# Evaluation of an Extremum Seeking Control Based Optimization and Sequencing Strategy for a Chilled-water Plant

**Zhongfan Zhao & Yaoyu Li**
University of Texas at Dallas

**Timothy I. Salsbury & John M. House**
Johnson Controls, Inc.

**Baojie Mu**
Whirlpool, Inc.

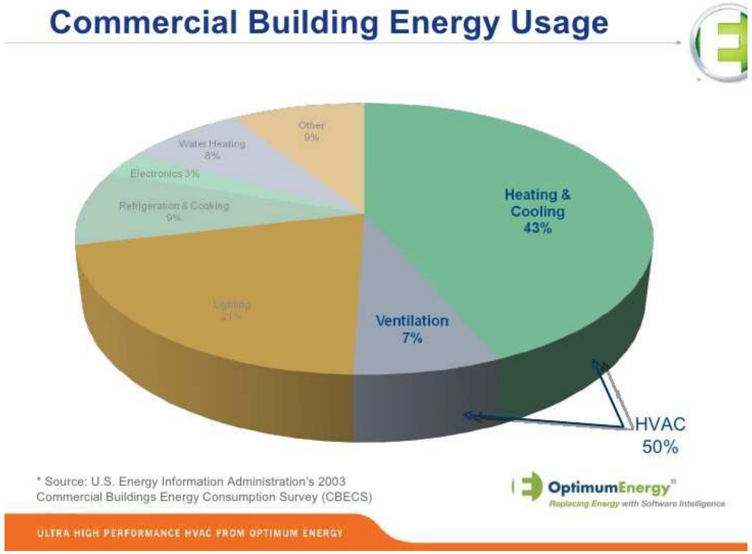
July 12, 2016

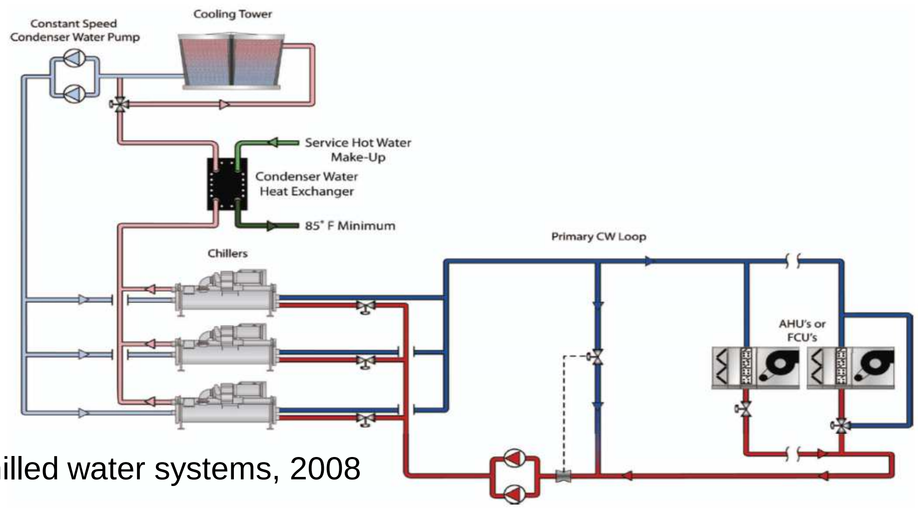
# Outline

- Description of chilled-water plant with two chillers in parallel
- Concept of two schemes (Scheme A and Scheme B) for chillers sequencing
- Penalty function based anti-windup for multi-variable ESC
- Simulation results

# Background

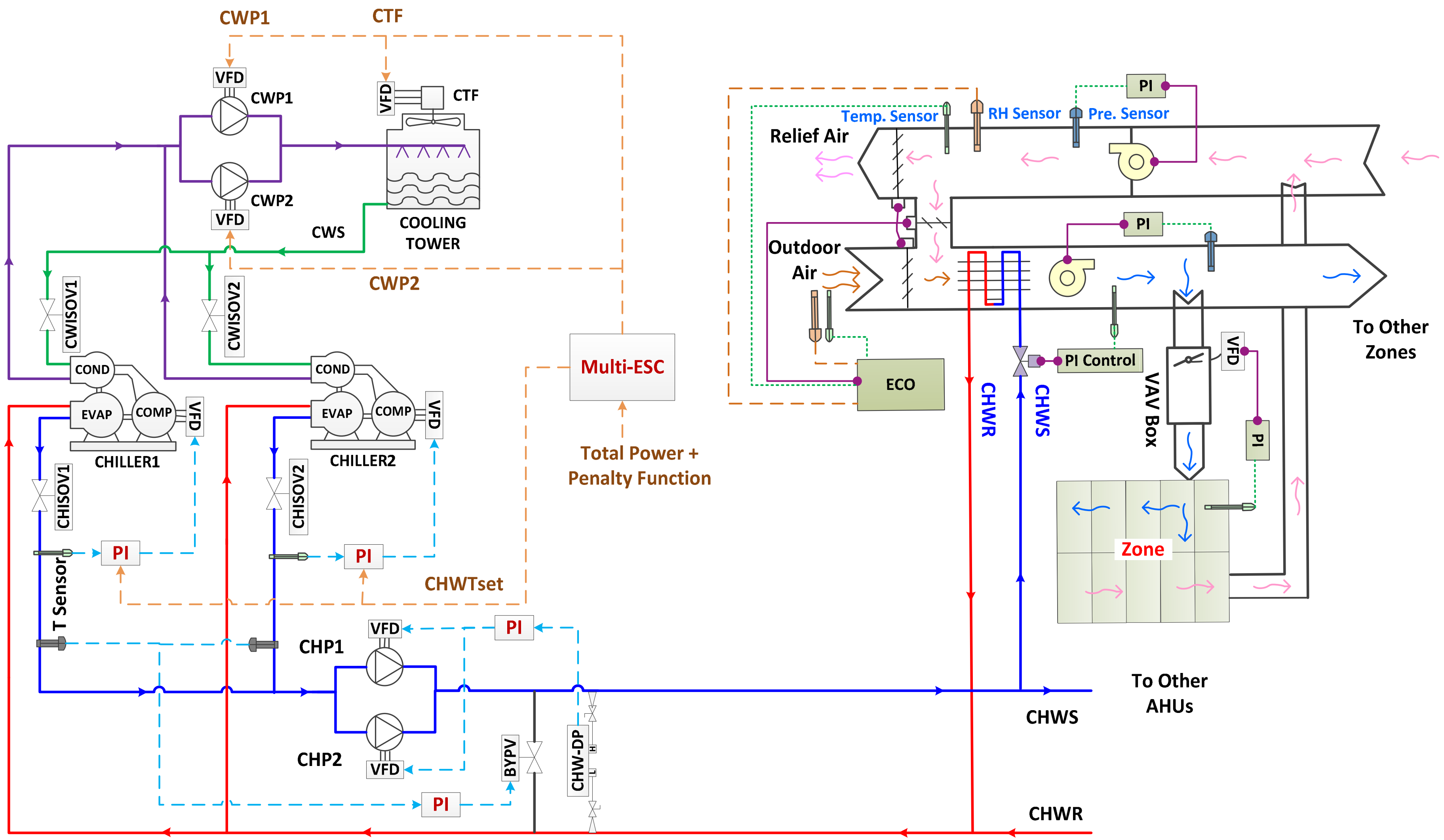
- Commercial buildings are responsible for a significant portion of energy consumption
- Chilled-water plants with multiple chillers account for primary energy use in large commercial buildings
- Real-time optimization and sequencing is thus critical for large chilled-water plants




Carrier, Heat recovery from chilled water systems, 2008

# Schematic of a Chilled-water Plant with Two Chillers in Parallel



# Existing Work on Chilled-water Plant Optimization & Sequencing

- **Rule based control**
- **Model based control/optimization**
  - » Mode Predictive Control
  - » Dynamic Programming
  - » Sequential Quadratic Programming
  - » Mixed-integer Linear Programming
  - » …
- **Model-free control/optimization**
  - » Neural Networks
  - » Genetic Algorithms, Particle Swarm Optimization, …
  - » Extremum Seeking Control
  - » …

# Previous Work on Chiller Plant Optimization

- Mu *et al*. (2015) present a model-free optimization and sequencing scheme
- Chiller optimization: multi-variable extremum seeking control
- Two schemes of chiller sequencing
  - **Scheme A**: a chiller is turned on based on the measurement of chilled water valve position and is turned off when the chiller compressor speed is at its nominal minimum.
  - **Scheme B**: a chiller is turned on and off based on the measurement of cooling load.

Mu, B., Li, Y., Salsbury, T.I., House, J.M. (2015) "Extremum Seeking Based Control Strategy for a Chilled-Water Plant with Parallel Chillers," *ASME Dynamic Systems and Control Conf*., Columbus, OH.

# Model-free Chiller Plant Optimization and Sequencing Scheme by Mu et al. (2015)

## Problem Formulation

Find the optimum input $u$ such that :

$$u^*(t) = \arg\min_{u} P_t(t) = \arg\min_{u} \left\{ P_{CTA}(t) + \sum_{i=1}^{n} \delta_i \left[ P_{COMP,i}(t) + P_{CWF,i}(t) + P_{CHF,i}(t) \right] \right\}$$

subject to

$$\dot{m}_{CTA,\min} \le \dot{m}_{CTA} \le \dot{m}_{CTA,\max}$$

$$\dot{m}_{CWF,i,\min} \le \dot{m}_{CWF,i} \le \dot{m}_{CWF,i,\max}$$

$$\dot{m}_{CHF,i,\min} \le \dot{m}_{CHF,i} \le \dot{m}_{CHF,i,\max}$$

$$\Omega_{COMP,i,\min} \le \Omega_{COMP,i} \le \Omega_{COMP,i,\max}$$

$$T_{SH,i,\min} \le T_{SH,i} \le T_{SH,i,\max}$$

$$\delta_i = \begin{cases} 1 & \text{if chiller } i \text{ is ON} \\ 0 & \text{if chiller } i \text{ is OFF} \end{cases}$$

$$u \triangleq [\dot{m}_{CTA}, \dot{m}_{CWF,1}, \dot{m}_{CHF,1}, T_{SH,1}, \cdots, \dot{m}_{CWF,n}, \dot{m}_{CHF,n}, T_{SH,n}]$$

Cooling tower air mass flow rate (CTA)

Condenser water mass flow rate (CWF)

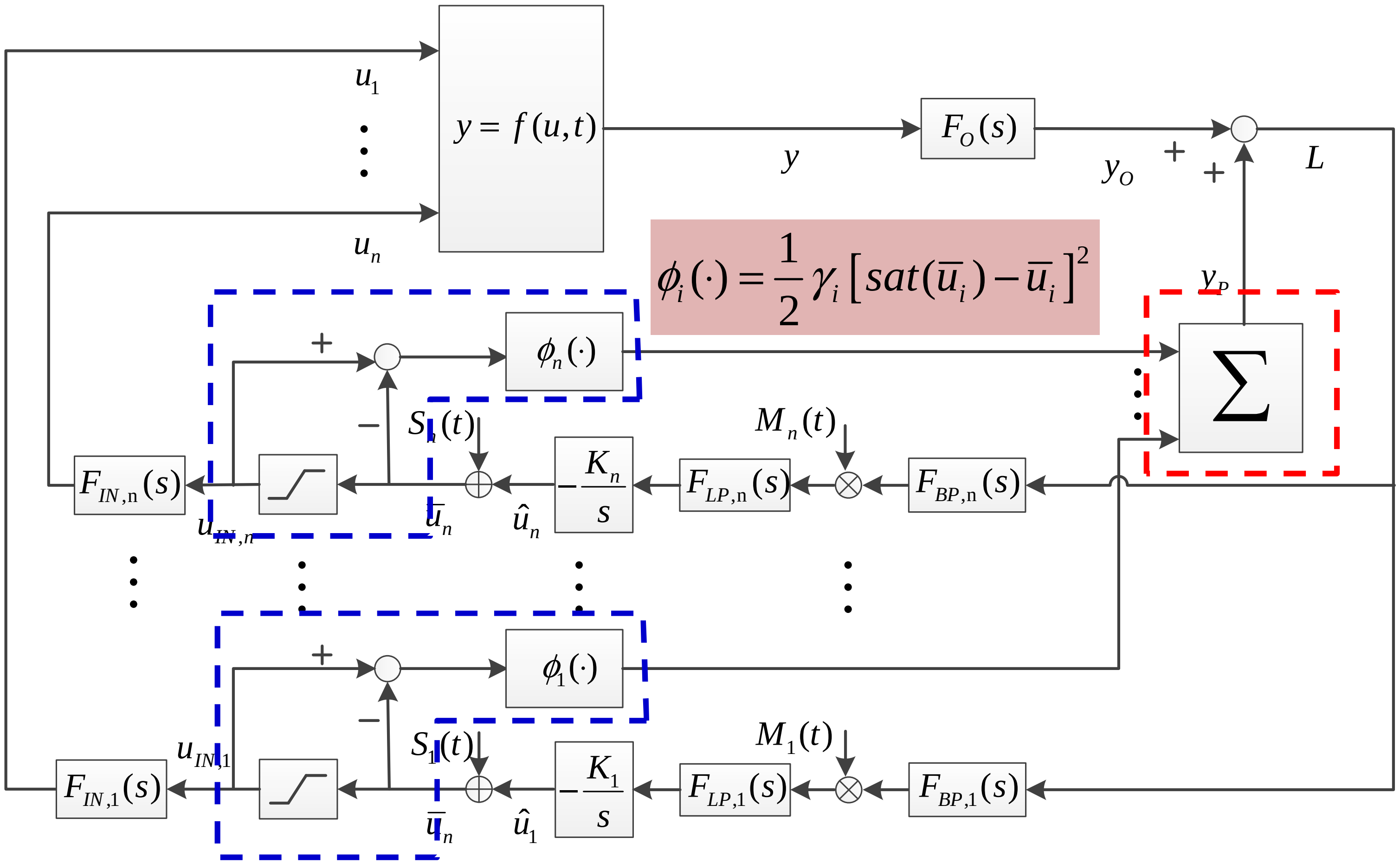
Chilled water mass flow rate (CHF)

Compressor speed (COMP)

Evaporator superheat (SH)

# Penalty Function based Anti-windup Multi-variable ESC

- When actuation saturation is present, integral windup could <u>disable the extremum seeking process</u>.
- **Solution: feedback of the saturated action**



# Chiller Sequencing: Scheme A and B

| | Scheme B | Scheme A |
|---|---|---|
| Turn on/off a chiller | on/off: chiller capacity related to supply / return water | On: AHU chilled-water valve opening<br>Off: Compressor minimum speed |
| Chiller startup / shutdown | **Turn on:**<br>• Comp. speed: 0 → nominal min speed (LCWT)<br>• Chilled water pump: 0 → nominal min flow (SAT)<br>• Condenser water pump: 0 → preset value<br>**Turn off:**<br>• Comp. speed: disconnected from control loop<br>• Chilled water pump: disconnected from control loop<br>• Cond. water pump: disconnected from control loop | Same |
| Enable / Disable ESC | Turn on/off: disable ESC at immediate value and restart from previous frozen value | Same |

# Simulation Scenarios: Operating and Ambient Conditions

| Scenario# | Description |
|---|---|
| 1 | Two-chiller ESC with no sequencing under fixed ambient conditions |
| 2 | Chiller sequencing under variable load and fixed ambient conditions |
| 3 | Chiller sequencing with realistic ambient and load profile |
| 4 | Penalty Function based ESC Chiller Sequencing |
| 5 | ESC for Efficiency Recovery: Chiller 1 properly charged and Chiller 2 with a low charge |
| 6 | ESC for Efficiency Recovery: Chiller 1 nominal + Chiller 2 with heat exchanger fouling |

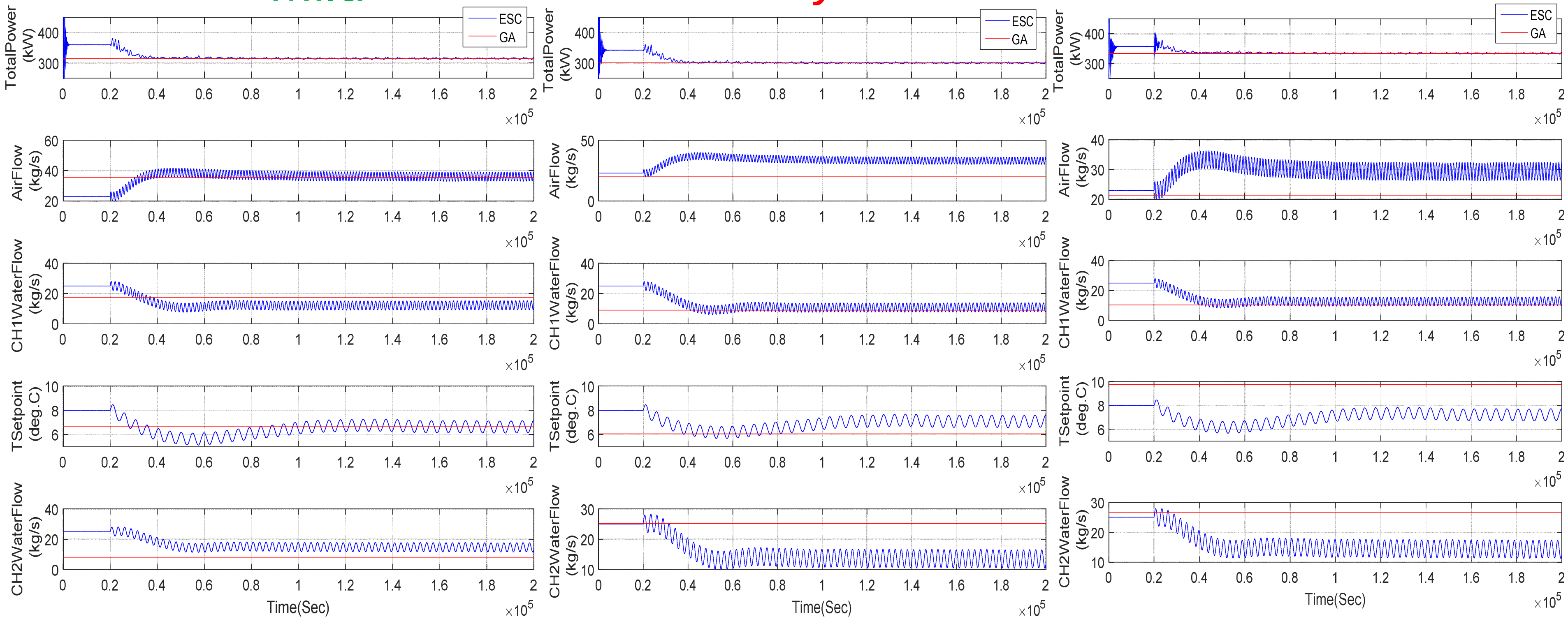
**Ambient Conditions:**

Mild (27°C,RH: 60%), Dry-hot (37°C,RH:30%), Humid-hot (37°C,RH:80%)

# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

## Input and Output Trajectories

Mild | Dry-hot | Humid-hot




| Mild | Dry-hot | Humid-hot |
|---|---|---|
| Load: 500 kW | Load: 350 kW | Load: 350 kW |
| P = 315.7 kW (12.4%↓) | P = 302.4 kW (6.4%↓) | P = 335.9 kW (6.1%↓) |

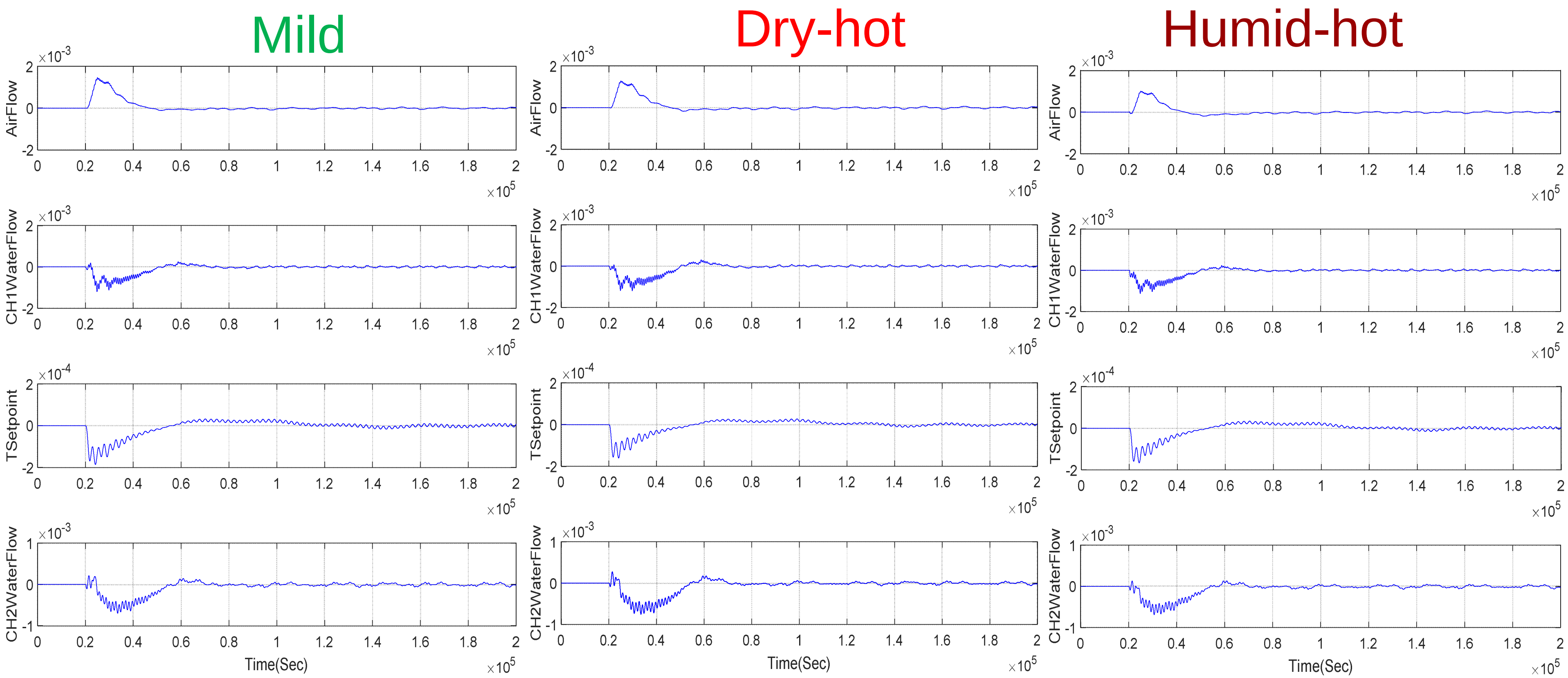
# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

## Steady-state Error

| | Mild | Dry-hot | Humid-hot |
|---|---|---|---|
| Total Power | 0.06% | 0.073% | 0.055% |
| Air Flow | 1.99% | 66.32% | 38.03% |
| Chiller #1 Water Flow | 30.87% | 13.63% | 26.11% |
| LCWT Setpoint | 0.3% | 19.8% | 25.46% |
| Chiller #2 Water Flow | 78.61% | 45.53% | 45.35% |

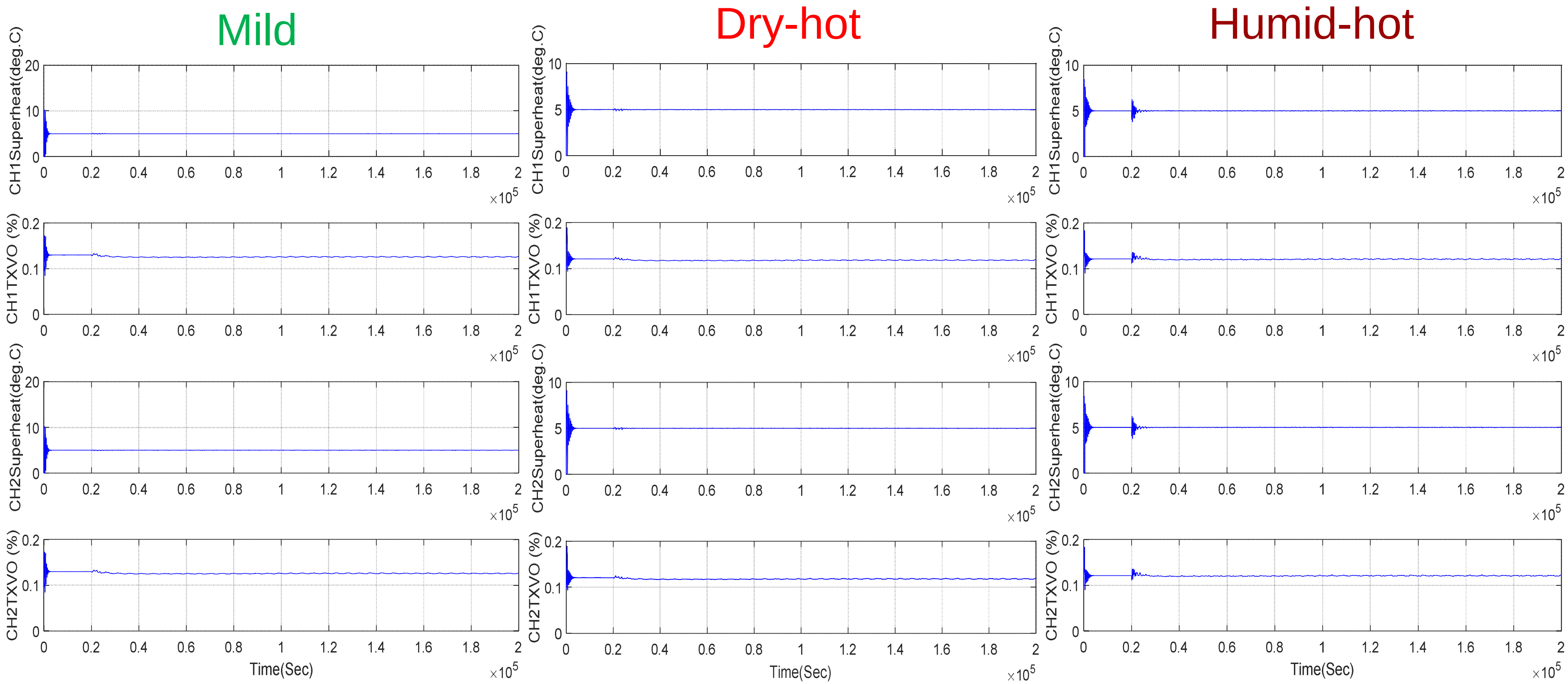
# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

## ESC Input Gradient Trajectories



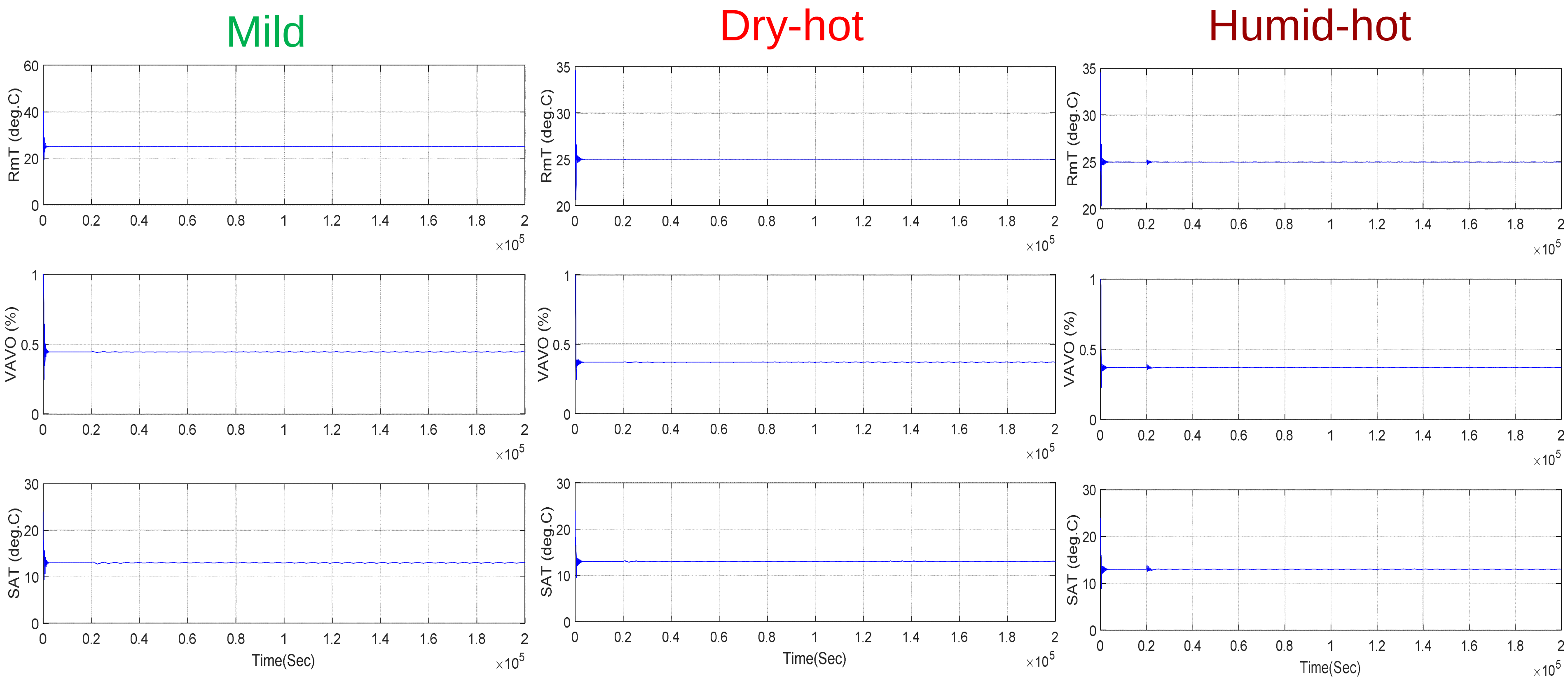
# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

## Superheat and Chiller TEV Opening



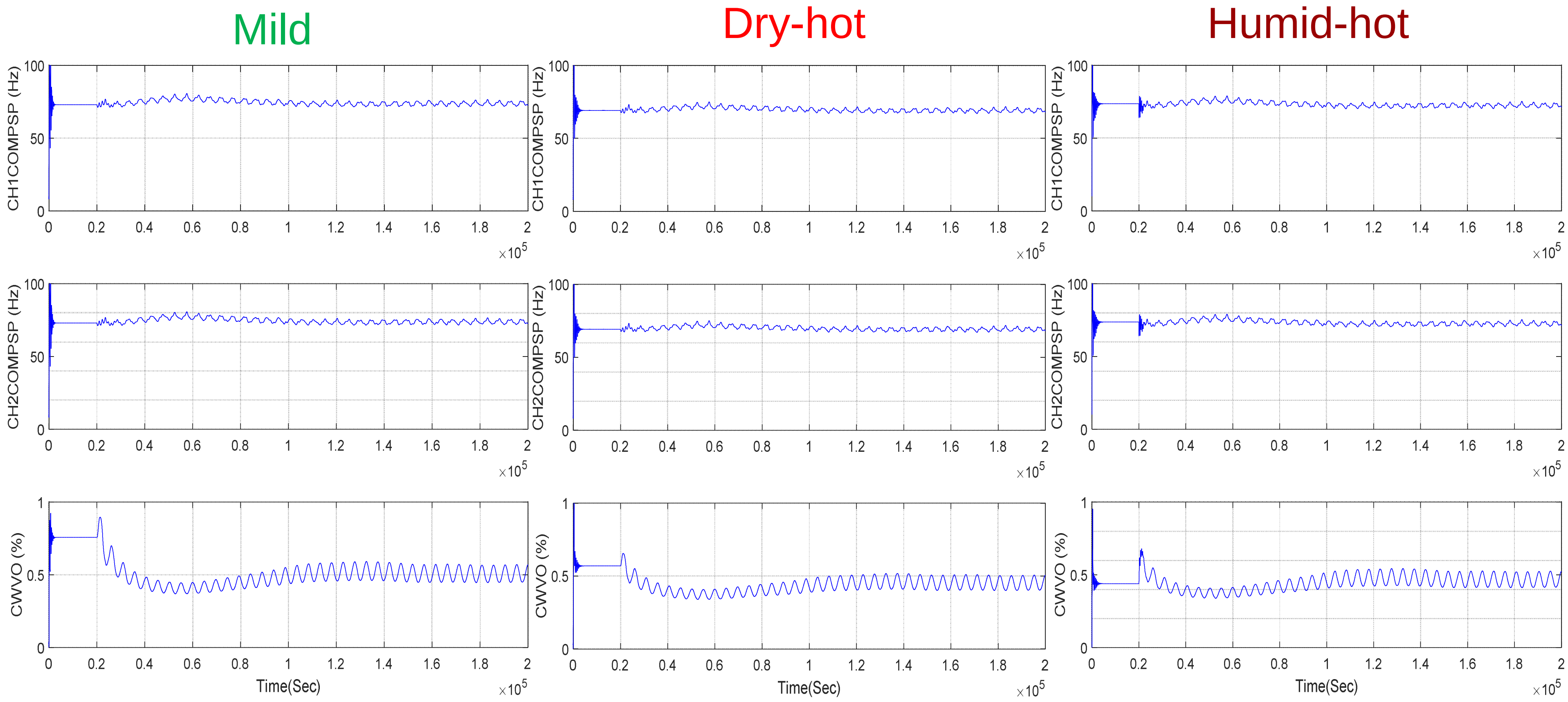
# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

- The supply-air temperature and zone temperature are well regulated about their respective setpoints of 13°C and 25°C



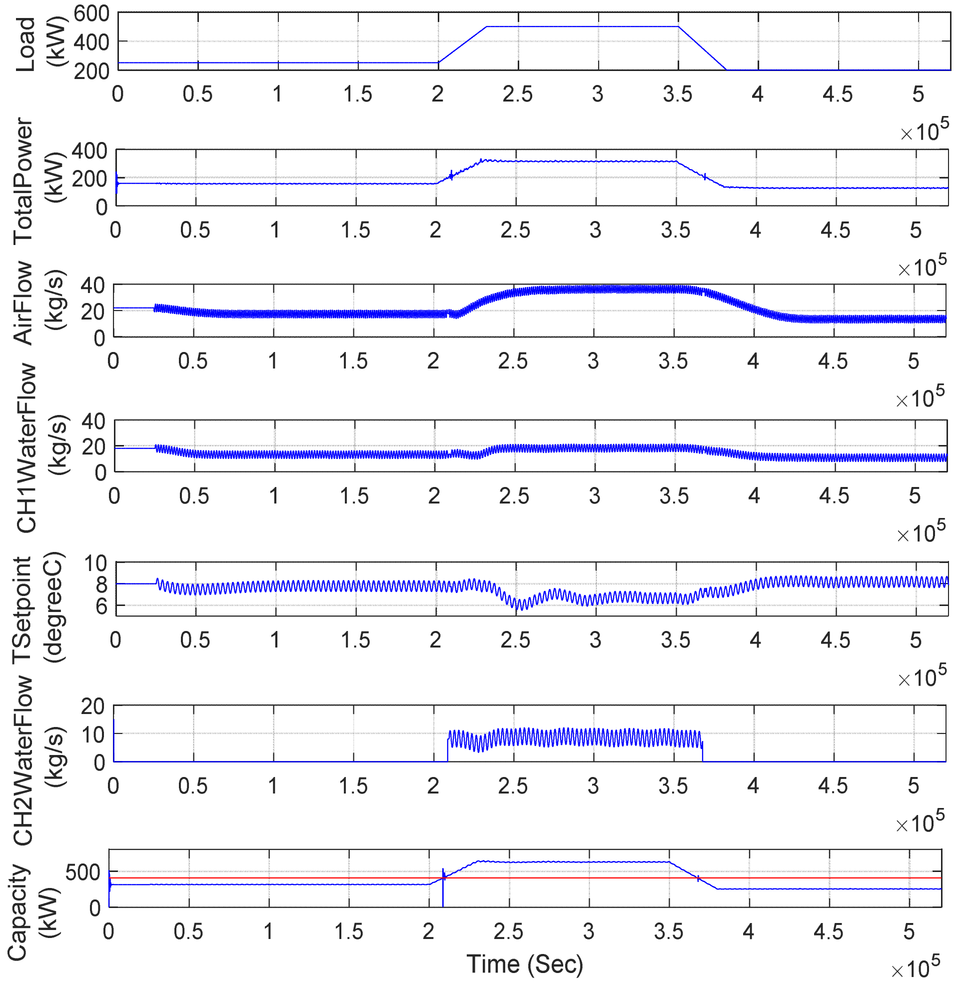
# Case#1: Two-chiller ESC under Fixed Ambient Conditions (No Sequencing)

## Compressor Speed and Chilled-water Valve Opening



# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

**Load, Input, output and Scheme B indicator trajectories**

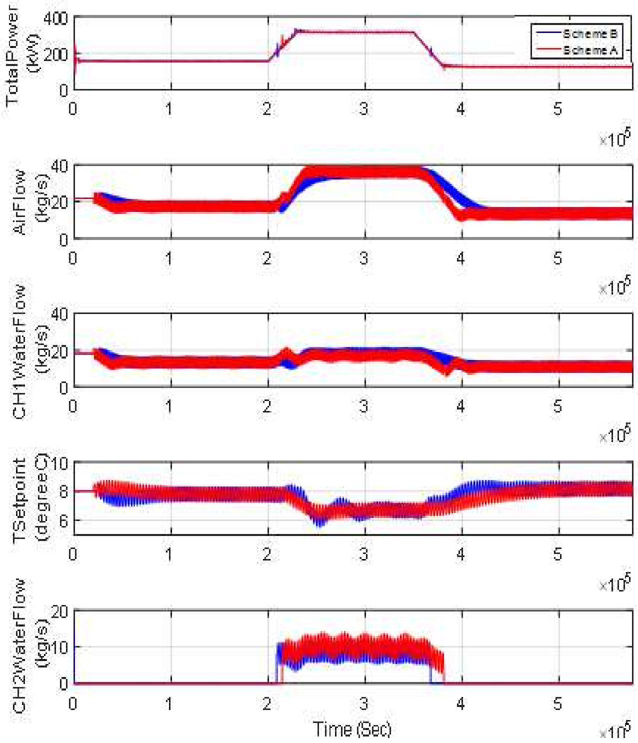



**When measured capacity of operating chiller is greater than 405kW(red line), the second chiller is turned on. And when it is smaller than 405kW, the second chiller is turned off**

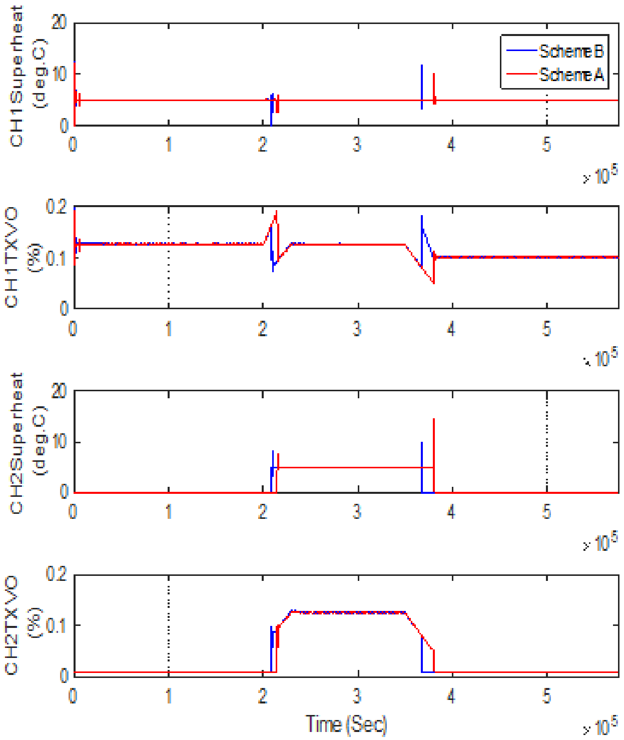
# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

## Mild Condition

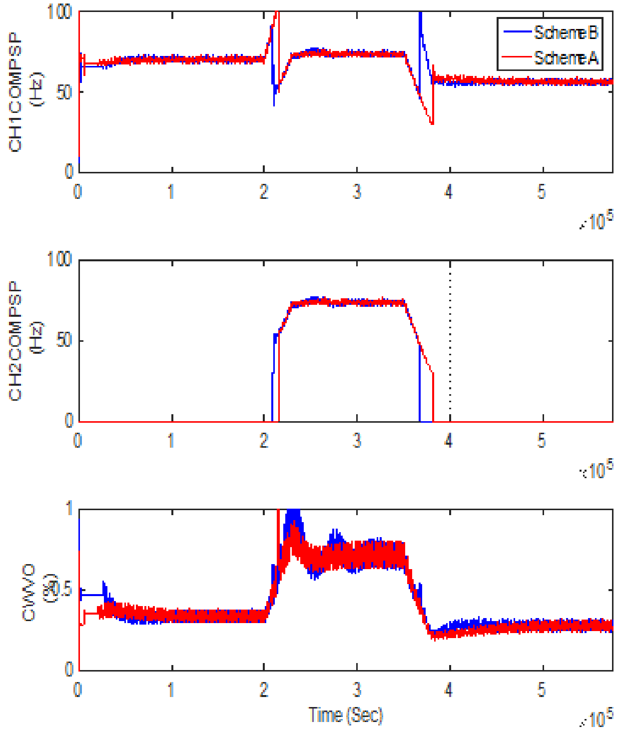
### Input and output trajectories




### Superheat and chiller TEV opening




### Compressor speed and chilled water valve opening




Compared to Scheme A, Scheme B turns on chiller 2 6000s earlier and turns off 13400s earlier

# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

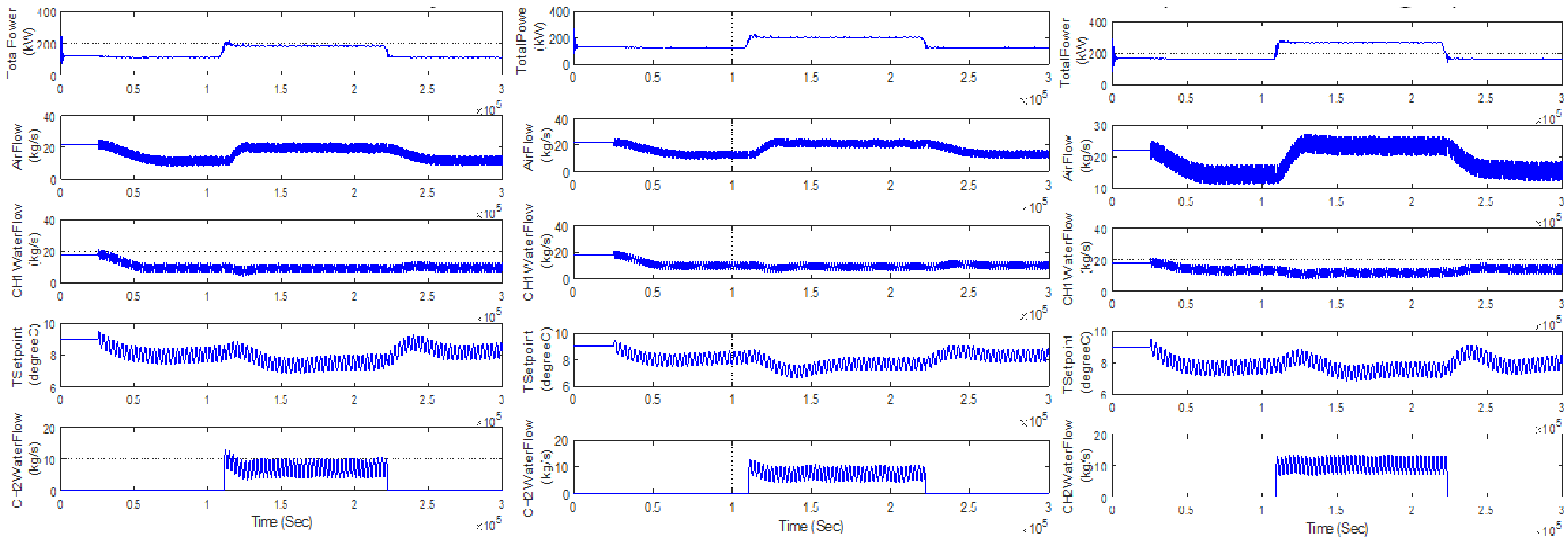
| | Scheme A | | | Scheme B | | |
|---|---|---|---|---|---|---|
| | Period 1 | Period 2 | Period 3 | Period 1 | Period 2 | Period 3 |
| Total power(kW) | 156.9 | 316.2 | 126.3 | 158.9 | 315.3 | 125.7 |
| Air flow(kg/s) | 17.2 | 36.7 | 13.5 | 17.6 | 36.4 | 13.3 |
| Chiller1 water flow (kg/s) | 13.2 | 16.7 | 10.5 | 13.4 | 17.4 | 10.9 |
| T setpoint(°C) | 7.6 | 6.6 | 7.9 | 7.7 | 6.7 | 8.1 |
| Chiller2 water flow (kg/s) | | 10.1 | | | 9.2 | |

- During period 2 and period 3, Scheme B achieves better performance.
- During period 1, Scheme A has better efficiency.
- The chiller 2 is turned on earlier and turned off earlier when Scheme B is applied.

# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

## Input and Output Trajectories

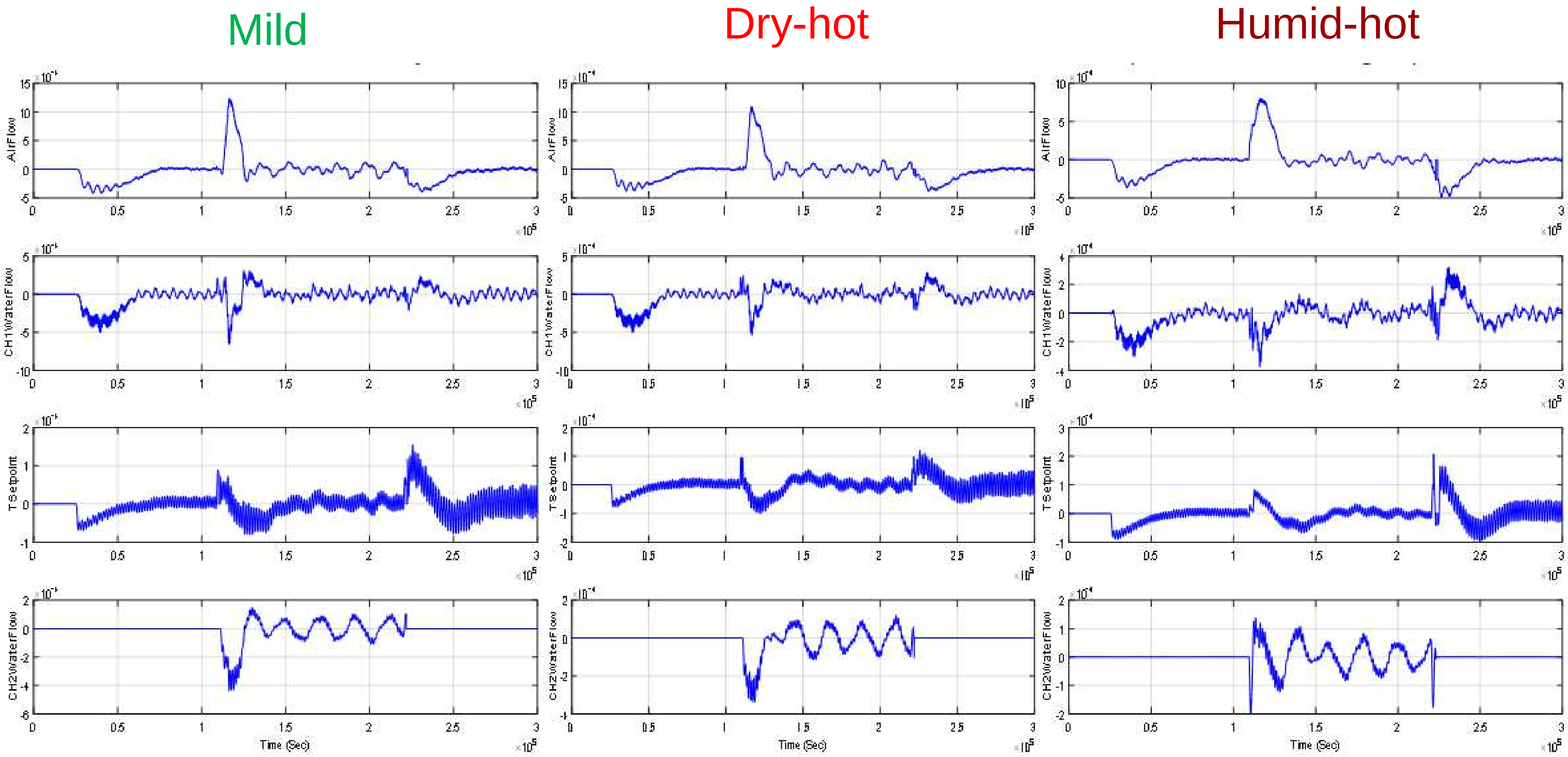
Mild | Dry-hot | Humid-hot




- Total power consumption when only chiller 1 is on: 115.1kW, 124.5kW and 164.5 kW, respectively.
- For increased load, both chiller 1 and chiller 2 are on, and the total power are 184.5kW, 204.6kW and 268.1kW, respectively.

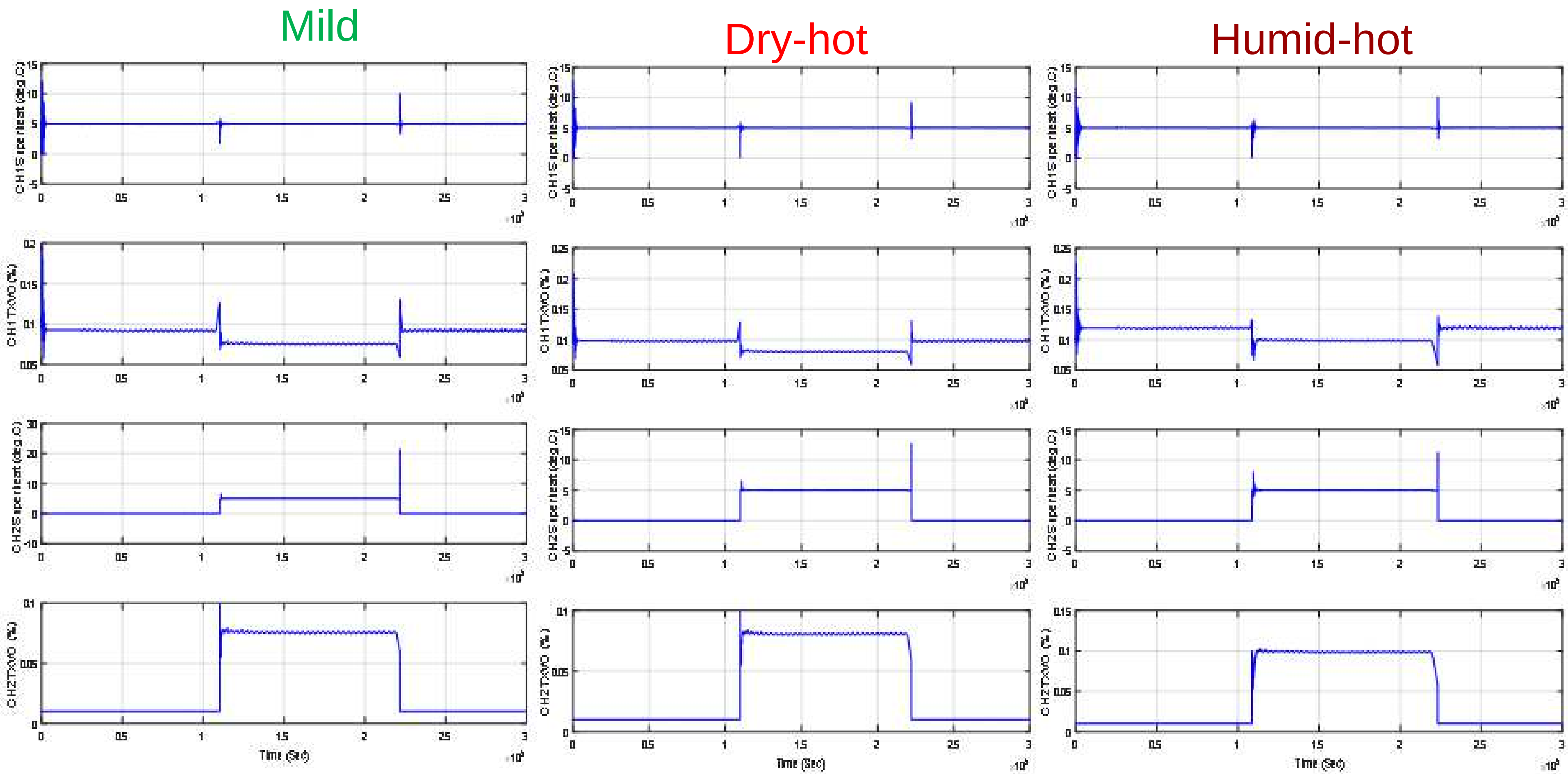
# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

## ESC Inputs Gradient Trajectories



# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

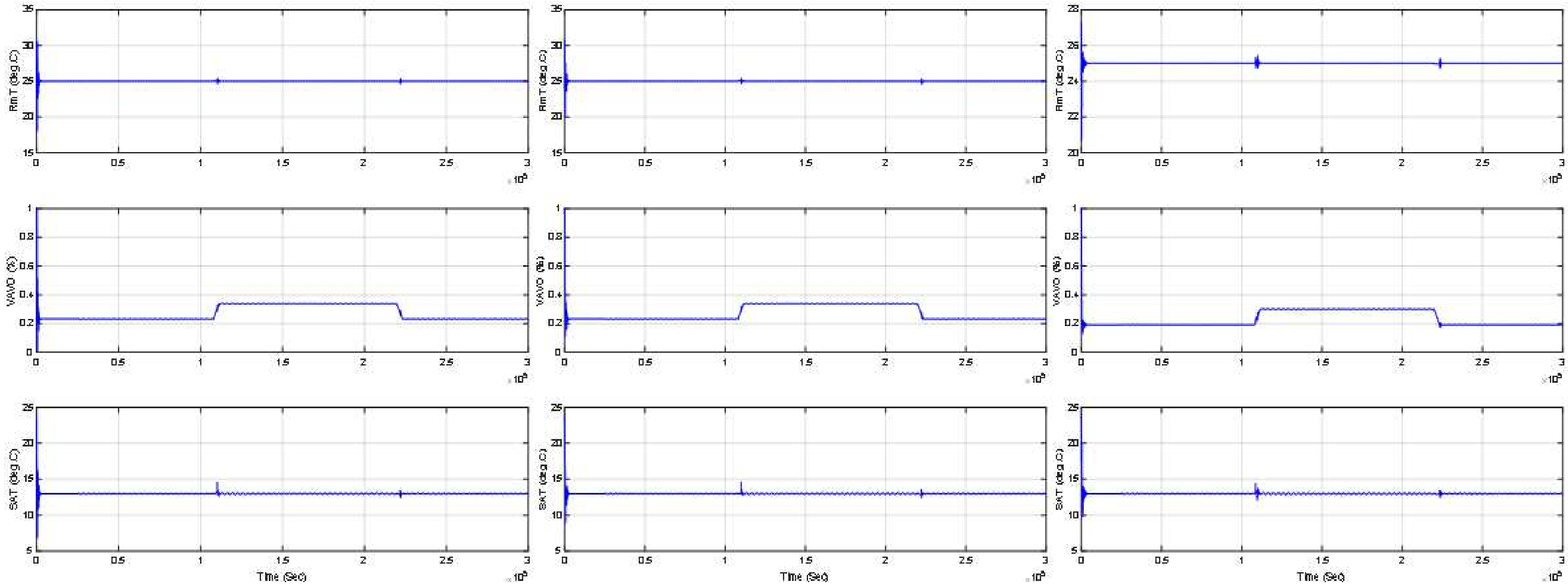
Superheat and chiller TXV opening



# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

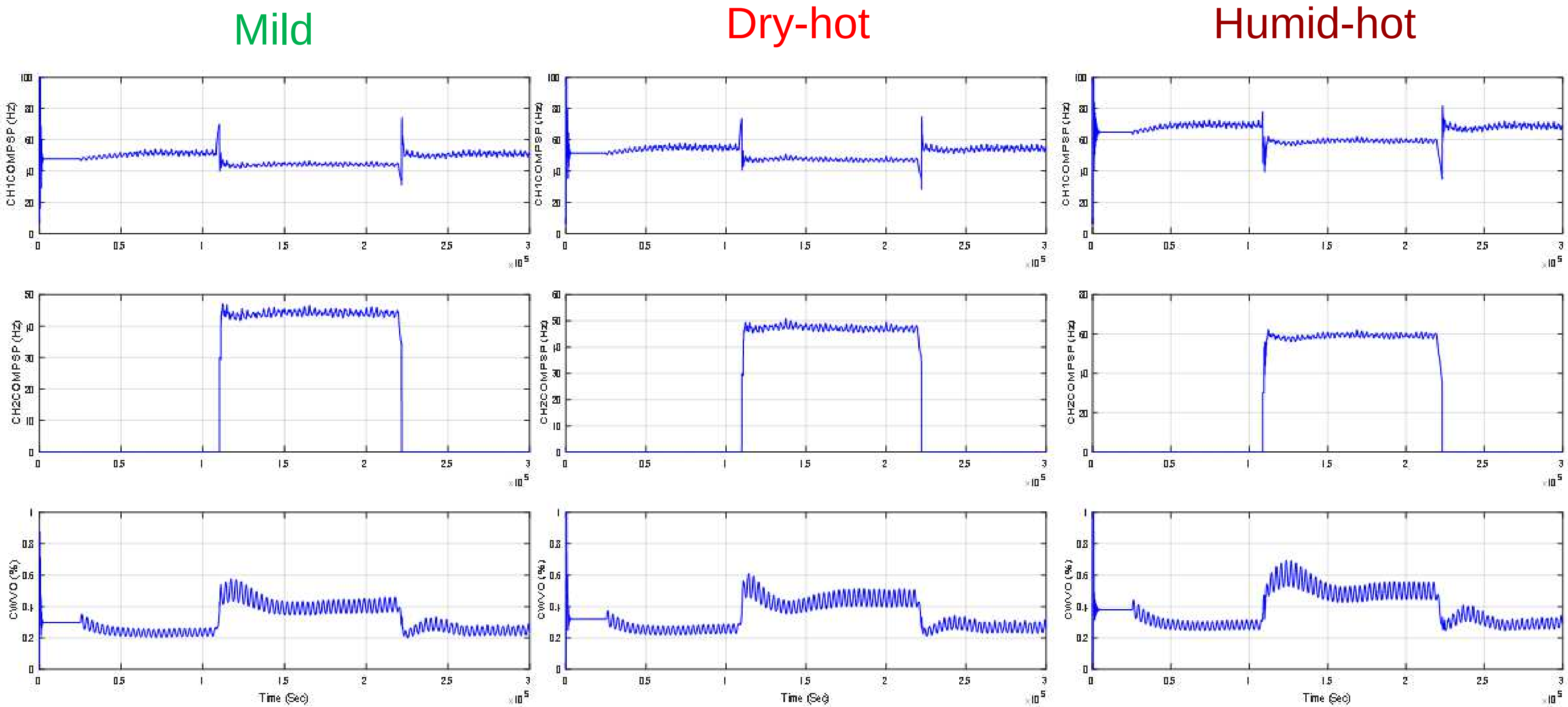
- Supply-air temperature and zone temperature are well regulated about their respective setpoints of 13°C and 25°C

Mild | Dry-hot | Humid-hot



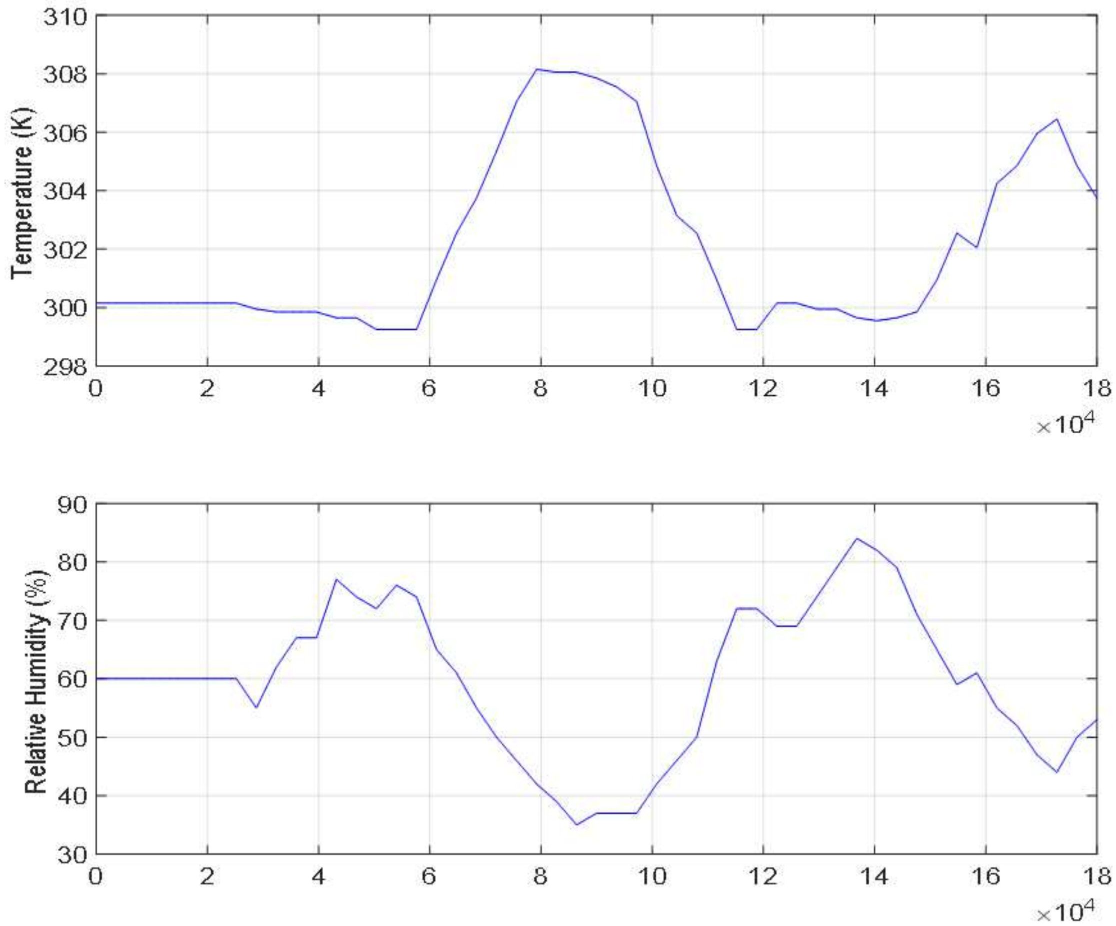
# Case#2: Chiller Sequencing under Variable Load and Fixed Ambient Conditions

## Compressor Speed and Chilled-water Valve Opening



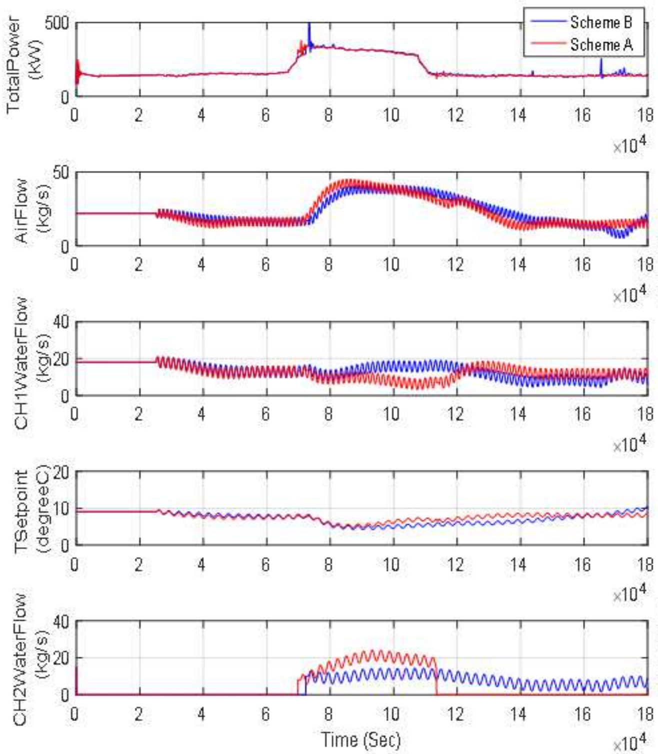
# Case#3: Chiller Sequencing with Realistic Ambient and Load Profile

- Ambient temperature and RH profile developed from the TMY2 data for the Dallas-Fort Worth area (National Solar Radiation Data Base)

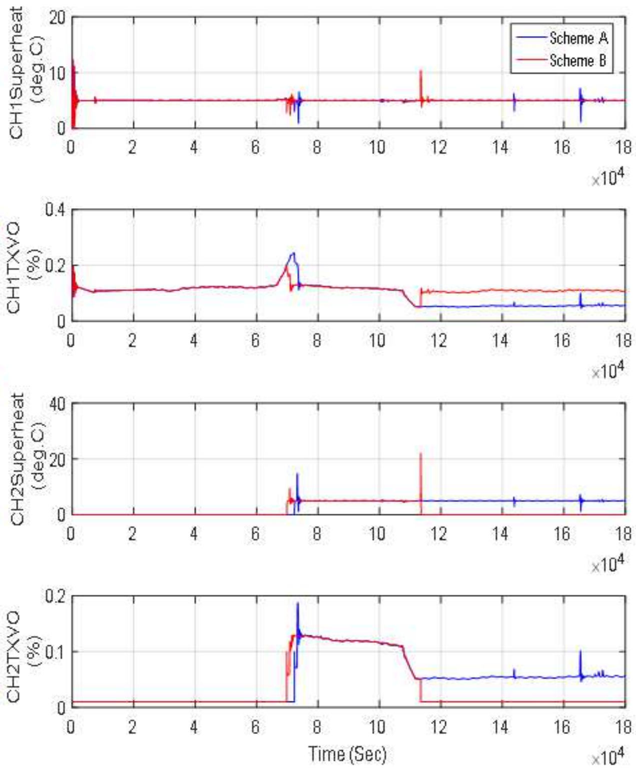


# Case#3: Chiller Sequencing with Realistic Ambient and Load Profile

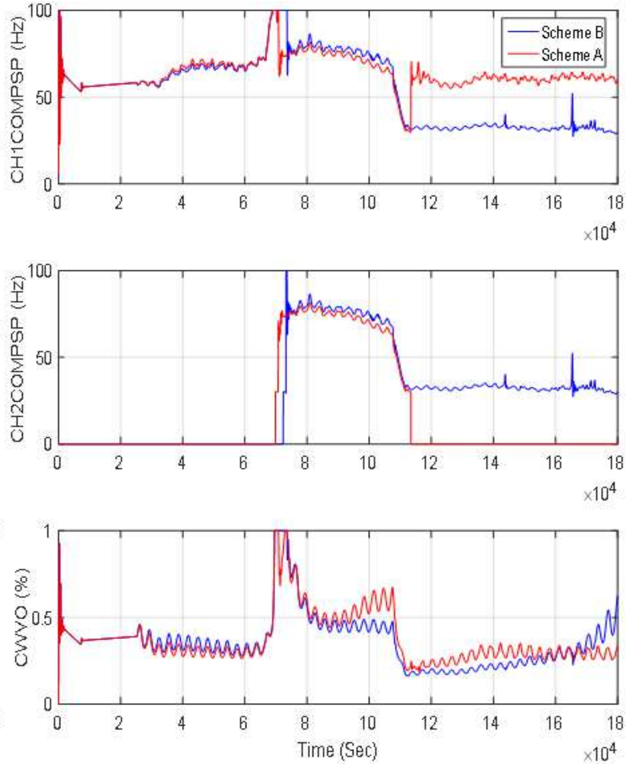
## Input and output trajectories




## Superheat and chiller TEV opening



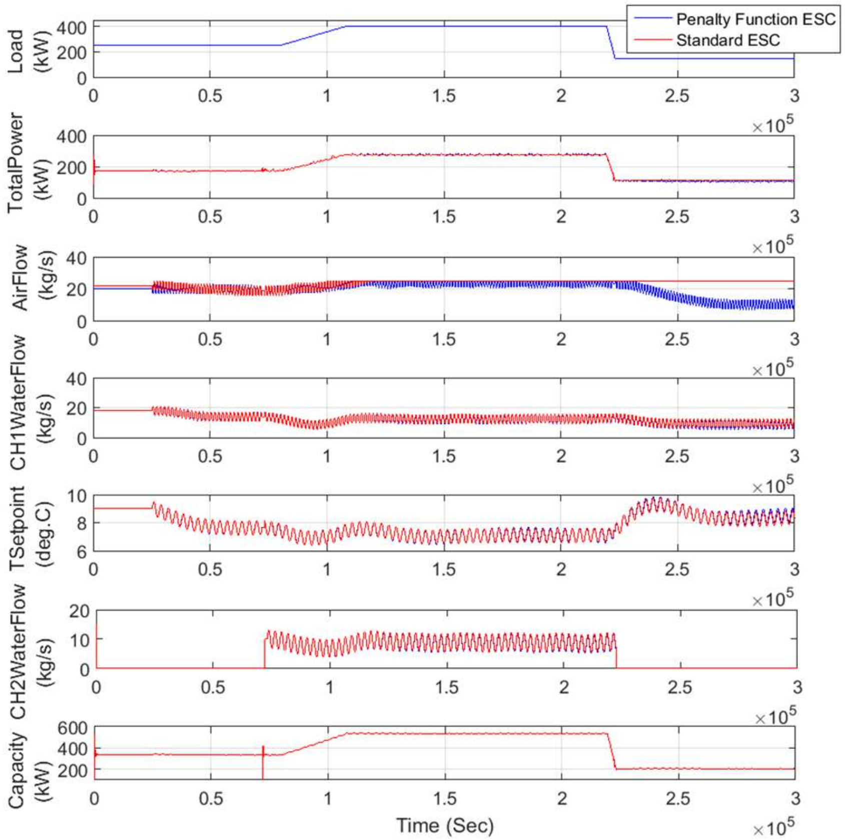

## Compressor speed and chilled water valve opening



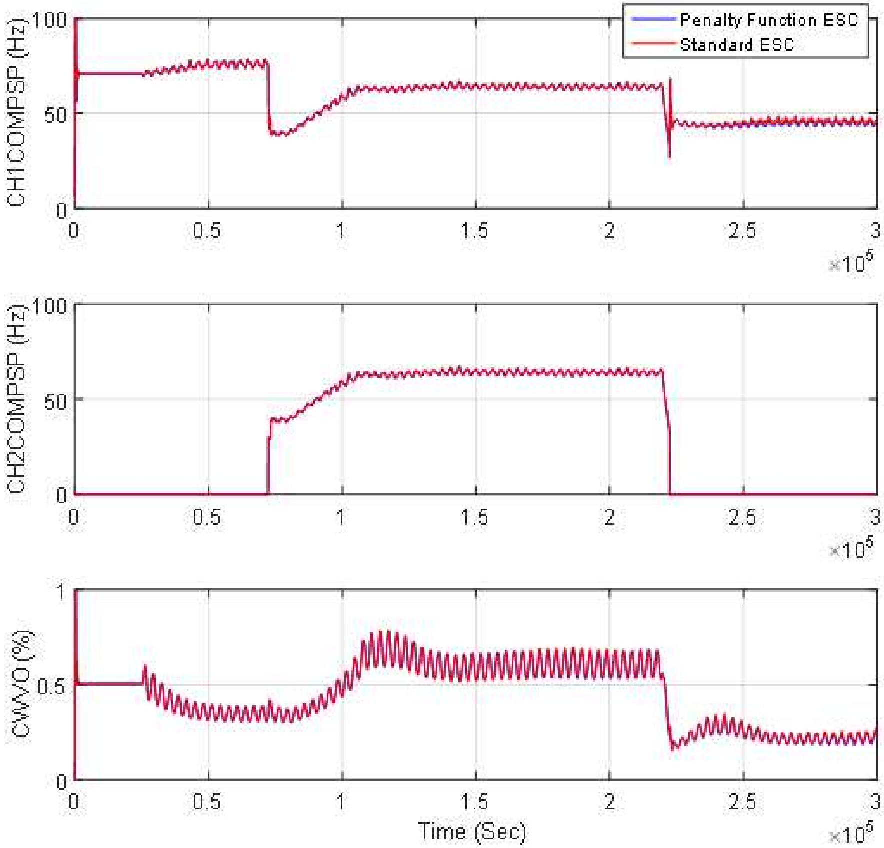
# Case#4 : Penalty Function based ESC and Chiller Sequencing

- Dry-hot condition; Internal cooling load: 250kW $\rightarrow$ 400kW $\rightarrow$ 150kW.

Inputs & Output Trajectories with vs. without Penalty Function




Compressor speed and chilled water valve opening



# Conclusion & Future Work

- A multivariate ESC based real-time optimization and sequencing algorithm is studied under different operating conditions
- Scheme B based chiller sequencing is evaluated and compared with Scheme A sequencing scheme
- Work under way: more evaluation and comparison

# Acknowledgments


- Financial Support by Johnson Controls Building Efficiency Research Group
- TLK-Thermo for the permission of using TIL Library and technical assistance


*Thanks!*

*Any Questions?*