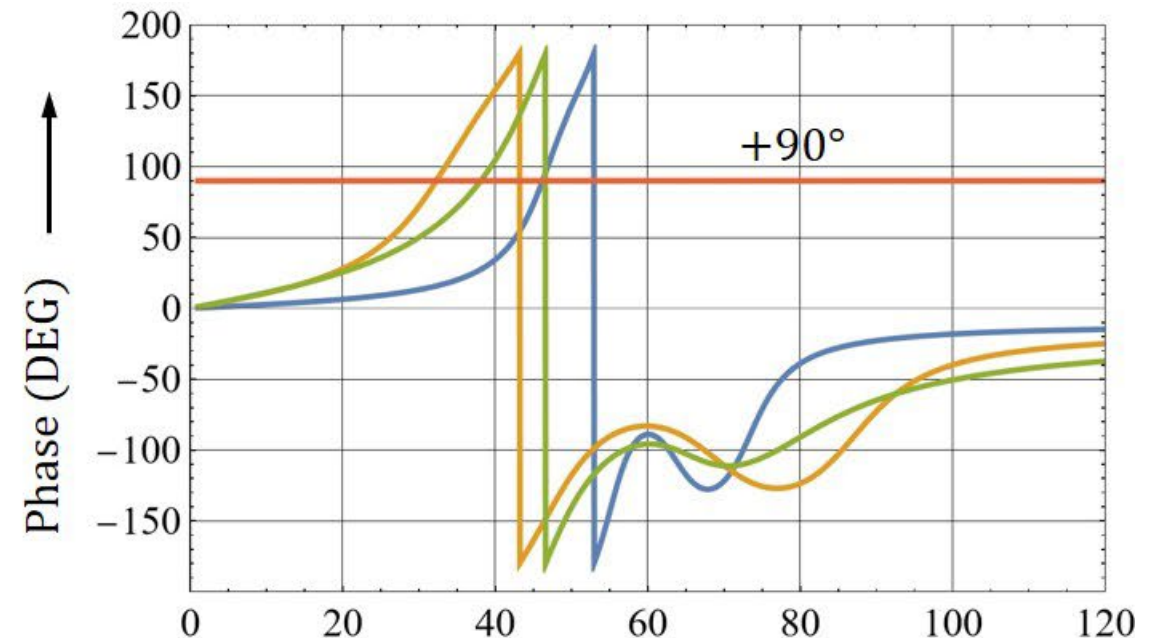
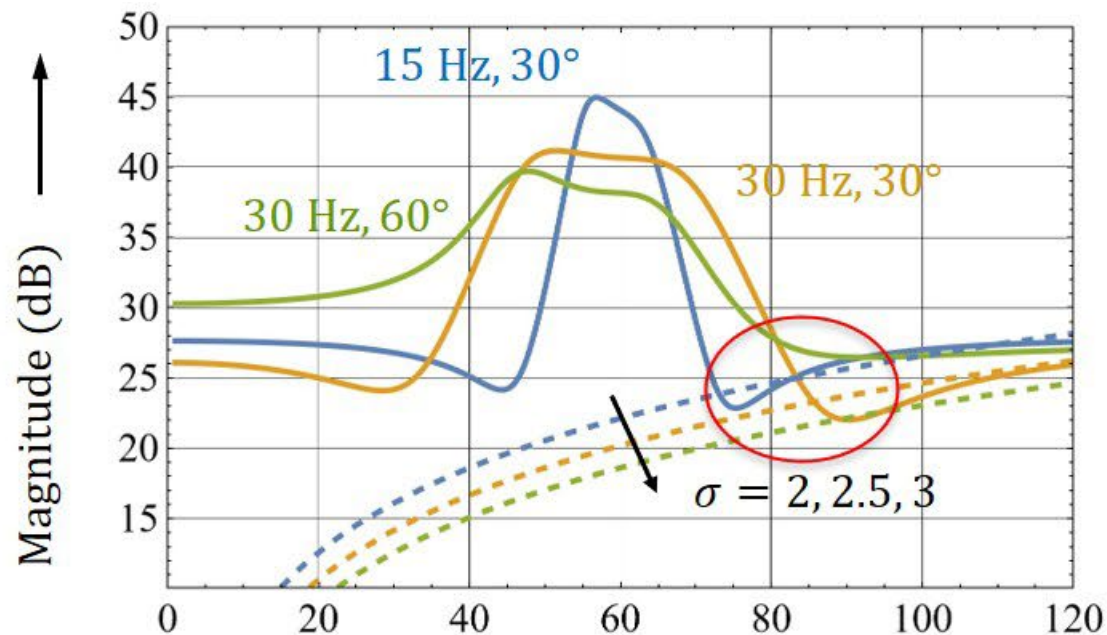
$$Y_{ap}(s) \approx \frac{1}{sL + H_{c0}(s - j\omega_1)} - \frac{\underline{Y_1} G_\theta(s - j\omega_1)}{2} - \frac{jH_{va}(s - j\omega_1)}{2}$$

- Integral Current Control Gain Defines a Dominating Capacitive Impedance
- PLL Introduces Negative Damping in a Frequency Range Symmetrical about f_1
 - Bandwidth Corresponds to PLL Crossover Frequency
 - Effects Reverse with Change of Power Flow Direction
- Integral Gain of AC Voltage Control Introduce Negative Damping Above f_1
 - But Positive Below f_1
- DC Bus Voltage Control Introduces Negative Damping Similar to PLL
-



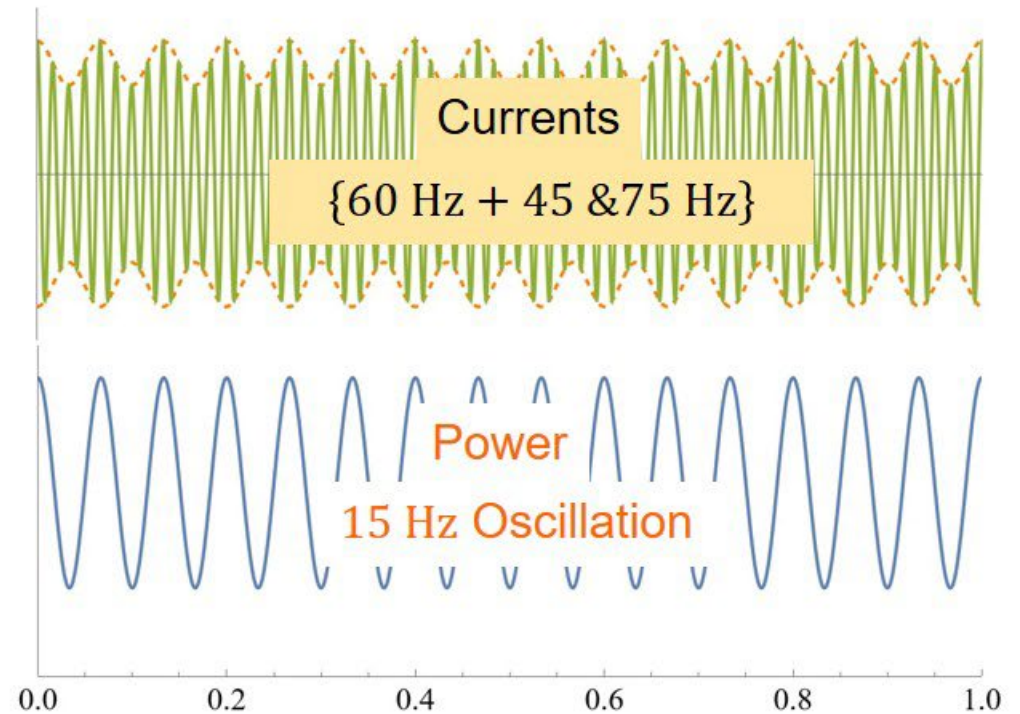
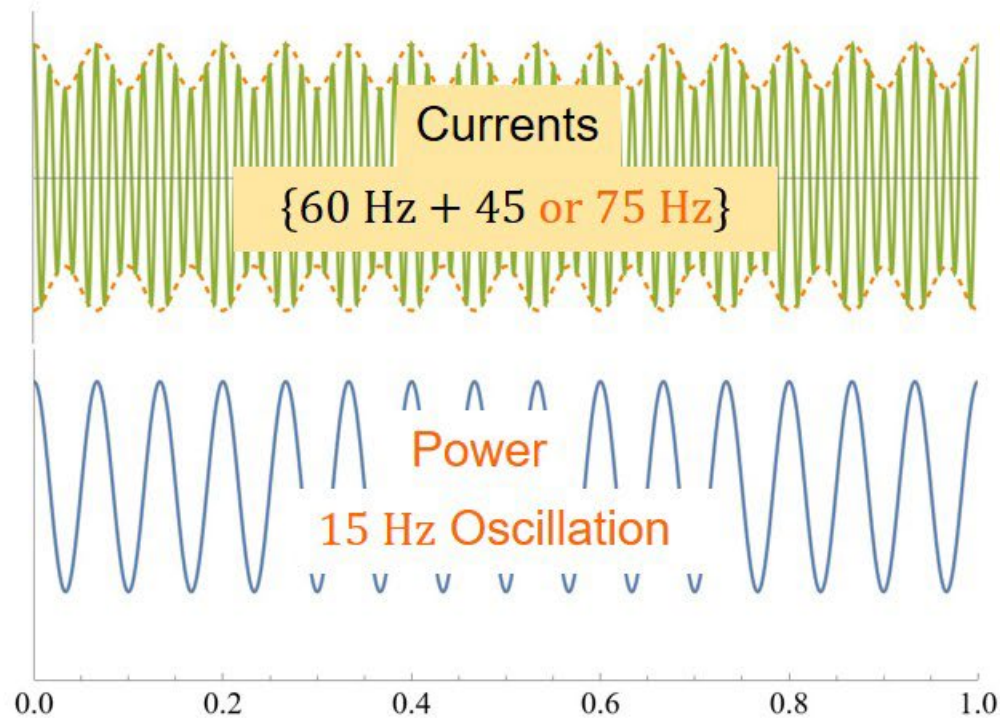
Supersynchronous Resonance of PSUs in Weak Grid

- V_{dc} Control Creates Capacitive Impedance with Negative Damping above f_1
- Supersynchronous Resonance with Inductive Grid Impedance in Weak Grid



Supersynchronous Resonance and SSO

- SSO can be the Result of Subsynchronous or/and Supersynchronous Harmonics
- With IBRs, Supersynchronous Resonance is Usually the Root Cause for SSO



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Keep Data Centers Stable (Away from SSO)

- Adopt Impedance-Based Stability Specifications
 - Magnitude Separation Below 120 Hz; Positive Damping Above 120 Hz
 - <https://www.youtube.com/watch?v=lxUXLGi5-C8> (PSU Impedance Specs)
 - <https://www.youtube.com/watch?v=K85Ku7pAz2E> (UPS Impedance Specs)
 - <https://www.youtube.com/watch?v=8oGdBS3VNiA> (System Impedance Specs)
 - See Also J. Sun et al., Data Center Power System Stability
 - Part I: <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9713963>
 - Part II: <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9713964>
- Ensure $SCR > 8$ on the Grid Side
 - SCR Calculation Must Consider Other Data Centers and IBR Plants in Proximity

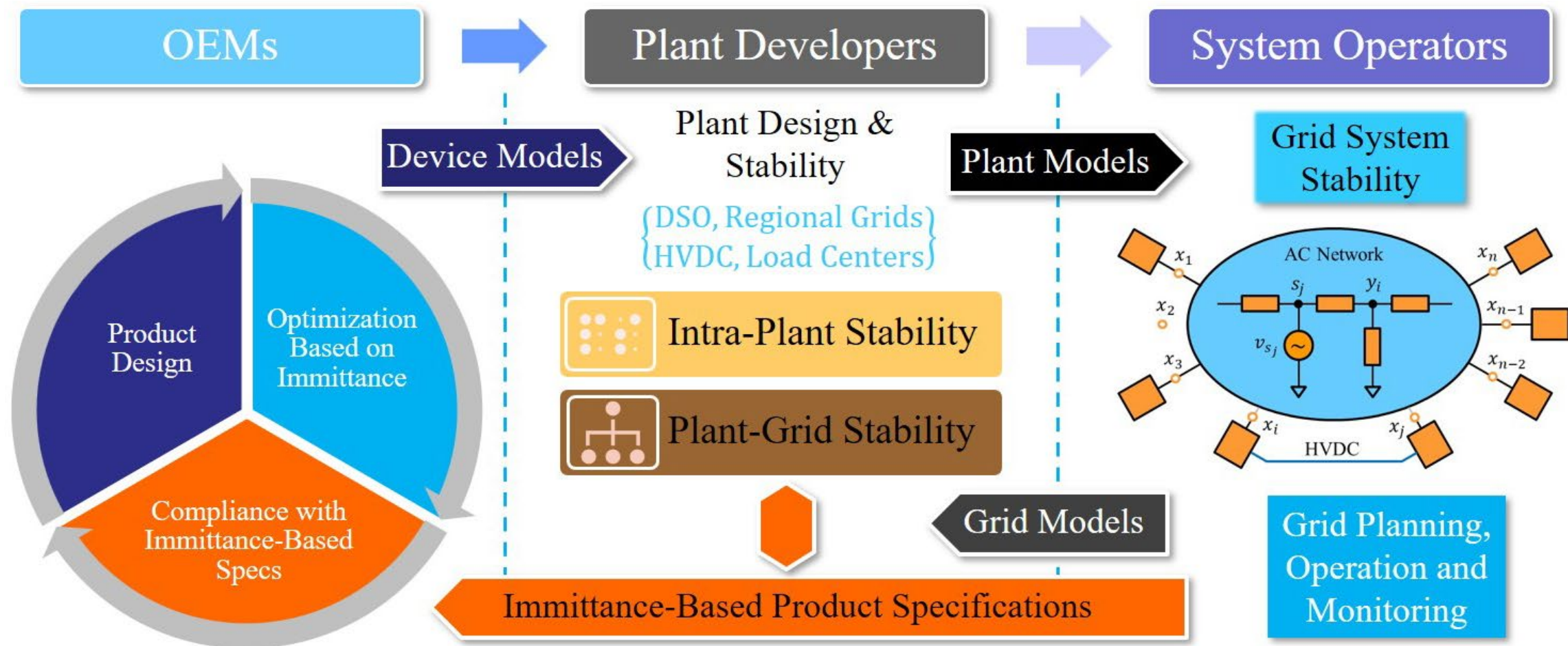
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Holistic Approach to Stability



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Upcoming Online Course

<https://immittance-methods.net/>

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