Physics-Constrained Neural Network-Based Load Torque Observer for Traction Electric Machine

A. H. Safder, A. Hanif and Q. Ahmed, "Physics-Constrained Neural Network-Based Load Torque Observer for Traction Electric Machine," 2024 IEEE Conference on Control Technology and Applications (CCTA), Newcastle upon Tyne, United Kingdom, 2024, pp. 114-119, doi: 10.1109/CCTA60707.2024.10666631.

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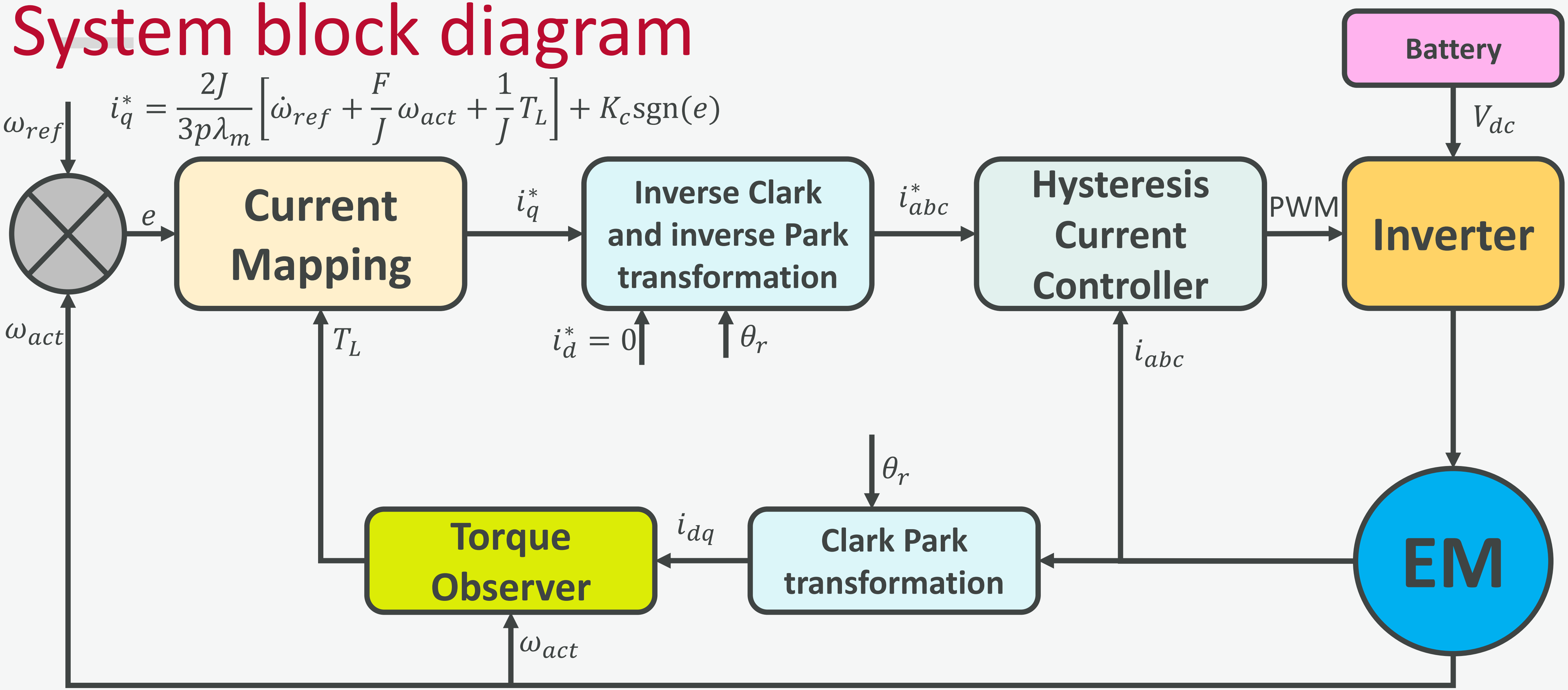
System block diagram

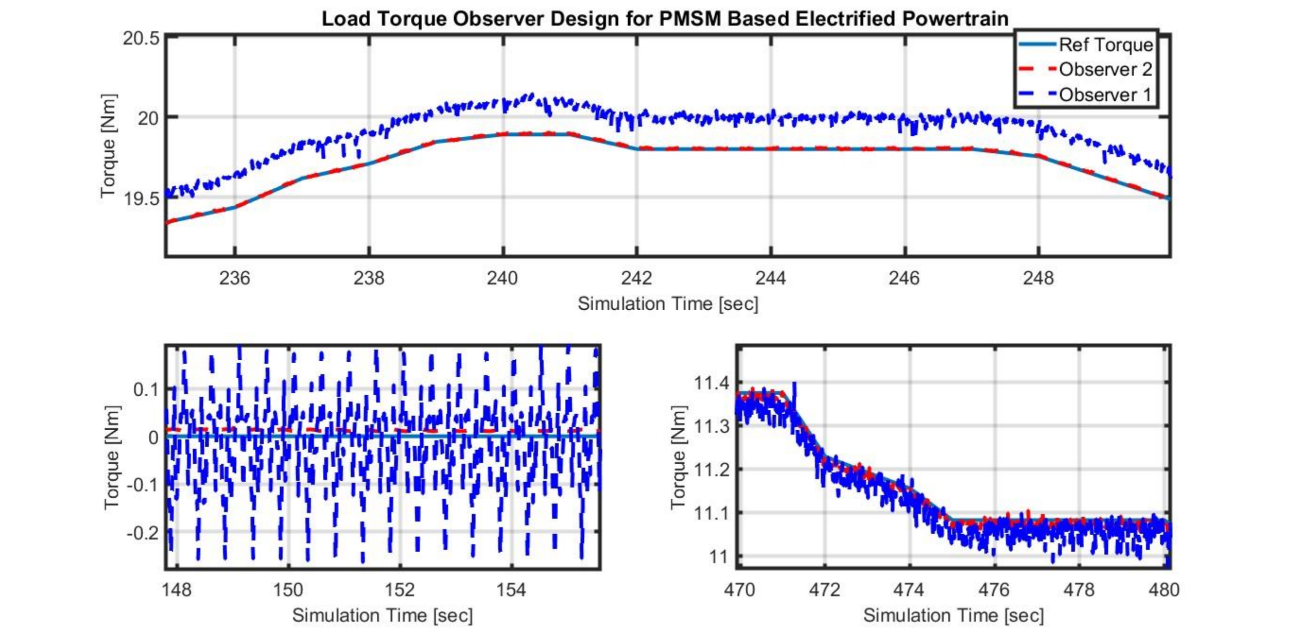
$$i_q^* = \frac{2J}{3p\lambda_m}\left[\dot{\omega}_{ref} + \frac{F}{J}\omega_{act} + \frac{1}{J}T_L\right] + K_c \mathrm{sgn}(e)$$



Torque observer – Dynamics based

$$\hat{T}_L = \frac{\alpha}{\beta + \left(1 + \left|\frac{1}{i_q}\right| - \beta\right) e^{\gamma|e|}} + A\left[J \int \left(\left(\frac{3}{2J} p\lambda_m i_q\right) - \left(\frac{F-J}{J}\right)\omega_{act}\right) dt\right]$$

- A dynamics-based torque observer has extensive computational requirements
- Difficult to implement on hardware
- The estimation of load torque will be highly accurate



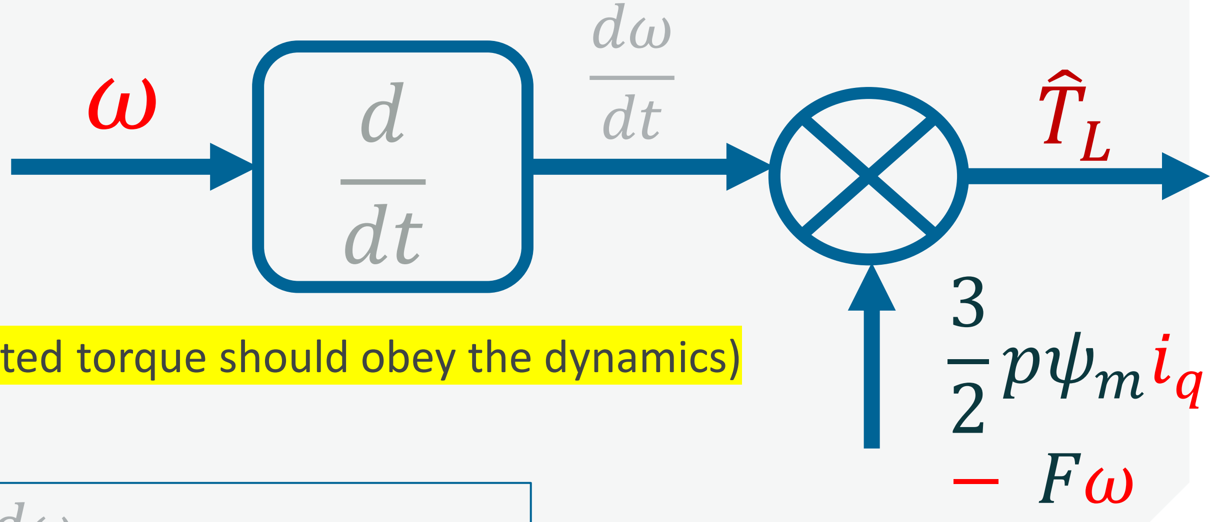
Physics Constraint Neural Network (PCNN) Torque Observer

System Dynamics $J\frac{d\omega}{dt} = \underbrace{\frac{3}{2}p\psi_m i_q}_{T_e} - F\omega - T_L$

- Unknown
- Feedback states
- Constant
- Computed

Assumption: $T_e - T_L \geq 0$ for $\omega > 0$

This implies that EM is capable to fulfill all torque requests



Physics based constraint

$$\boxed{\hat{T}_L = \frac{3}{2}p\psi_m i_q - J\frac{d\omega}{dt} - F\omega}$$

(Predicted torque should obey the dynamics)

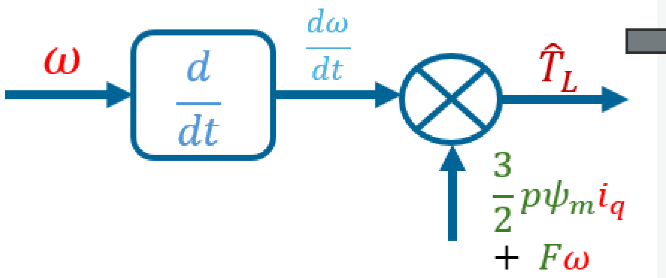
Powertrain level constraint

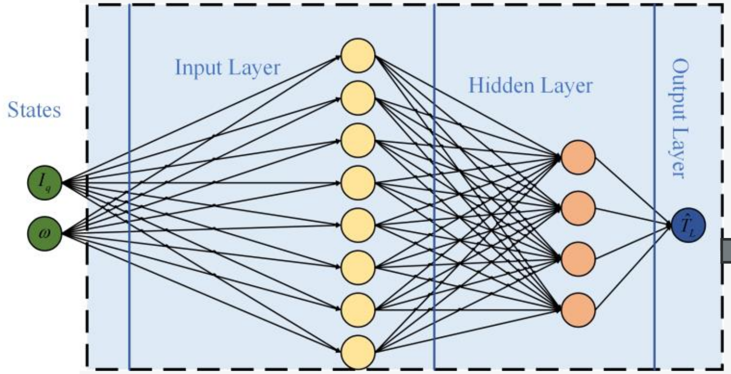
$$\boxed{\lambda_{gear}T_{L\,min} < \frac{3}{2}p\psi_m i_q - F\omega - J\frac{d\omega}{dt} < \lambda_{gear}T_{L\,max}}$$

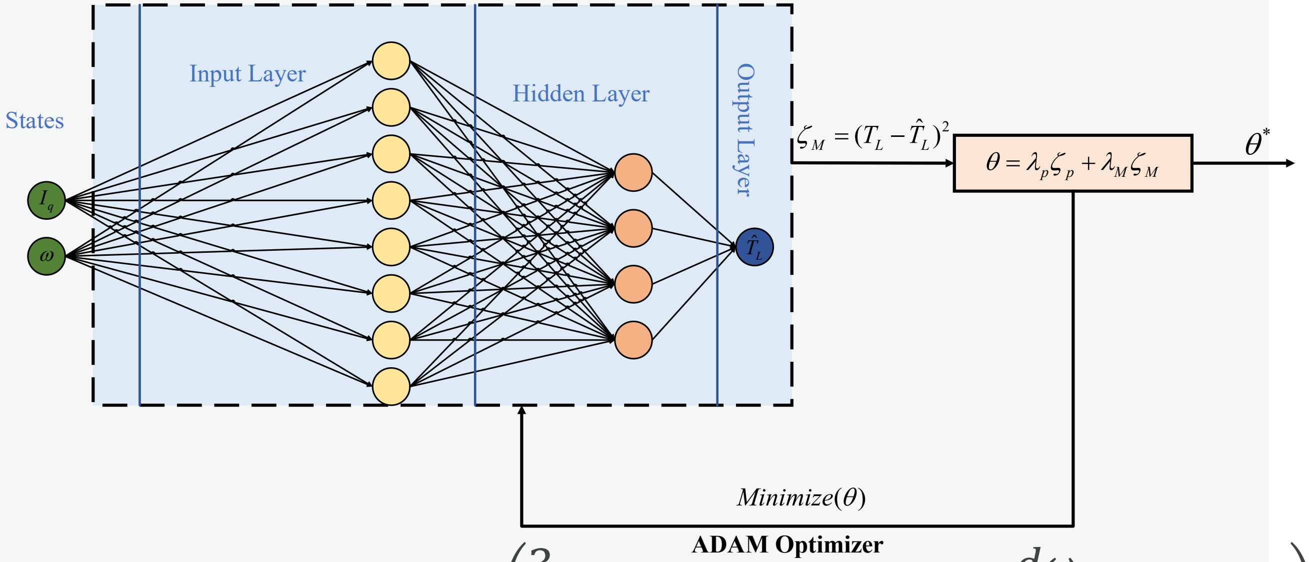
Physics Constraint Neural Network (PCNN) Torque Observer

System Dynamics

$$\hat{T}_L = J\frac{d\omega}{dt} - \frac{3}{2}p\psi_m i_q - F\omega$$

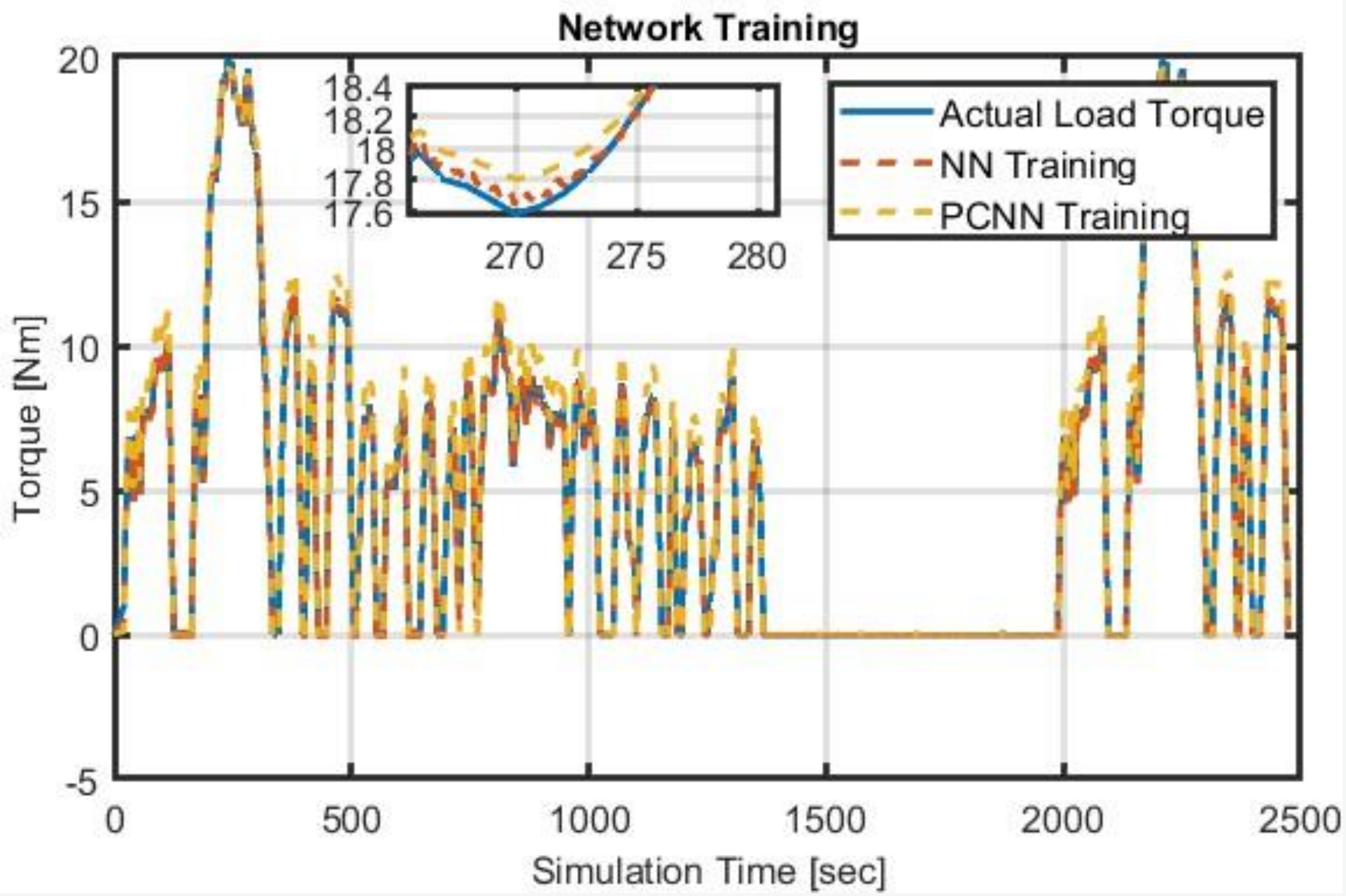


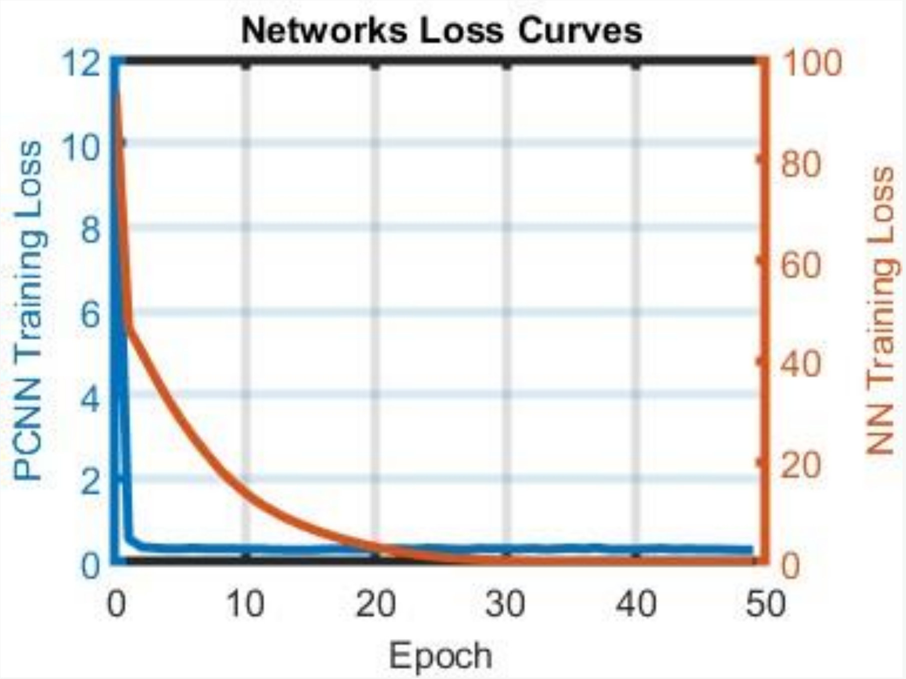




$$\theta = \underbrace{\zeta_m \sum \left(T_{L_{data}}[i] - \hat{T}_{L_{net}}[i]\right)^2}_{\text{MSE Loss}} + \underbrace{\zeta_p \sum \left(\frac{3}{2}p\psi_m i_q[i] - F\omega[i] - J\frac{d\omega}{dt}[i] - \hat{T}_L[i]\right)^2}_{\text{Physics Based Loss}}$$

PCNN Training

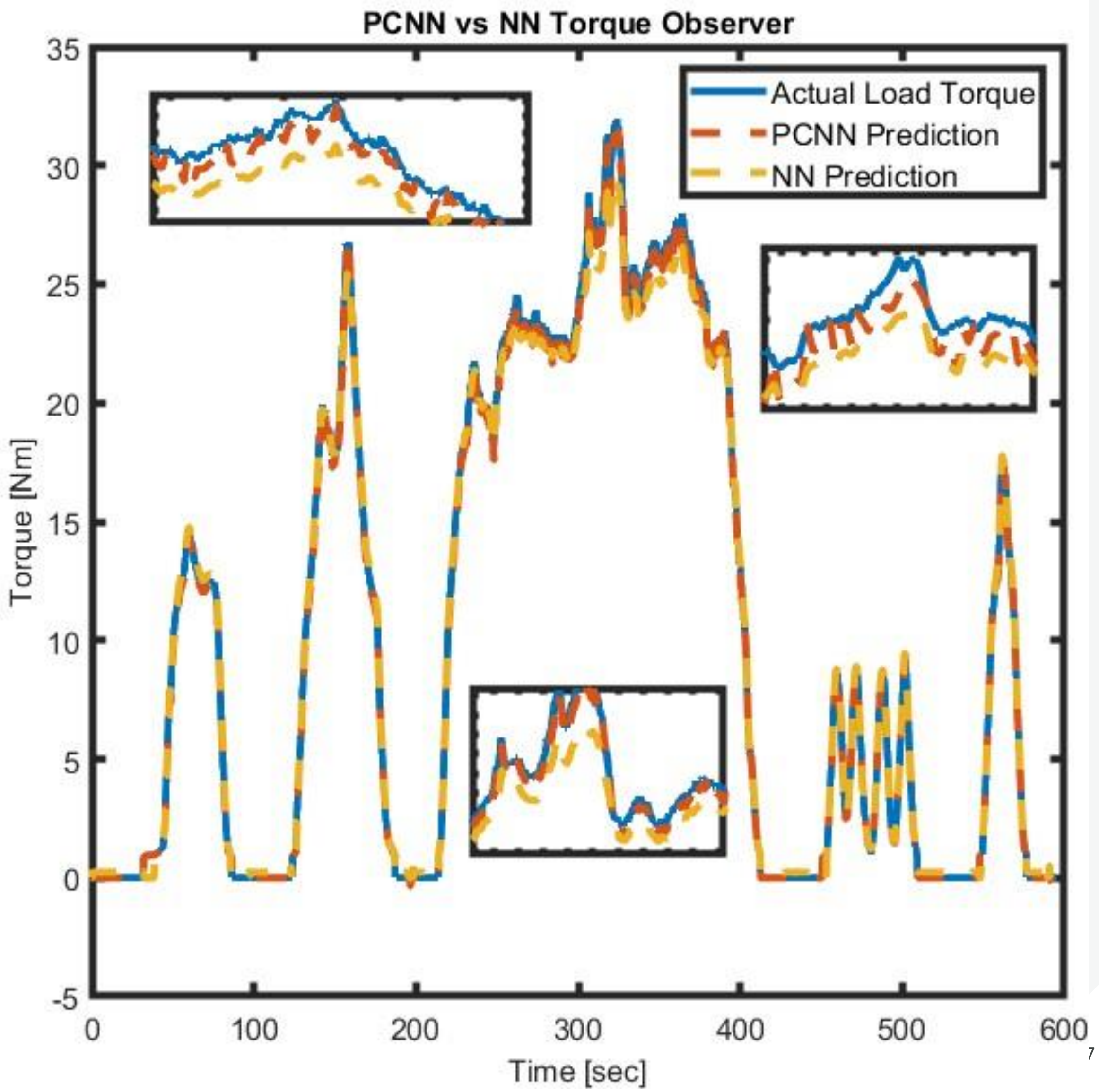




PCNN Validation (US06)

- US06 has mostly operating points similar to FT75 speed profile
- PCNN and NN performance is comparable

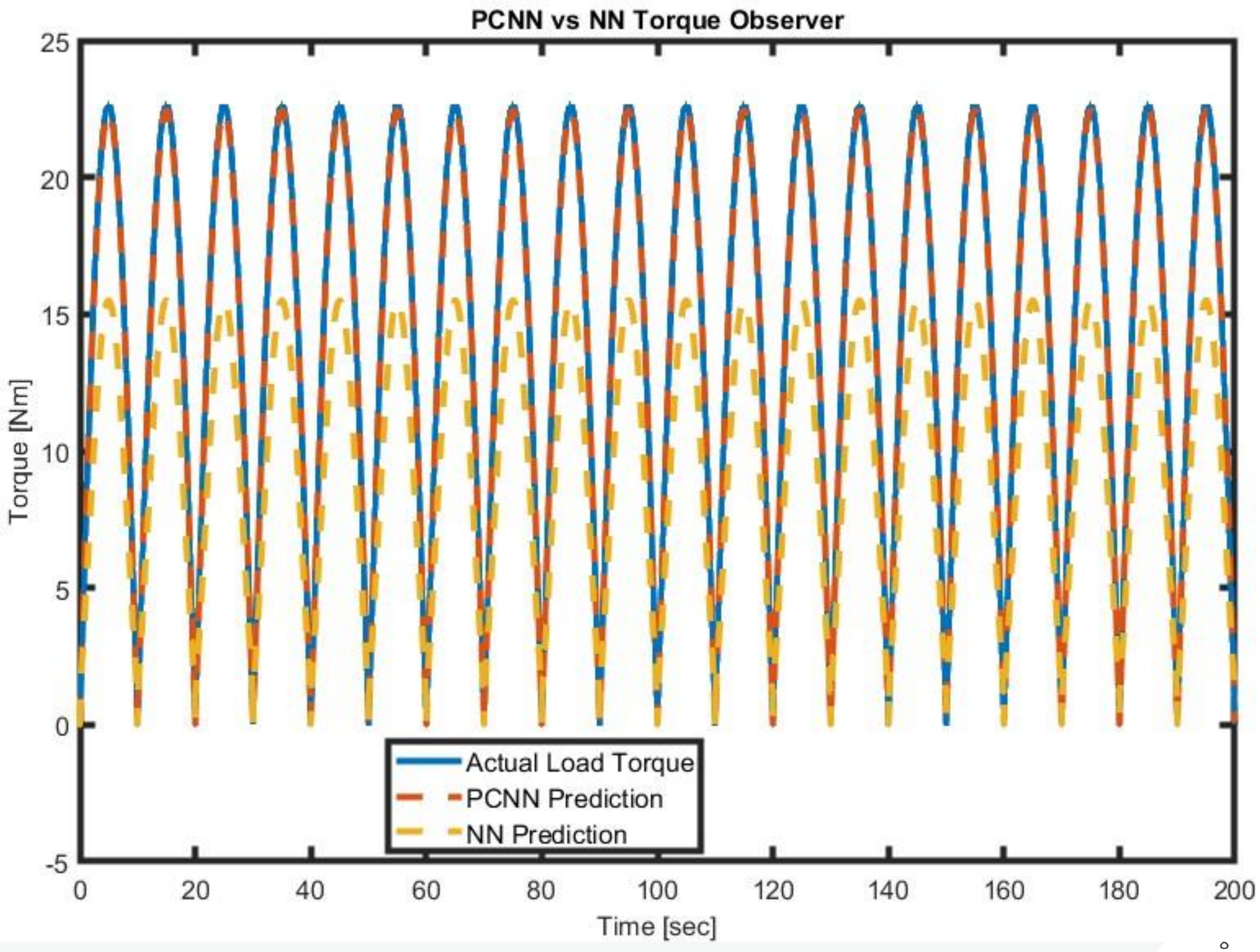
Torque Observer	MAE	MSE	R^2
NN	0.3888	0.3287	0.997
PCNN	0.1343	0.0005	0.999



PCNN Validation (Sinusoidal)

- Sinusoidal waveform helps to test the performance of torque observers under fluctuation
- It also tests the capability of extrapolation
- NN fails to predict load torque

Torque Observer	MAE	MSE	R^2
NN	4.8951	29.0872	0.4020
PCNN	0.0796	0.0075	0.999



Thank you

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