Lin et al introduction

Stability Assessment of a System Comprising a Single Machine and Inverter with Scalable Ratings

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EE290O Power Dynamics
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Single-machine inverter system model (EV)

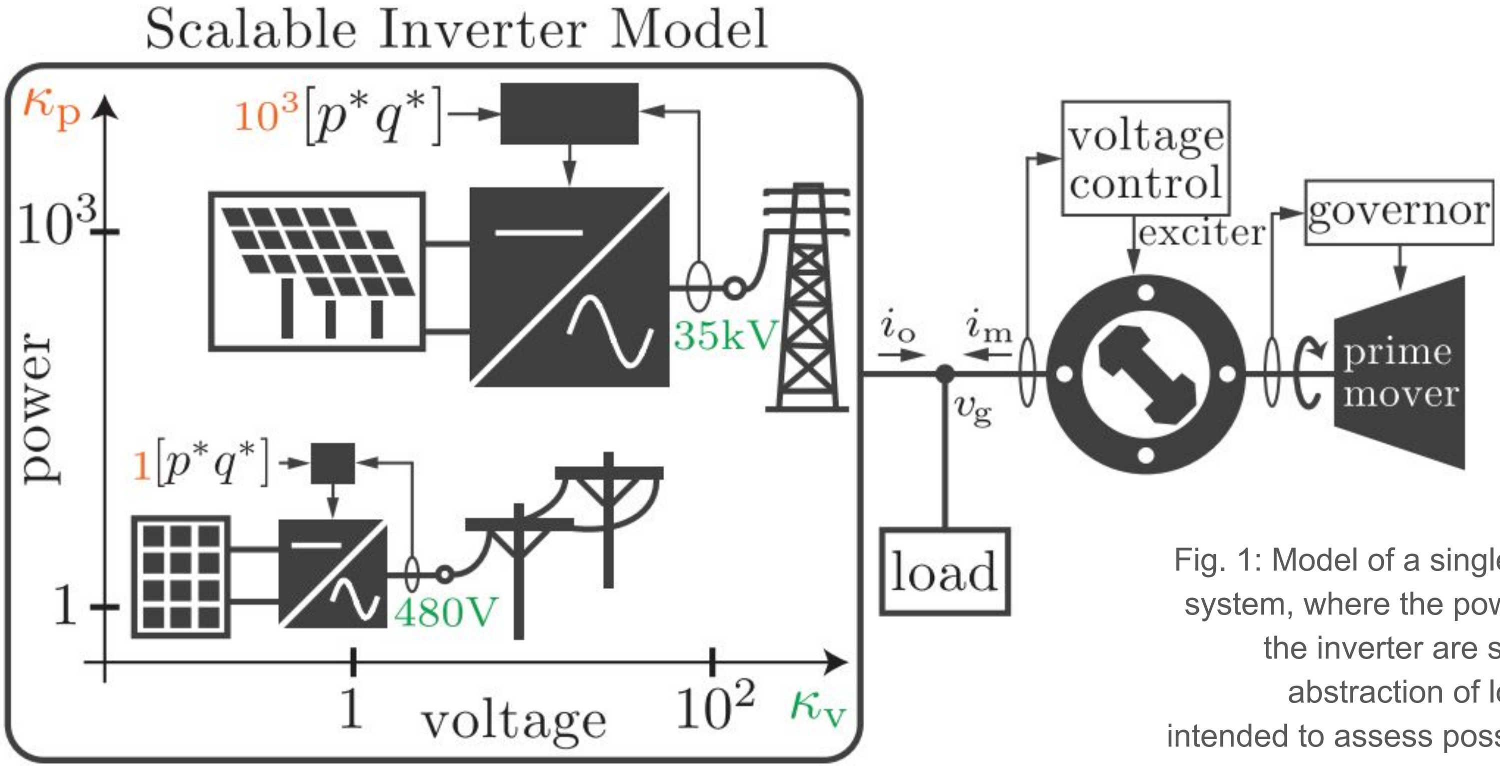
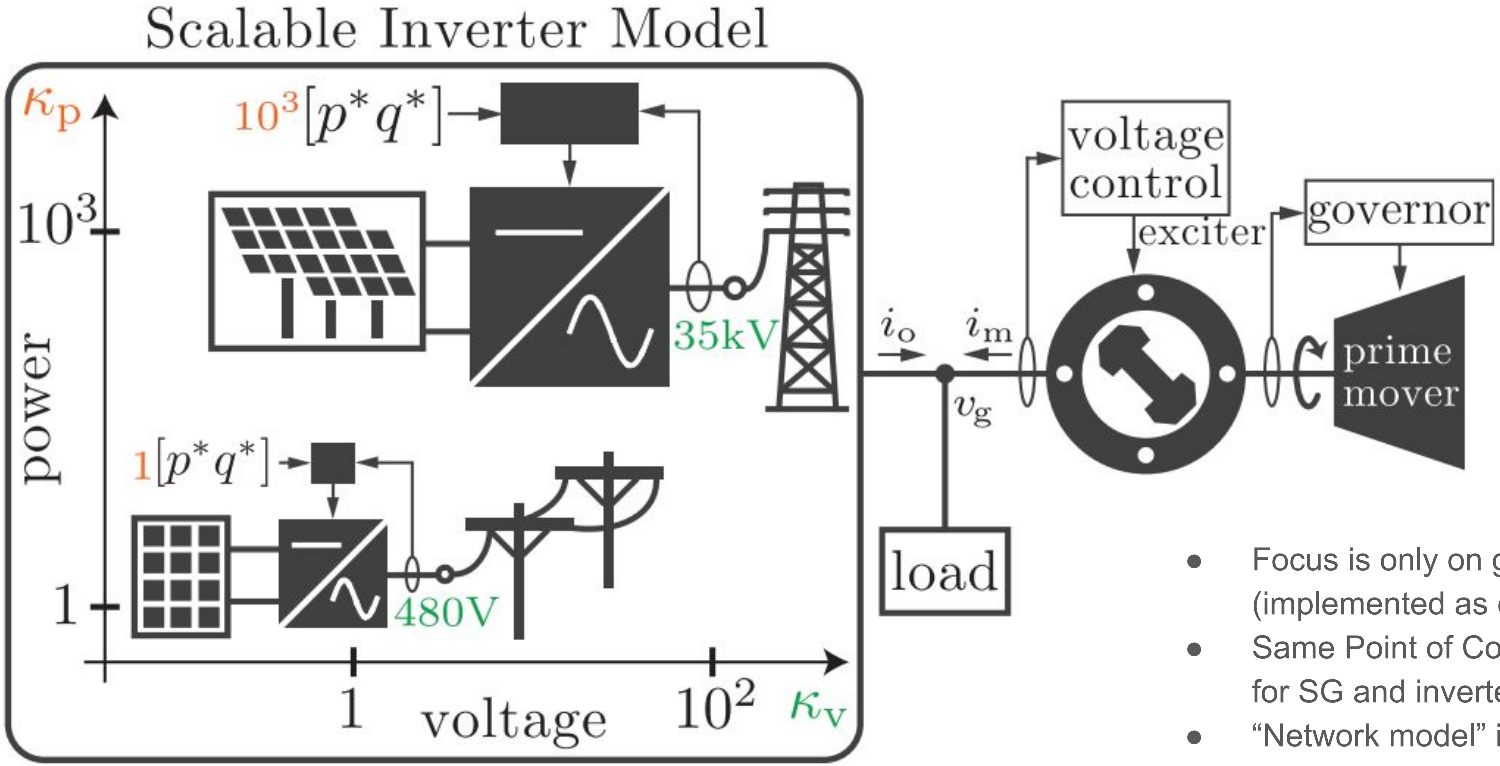


Fig. 1: Model of a single-machine single-inverter system, where the power and voltage ratings of the inverter are scalable. This model is an abstraction of low-inertia systems and is intended to assess possibly unforeseen dynamic interactions between machines and inverters as more inverters are installed in networks.

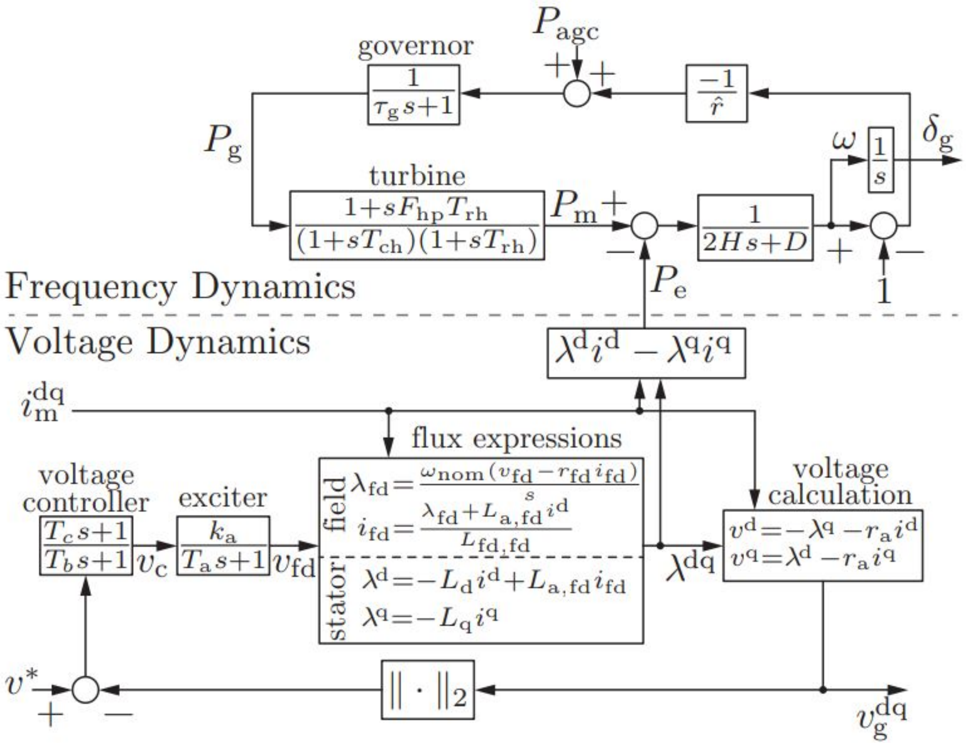
Single-machine inverter system model (EV)



- Focus is only on grid-following inverter (implemented as current source inverter).
- Same Point of Common Coupling (PCC) for SG and inverter.
- “Network model” is a shunt load but not transmission line connection is modeled.

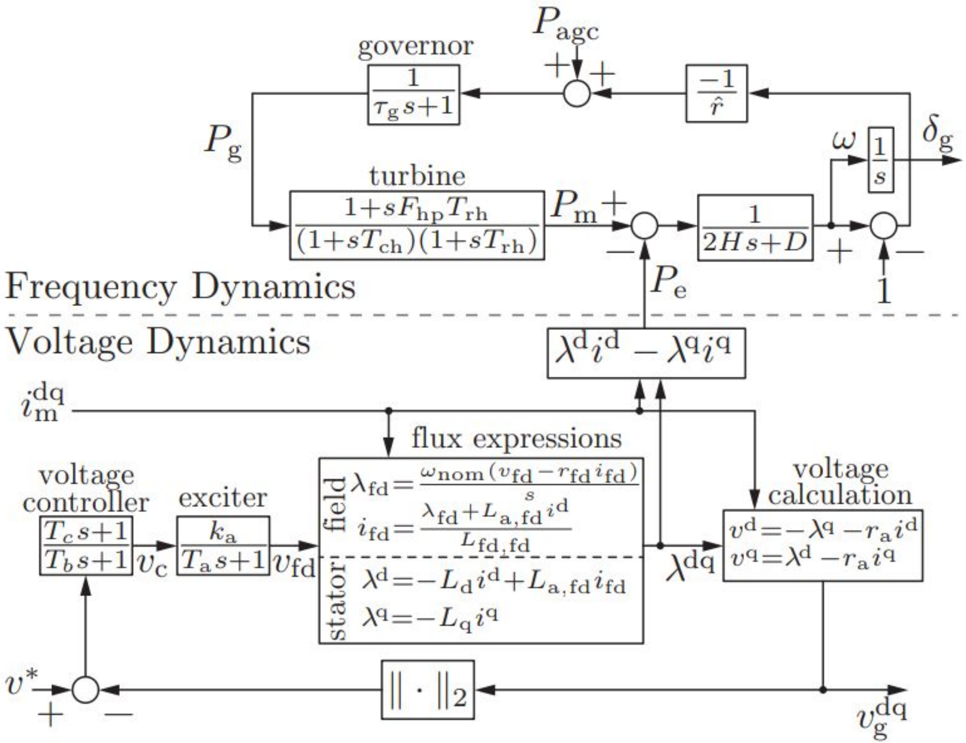
Synchronous Machine Model - Assumptions

- Machine dynamics well established - refer readers to see “Power System Stability and Control”
- Assumptions:
  - Balanced 3 phase
  - Perfect knowledge of the numerous parameters (18)
  - Linear magnetics
  - No spatial harmonics
  - No non-linear control (voltage/current limiters omitted)
  - No power system stabilizer



Synchronous Machine Model - Questions

- How sensitive is the model to each parameter?
- Over what parameter values is the model stable with different feedback schemes?
- From where are the parameters derived?
- How is P_agc generated? What are its dynamics?



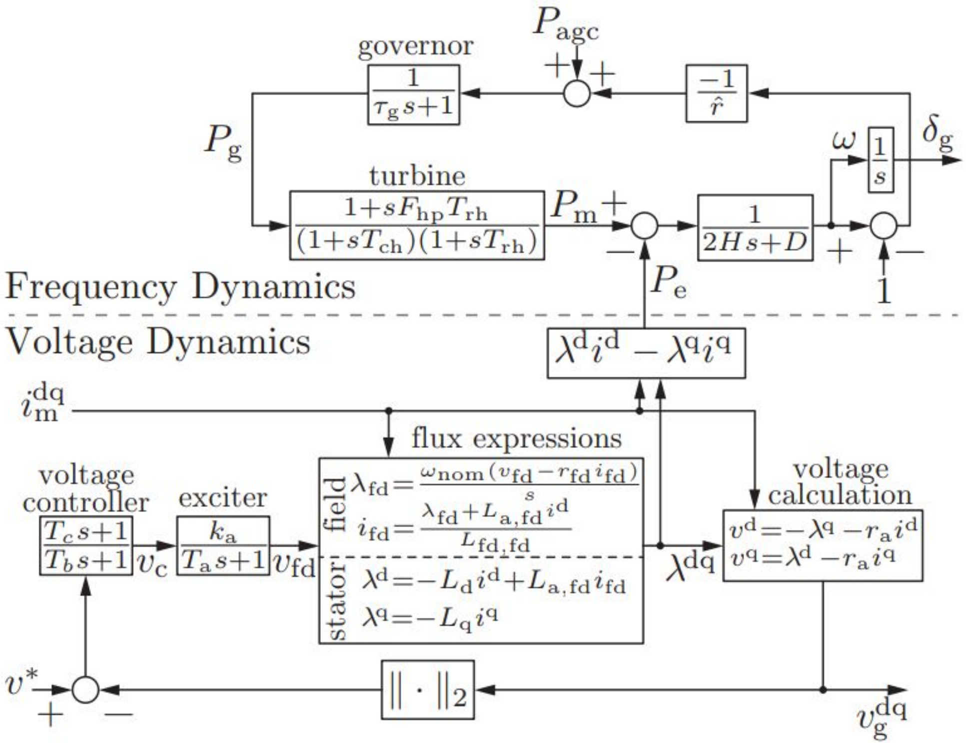
Synchronous Machine Model - Further Exploration

- Compare this more detailed model (8 states) to less detailed ones

$$x_{\mathrm{m}} = [\delta_{\mathrm{g}}, \omega, P_{\mathrm{g}}, P_{\mathrm{gt}}, P_{\mathrm{m}}, v_{\mathrm{c}}, v_{\mathrm{fd}}, \lambda_{\mathrm{fd}}]^{\top},$$
$$u_{\mathrm{m}} = [P_{\mathrm{agc}}, v^{*}, i_{\mathrm{m}}^{\mathrm{dq}}]^{\top}.$$

- Curie has 4 states per generator
  - Collaborate?

$$\begin{aligned}\dot{\theta}_{g,k} &= \omega_{g,k} - \omega_0,\\ M_k \dot{\omega}_{g,k} &= -D_k \omega_{g,k} + \tau_{m,k} - \tau_{e,k},\\ L_{g,k} \dot{i}_{g,k} &= -Z_{g,k} i_{g,k} + \mathcal{I}_{g,k}^{\top} v - v_{\mathrm{ind},k},\end{aligned}$$



“Scalable” Inverter Model Assumptions

Assumption: Average model where PWM and switching dynamics are ignored.

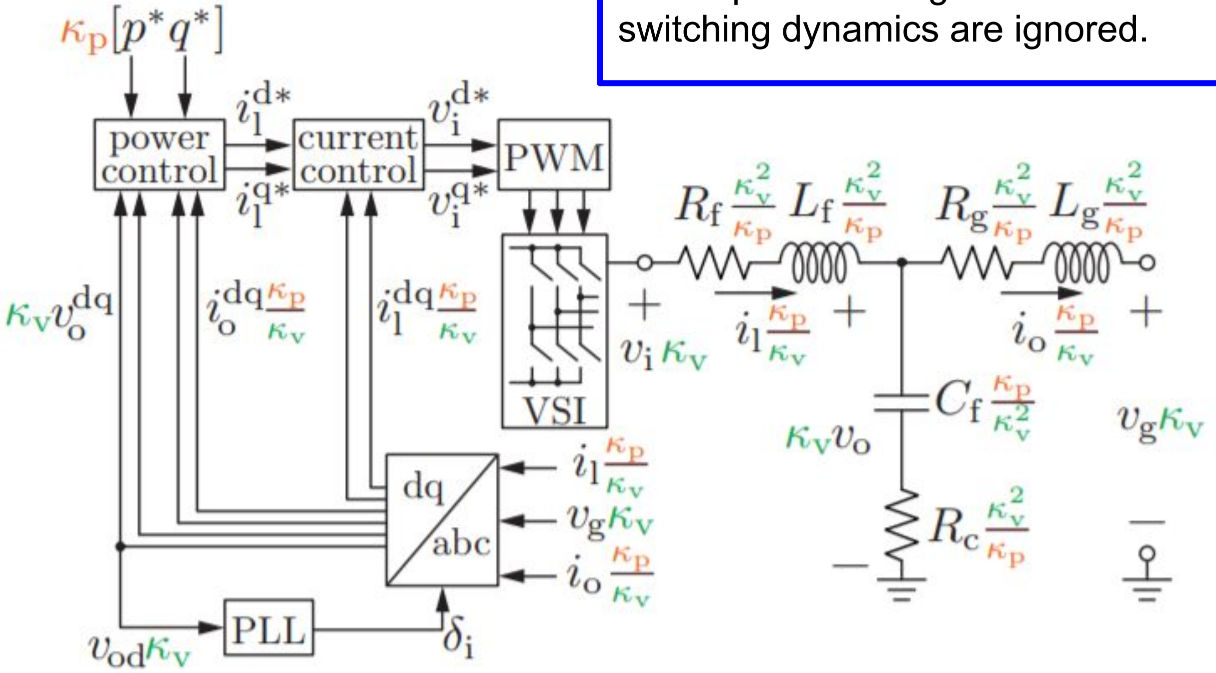


Fig. 3 Scalable Inverter Model

“Scalable” Inverter Model

- LCL filter: $\frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}L_\mathrm{f}, \frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}R_\mathrm{f}, \frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}L_\mathrm{o}, \frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}R_\mathrm{o}, \frac{\kappa_\mathrm{p}}{\kappa_\mathrm{v}^2}C, \frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}R_\mathrm{c}$.
- Power controller: $k^p_\mathrm{PQ}/\kappa_\mathrm{v}, k^i_\mathrm{PQ}/\kappa_\mathrm{v}$.
- Current controller: $\frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}k^p_\mathrm{i}, \frac{\kappa_\mathrm{v}^2}{\kappa_\mathrm{p}}k^i_\mathrm{i}$.
- PLL: $k^p_\mathrm{PLL}/\kappa_\mathrm{v}, k^i_\mathrm{PLL}/\kappa_\mathrm{v}$.

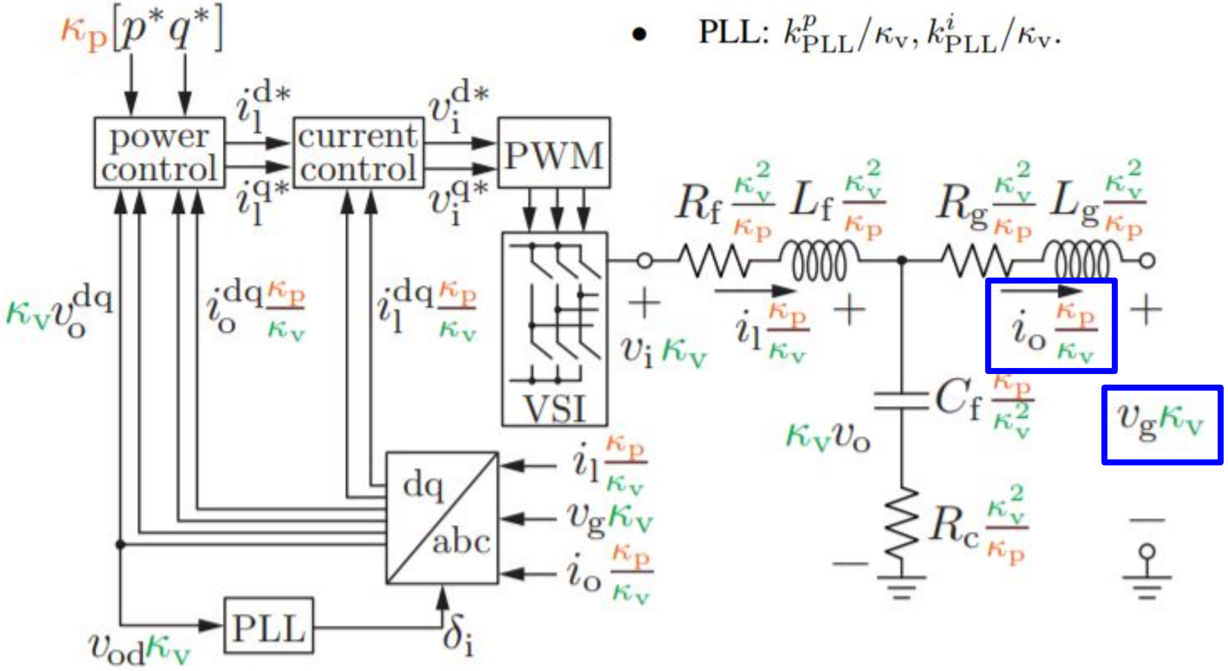


Fig. 3 Scalable Inverter Model

Kp and Kv are proportional gains to scale the voltage and power with scaled inverters.

How scalable is the model?

Are the effects of a “large” or “small” inverter similar?

Do these effects scale linearly?

Figure ES-2. Small inverter-based power plant relative to grid

Figure ES-3. Large inverter-based power plant relative to grid

Fig. 4 Comparison of differently sized inverters on grid interactions. [1]

[1] https://www.nrel.gov/docs/fy16osti/64822.pdf

"Scalable" Inverter Model

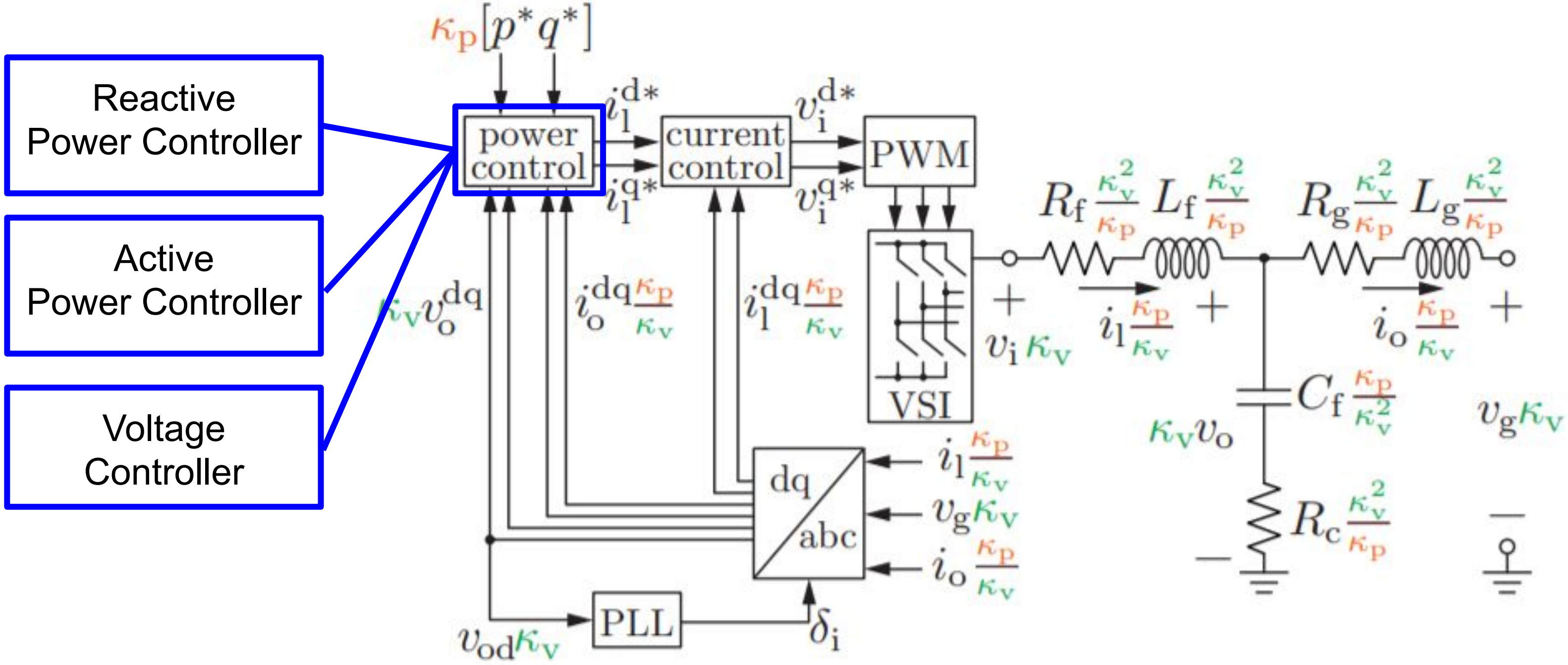


Fig. 3 Scalable Inverter Model

"Scalable" Inverter Model

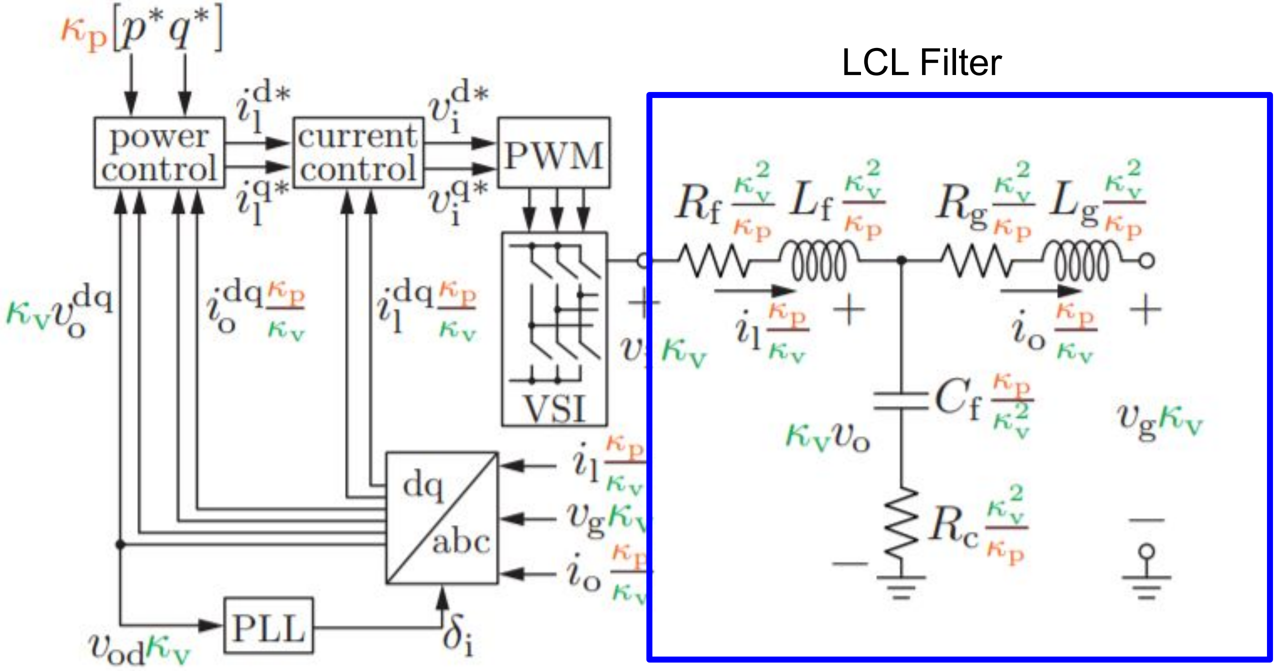


Fig. 3 Scalable Inverter Model

“Scalable” Inverter Model

$$x_i = [i_l^{dq}, i_o^{dq}, v_o^{dq}, \gamma^{dq}, p_{avg}, q_{avg}, \phi_{pq}, v_{PLL}, \phi_{PLL}, \delta_i]^\top$$
$$u_i = [p^*, q^*, v_g^{dq}]^\top.$$

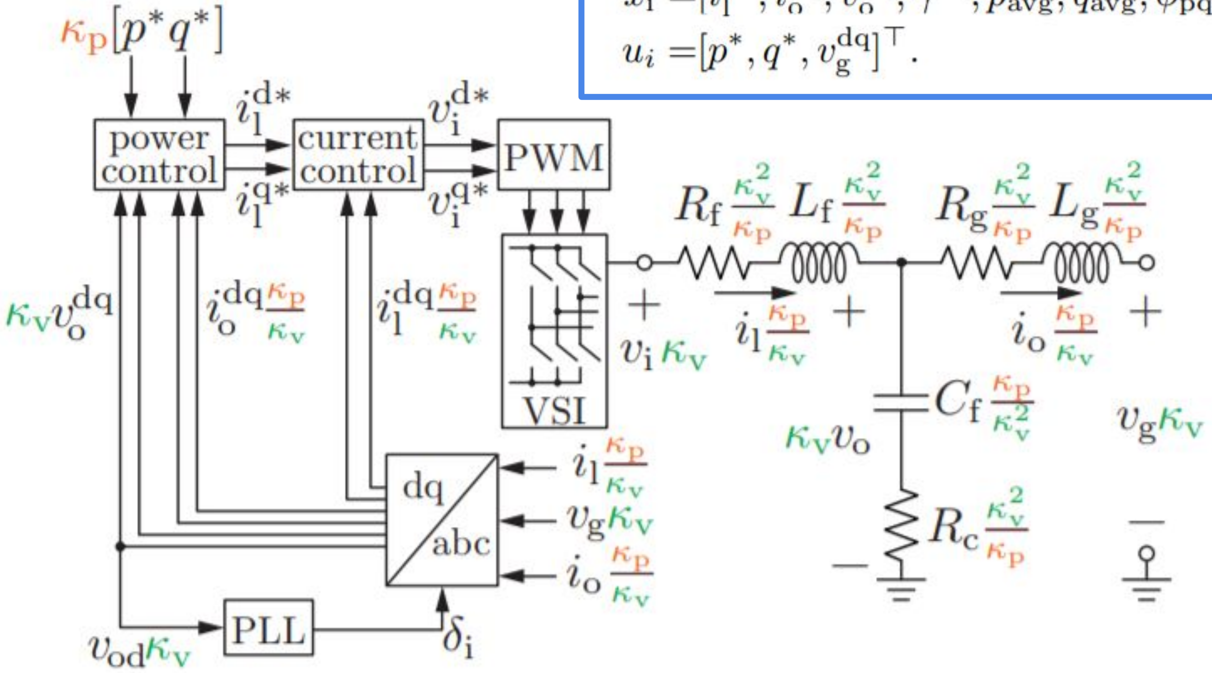


Fig. 3 Scalable Inverter Model

Small-signal stability analysis under varying inverter penetration

- Linearized version of coupled machine-inverter system
  - Load impedance: 500 MW and 50 MVAR
  - Inverter real power reference up to 250 MW
- Eigenvalues of system matrix
  - If max(Re(λ)) > 0,the small-signal model is unstable.

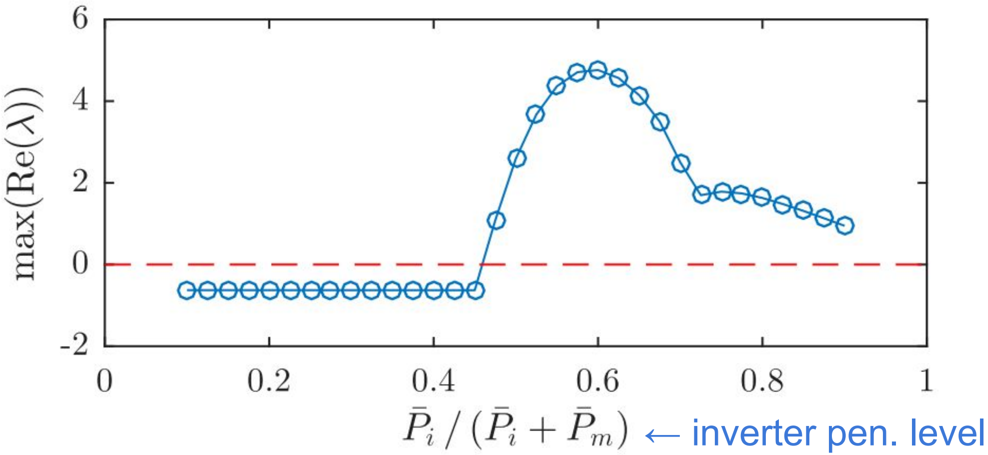


Fig. 4: Nominal case: Small-signal stability is ensured for penetration levels approaching 50%.

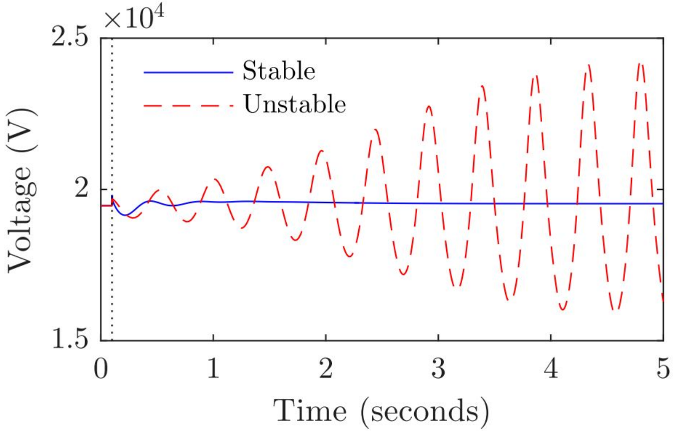


Fig. 10: Time domain response of the original nonlinear model. The blue solid line represents a stable case where inverter penetration level of 44%; the red dashed line represents an unstable case where inverter penetration level of 55%.

Machine exciter and automatic voltage regulator

Model impact of bypassing automatic voltage regulator and exciter circuit dynamics in the machine model

Machine voltage amplitude fixed to its nominal value

Results suggest: AVR type may significantly impact stability

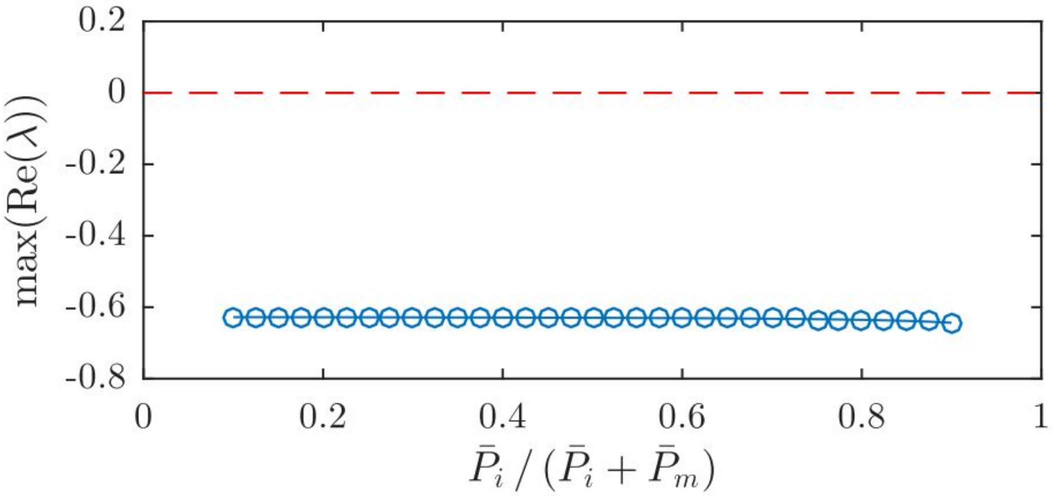


Fig. 5: Bypassing the machine AVR and exciter circuit significantly improves stability margins.

Current control compensator gains

Scaled by 5 and ⅕ from nominal values

Current control sets switch terminal voltage

More aggressive current control permits greater stable inverter penetration levels

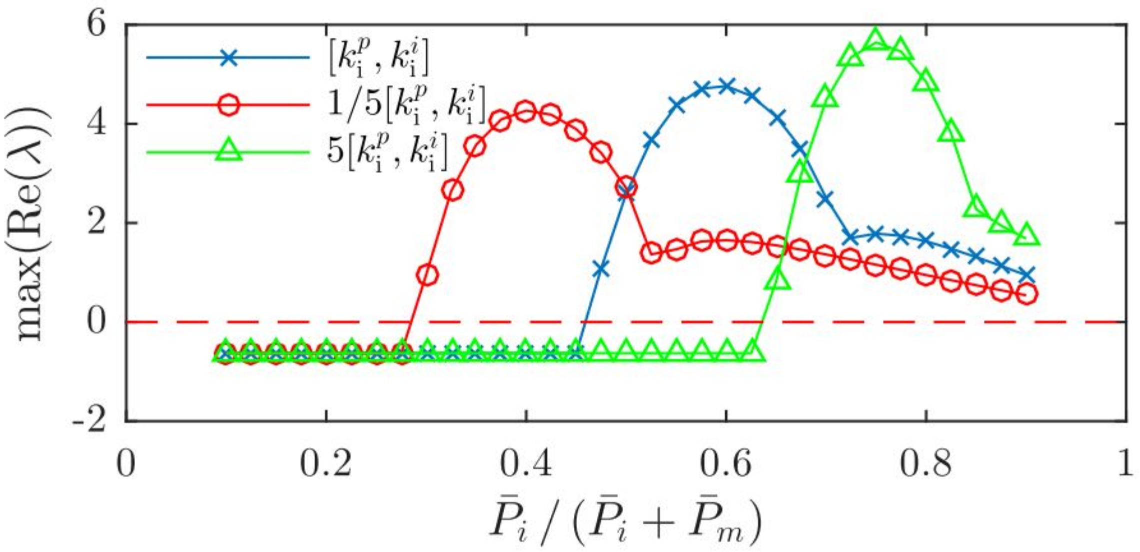


Fig. 6: Reduced current-controller gains adversely impact small-signal stability.

Phase locked-loop

- PLL synchronizes inverter to measured terminal AC voltage v_0
  - PLL performance impacts downstream controllers
- Bypassing assumes inverter has perfect knowledge of rotor angle (i.e., δi = δg)
- Significantly enlarged stability region

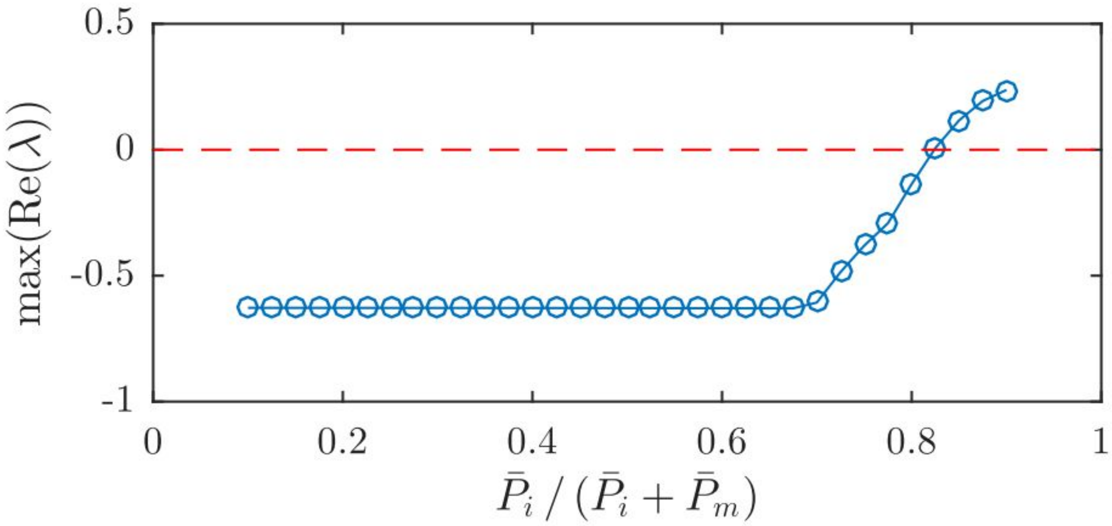


Fig. 7: Bypassing the PLL (assuming $\delta_{\mathrm{i}} = \delta_{\mathrm{m}}$) guarantees stability for penetration levels greater than 80%.

Machine rotor inertia

Scaling machine inertia by 0.01 and 100

While inertia has significant impact on frequency, less impact here on small-signal stability

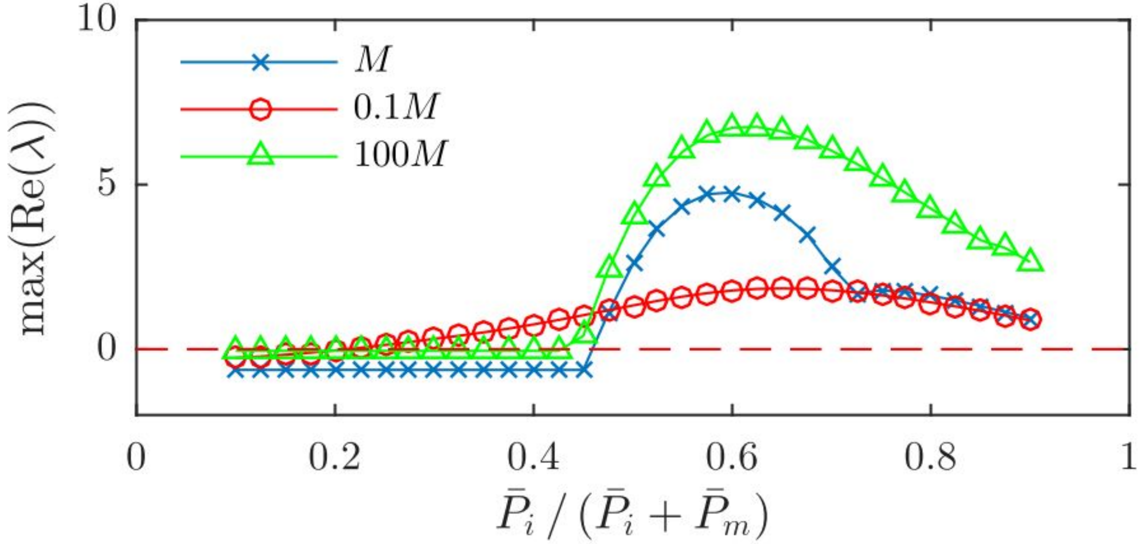


Fig. 8: System eigenvalues after modifying the machine rotor inertia.

Power controller

Power controller disabled by fixing current reference values

Minimal impact on small-signal stability

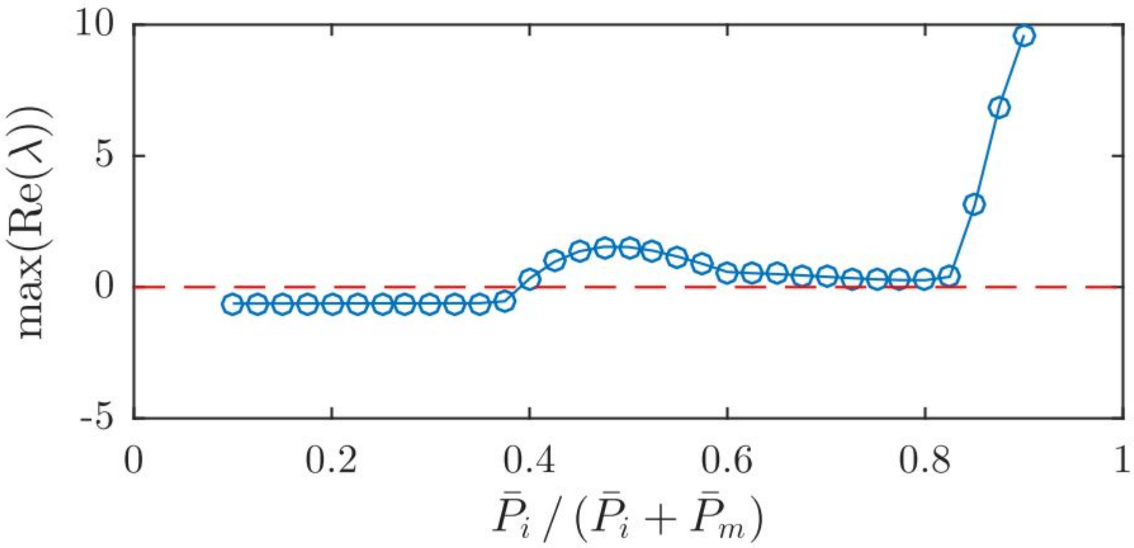


Fig. 9: Eigenvalues with the inverter power controller bypassed.

Summary: key results and limitations

- Focused on grid-following inverter only.
- Reasonable tradeoff between model complexity and simplicity → should be relatively easy to set up the model in Matlab.
- Reported maximum eigenvalue real part as a function of inverter penetration.
  - However, it is not necessary the same eigenvalue that is unstable for each penetration level (no participation factor analysis).
- Main observation: adverse dynamic interactions between the Automatic Voltage Regulator (AVR) and associated exciter system and inverter controllers.

Summary: key results and limitations

- Scalable inverter approach: not clear if this is a “must” or if a simple per-unitization would do the job.
- “Network model” (shunt load) is purely algebraic → no dynamics considered.
  - Connection impedance (Rg, Lg) is depicted in inverter model schematic, but seems to be set to 0 in small-signal analysis.
  - How generalizable are the stability results due to the absence of realistic grid topology?
- Due to very simple “network model”, DAE system can be readily transformed to an ODE system and small-signal analysis is thus straightforward.
  - How easy is to do similar analysis for more complex systems where algebraic variable substitutions are not trivial?

Thoughts on follow-up work

- Modeling:
  - Inverter model could be enhanced by moving from a current source model to a voltage source model with inclusion of PI for voltage controller (Markovic paper).
  - Grid-forming inverter model can be implemented and tested in the same setup.
  - SG model can be modified by including saturation/limiter effects, Power System Stabilizer (PSS), and different AVR models to check if observed adverse dynamic interaction still applies.
  - Transmission line between SG and inverter: Case 1: Kirchoff's Laws (KL) only (algebraic); Case 2: KL + ODEs for currents.
- Small-signal analysis:
  - Uncertainty quantification: quantify sensitivity of critical inverter penetration levels to parameter sensitivity (R, L, C values, filter and control gain parameters).
- Tool: implement Lin's paper models in Matlab (possibly using open-source repository as a starting point: https://github.com/TSadamoto/CSM2018