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Stability of High-Bandwidth Power Electronic Systems with Transmission Lines

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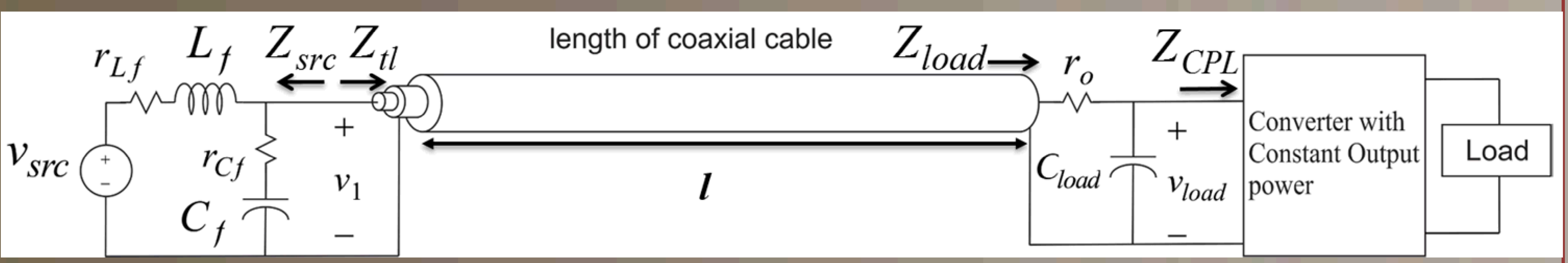
Motivation:

A new generation of power electronic conversion systems is being enabled by wide bandgap (WBG) devices. Applications in both civilian and defense sectors are benefiting from the improved size, weight, and power (SWaP) in power converters utilizing silicon carbide (SiC) and/or gallium nitride (GaN) switches. By switching at higher frequency, inductors and capacitors may be shrunk in size while maintaining the same voltage and current ripple specification. However, the resulting circuit also stores less energy, requiring the closed-loop control bandwidth be increased in order to maintain good disturbance rejection. This increasing closed-loop control bandwidth operation poses a special problem for large distributed multi-converter systems like those on a Naval electric warship.

This work focuses on the effect of transmission lines on the stability of distributed power systems and investigates the trade-off between increased control bandwidth and limits on cable length.

Test Case: This circuit example is an extension of the iconic input filter + constant power load (CPL) problem, but with a long cable added between filter and load converter.



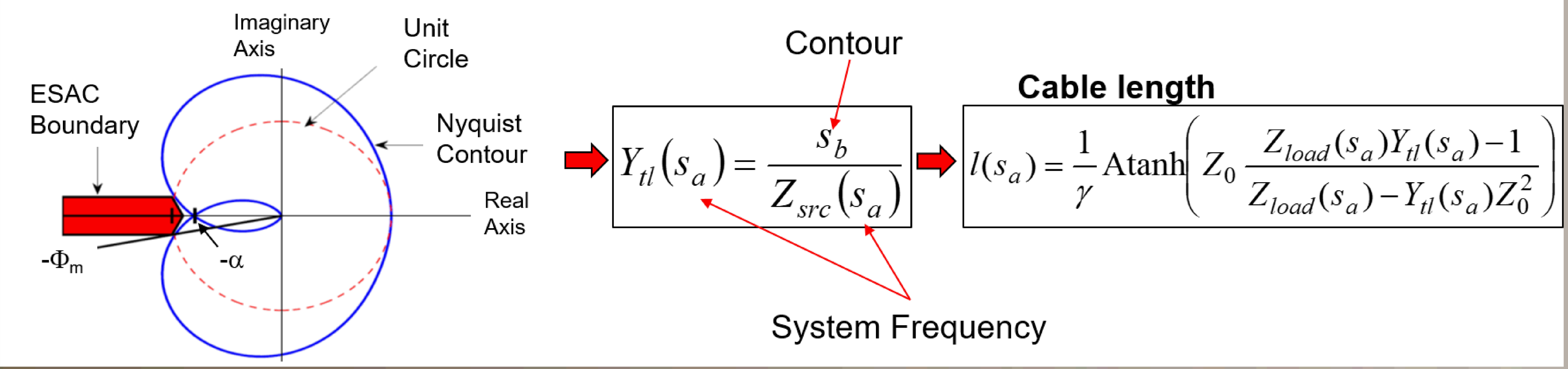
- An extension of the iconic input filter + constant power load problem with a transition line of length *l* was examined.
- ESAC stability criteria was applied to the transfer function $\frac{v_1}{v_{src}}(s) = \frac{1}{1+Z_{src}(s)Y_{tl}(s)}$
- $Y_{tl}(s) = \frac{1}{Z_{tl}(s)} = Z_0\frac{Z_0+Z_{load}(s)\tanh(\gamma l)}{Z_{load}(s)+Z_0\tanh(\gamma l)}$
- At a given operational frequency, we can solve for the length as:

$$l(\omega_a) = \frac{1}{\gamma}\text{atanh}\left(Z_0\frac{Z_{load}(s_a)Y_{tl}(s_a)-1}{Z_{load}(s_a)-Y_{tl}(s_a)Z_0^2}\right)$$

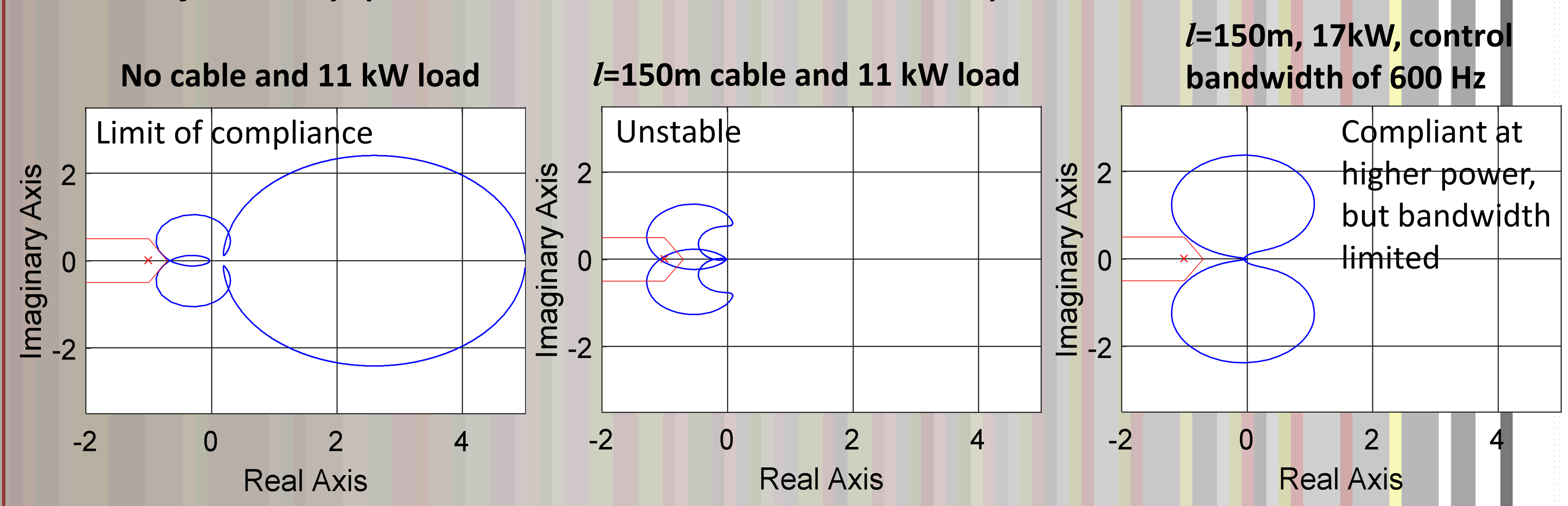
Adapted *Energy Systems Analysis Consortium* (ESAC) Method:

1) Sweep operating frequency, $s_a = j2\pi f_a$
2) Find $Y_{tl}(s_a) = \frac{s_b}{Z_{src}(s_a)}$ for ESAC boundary defended by s_b
3) Map the boundary of denied load admittances to allowable cable lengths at each frequency
4) Repeat 1-3 for each power level

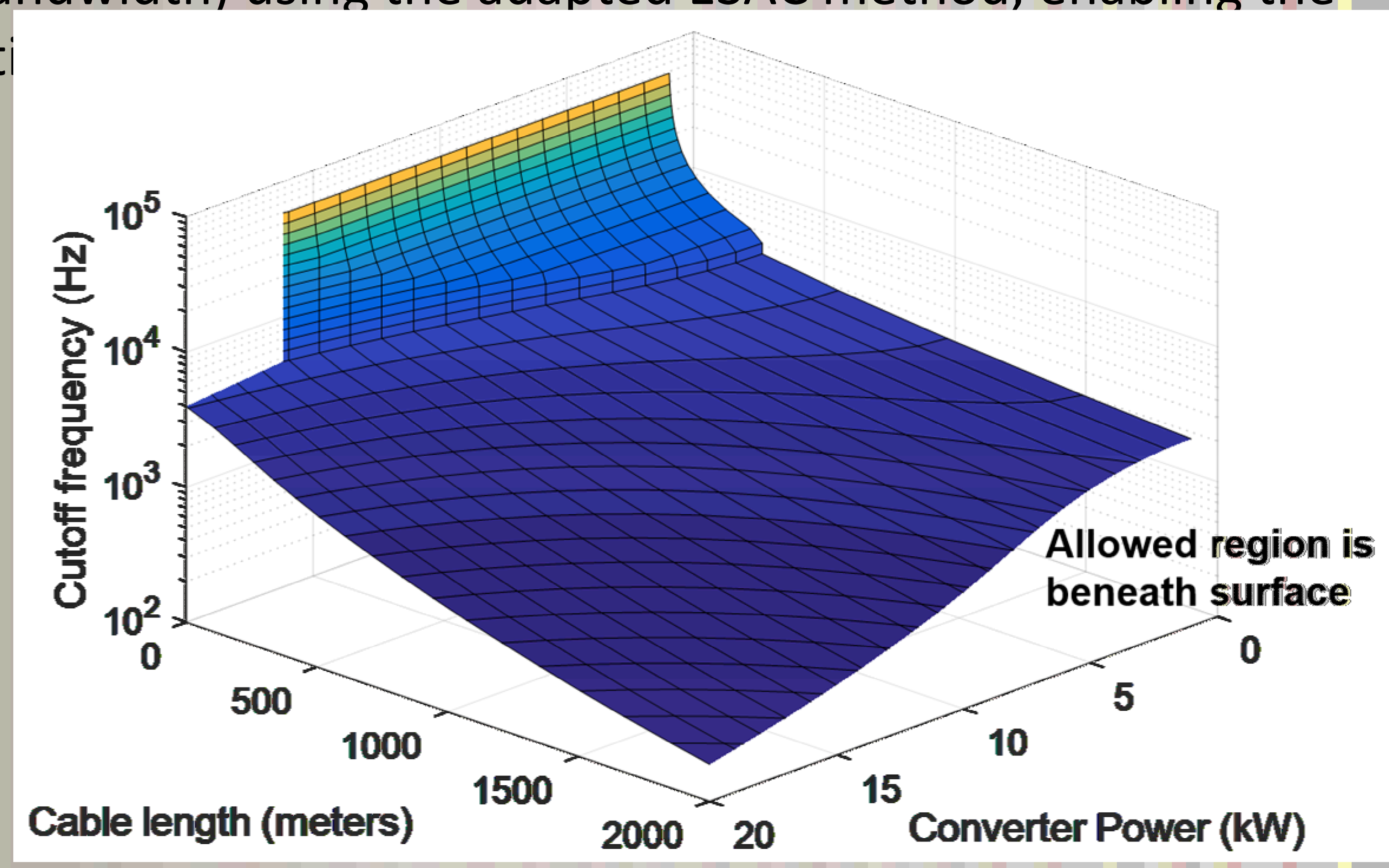
Gain Margin = $20\log_{10}(1/\alpha)$
Phase Margin = Φ_m



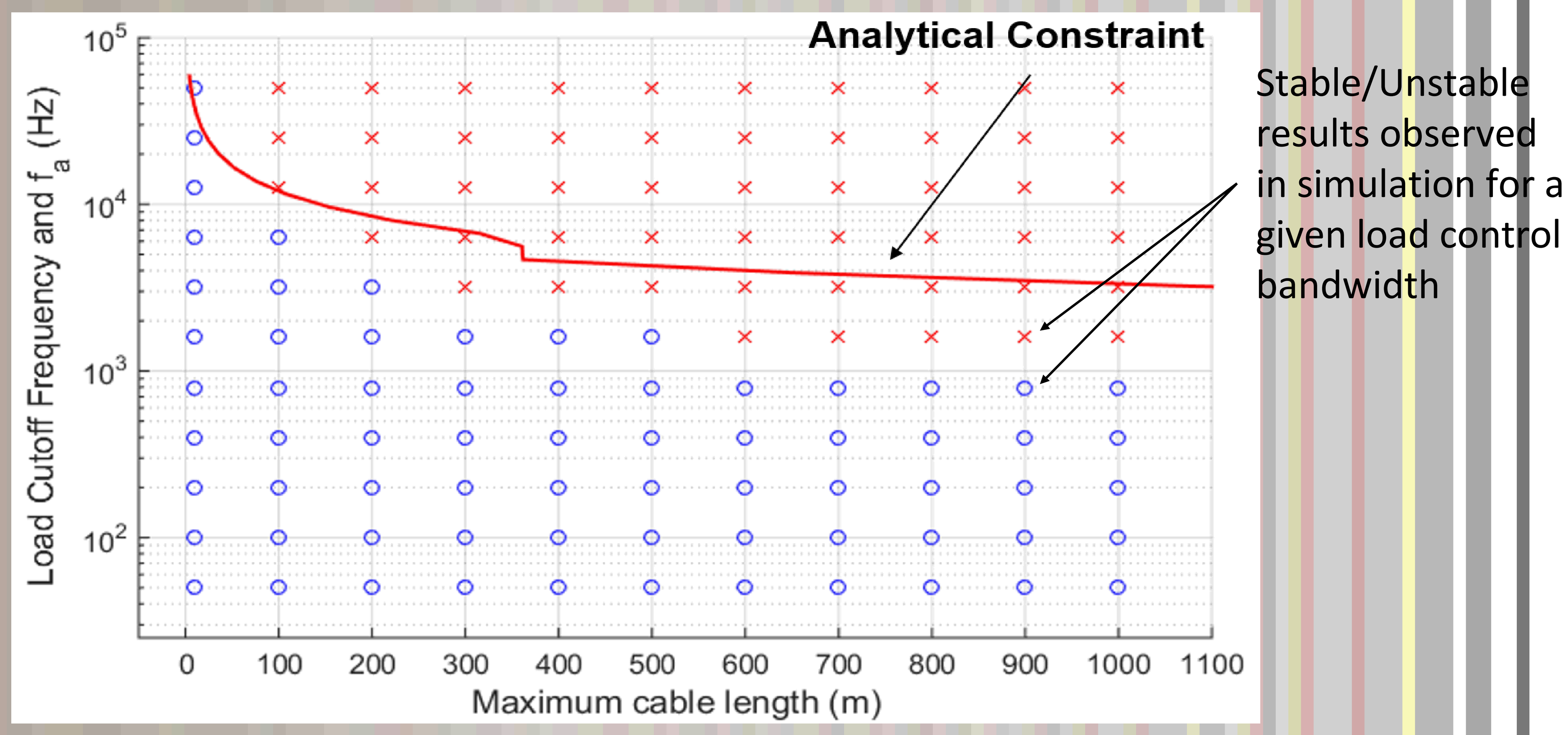
Examples: Nyquist contours for select examples …



The entire operating space is evaluated (power levels, cable lengths, and bandwidth) using the adapted ESAC method, enabling the definiti



Simulation: A Simulink simulation of the system was run to find unstable configurations, denoted by x, and stable configurations, denoted by o (below)



Summary: A general method, based on the Energy Sources Analysis Consortium (ESAC) method, was developed to account for the transmission line impedance and even to compute maximum allowable cable lengths as a function of system frequency and power level. Simulation results indicate that cable length is relevant in systems with higher frequency control bandwidth and even modest cable lengths. The results show reasonable agreement with analytical prediction.

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