

Deep Recurrent Neural Network Control Applied in Solar Inverters for Grid Integration

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Outline

- I. Background**
- II. Deep Recurrent Neural Network Controller**
- III. Trajectory based Training**
- IV. Local Stability and Local Convergence**
- V. Hardware-in-the-loop Experiment**
- VI. Discussions about RNN Control**

Outline

I. Background

II. Deep Recurrent Neural Network Controller

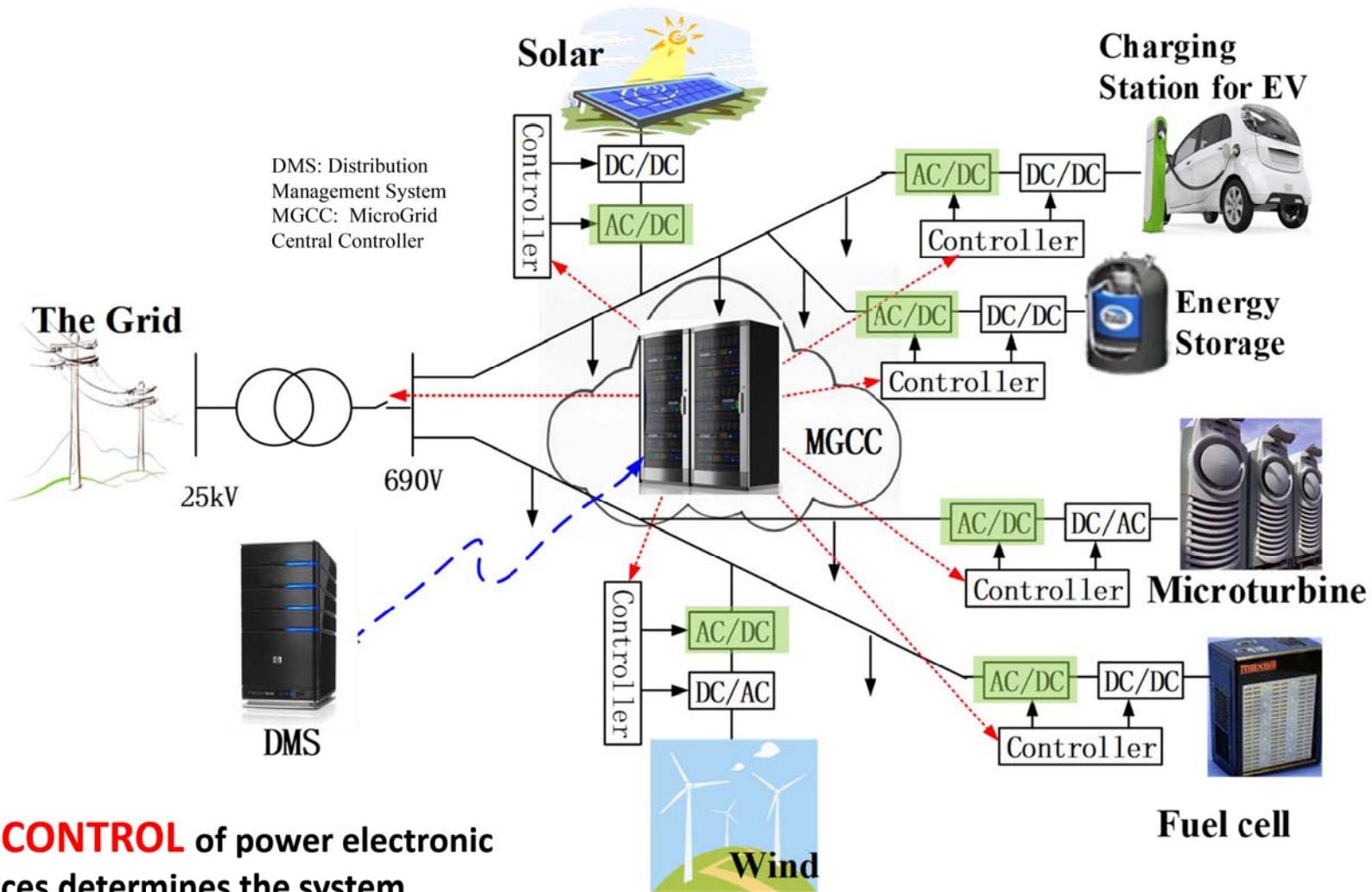
III. Trajectory based Training

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VI. Discussions about RNN Control

Smart Grid



The **CONTROL** of power electronic devices determines the system performance to a **GREAT** degree.

California's Rooftop Solar Mandate Wins Final Approval

The California Building Standards Commission has signed off on the residential solar mandate—a first of its kind for the nation.

JULIA PYPER | DECEMBER 05, 2018



The solar mandate marks a groundbreaking development for the clean energy sector.

It's official. All new homes in California must incorporate solar power starting in 2020.

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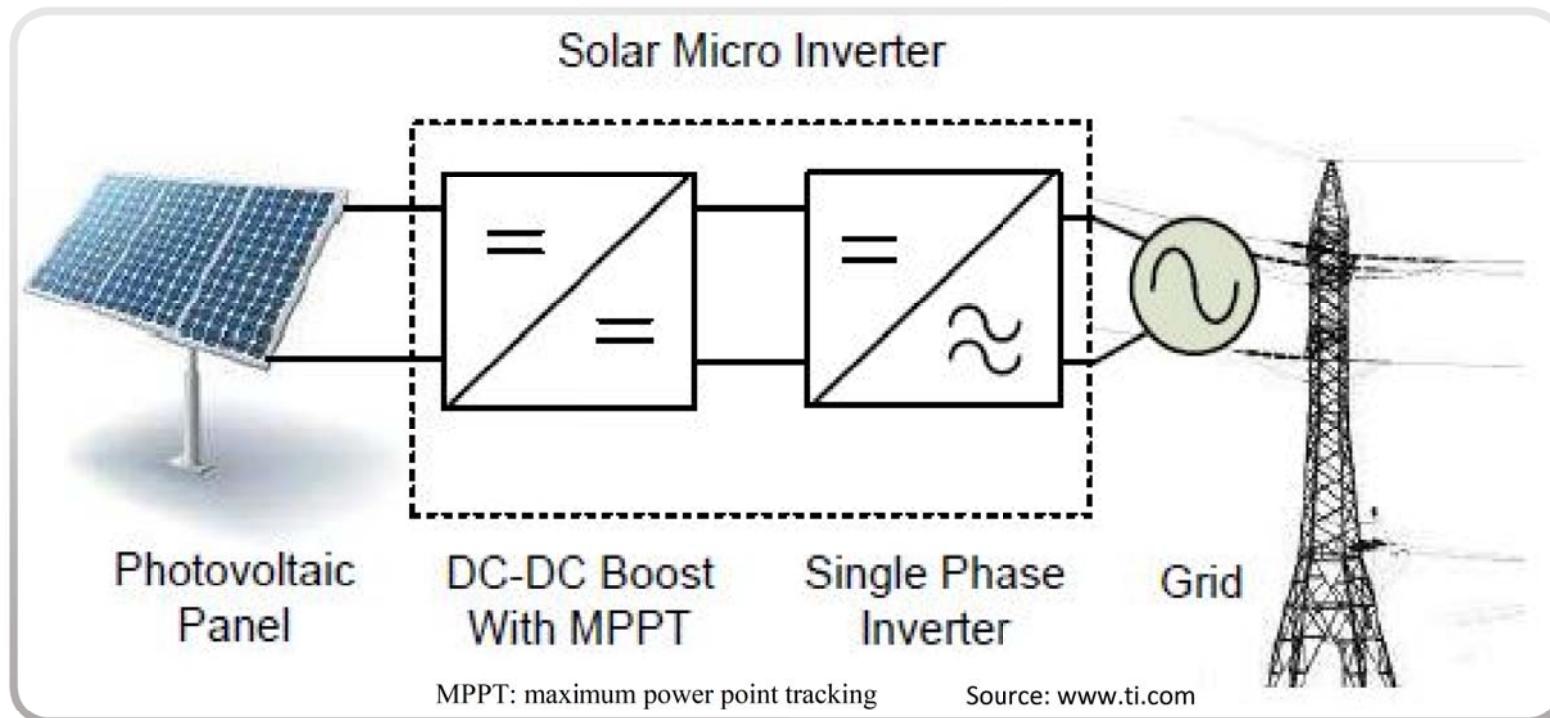


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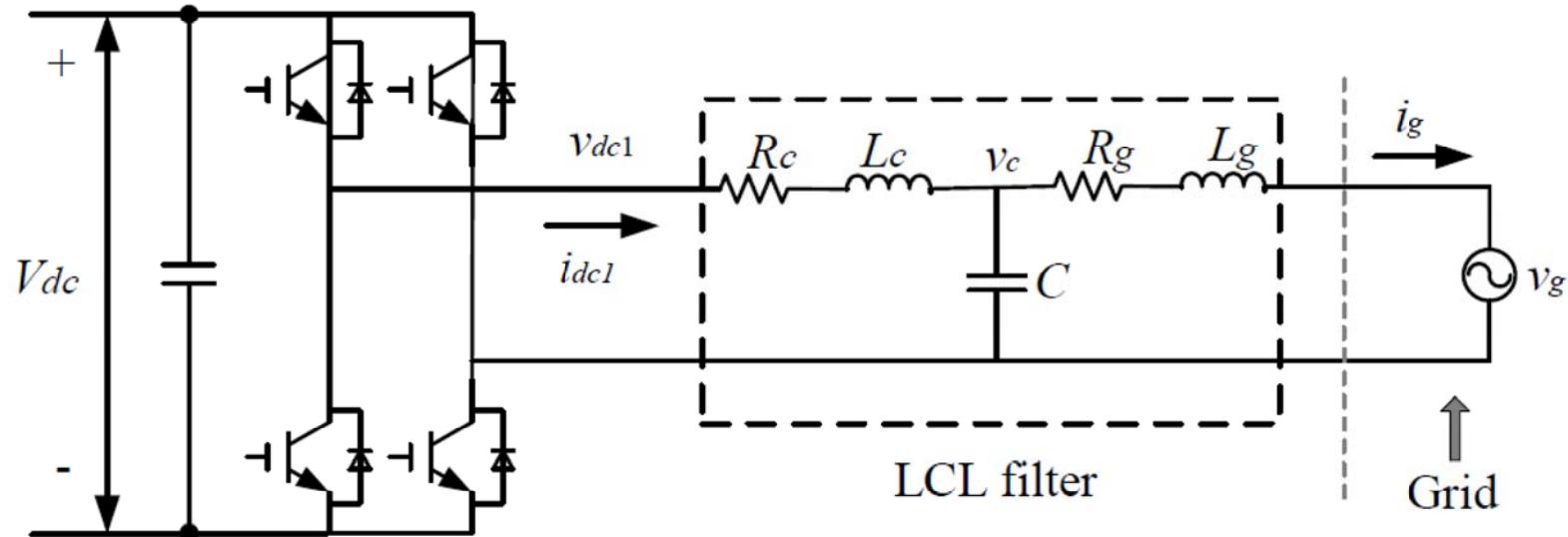
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Solar Microinverter



- A Solar Microinverter converts DC generated by the single solar module to AC, and generally is connected to the grid. It allows two-way power flow.

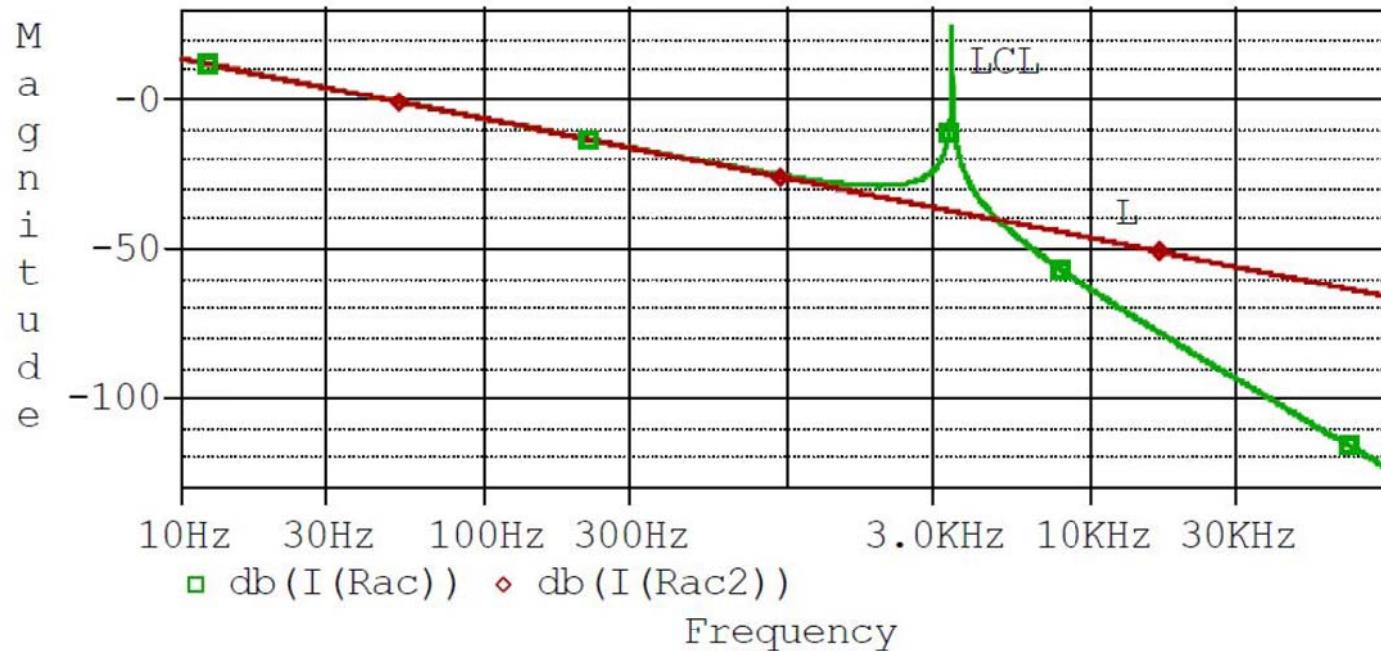
Single-phase Solar Grid-tied Inverter/ Converter



- Single phase inverter is for home application.
- To reduce harmonics, the LCL filter is a wise choice and generally used.

Resonant Problem

- ❖ However, as the LCL filter has a **Resonant Problem** and tends to be **unstable**.



That **Peak** point (resonance frequency) causes the unstable problem and control difficulty.

- ❖ *The control of the LCL filter is a challenge!*

- ✓ Many damping / control methods have been proposed to handle this.

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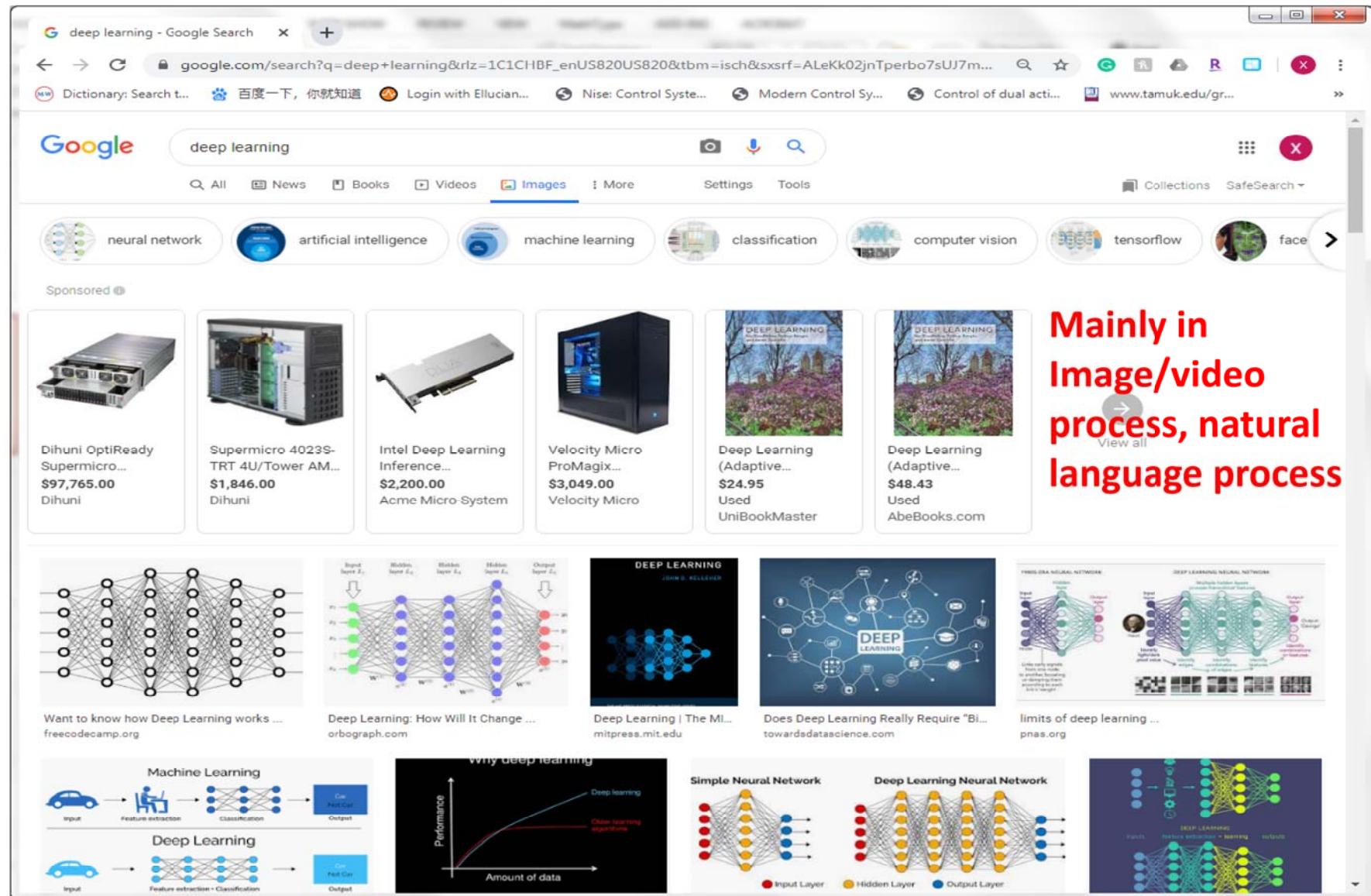
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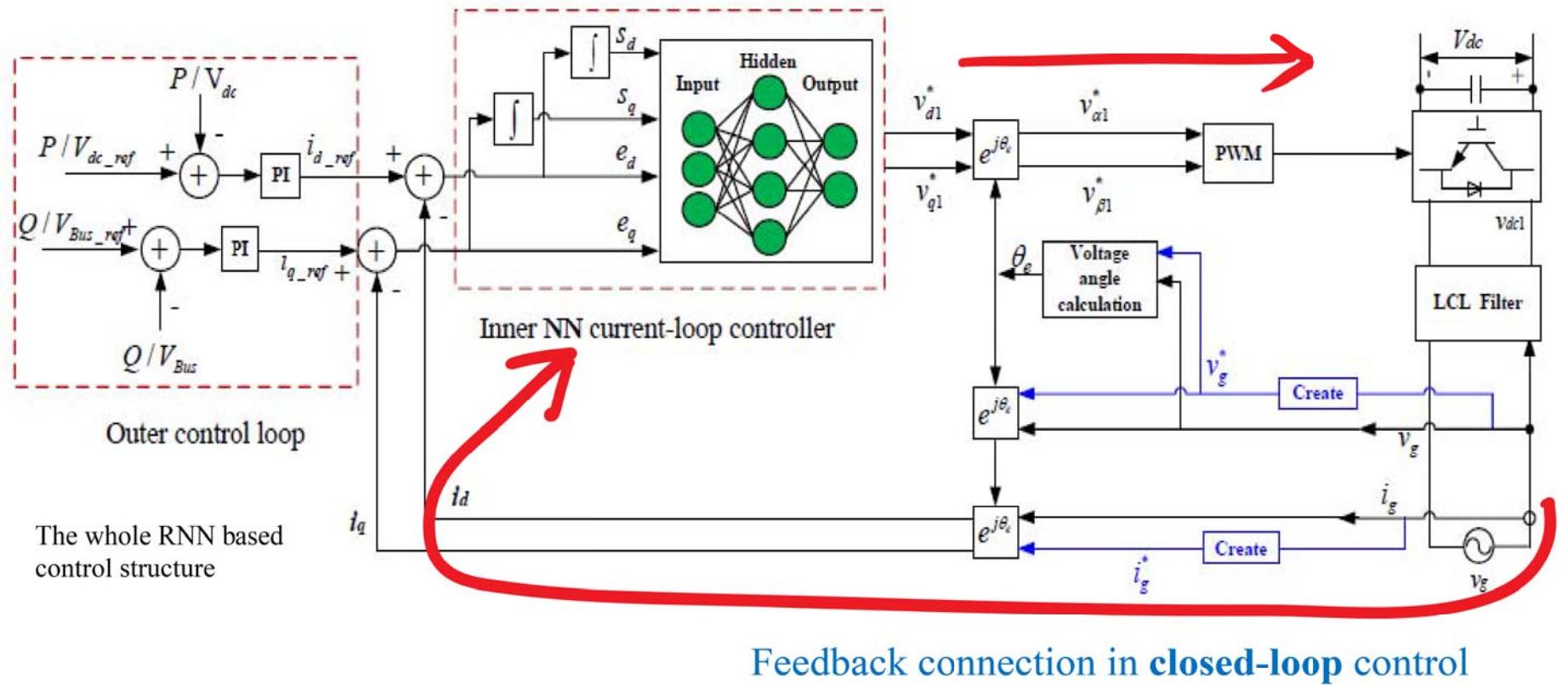
Deep Learning



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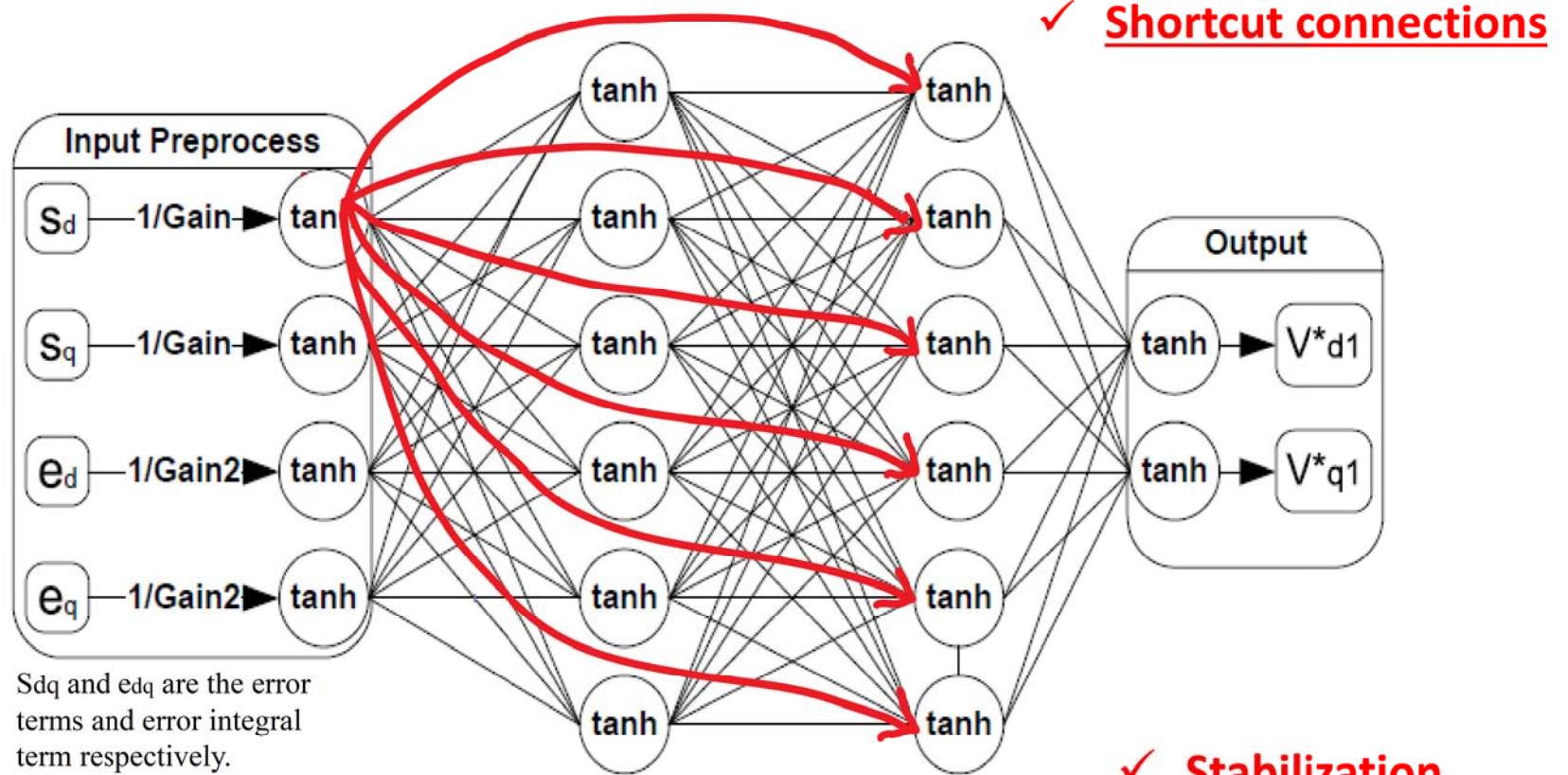
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Proposed Neural Network in Feedback Control Loops



Recurrent Neural Network

Feature - Error Integral



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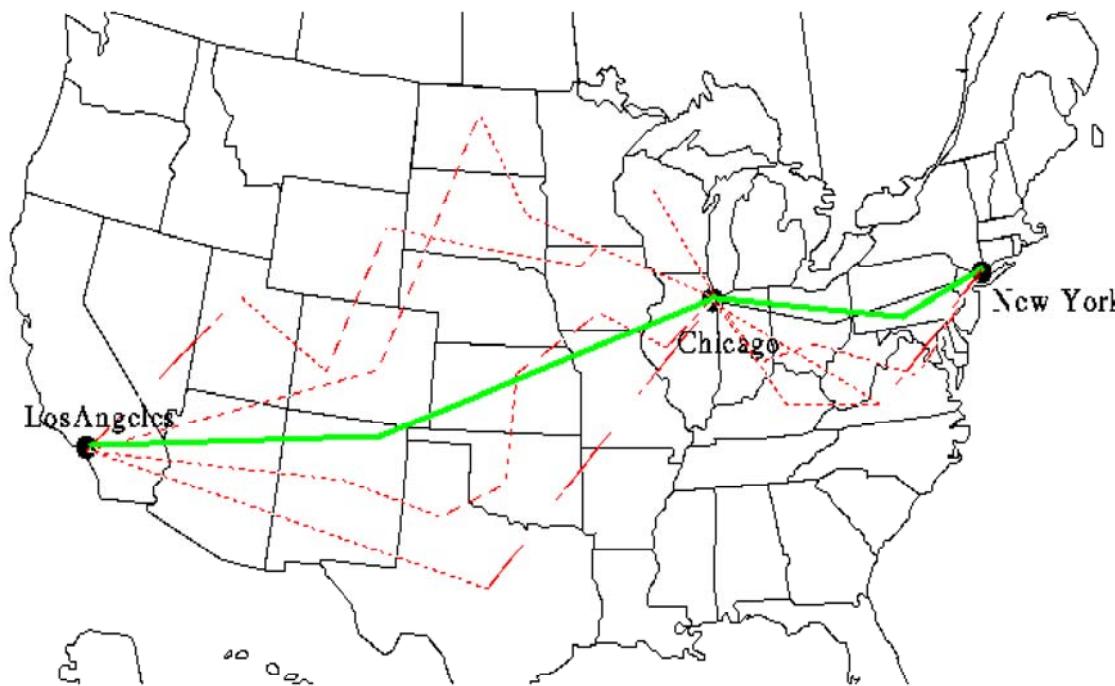
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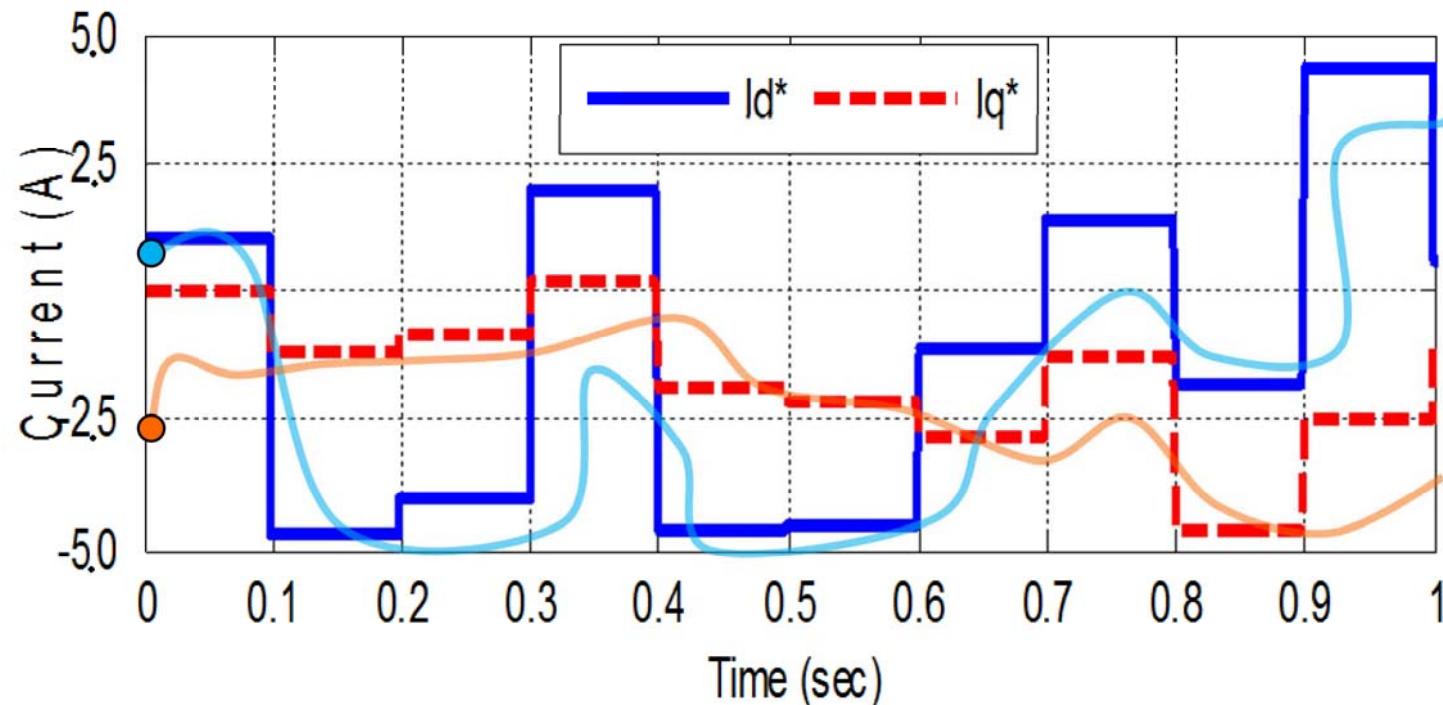
Approximate Dynamic Programming

- **Dynamic programming** (DP) employs Bellman's optimality principle and provides powerful tool for solving optimization,



- DP can also be powerful for **OPTIMAL CONTROL** problems, e.g. Adaptive Critic Designs (ACDs) is one class of **Approximate Dynamic Programming** to approximate optimal control.

Approximate Dynamic Programming Based Trajectory Training

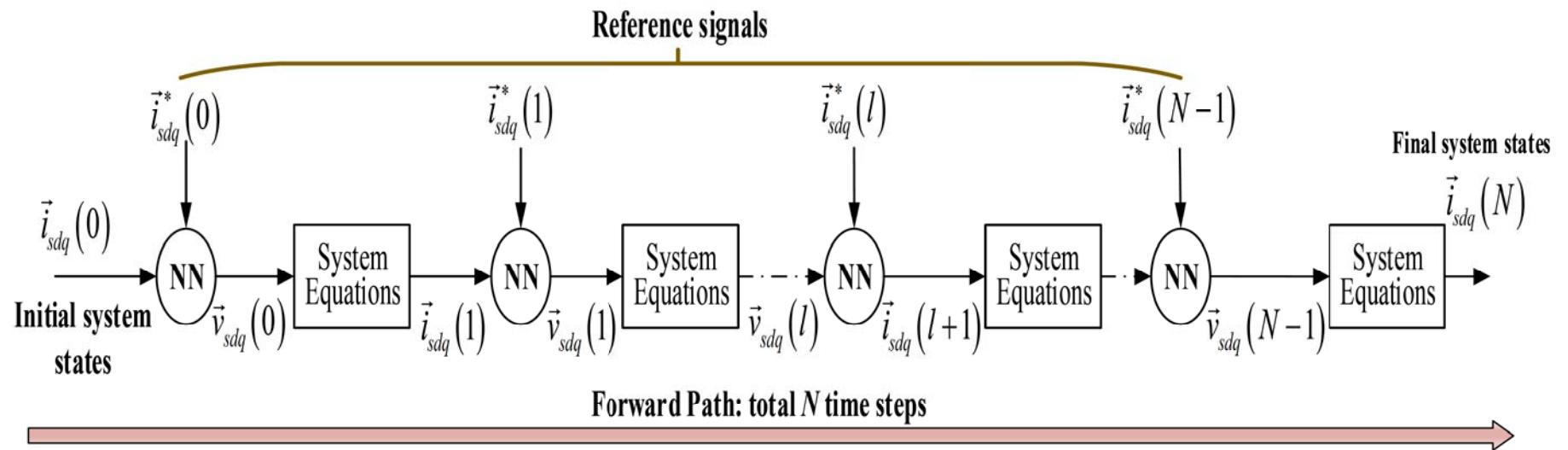


Note that: before training, the NN controller **cannot** adjust the currents to follow the reference.

- ✓ The goal of training is to **adjust the actual currents to follow the reference current trajectories** through minimizing the cost function based on the **Approximate Dynamic Programming principle**.

$$C_{dp} = \sum_{k=j}^{\infty} \gamma^{k-j} U(\vec{e}_{dq}(k)) = \sum_{k=j}^{\infty} \gamma^{k-j} \sqrt{[i_d(k) - i_{d_ref}(k)]^2 + [i_q(k) - i_{q_ref}(k)]^2}$$

Deep Network



- In the training, the NN needs to be expanded along the trajectory.
- Think of this process as a big network, for a 1000-step calculation, the total number of NN layers will be $4 \times 1000 = 4000$.
 - ✓ it is a **large and deep** network, which requires lots of calculation.

Forward Accumulation Through Time Algorithm

Algorithm 3.2 FATT algorithm to calculate the Jacobian matrix.

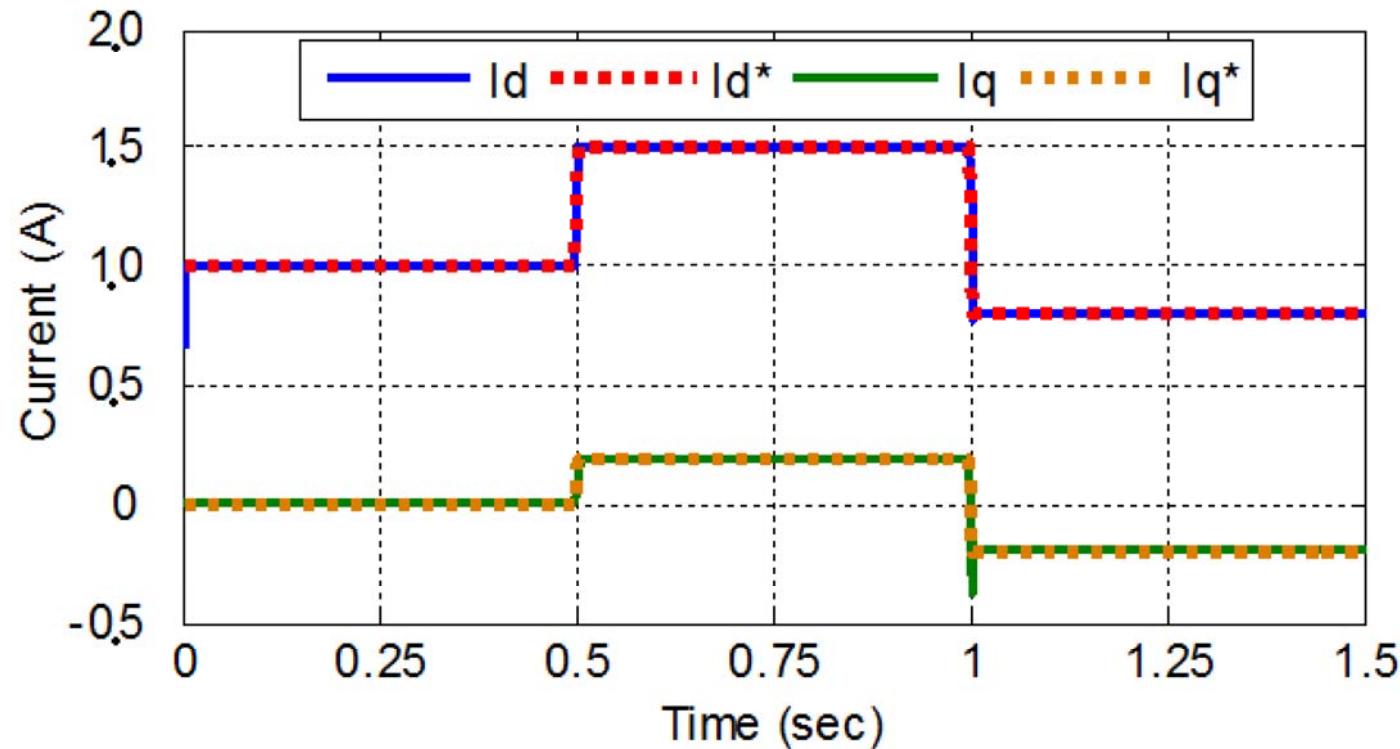
```

1:  $C \leftarrow 0, \vec{e}_{dq}(0) \leftarrow 0, \vec{s}_{dq}(0) \leftarrow 0, \frac{\partial \vec{i}_{dq}(0)}{\partial \vec{w}} \leftarrow 0, \frac{\partial \vec{\phi}_{dq}(0)}{\partial \vec{w}} \leftarrow 0$ 
2: {Calculate the Jacobian matrix  $J(\vec{w})$ }
3: for  $k = 0$  to  $N - 1$  do
4:    $\vec{u}_{dq}(k) \leftarrow k_{PWM} R(\vec{e}_{dq}(k), \vec{s}_{dq}(k), \vec{w}) - \vec{v}_{dq}$ 
5:    $\frac{\partial \vec{s}_{dq}(k)}{\partial \vec{w}} \leftarrow T_s \left[ \frac{\partial \vec{\phi}_{dq}(k)}{\partial \vec{w}} - \frac{1}{2} \frac{\partial \vec{i}_{dq}(k)}{\partial \vec{w}} \right]$ 
6:    $\frac{\partial \vec{u}_{dq}(k)}{\partial \vec{w}} \leftarrow k_{PWM} \left[ \frac{\partial R(k)}{\partial \vec{w}} + \frac{\partial R(k)}{\partial \vec{e}_{dq}(k)} \frac{\partial i_{dq}(k)}{\partial \vec{w}} + \frac{\partial R(k)}{\partial \vec{s}_{dq}(k)} \frac{\partial s_{dq}(k)}{\partial \vec{w}} \right]$ 
7:    $\frac{\partial \vec{i}_{dq}(k+1)}{\partial \vec{w}} \leftarrow A \frac{\partial \vec{i}_{dq}(k)}{\partial \vec{w}} + B \frac{\partial \vec{u}_{dq}(k+1)}{\partial \vec{w}}$ 
8:    $\vec{i}_{dq}(k+1) \leftarrow A \vec{i}_{dq}(k) + B \vec{u}_{dq}(k)$ 
9:    $\vec{e}_{dq}(k+1) \leftarrow \vec{i}_{dq}(k+1) - \vec{i}_{dq\_ref}(k+1)$ 
10:   $\vec{s}_{dq}(k+1) \leftarrow \vec{s}_{dq}(k) + \frac{T_s}{2} [\vec{e}_{dq}(k) + \vec{e}_{dq}(k+1)]$ 
11:   $C \leftarrow C + U(\vec{e}_{dq}(k+1)) \{ \text{accumulate DP cost} \}$ 
12:   $\frac{\partial \vec{\phi}(k+1)}{\partial \vec{w}} \leftarrow \frac{\partial \vec{\phi}(k)}{\partial \vec{w}} + \frac{\partial \vec{i}_{dq}(k+1)}{\partial \vec{w}}$ 
13:   $\frac{\partial V(k+1)}{\partial \vec{w}} \leftarrow \frac{\partial V(k+1)}{\partial \vec{e}_{dq}(k+1)} \frac{\partial \vec{i}_{dq}(k+1)}{\partial \vec{w}}$ 
14:  the  $(k+1)$ th row of  $J(\vec{w}) \leftarrow \frac{\partial V(k+1)}{\partial \vec{w}}$ 
15: end for
16: {On exit, the Jacobian matrix  $J(\vec{w})$  is finished for the whole trajectory.}

```

Introducing of error integral terms brings difficulties in calculating gradients

Well-trained RNN Controller



The actual currents can follow the reference trajectories quite well!

The detailed training algorithm: **LM** (Levenberg–Marquardt) + **FATT** (Forward Accumulation Through Time)

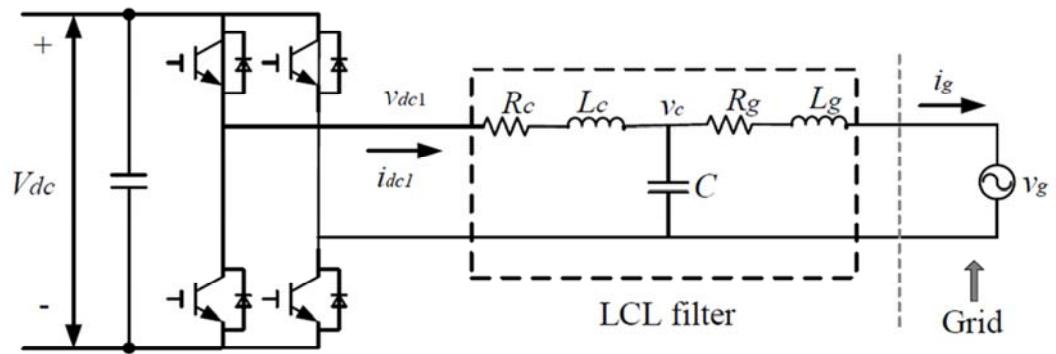
Outline

IV. Local Stability and Local Convergence

System Dynamic Equation

➤ State-space model

Ignoring the capacitor, the **two-dimensional** system equation will be simplified as



$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = A \begin{bmatrix} i_d \\ i_q \end{bmatrix} + B \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

Control vector:

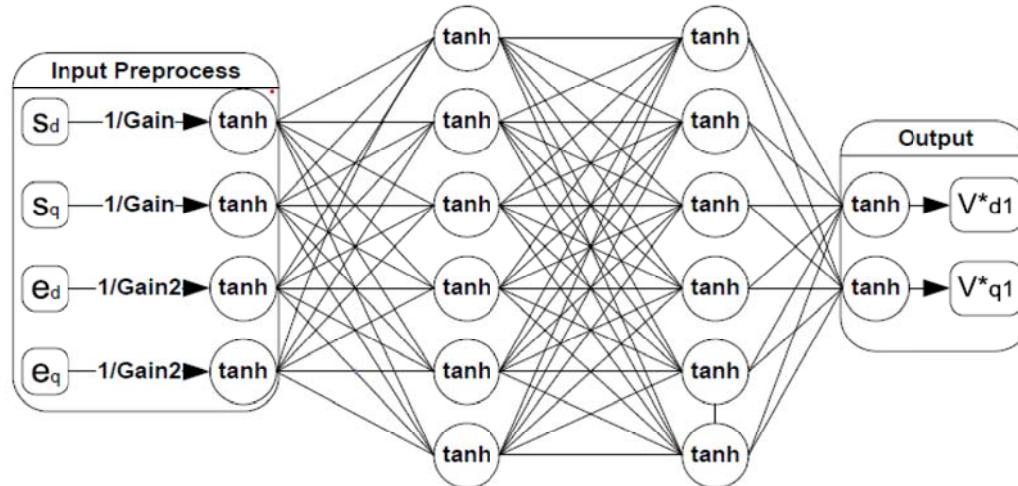
$$\begin{aligned} u_{dq} &= R(e_{dq}, s_{dq}) \\ &= K_{pwm} N(e_{dq}, s_{dq}, w) - v_{dq} \end{aligned}$$

$$\text{where } A = - \begin{bmatrix} \frac{R_g + R_c}{L_g + L_c} & -\omega_s \\ -\omega_s & \frac{R_g + R_c}{L_g + L_c} \end{bmatrix},$$

$$B = - \begin{bmatrix} \frac{1}{L_g + L_c} \\ \frac{1}{L_g + L_c} \end{bmatrix}$$

Function format of RNN controller

➤ NN function representation



$$N(e_{dq}, s_{dq}, w) = \tanh \left(w_3 \left[\tanh \left(w_2 \left[\tanh \left(w_1 \left[\begin{matrix} \tanh \left[\frac{e_{dq}}{\text{Gain}} \right] \\ \tanh \left[\frac{s_{dq}}{\text{Gain2}} \right] \\ -1 \\ -1 \\ -1 \end{matrix} \right] \right] \right] \right] \right)$$

Augmented System Equations

➤ System Equation Transformation

From the definition of error and error integral

$$e_{dq} = \begin{bmatrix} e_d \\ e_q \end{bmatrix} = i_{dq_ref} - i_{dq}, \quad s_{dq} = \int_0^t e_{dq} dt$$
$$\Rightarrow \dot{e}_{dq} = -\frac{d}{dt} i_{dq}, \quad \dot{s}_{dq} = e_{dq}$$

The original **Two-dimensional** system equations can be augmented into the following **Four-dimensional** one:

$$\begin{cases} \dot{e}_{dq} = A(e_{dq} - i_{dq_ref}) - BR(e_{dq}, s_{dq}) \\ \dot{s}_{dq} = e_{dq} \end{cases}$$

- ✓ The equilibrium point of the system can be noted as $(0, s^*)$, which means $e_{dq}=0$ and $s_{dq}=s^*$.

Local Stability and Local Convergence

- To guarantee **local asymptotic stability** and **local exponential convergence**, the weight matrix and bias vector of the NN need to satisfy the following condition:

$$\text{Re} \left\{ \text{eig} \left(\begin{bmatrix} G_{11} & G_{12} \\ I & 0 \end{bmatrix} \right) \right\} < 0$$

Linearizing the RNN controller

where

$$G_{11} = A - B \frac{\partial R(e_{dq}, s_{dq})}{\partial e_{dq}} \Bigg|_{e_{dq}=0, s_{dq}=s^*}$$

$$G_{12} = -B \frac{\partial R(e_{dq}, s_{dq})}{\partial s_{dq}} \Bigg|_{e_{dq}=0, s_{dq}=s^*}$$

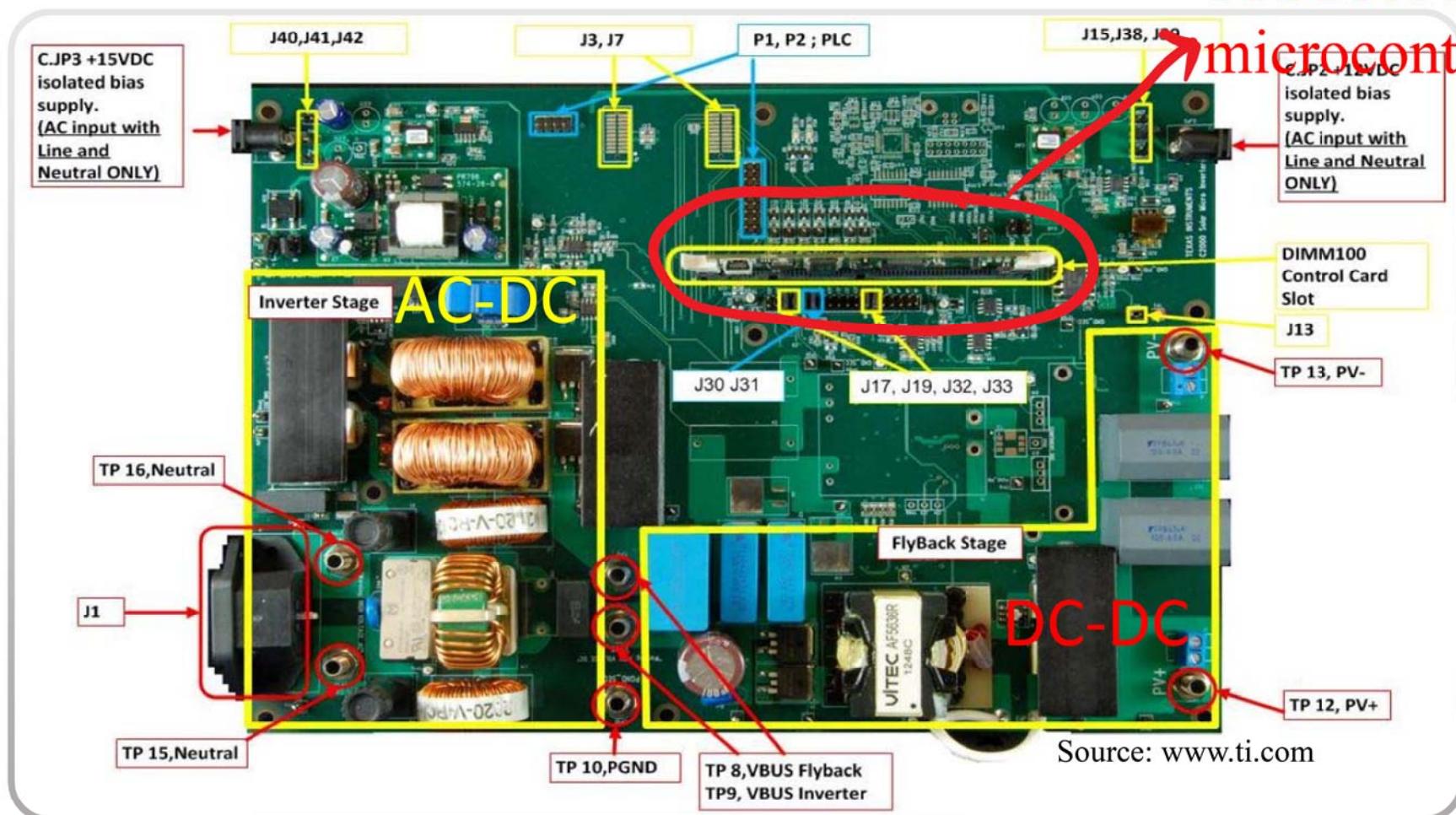
✓ Which means **all the eigenvalues have the negative real parts.**

Outline

V. Hardware-in-the-loop Experiment

TI Solar Micro Inverter Kit

TI F28035
microcontroller

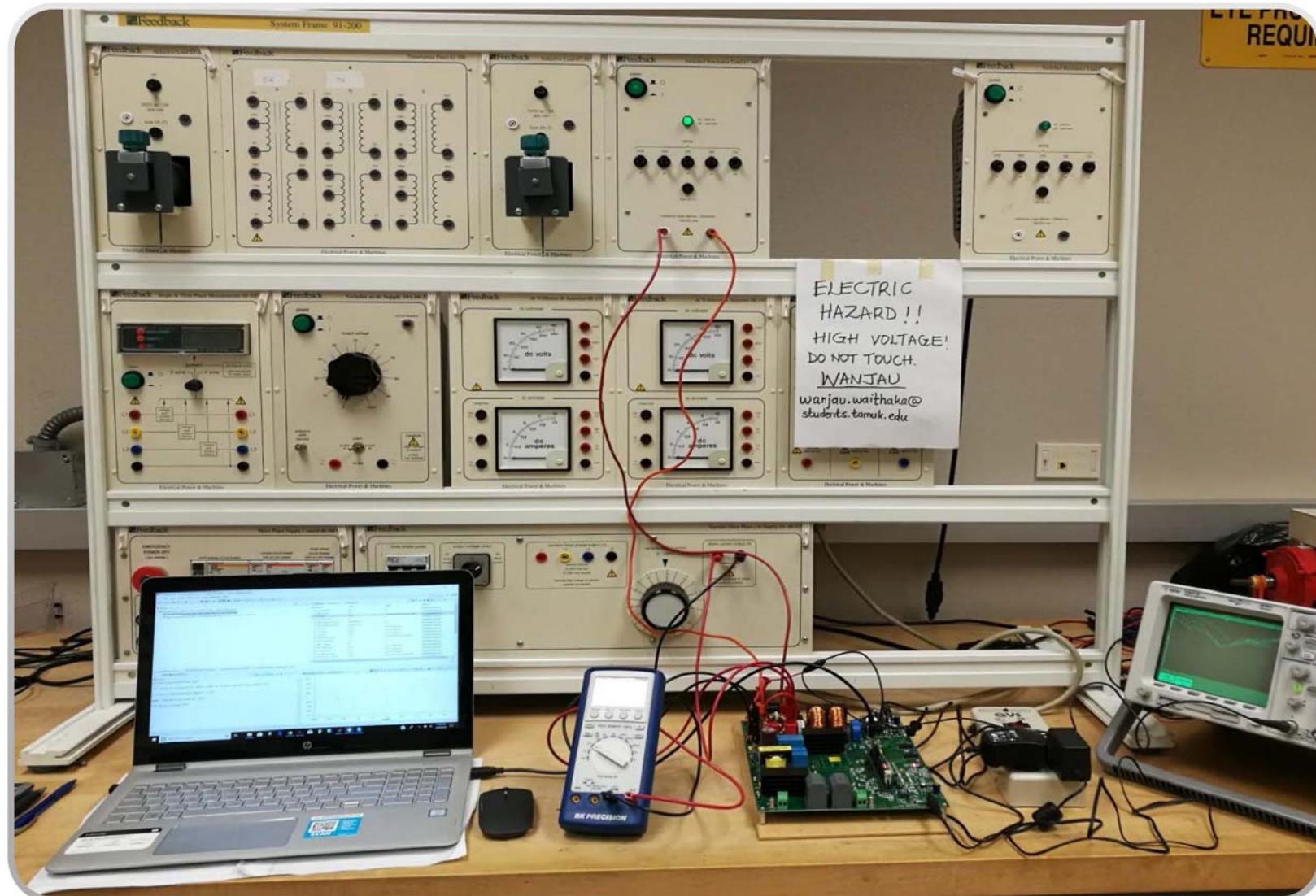


Source: www.ti.com

Features:

- 1) 28 to 45V at input; 280W for 220VAC, 140W for 110VAC;
- 2) C2000 Piccolo F28035 32-bit 60MHz MCU

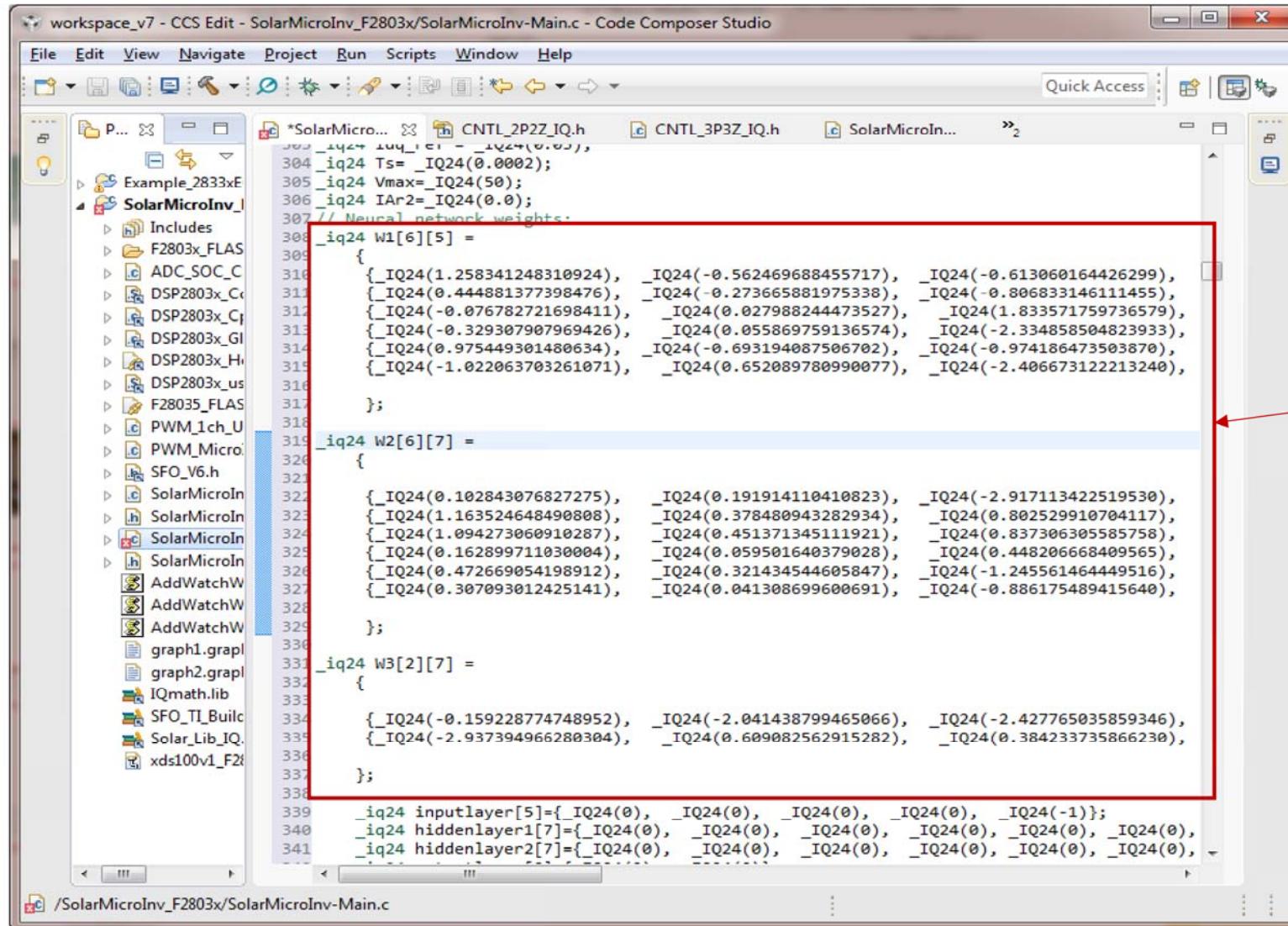
Hardware Validation Laboratory Set-up



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C Code Implementation



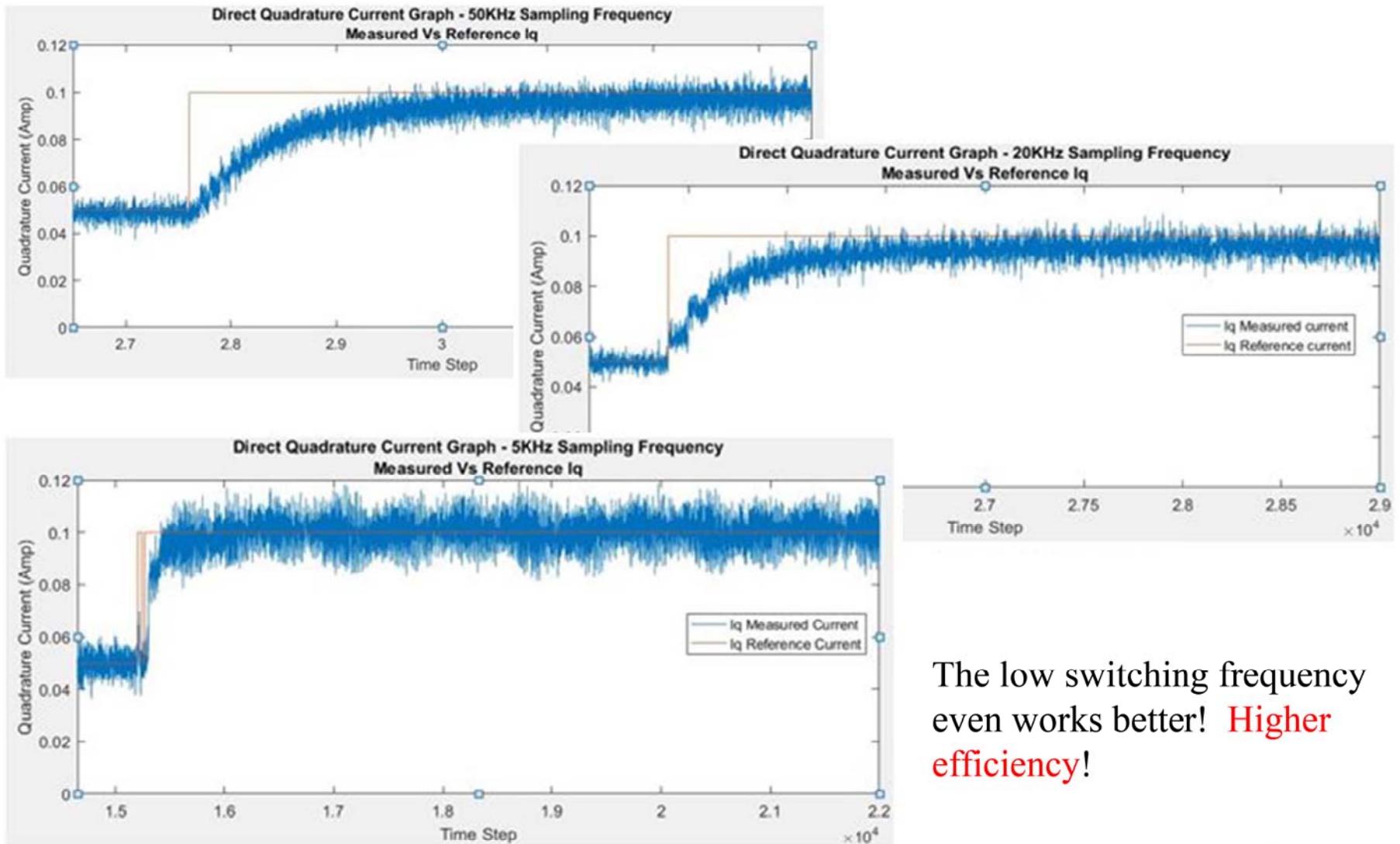
The screenshot shows the Code Composer Studio interface with the project "SolarMicroInv_F2803x/SolarMicroInv-Main.c". The code editor displays the following C code snippet, which defines weight matrices for an RNN:

```

304 _iq24 Ts=_IQ24(0.0002);
305 _iq24 Vmax=_IQ24(50);
306 _iq24 IAr2=_IQ24(0.0);
307 // Neural network weights
308 _iq24 W1[6][5] =
309 {
310     {_IQ24(1.258341248310924), _IQ24(-0.562469688455717), _IQ24(-0.613060164426299),
311      {_IQ24(0.444881377398476), _IQ24(-0.273665881975338), _IQ24(-0.806833146111455),
312      {_IQ24(-0.076782721698411), _IQ24(0.027988244473527), _IQ24(1.833571759736579),
313      {_IQ24(-0.329307907969426), _IQ24(0.055869759136574), _IQ24(-2.334858504823933),
314      {_IQ24(0.975449301480634), _IQ24(-0.693194087506702), _IQ24(-0.974186473503870),
315      {_IQ24(-1.022063703261071), _IQ24(0.652089780990077), _IQ24(-2.406673122213240),
316    };
317
318 _iq24 W2[6][7] =
319 {
320     {_IQ24(0.102843076827275), _IQ24(0.191914110410823), _IQ24(-2.917113422519530),
321     {_IQ24(1.163524648490808), _IQ24(0.378480943282934), _IQ24(0.802529910704117),
322     {_IQ24(1.094273060910287), _IQ24(0.451371345111921), _IQ24(0.837306305585758),
323     {_IQ24(0.162899711030004), _IQ24(0.059501640379028), _IQ24(0.448206668409565),
324     {_IQ24(0.472669054198912), _IQ24(0.321434544605847), _IQ24(-1.245561464449516),
325     {_IQ24(0.307093012425141), _IQ24(0.041308699600691), _IQ24(-0.886175489415640),
326   };
327
328
329 _iq24 W3[2][7] =
330 {
331     {_IQ24(-0.159228774748952), _IQ24(-2.041438799465066), _IQ24(-2.427765035859346),
332     {_IQ24(-2.937394966280304), _IQ24(0.609082562915282), _IQ24(0.384233735866230),
333   };
334
335 _iq24 inputlayer[5]={_IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(-1)};
336 _iq24 hiddenlayer1[7]={_IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0),
337 _iq24 hiddenlayer2[7]={_IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0), _IQ24(0),
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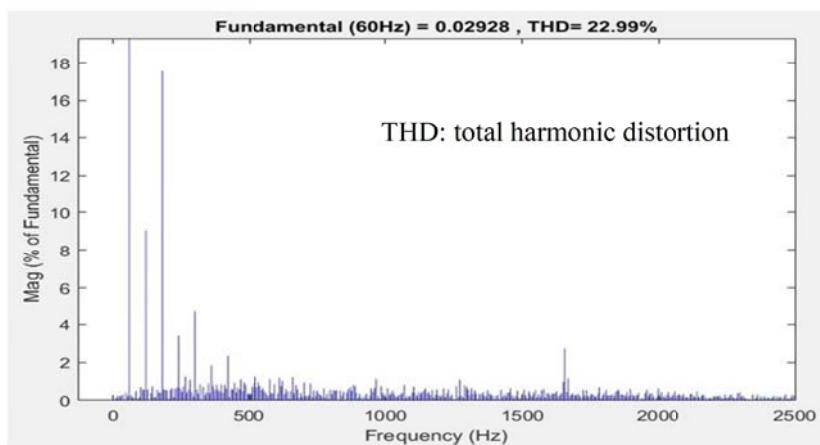
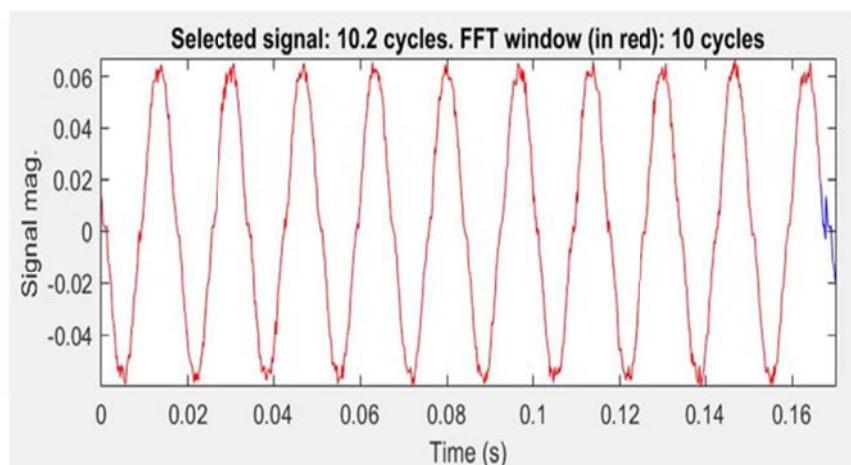
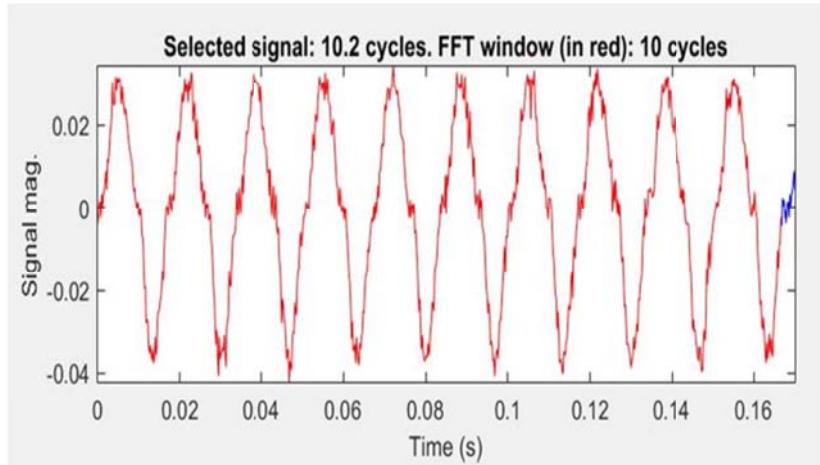
Current Tracking



The low switching frequency even works better! **Higher efficiency!**

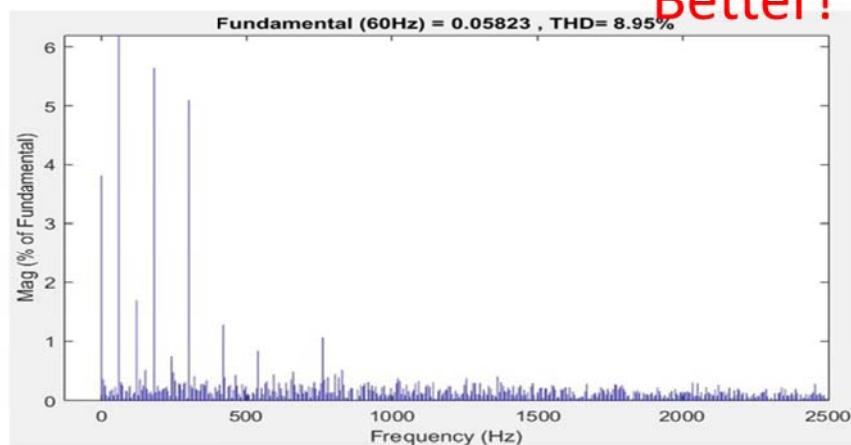
THD Comparison

- 5KHz sampling and switching frequency



3P3Z controller by TI in CCS

2/18/2021 2:04 PM



RNN Controller

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Outline

VI. Discussions about RNN Control

Discussions about RNN Control

➤ Advantages

- a **damping free** technique;
- allows for **low sampling & switching** frequency while maintaining high performance;
- ✓ strong ability of tracking the references, fast response, lower overshoot,
- ✓ **Robust, adaptive**, can tolerate a wide range of system parameter changes;
- ✓ approximate optimal control trained by Approximate Dynamic Programming principle
- ✓

➤ Further Improvements

- ✓ **DSP+FPGA** implementation or Special Chip to solve calculation problem ? Not Available
- ✓ **Refine the structure of RNN** to better fit the embedded controller application.
- ✓ **Reducing** training hardware (gpu/cloud, supercomputer)
- ✓ **Global** stability problem, global convergence problem



Thank You

