NAPS 2016

UNIVERSITY of DENVER

IEEE

IEEE PES Power & Energy Society™

Design A Robust Power System Stabilizer on SMIB Using Lyapunov Theory

Authors: Yin Li, *Student Member, IEEE,*
Lingling Fan, *Senior Member, IEEE*

Presented by: Yin Li

Smart Grid Power System Laboratory
Department of Electrical Engineering, University of South Florida

Outline

* Motivation of robust power system stabilizer (PSS)
* Robust design based on Lyapunov stability criterion
  * **Our contribution**
* Application in PSS design
* Case study

Motivation

* Power system stabilizer (PSS) is used to providing damping to electro-mechanical oscillation modes for a synchronous generator.
  * There is damping issue related to automatic voltage regulator (AVR) at high power transfer level [1].
* Conventional PSS design is based on the linearized model of a typical operating condition.
  * At another operating condition, PSS may not work well.
* Robust PSS can work for a wide range of operating conditions.
  * Lyapunov stability theory:

  $\dot{x}=Ax$. If there exists a $P\geq 0$, that makes $A^T P+PA\leq 0$ true. Then, the system is stable.

  If $A^T P+PA \leq -\beta * P$, the system is exponentially stable where β is positive. .

[1] Y. Li and L. Fan, "Determine power transfer limits of an smib system through linear system analysis with nonlinear simulation validation," in *North American Power Symposium (NAPS), 2015, Oct 2015, pp. 1–6.*

Robust design based on Lyapunov stability criterion

- For different conditions, there are different *A* matrix and *B* matrix.
  - $\dot{x} = A_1 x + B_1 u$
  - $\dot{x} = A_2 x + B_2 u$
  - …
  - $\dot{x} = A_n x + B_n u$

$u = KCx$ that can stabilize all the closed-loop systems.

$\dot{x} = (A_i + B_i KC)x \rightarrow (Ai + B_i KC)^T P + P(A_i + B_i KC) \leq -\beta * P$

Not LMIs!

Convert the inequalities to LMI

* Using two variables X and Y to replace two unknown matrices, K and P [2].

$$0 \geq (A_i + B_i K C)^T P + P(A_i + B_i K C) + \beta P$$

If $X = P^{-1}$ and $Y = KCP^{-1}$

* Then, MATLAB CVX toolbox is used to find X matrix and Y matrix to satisfy this inequality.

$$0 \geq X A_i^T + Y^T B_i^T + A_i X + B_i Y + X\beta$$

* K matrix is estimated easily based on X and Y.

$$K = Y X^{-1} C^{-1}$$

LMIs!

[2] EE363 Linear Dynamic Systems by Professor Stephen Boyd, Stanford University.

Our contribution

* H_∞ design is based on a nominal system and considers a bounded uncertainty [3].
  * Solve one or two LMIs.

* Our design is based on many operating conditions.
  * Solve 50 LMIs.
  * Not possible without the advancement in computing of convex programming tools.
  * Matlab CVX toolbox – 2012.

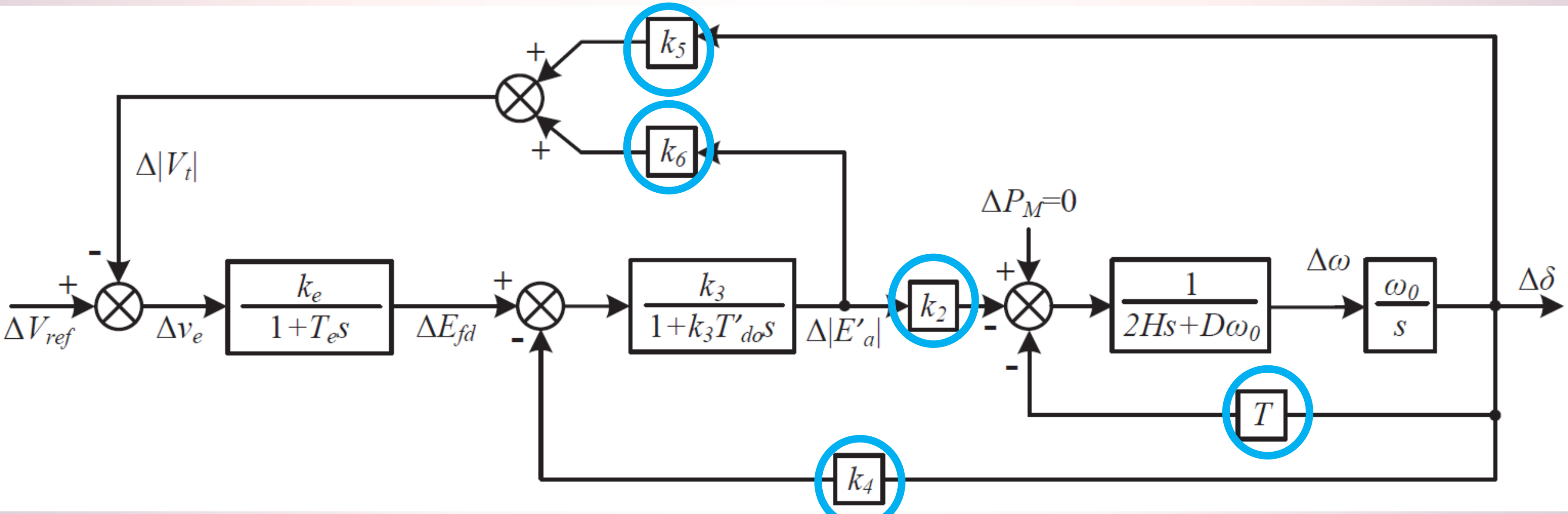
[3] J.-K. Shiau, G. N. Taranto, J. H. Chow, and G. Boukarim, "Power swing damping controller design using an iterative linear matrix inequality algorithm," IEEE Transactions on Control Systems Technology, vol. 7, no. 3, pp. 371–381, May 1999.

Application of PSS design

* The power system can be presented by the state space matrix.

$$\begin{cases} \dot{x} = A_i x + Bu \\ y = Cx \end{cases}$$

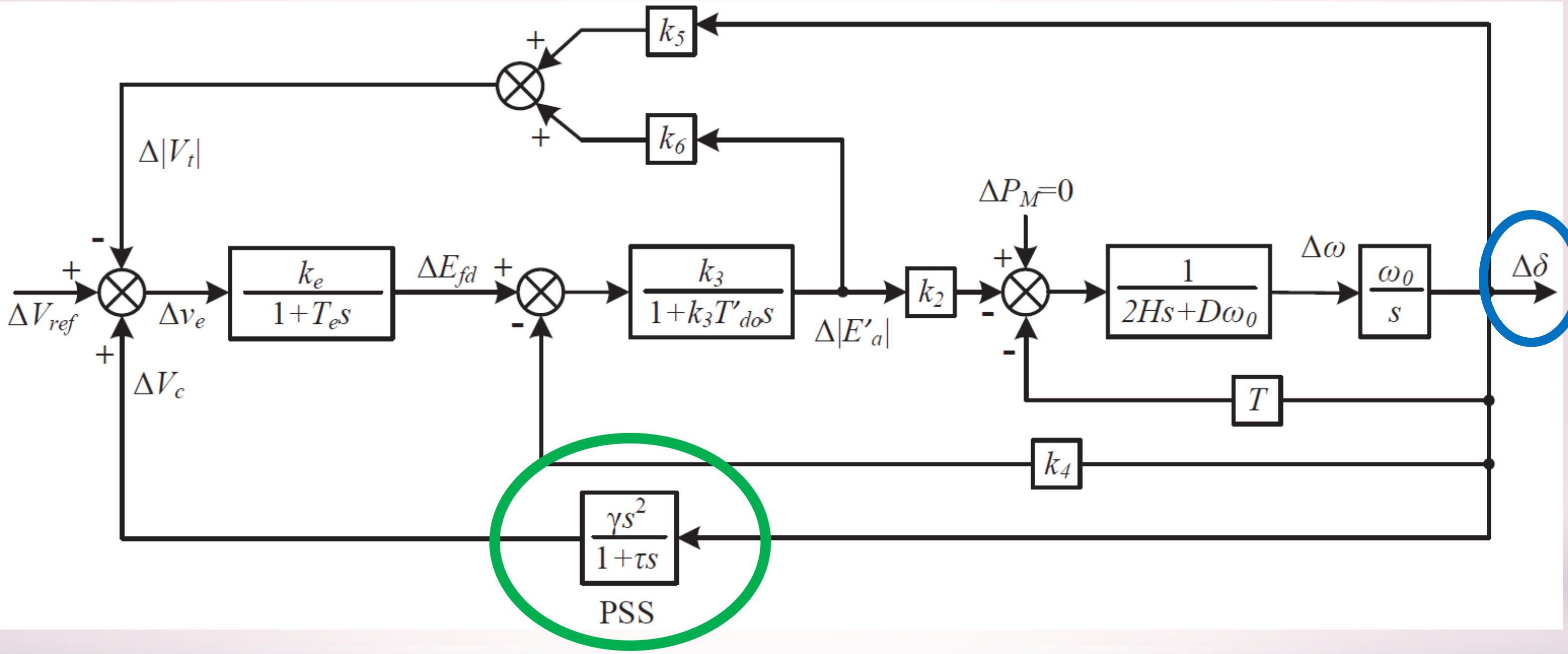
* Several values are changed under different operating conditions.



Block diagram of EMT+AVR model of SMIB system

Application of PSS design

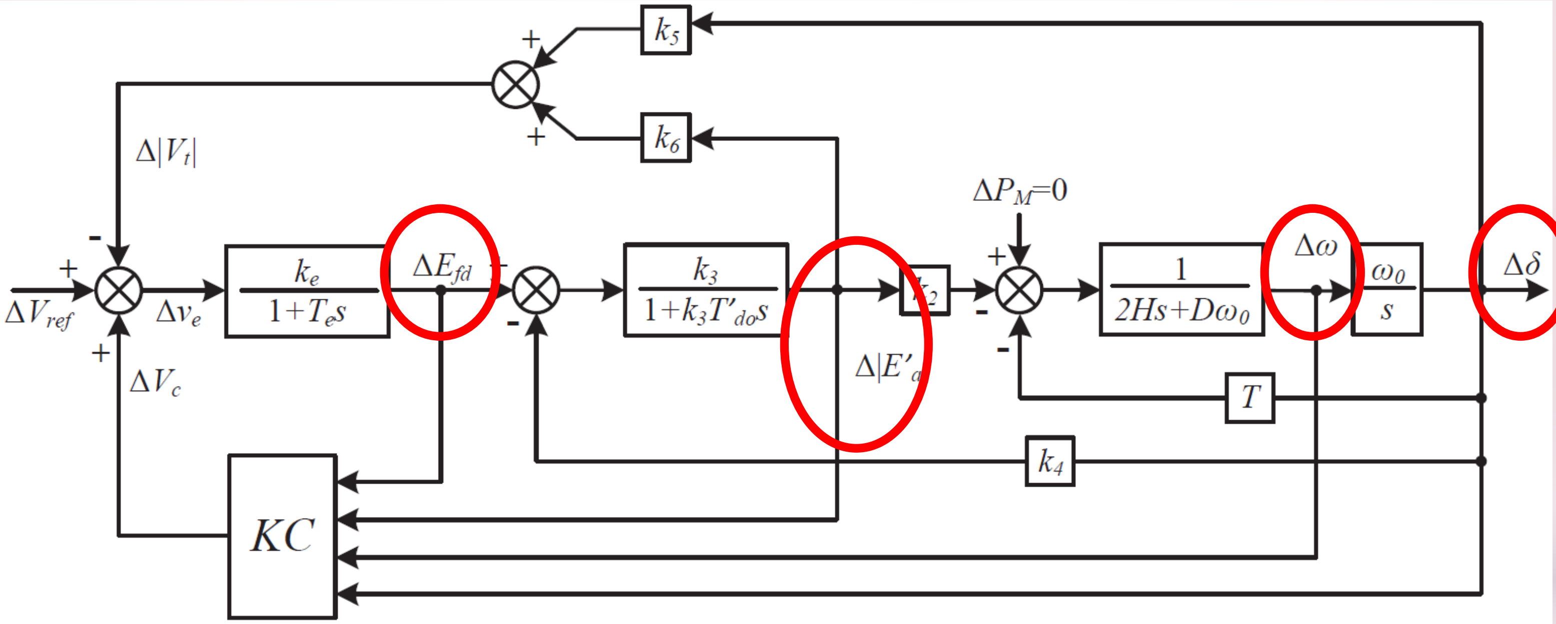
- Conventional PSS is applied to EMT+AVR model.



- Two zeros and one pole are added to change the system's root locus.

Application of PSS design

* Robust PSS is applied to EMT+AVR model.



* If all of state variables are considered as outputs, ***C*** matrix will be a unit one.

$$K = YX^{-1}C^{-1} \quad \Rightarrow \quad K = KC = YX^{-1}$$

Application of PSS design

- 50 conditions are considered totally.
  - 25 combinations of real power and reactive power generated by synchronous machine.
  - fault on one of transmission line
- 10 conditions are selected to verify if designed robust PSS works.

$X_L = 0.4$

P(p.u.) \ Q(p.u.)	-0.8	-0.5	0	0.5	0.8
1.28	Cond1 ★	Cond2	Cond3	Cond4	Cond5
1.26	Cond6	Cond7 ★	Cond8	Cond9	Cond10
1.0	Cond11	Cond12	Cond13	Cond14	Cond15 ★
0.8	Cond16	Cond17 ★	Cond18	Cond19	Cond20
0.6	Cond21	Cond22 ★	Cond23	Cond24	Cond25

$X_L = 0.2$

P(p.u.) \ Q(p.u.)	-0.8	-0.5	0	0.5	0.8
1.28	Cond26	Cond27	Cond28 ★	Cond29	Cond30
1.26	Cond31	Cond32	Cond33	Cond34 ★	Cond35
1.0	Cond36	Cond37	Cond38	Cond39 ★	Cond40
0.8	Cond41	Cond42	Cond43 ★	Cond44	Cond45
0.6	Cond46	Cond47	Cond48	Cond49	Cond50 ★

Application of PSS design

* *KC* can be found to satisfy all of fifty LMIs by running the following CVX code in MATLAB.

```
cvx_begin sdp
variable X(n,n) symmetric
variable Y(1,n)
X*A1'+ Y'*B'+A1*X+B*Y+X*beta <=0
X*A2'+ Y'*B'+A2*X+B*Y+X*beta <=0
               .
               .
               .
X>=eye(n)
cvx_end
KC=Y*inv(X)
```

```
KC =
   1.0e+03 *

    0.0080    7.6136   -0.1016   -0.0004
```

Case Study

* Comparison of eigenvalues
  * Case 1: no PSS
  * Case 2: conventional PSS
  * Case 3: robust PSS
* Nonlinear simulation results
  * Case 2: conventional PSS
  * Case 3: robust PSS

Comparison of Eigenvalues

- Closed-loop eigenvalues under selected 10 conditions.

	Eig 1, 2	Eig 3,4
Cond1	-4.2411 &-9.3056	-8.7674 ±53.0810i
Cond7	-6.5566 ± 2.6118i	-8.9842 ±53.0798i
Cond15	-3.4965 ± 7.9962i	-12.0443 ±53.1654i
Cond17	-6.2844 ± 2.6568i	-9.2564 ±53.0578i
Cond22	-5.9135 ± 2.8572i	-9.6273 ±53.0474i
Cond28	-8.6645 ± 4.6601i	-7.0430 ±53.3120i
Cond31	-6.2087 ± 7.9191i	-9.4988 ±53.0371i
Cond39	-7.1413 ± 7.6704i	-8.5662 ±53.0953i
Cond43	-7.1527 ± 5.3502i	-8.5547 ±53.1131i
Cond50	-3.4588 ± 9.2725i	-12.2486 ±53.1455i

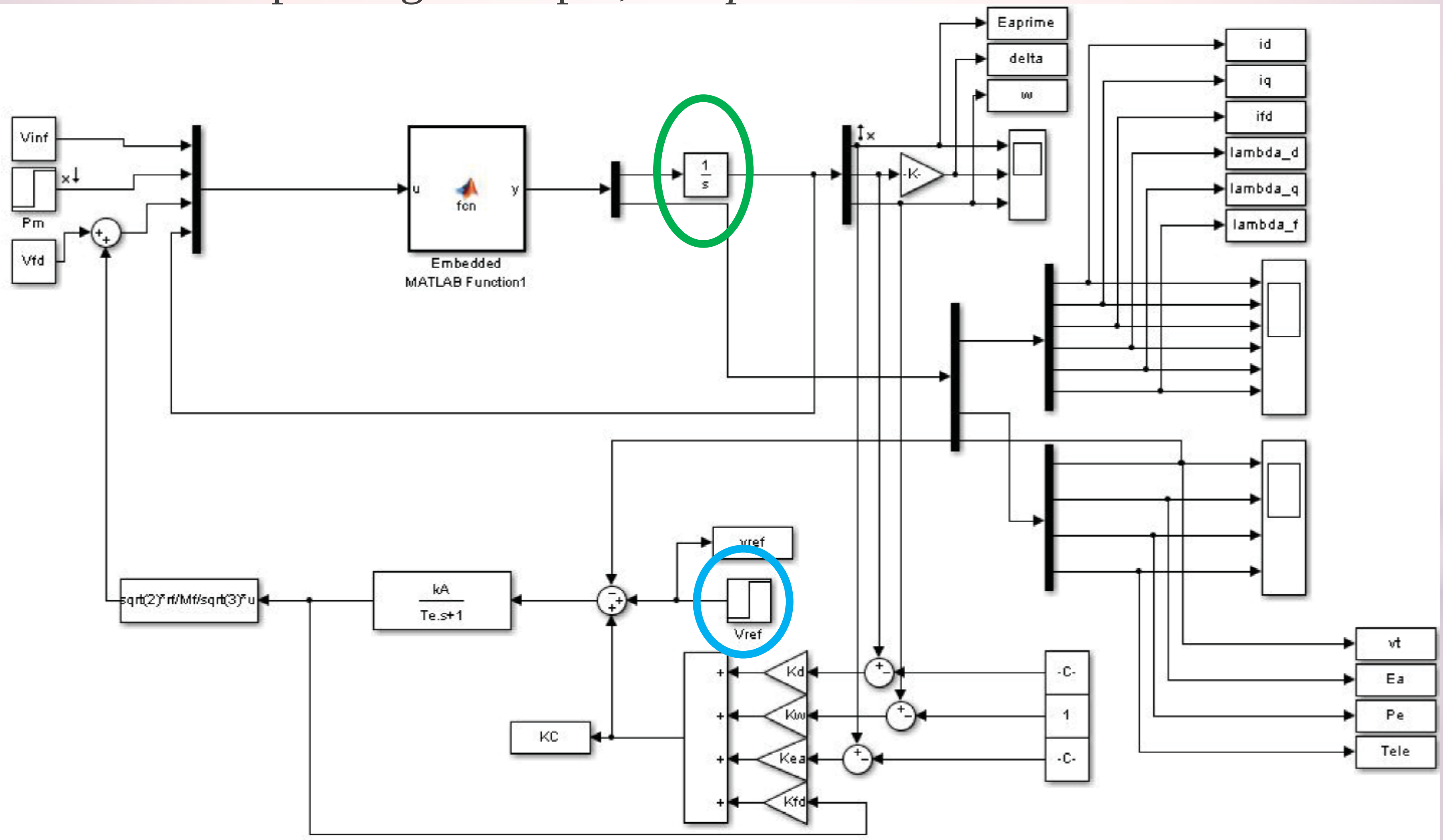
Case 2: EMT+AVR+Conventional PSS

Case 3: EMT+AVR+Robust PSS

τ=0.001; γ =0.1

Nonlinear Simulation Results

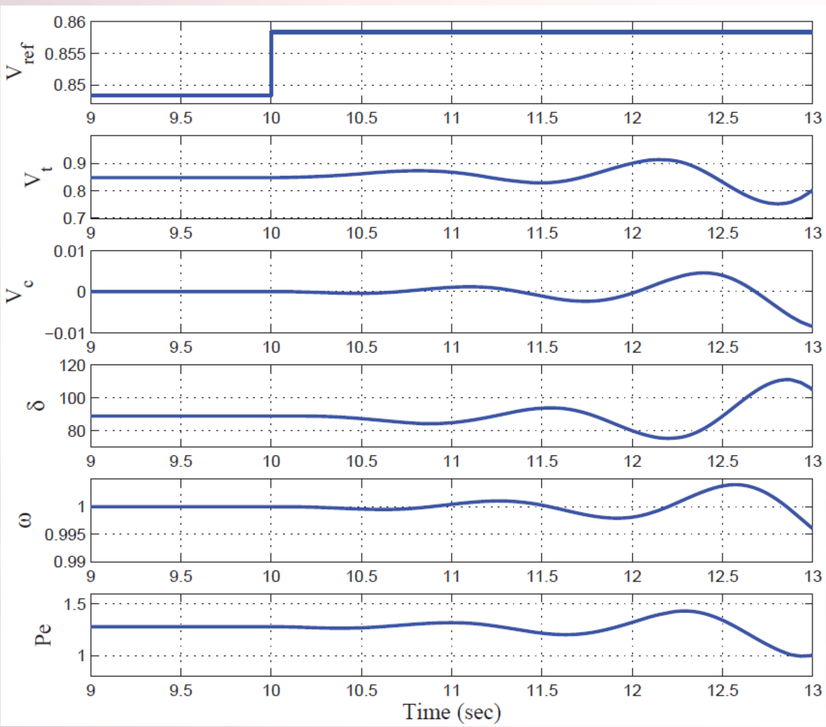
* Calculating initial values based on Cond1 and Cond7
* Step change on input, 0.01*p.u.*.

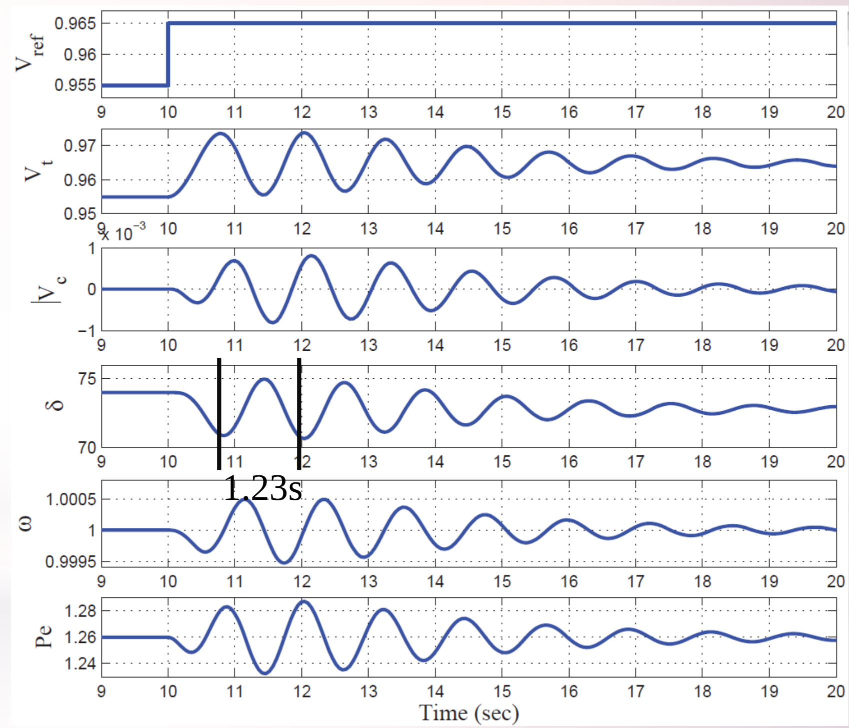


Nonlinear Simulation Results

Conventional PSS

- The right plot showed that the system became stable after a transient while the left plot presented an unstable system.
- The oscillation frequency was around 5.10*rad/s* (0.81*Hz*).





Cond 1: -2.1795 ± 5.3098*i*
0.9911 ± 4.7780*i*

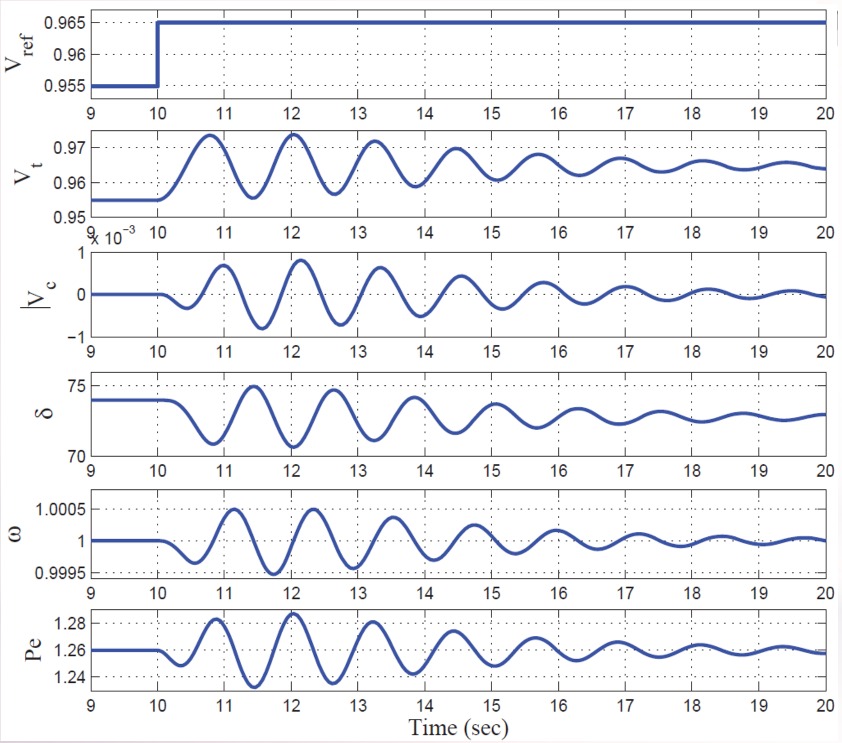
Cond 7: -0.8991 ± 5.7661*i*
-0.2979 ± 5.0637*i*

Nonlinear Simulation Results

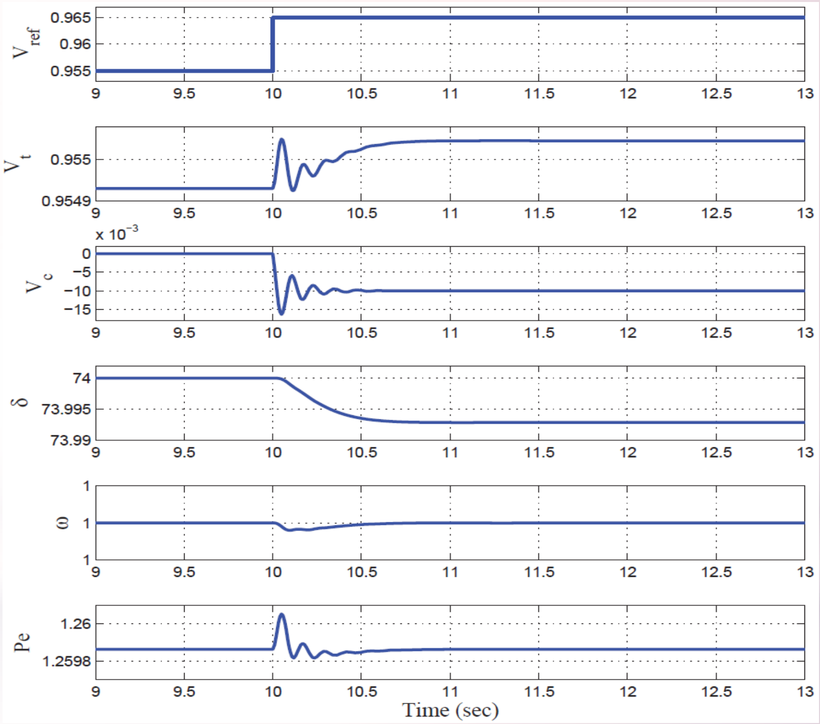
Robust PSS

* The system was stable under both of conditions.
* Robust PSS has the faster response speed and smaller oscillation.

Conventional PSS



Robust PSS



Cond 7: -4.2491 & -5.7656

-0.7079 ±53.0837i

Cond 7: -6.5566 ± 2.6118i

-8.9842 ±53.0798i

Conclusion

* Better robustness because of multiple operation conditions considered.

* The control design is based on LMI solving using convex programming tools.

Thank you!