ECE 595S

IFOC

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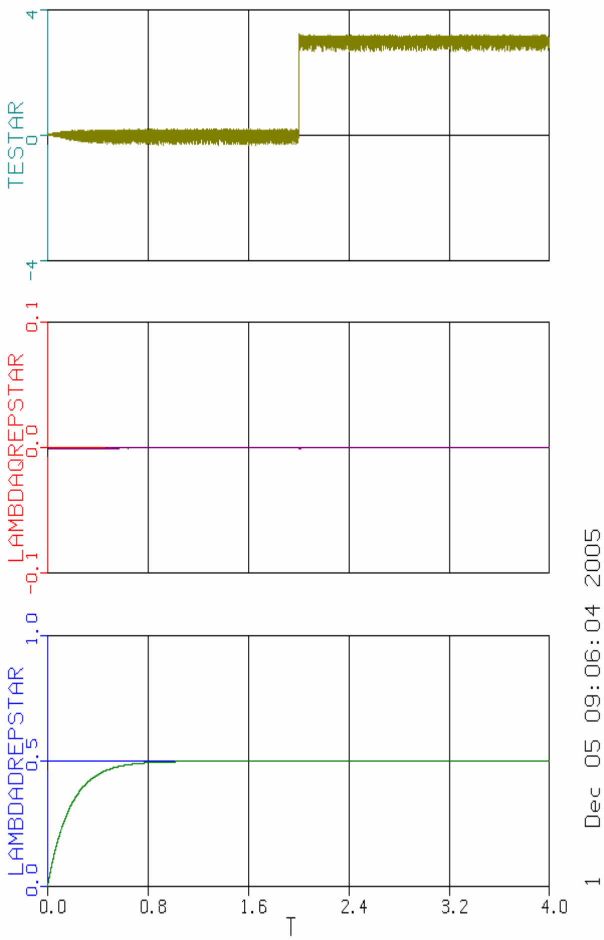
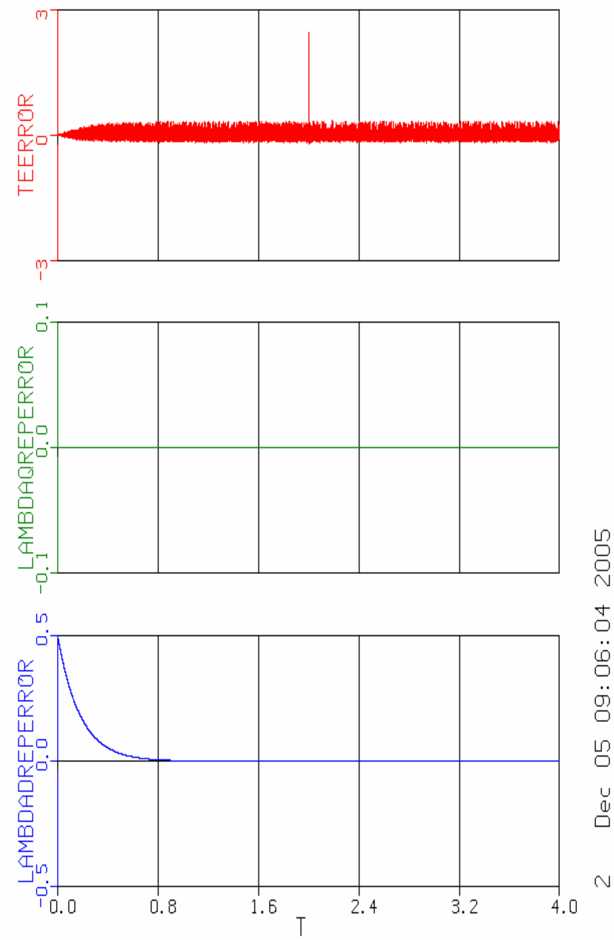
Torque Command Performance

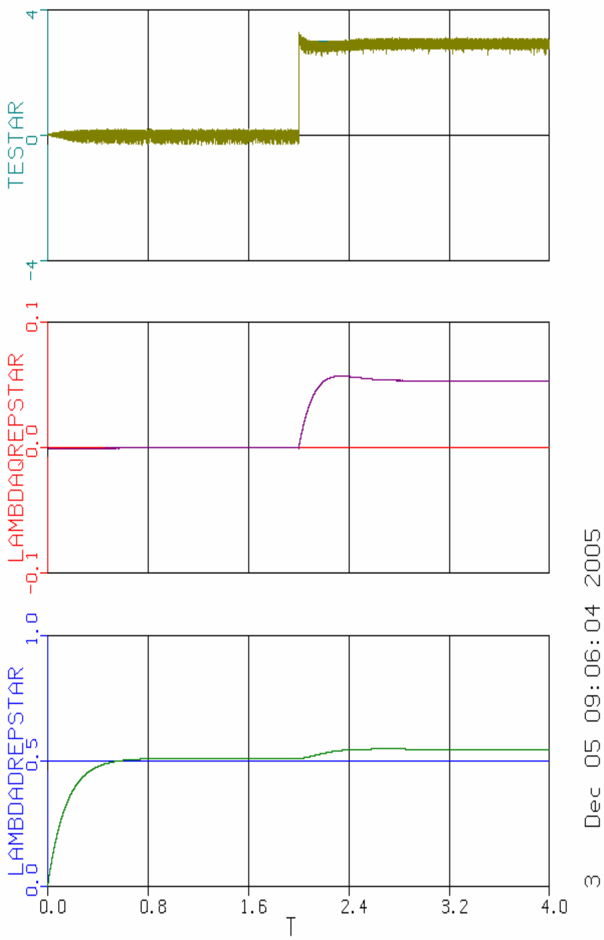
- Constant speed (1700 RPM)
- Torque command stepped from 0.0 Nm to 3.0 Nm at 2.0 s
- First with machine having “cold” parameters
- Then with machine having “warm” parameters

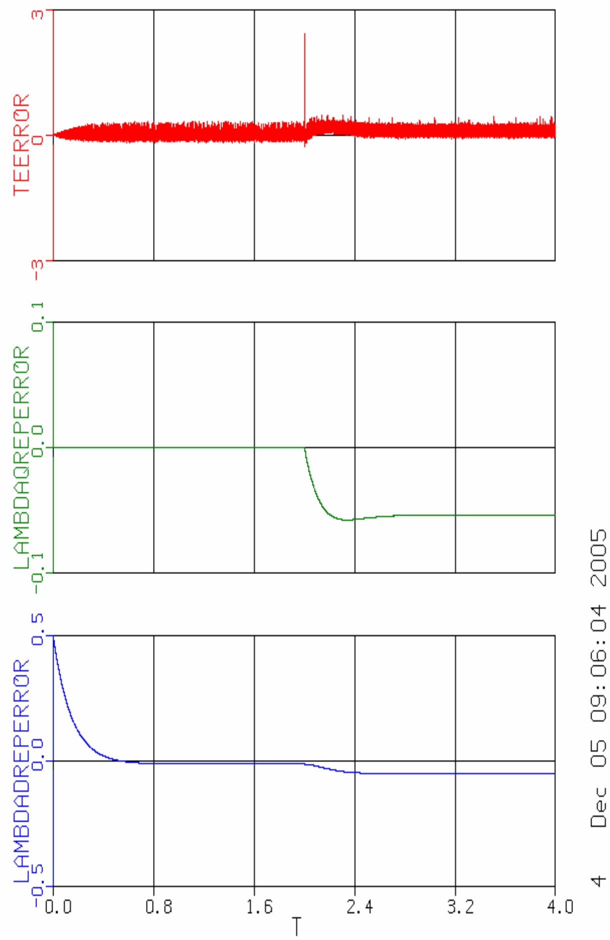
“Cold” Performance





“Warm” Performance





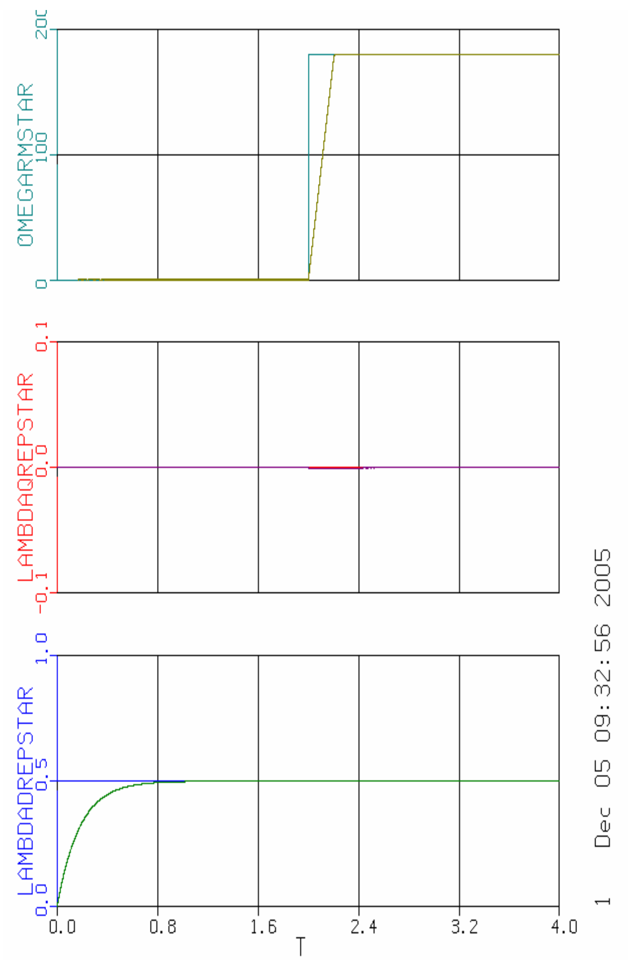
Torque Command Performance

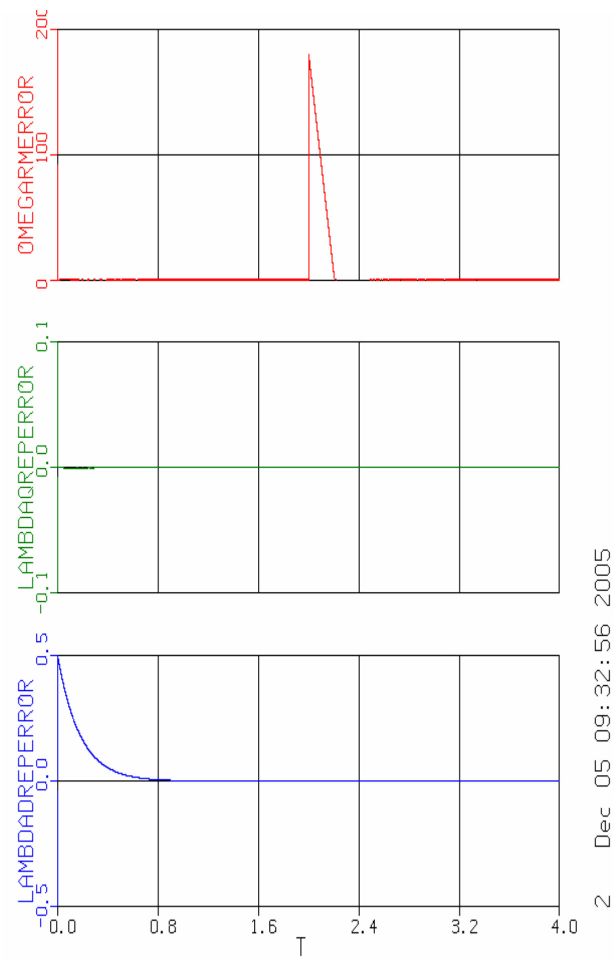
- When the machine has the “cold” parameters, IFOC effective
- When the machine has the “warm” parameters, steady-state torque error
- Also, steady-state error in the commanded flux linkages

Speed Control Performance

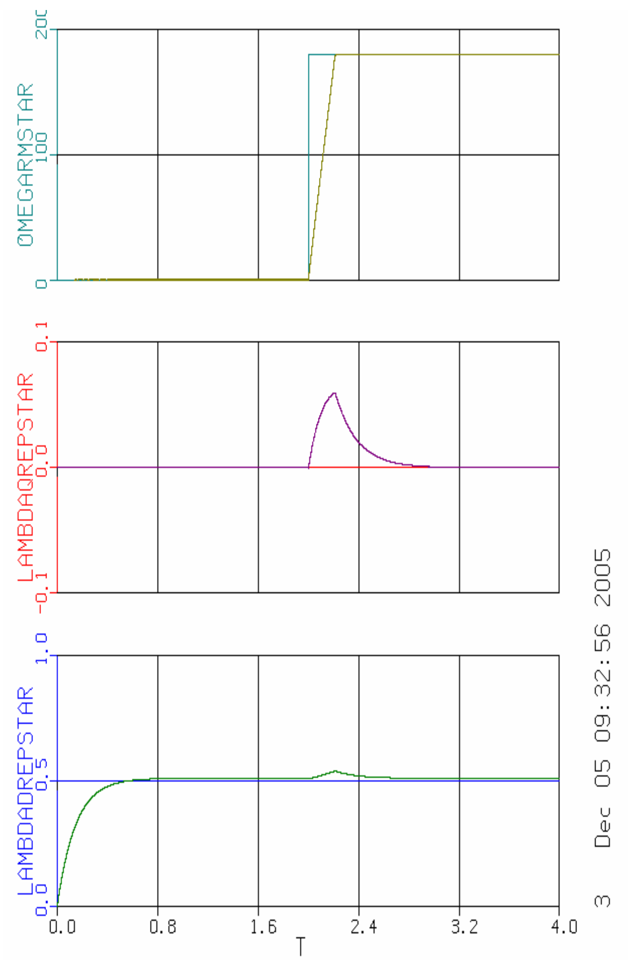
- Speed command stepped from 0.0 rad/s to 180.0 rad/s at 2.0 s
- Torque command limited to ±3.5 Nm
- Simple PI loop around IFOC
- First with “cold” parameters
- Then with “warm” parameters

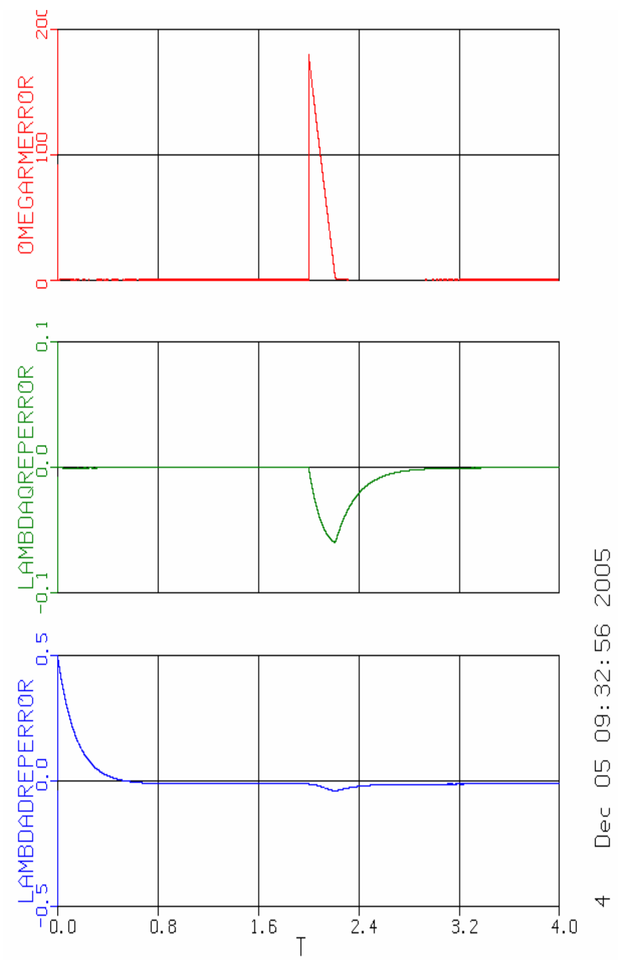
“Cold” Performance





“Warm” Performance





Speed Control Performance

- In both situations, the control is limited by the torque limit
- In both situations, the steady-state speed error is zero
- In both situations, the steady-state flux linkage error is zero
- In this situation the performance is acceptable
- We will not consider the application of speed control further in this discussion

IM model

- Consider the following representation of the IM in the stationary reference frame

$$
\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{A}(\omega_r)\mathbf{x} + \mathbf{B}\mathbf{u} \\
\mathbf{y} &= \mathbf{C}\mathbf{x} \\
\mathbf{A}(\omega_r) &= \mathbf{A_I} + \omega_r \mathbf{A_{II}}
\end{aligned}
$$

$$
\mathbf{A_I} = \begin{bmatrix}
\frac{-r_s L_{rr}^{'}}{L_{ss}L_{lr}^{'} + L_{ls}L_M} & 0 & \frac{r_s L_M}{L_{ss}L_{lr}^{'} + L_{ls}L_M} & 0 \\
0 & \frac{-r_s L_{rr}^{'}}{L_{ss}L_{lr}^{'} + L_{ls}L_M} & 0 & \frac{r_s L_M}{L_{ss}L_{lr}^{'} + L_{ls}L_M} \\
\frac{r_r^{'} L_M}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M} & 0 & \frac{-r_r^{'} L_{ss}}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M} & 0 \\
0 & \frac{r_r^{'} L_M}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M} & 0 & \frac{-r_r^{'} L_{ss}}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M}
\end{bmatrix}
$$

IM model

$$\mathbf{A_{II}} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} \frac{L_{rr}^{'}}{L_{ss}L_{lr}^{'} + L_{ls}L_M} & 0 & -\frac{L_M}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M} & 0 \\ 0 & \frac{L_{rr}^{'}}{L_{ss}L_{lr}^{'} + L_{ls}L_M} & 0 & -\frac{L_M}{L_{rr}^{'}L_{ls} + L_{lr}^{'}L_M} \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} \lambda_{qs}^{s} & \lambda_{ds}^{s} & \lambda_{qr}^{s'} & \lambda_{dr}^{s'} \end{bmatrix}^T$$

$$\mathbf{u} = \begin{bmatrix} v_{qs}^{s} & v_{ds}^{s} \end{bmatrix}^T$$

$$\mathbf{y} = \begin{bmatrix} i_{qs}^{s} & i_{ds}^{s} \end{bmatrix}^T$$

TSK model

$$\dot{\mathbf{x}} = \mathbf{A}(\alpha)\mathbf{x} + \mathbf{B}\mathbf{u}$$

$$\mathbf{A}(\alpha) = \sum_{k=1}^{K} \alpha_k \mathbf{A_k}$$

$$\sum_{k=1}^{K} \alpha_k = 1$$

$$\mathbf{A_1} = \mathbf{A_I} + \omega_{r,\min} \mathbf{A_{II}}$$

$$\mathbf{A}_2 = \mathbf{A_I} + \omega_{r,\max} \mathbf{A_{II}}$$

$$\alpha_1 = 1 - \alpha_2 = \frac{\omega_{r,\max} - \omega_r}{\omega_{r,\max} - \omega_{r,\min}}$$

Stable if

$$\exists \mathbf{P} = \mathbf{P}^T > \mathbf{0}$$

$$\forall k \in \{1,2,\ldots,K\}$$

$$\mathbf{A_k}^T \mathbf{P} + \mathbf{P}\mathbf{A_k} < \mathbf{0}$$

G. Strang, *Linear Algebra and its Applications*

S.H. Żak, *Systems and Control*

Observer design

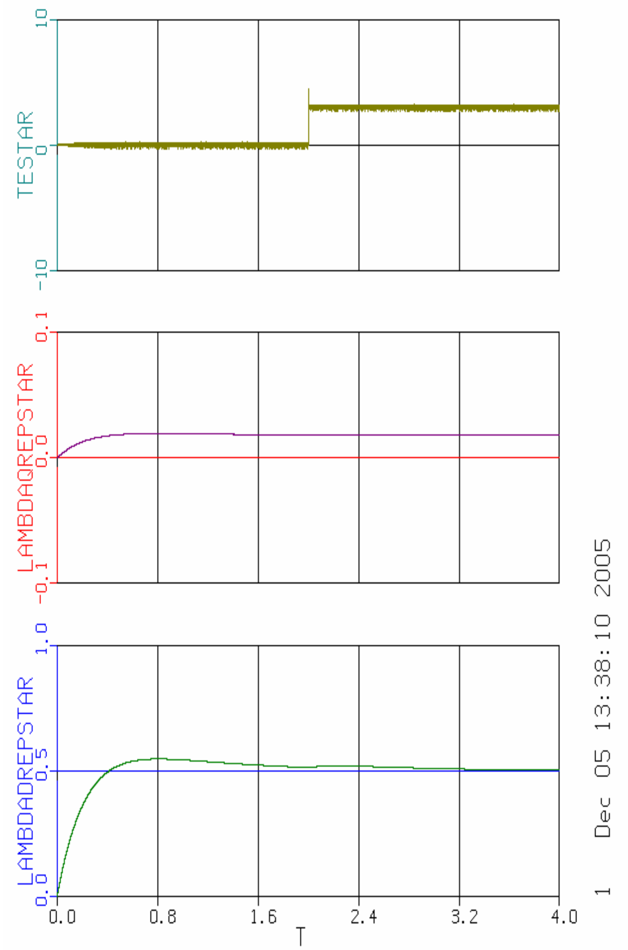
$$
\begin{aligned}
&\exists \mathbf{P} = \mathbf{P}^T > \mathbf{0} \\
&\exists \mathbf{Z} \\
&\forall k \in \{1, 2, \ldots, K\} \\
&\mathbf{A}_\mathbf{k}^T \mathbf{P} + \mathbf{P}\mathbf{A}_\mathbf{k} + 2\alpha \mathbf{P} > \mathbf{C}^T \mathbf{Z}^T + \mathbf{Z}\mathbf{C} \\
&\mathbf{L} = \mathbf{P}^{-1}\mathbf{Z} \\
&\dot{\hat{\mathbf{x}}} = \mathbf{A}(\alpha)\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} + \mathbf{L}(\mathbf{y} - \mathbf{C}\hat{\mathbf{x}})
\end{aligned}
$$

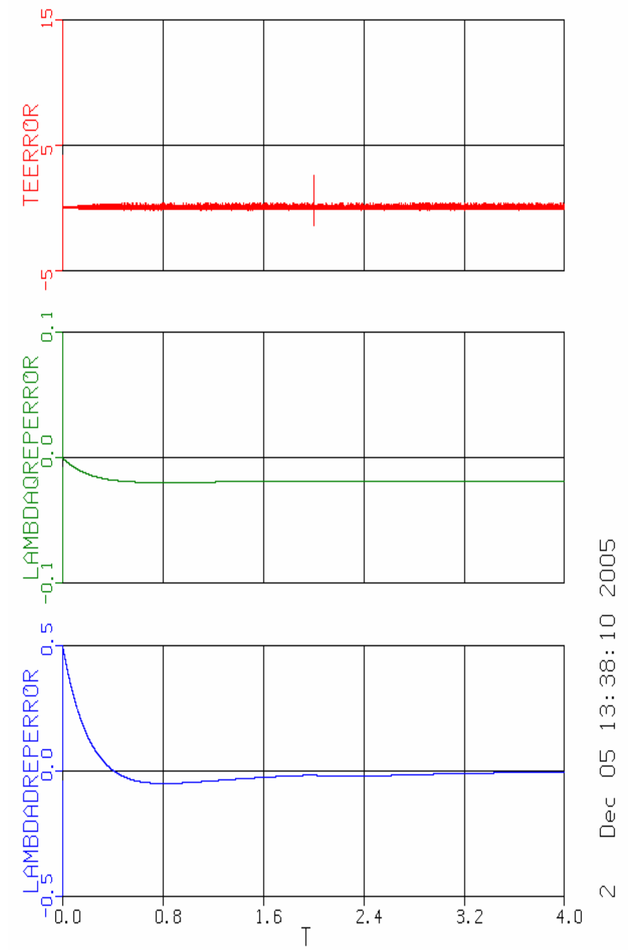
Try placing poles very deep in the left half plane $(\mathrm{Re}[\lambda] < -2000)$

M. Corless, *AAE 666 Course Notes*

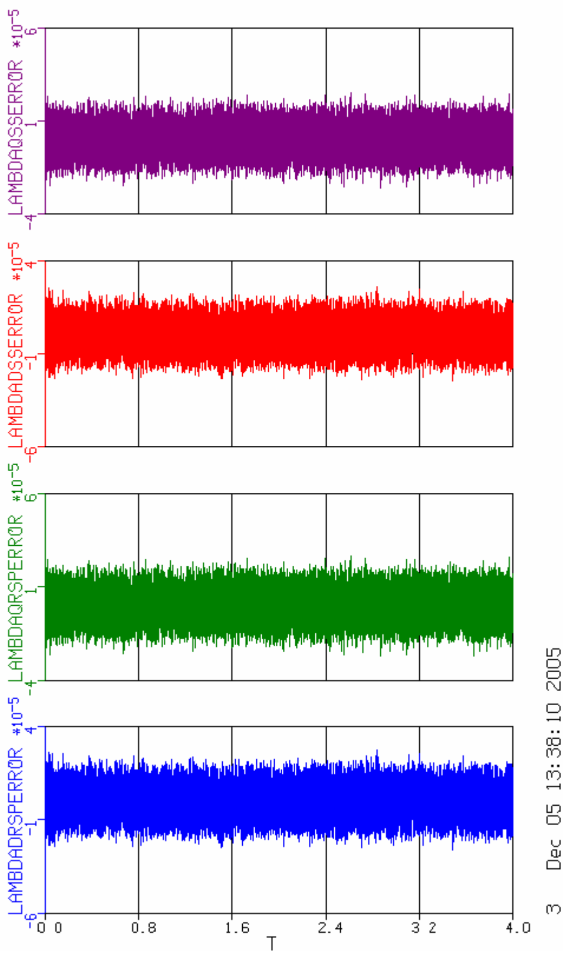
S. Boyd, L. El Ghaoui, E. Feron, V. Balakrishnan,
Linear Matrix Inequalities in System and Control Theory

“Cold” Performance



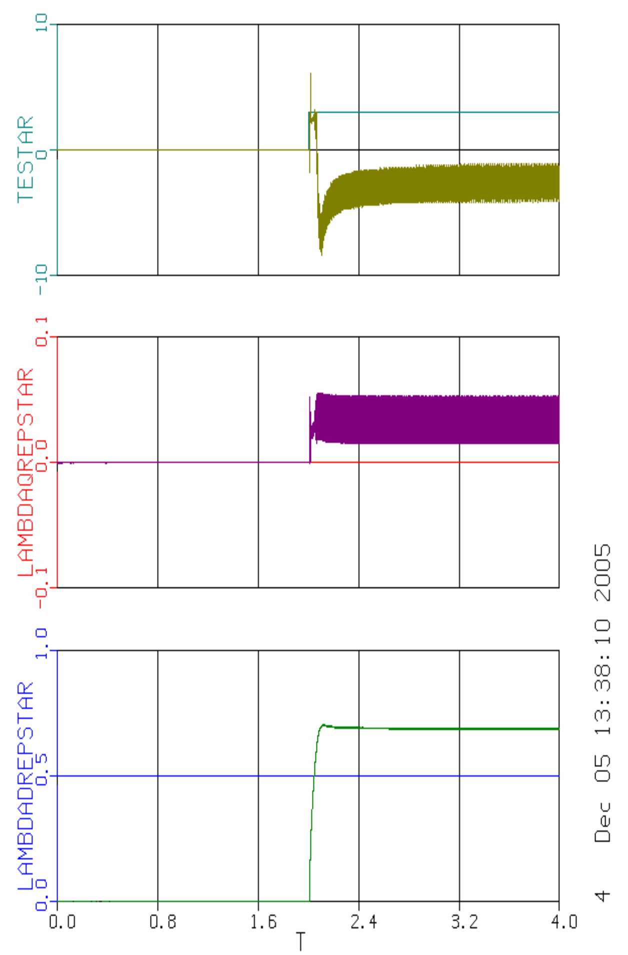


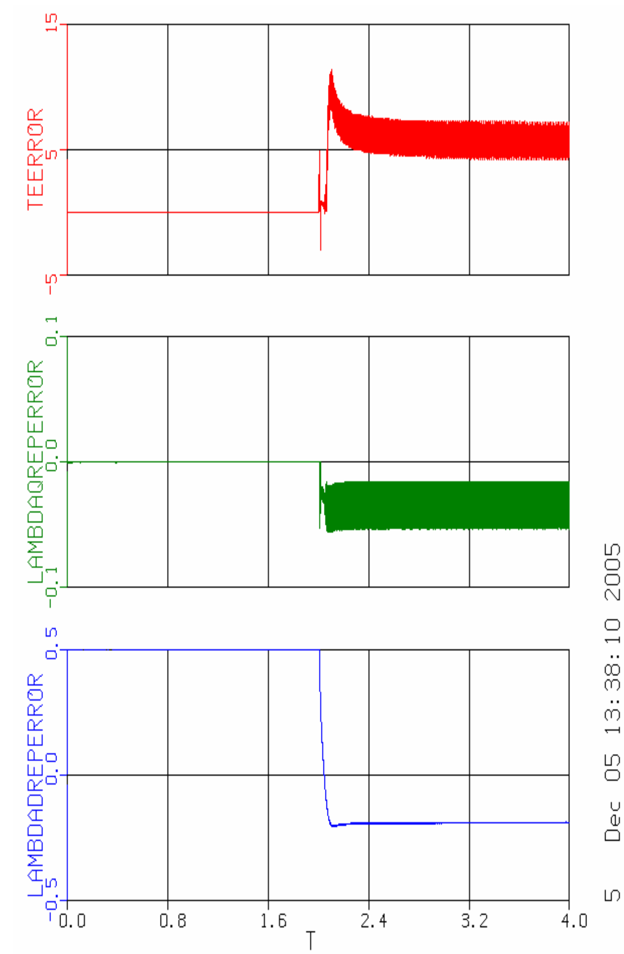
“Cold” Performance



- Observer error is less than 5.0×10^{-5} Vs
- It takes longer to establish the flux
- No steady-state torque error
- Some steady-state flux linkage error

“Warm” Performance





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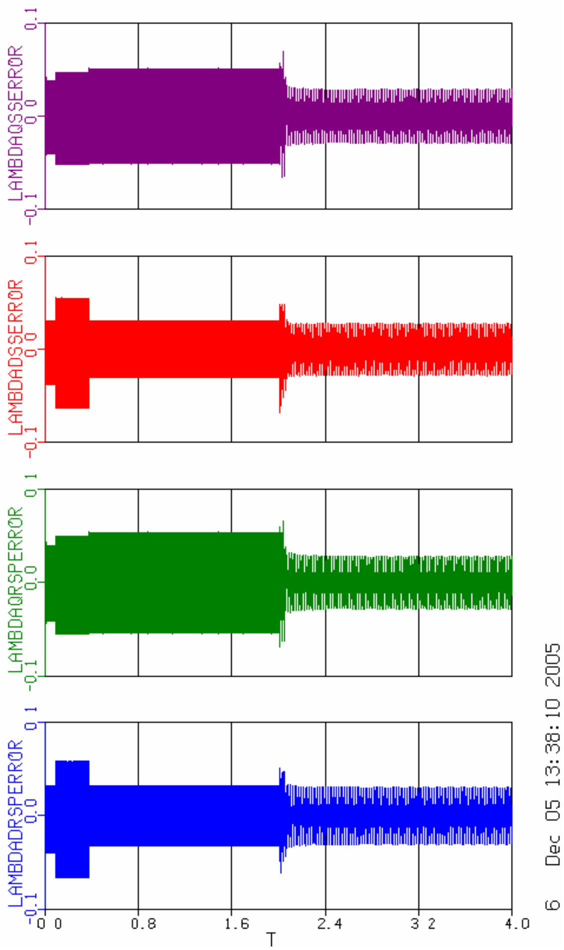


- Observer error is rather large (not decaying)
- There seems to be no convergence
- Torque actually becomes negative in response to a step command

What happened?

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x}$$

$$\dot{\hat{\mathbf{x}}} = \hat{\mathbf{A}}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} + \mathbf{L}\left(\mathbf{y} - \hat{\mathbf{C}}\hat{\mathbf{x}}\right)$$

$$\mathbf{e} = \mathbf{x} - \hat{\mathbf{x}}$$

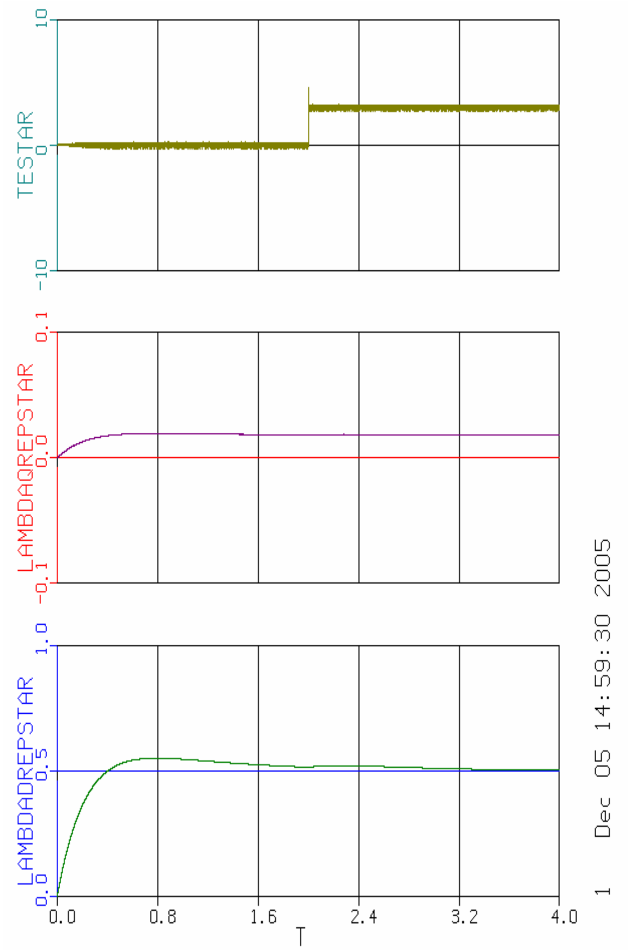
$$\dot{\mathbf{e}} = \left(\hat{\mathbf{A}} - \hat{\mathbf{L}}\hat{\mathbf{C}}\right)\mathbf{e} + \left(\mathbf{\Delta A} - \mathbf{L\Delta\Delta}\right)\mathbf{x}$$

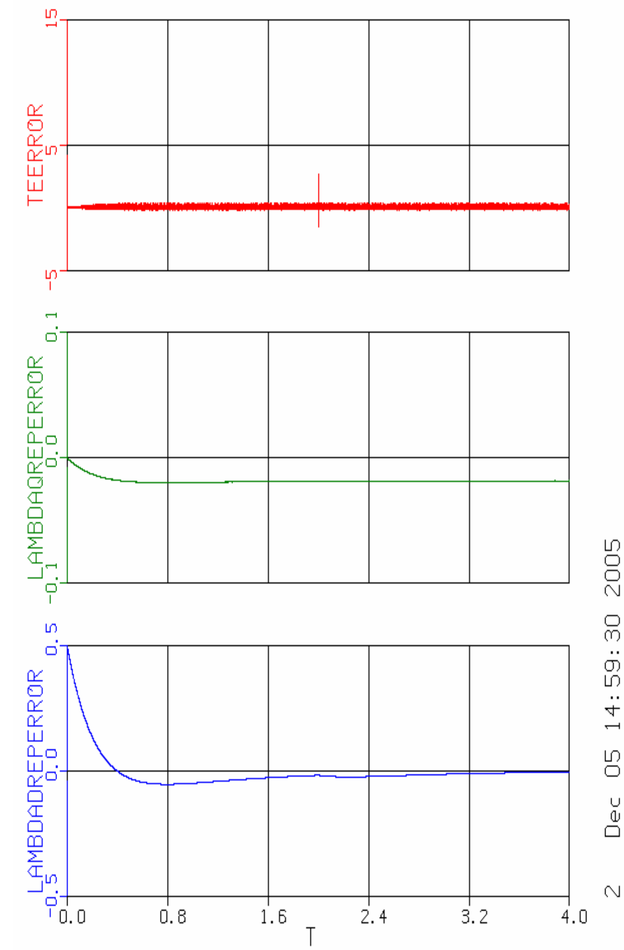
$$\mathbf{\Delta A} = \mathbf{A} - \hat{\mathbf{A}}$$

$$\mathbf{\Delta C} = \mathbf{C} - \hat{\mathbf{C}}$$

$$\mathbf{e}(t) = e^{\left(\hat{\mathbf{A}} - \hat{\mathbf{L}}\hat{\mathbf{C}}\right)(t - t_0)}\mathbf{e}(t_0) + \int_{t_0}^{t} e^{\left(\hat{\mathbf{A}} - \hat{\mathbf{L}}\hat{\mathbf{C}}\right)(t-\tau)}\left(\mathbf{\Delta A} - \mathbf{L\Delta\Delta}\right)\mathbf{x}(\tau)\,d\tau$$

“Cold” Performance





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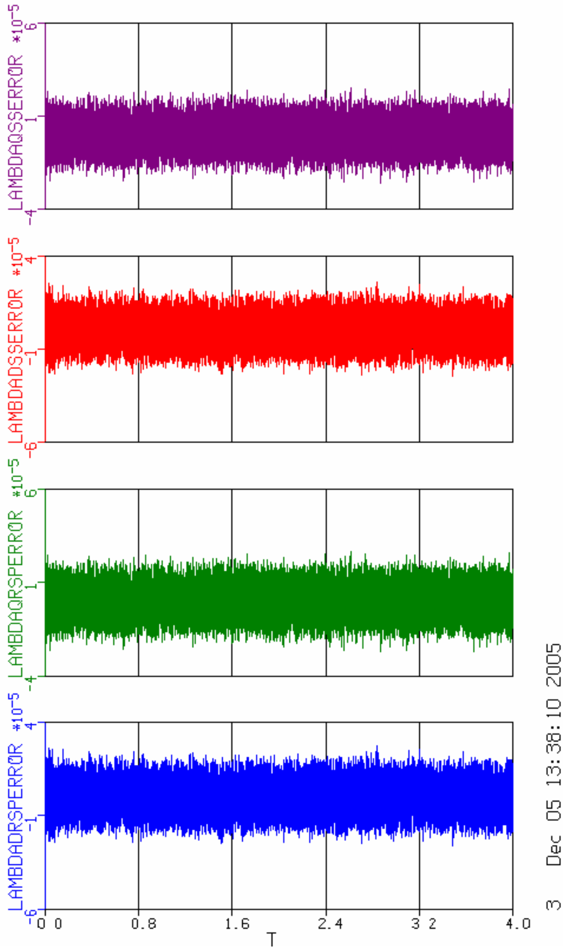

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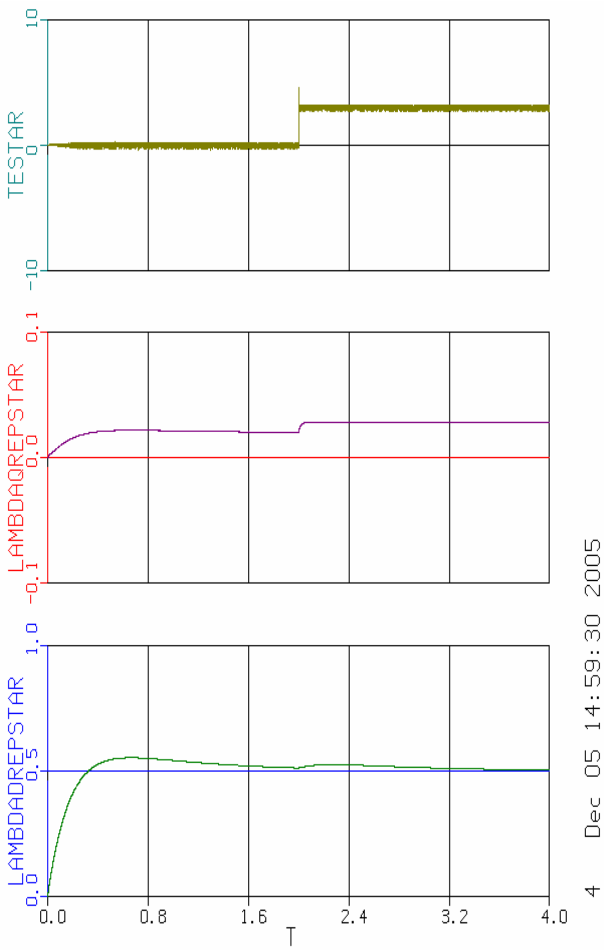
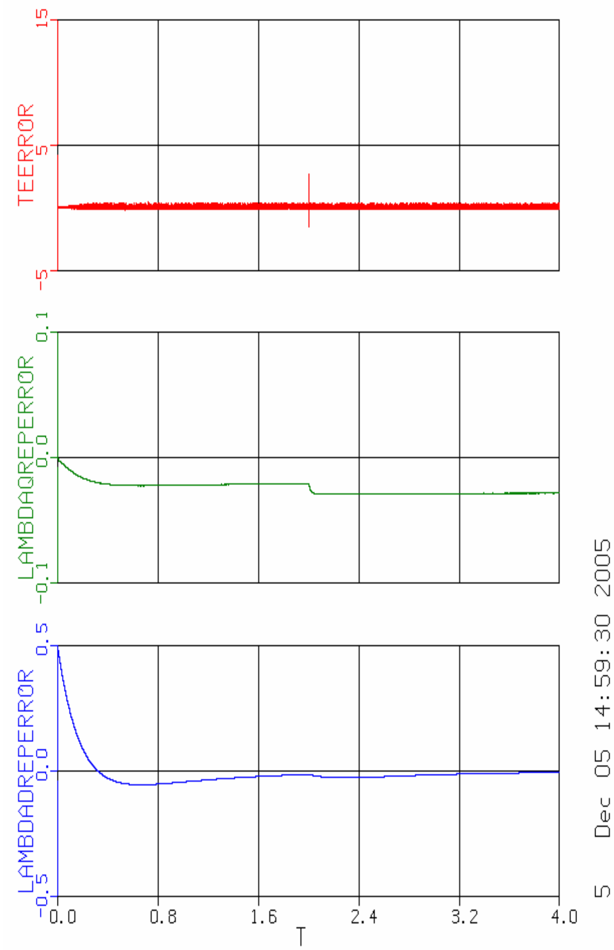
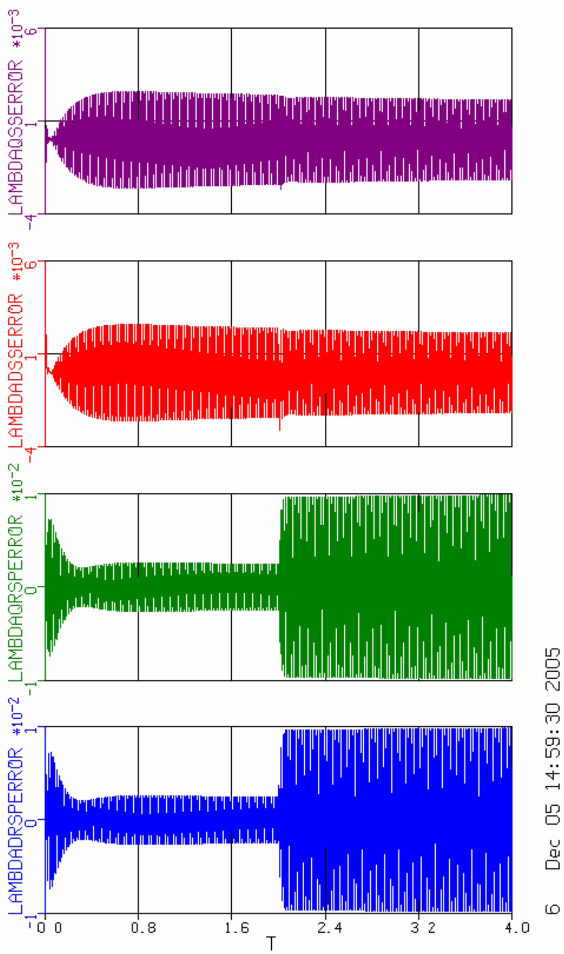
"Warm" Performance



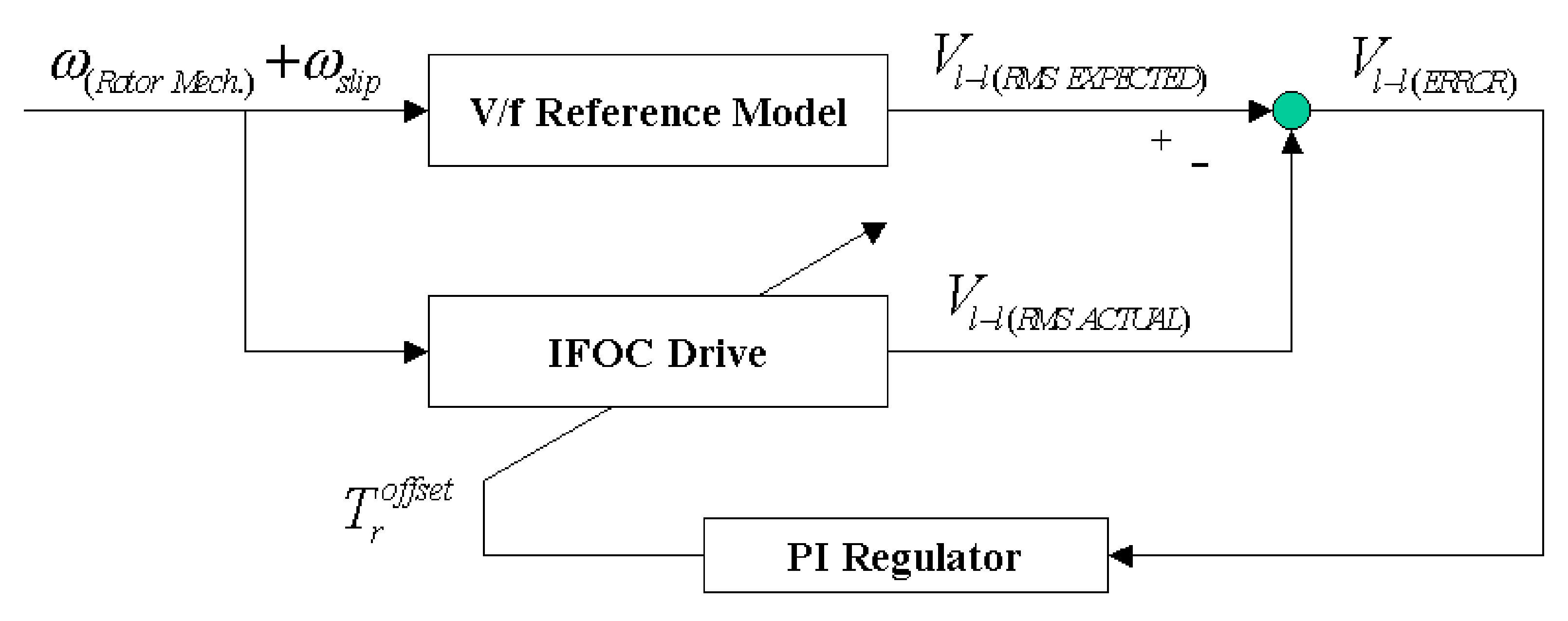


"Warm" Performance



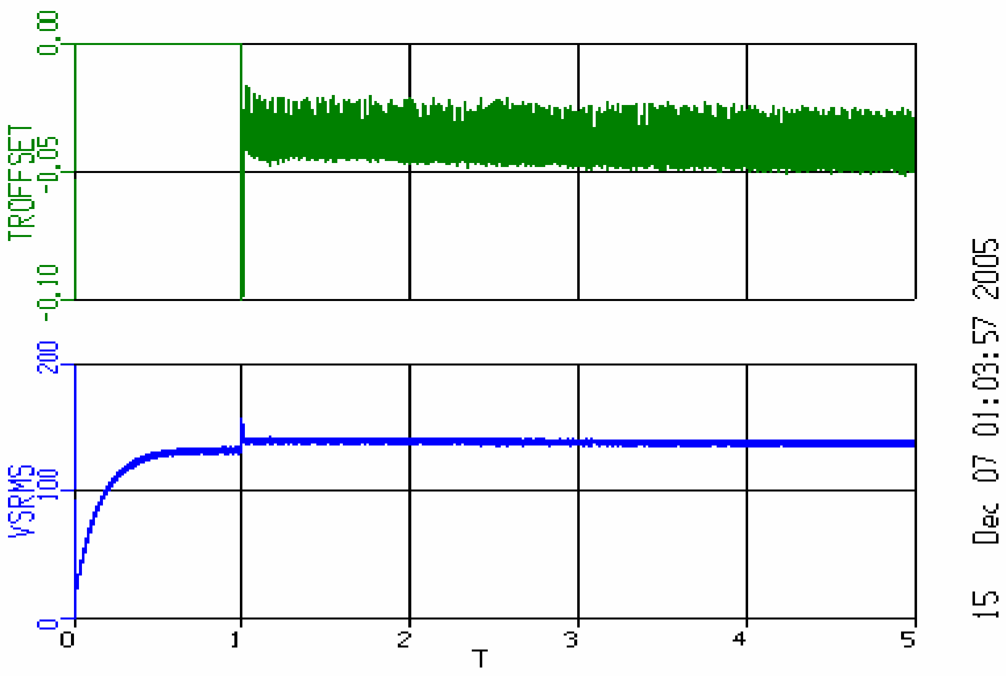
- Observer error is smaller than before
- No steady-state torque error
- Uses same input measurements as IFOC (± a voltage sensor or two)

Tr adaptation



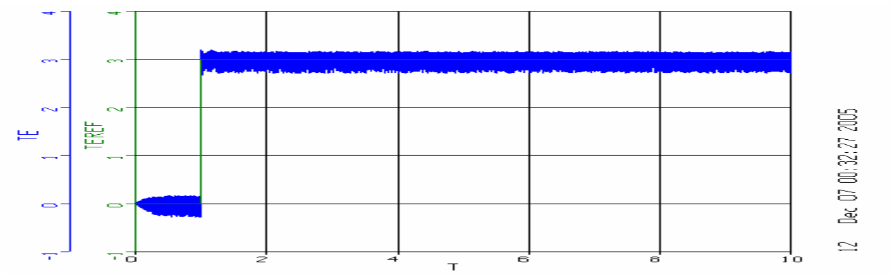
$$\frac{V_{L-L(RMS\ \ RATED)}}{\omega_{SYNC}} = \frac{V_{L-L(RMS\ \ EXPECTED)}}{\omega_{(Rotor\ \ Mech.)} + \omega_{slip}}$$

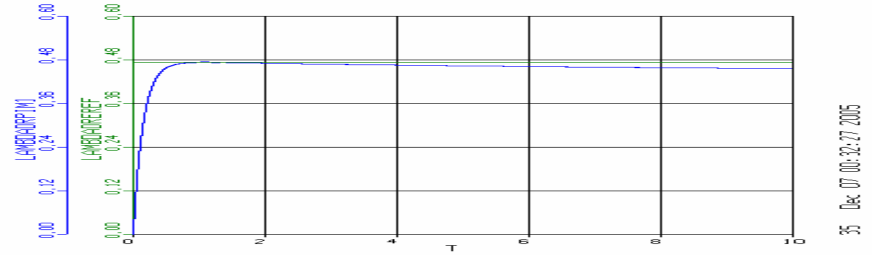
Tr offset adapted(wrm=1800 rpm)

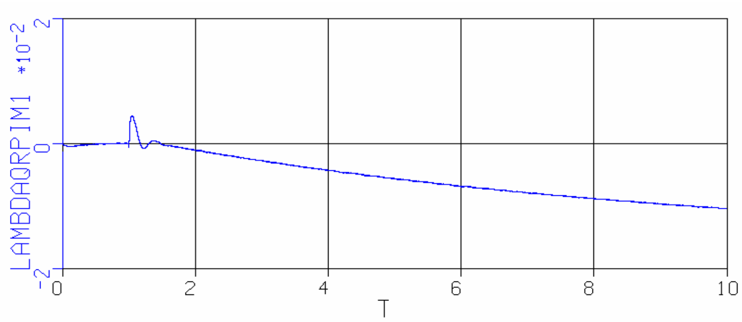


Tr offset should be
0.65 s

Warm performance(Tr)







At low speed(wrm=50 rpm)