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High Performance Buildings

Extremum Seeking Control of Hybrid Ground Source Heat Pump System

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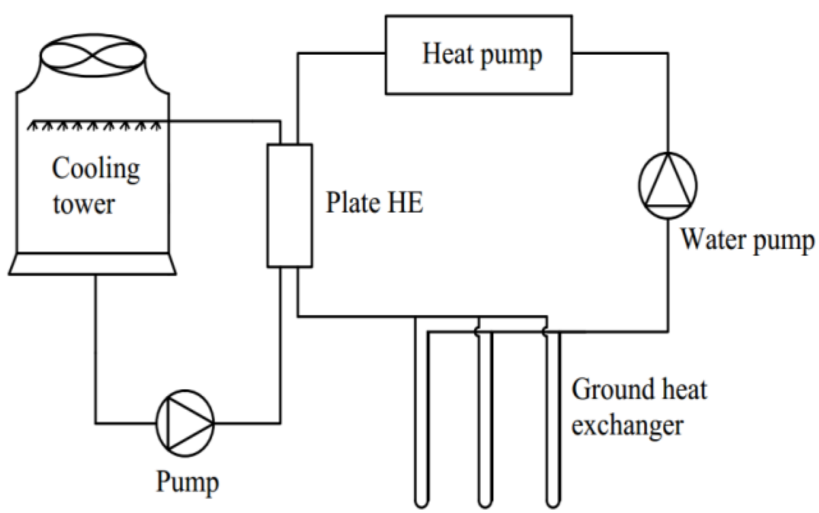
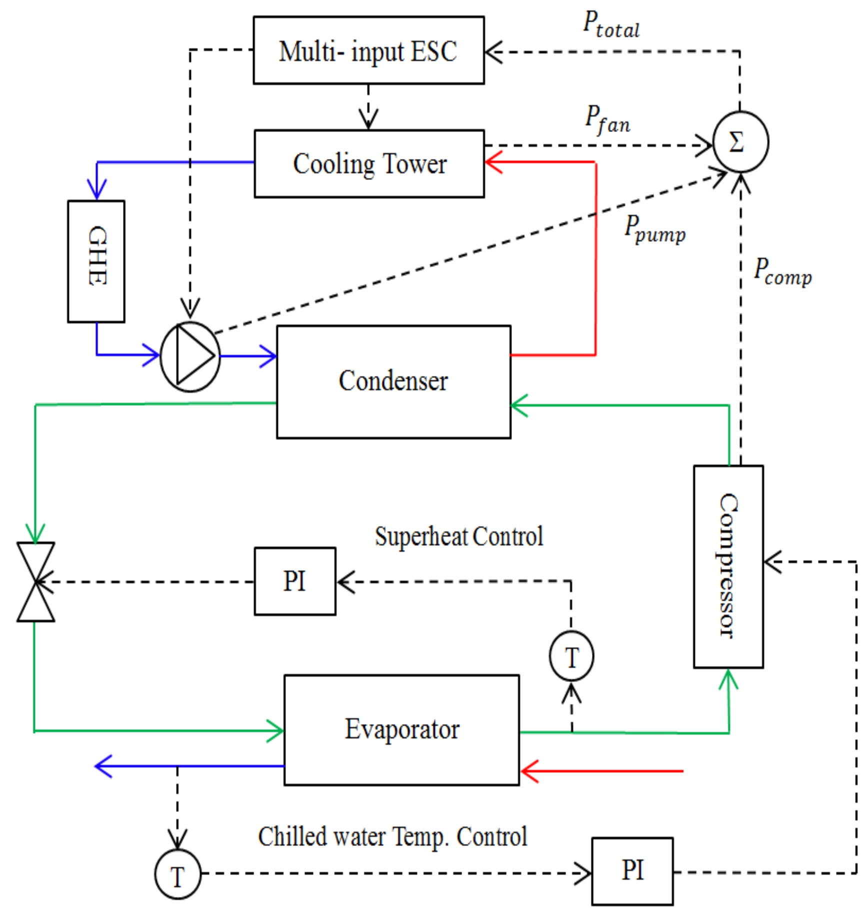
1. INTRODUCTION

- The ground source heat pump (GSHP) has higher energy efficiency in balanced loads buildings.
- Many commercial buildings are cooling-dominated with unbalanced loads, especially those located in warm-climate areas.
- The hybrid GSHP system by utilizing supplemental heat rejecters is a cost-effective alternative.
- Extensive studies on the design strategies of the hybrid GSHP systems:
  - » Caneta Research (1995); Kavanaugh and Rafferty (1998);
  - » Chiasson et al. (2010); Ni *et al*. (2011)

1. INTRODUCTION

Various approaches have been studied in simulation and analysis of optimal control and operation of hybrid GSHP systems for cooling-dominated applications.





1. INTRODUCTION

- Yavuzturk and Spitler investigated the various control strategies for a hybrid GSHP system with a cooling tower under different climatic conditions.
- Ramamoorthy *et al*. used a system simulation approach to finding the optimal size of a supplemental cooling with a GHP system .
- Wrobel presented a parameter estimation scheme for the hybrid GSHP design.
- Hackel proposed a design optimization algorithm to minimizes the hybrid GSHP life-cycle.
- Man *et al*. developed an hourly simulation to model and analyze the heat transfer processes of hybrid GSHP. Some operational strategies are investigated for a sample building.

1. INTRODUCTION

- Most control and optimization methods for hybrid GSHP are based on nominal/empirical models. In practice, due to hard-to-estimate system degradation, such models are inaccurate.
- Therefore, real-time setpoint optimization not replying on exact system knowledge is more desirable for operations of the hybrid GSHP systems.
- The Extremum Seeking Control (ESC) can search for the optimal input in real time in a nearly model-free fashion.

2. GHE MODEL

Quasi -three-dimensional model

- The heat flows per unit length for two pipes are denoted as q_1 and q_2, respectively:

$$T_{f1} - T_b = R_{11} q_1 + R_{12} q_2$$

$$T_{f2} - T_b = R_{12} q_1 + R_{22} q_2$$

- R_{11} and R_{22} are the thermal resistances between the two pipes and borehole wall, respectively. R_{12} is the thermal resistance between the two pipes.

$$R_{11} = R_{22} = \frac{1}{2\pi k_b}\left[\ln\frac{r_b}{r_p} + \sigma \cdot \ln\left(\frac{{r_b}^2}{{r_b}^2 - D^2}\right)\right] + R_p$$

$$R_{12} = \frac{1}{2\pi k_b}\left[\ln\frac{r_b}{2D} + \sigma \cdot \ln\left(\frac{{r_b}^2}{{r_b}^2 - D^2}\right)\right]$$

- where $\sigma = \frac{k_b - k}{k_b + k}$ and $R_p = \frac{1}{2\pi k_p}\ln\frac{r_b}{r_{pi}} + \frac{1}{2\pi r_{pi} h}$ is the thermal resistances between the fluid and outer pipe wall.

2. GHE MODEL

Quasi -three-dimensional model

- The convective heat flow along the fluid channels is balanced by the conductive heat flows among the fluid channels and borehole wall.

$$-MC_P \frac{dT_{f1}(z)}{dz} = \frac{R_{12}(T_{f2}(z) - T_b) - R_{11}(T_{f1}(z) - T_b)}{R^2{}_{12} - R^2{}_{11}}$$

$$MC_P \frac{dT_{f2}(z)}{dz} = \frac{R_{12}(T_{f1}(z) - T_b) - R_{11}(T_{f2}(z) - T_b)}{R^2{}_{12} - R^2{}_{11}}$$

- The boundary conditions:

$$0 \leq z \leq H\,;\ z = 0\,, T_{f1} = T_{f,in};\ z = H\,, T_{f1} = T_{f2}$$

2. GHE MODEL

Cylindrical source model

- The transient conductive heat transfer in the borehole, in the soil and for the far-field boundary condition.

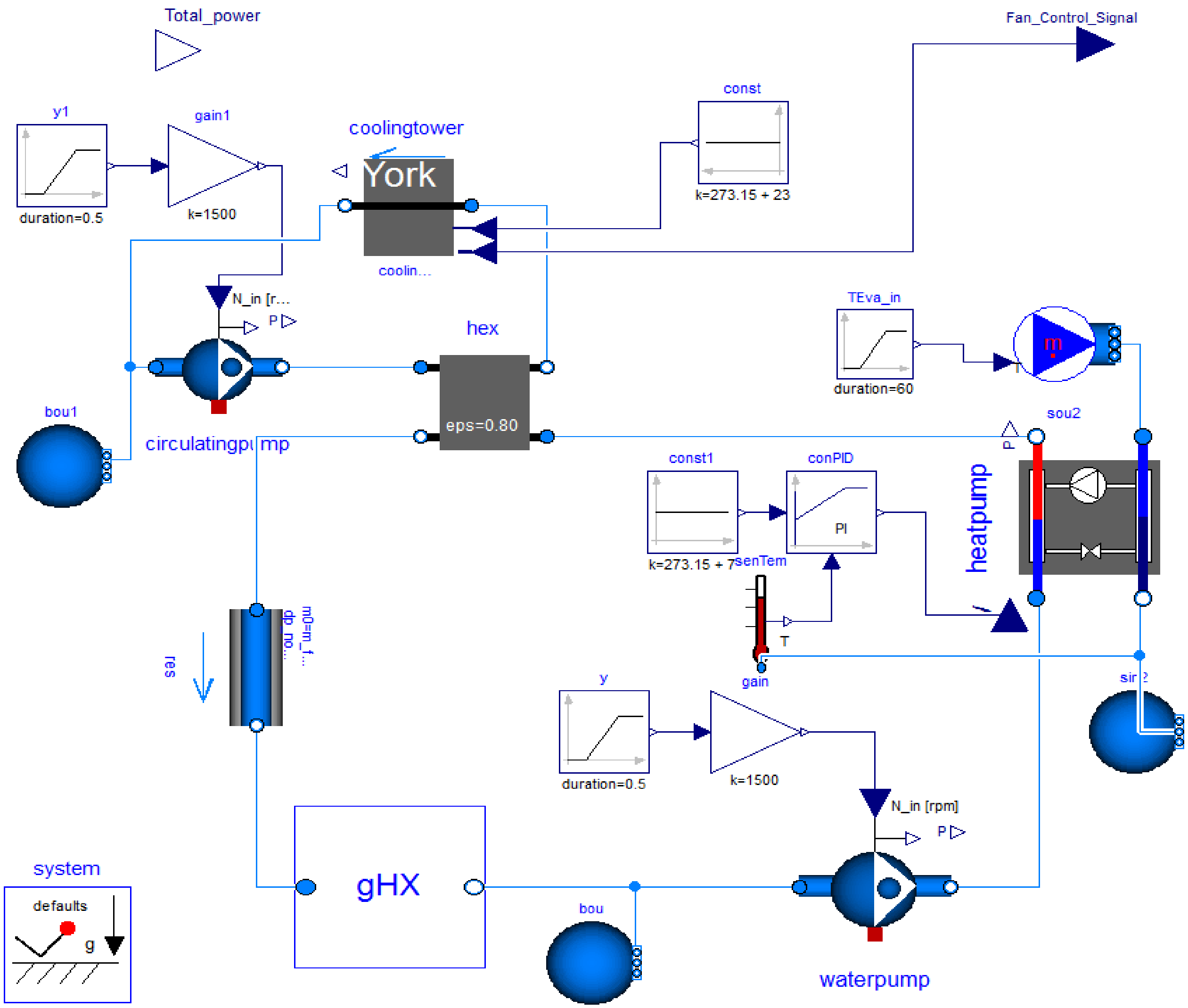
$$\rho c \left(\frac{\partial T(r,t)}{\partial t}\right) = k\left(\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,t)}{\partial r}\right)$$

- *T* (*r*, *t*) is the temperature at radius *r* and time *t*.
- The boundary conditions:

$$-2\pi r_b k \frac{\partial T(r,t)}{\partial r}\bigg|_{r=r_b} = q_1 \qquad \text{for } t \geq 0$$

$$T(t=0) = T_0 \qquad \text{for } r \gg r_b$$

3. HYBRID GSHP MODEL



3. HYBRID GSHP MODEL

Cooling tower model

- *Buildings.Fluid.HeatExchangers.CoolingTowers.YorkCalc* in the Modelica Buildings Library 1.5 is adopted.

$$P_{fan,nom} = fraP_{fan,nom} \cdot m_{w,nom}$$

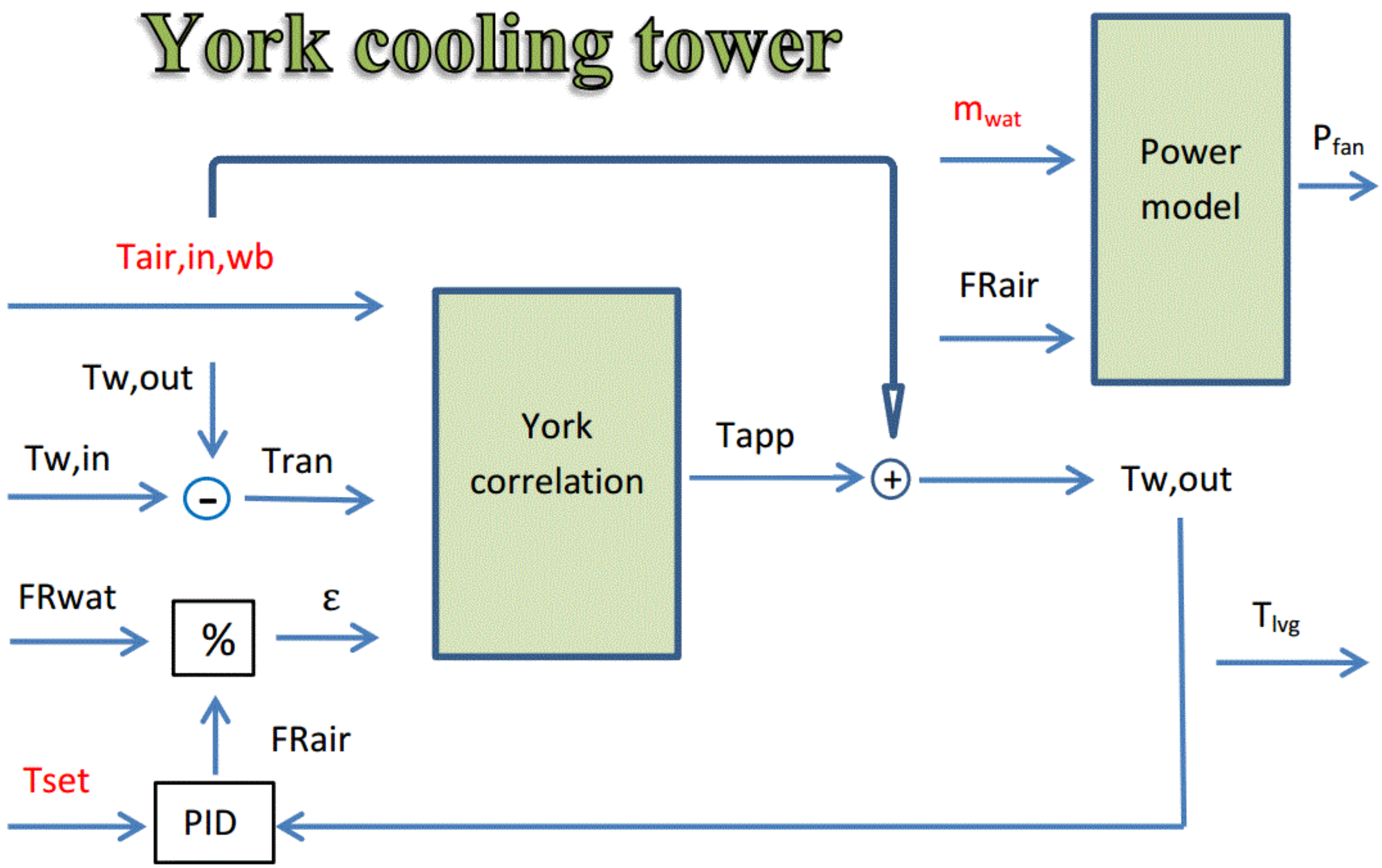
$fraP_{fan,nom}$ [W/ (kg/s)] is defined as the fan power divided by the water mass flow rate at the nominal condition, with the default value being 275 Watts for a water flow rate of 0.15 kg/s .

$$P_{fan} = y^{3} \cdot fraP_{fan,nom} \cdot m_{w}$$

where y is the relative air flow rate, $m_w$is water mass flow rate $fraPfan,nom$ is the ratio of fan power and water mass flow rate with the default value 1833[W/ (kg/s)].

3. HYBRID GSHP MODEL

Cooling tower model



3. HYBRID GSHP MODEL

Heat pump model

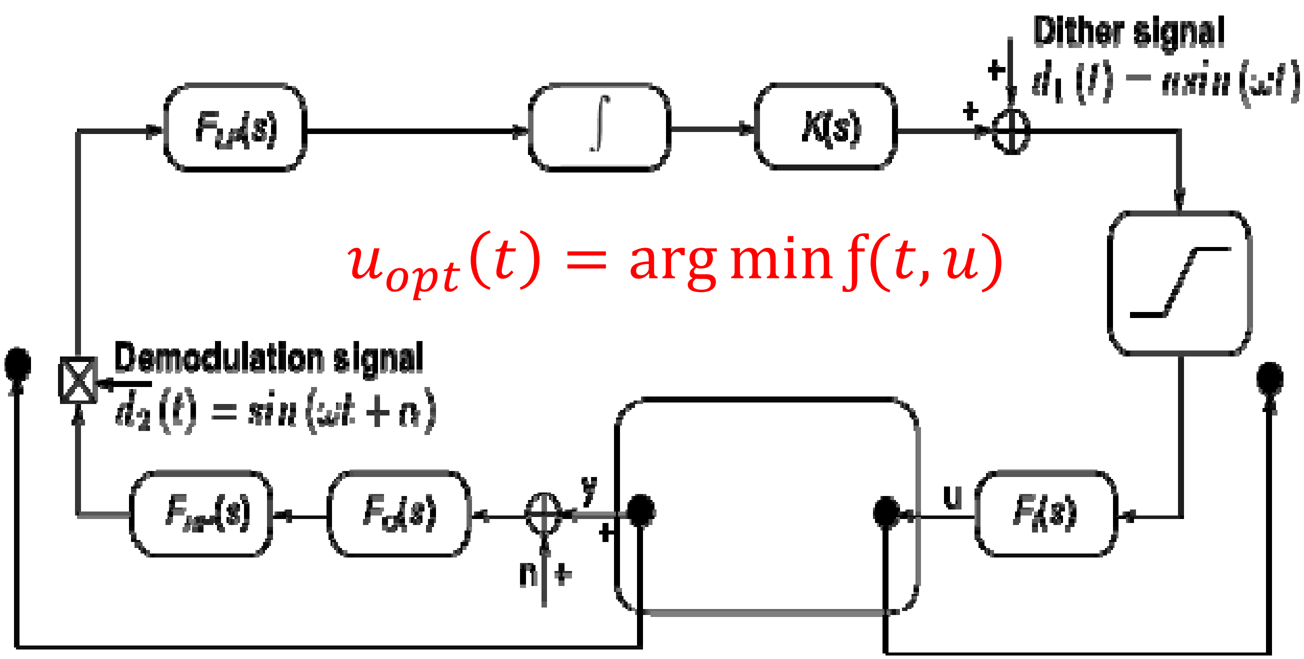
- A simplified heat pump model is used to simulate the operation of whole hybrid GSHP system. The COP of this model changes with temperatures in the same way as the Carnot efficiency changes.

$$COP_0 = \eta_{car} \, COP_{car} = \eta_{car} \cdot \frac{T_{eva}}{T_{con} - T_{eva}}$$

- An inner-loop proportional-integral (PI) controller is implemented to regulate the evaporator leaving water temperature at 280.15K.

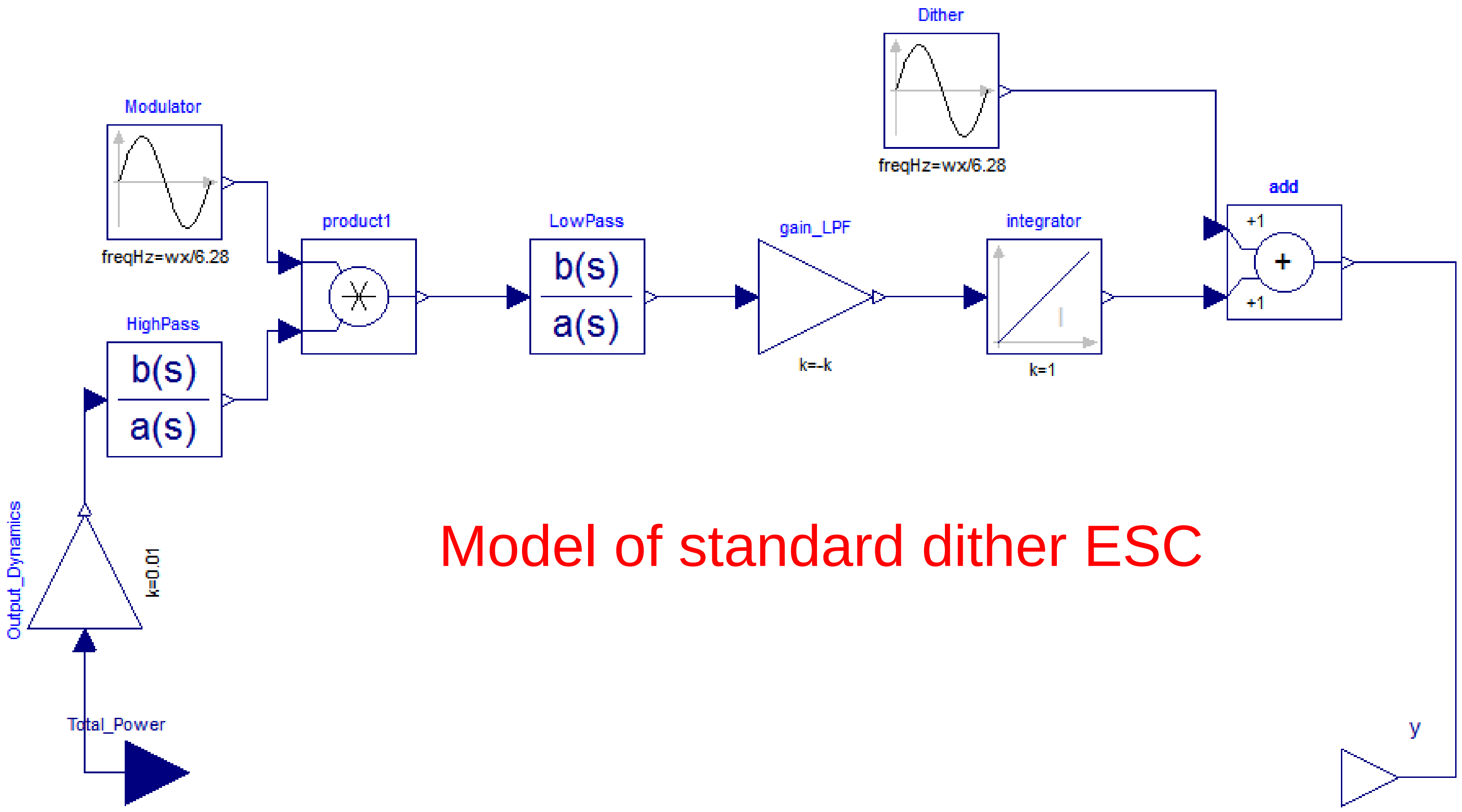
4. EXTREMUM SEEKING CONTROL

- The objective for ESC is to find the optimal input $u_{opt}(t)$ in real time for a generally unknown and/or time-varying performance function $f(t,u)$ with the online measurement of the objective value to be minimized.



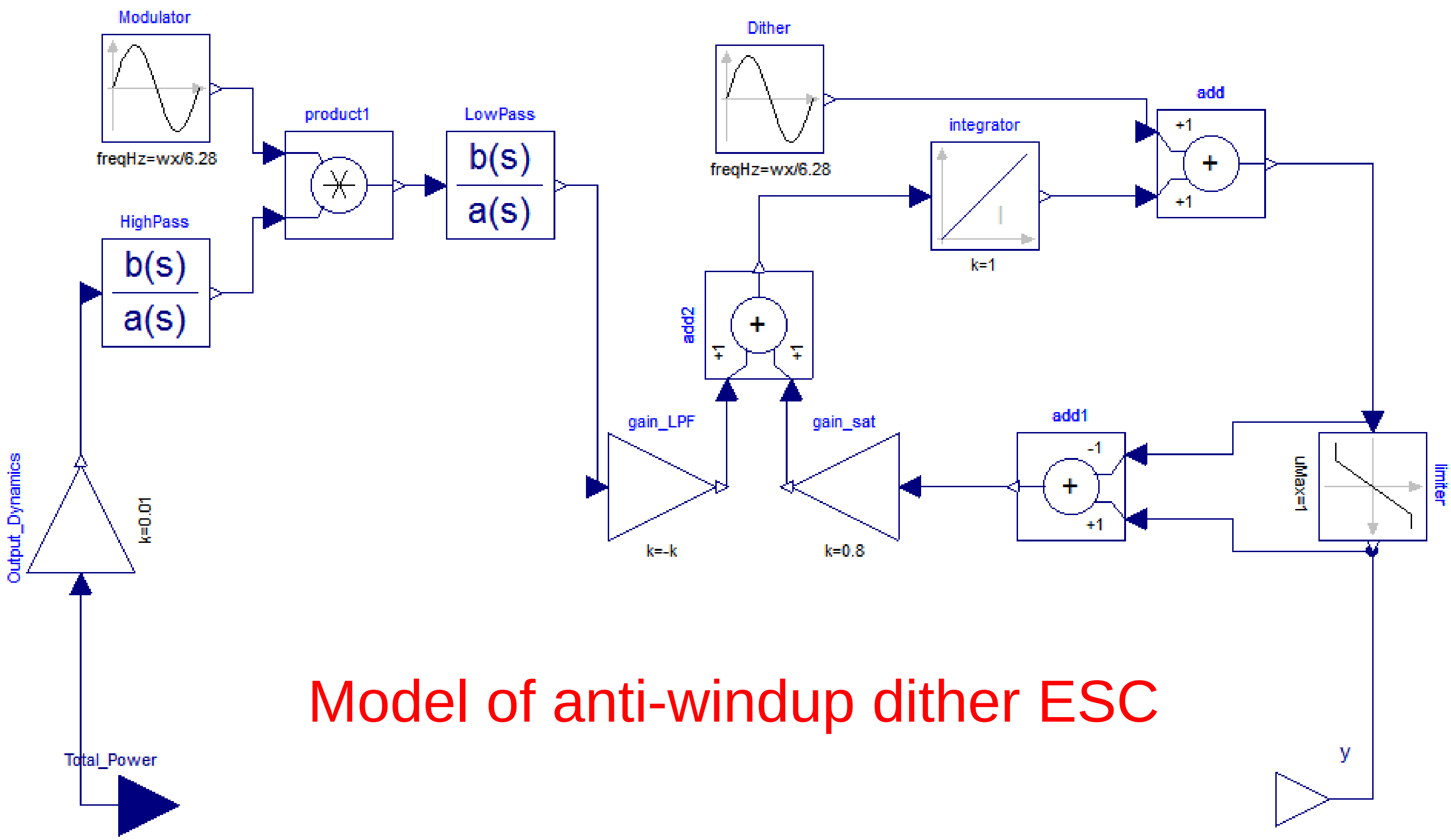
$$u_{opt}(t) = \arg\min f(t,u)$$

4. EXTREMUM SEEKING CONTROL



Model of standard dither ESC

4. EXTREMUM SEEKING CONTROL



Model of anti-windup dither ESC

5. SIMULATION AND DISCUSSION

- The building described by Chiasson, a generic office building located in Dallas for cooling-dominated applications is presented.
- The input dynamics is followed:

$$F_I(s) = \frac{5580 \cdot 0.001029^2}{s^2 + 2 \cdot 0.0179 \cdot 0.001029 \cdot s + 0.001029^2}$$

The cutoff frequency of the input dynamics ω_c is about 0.000827 rad/s. The dither frequency ω_{dis} selected as 0.0000628 rad/s. F_{HP}(s) and F_{LP}(s) are chosen as

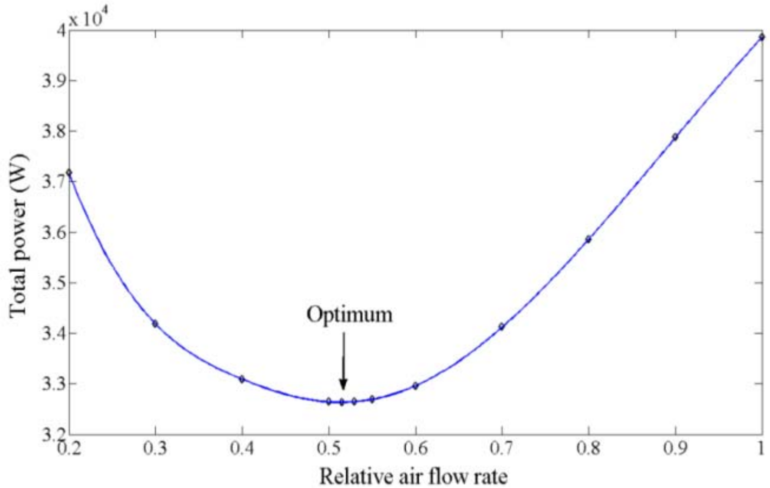
$$F_{HP}(s) = \frac{s^2}{s^2 + 2 \cdot 1.11 \cdot 0.0000314 \cdot s + 0.0000314^2}$$

$$F_{LP}(s) = \frac{0.0000314^2}{s^2 + 2 \cdot 1.11 \cdot 0.0000314 \cdot s + 0.0000314^2}$$

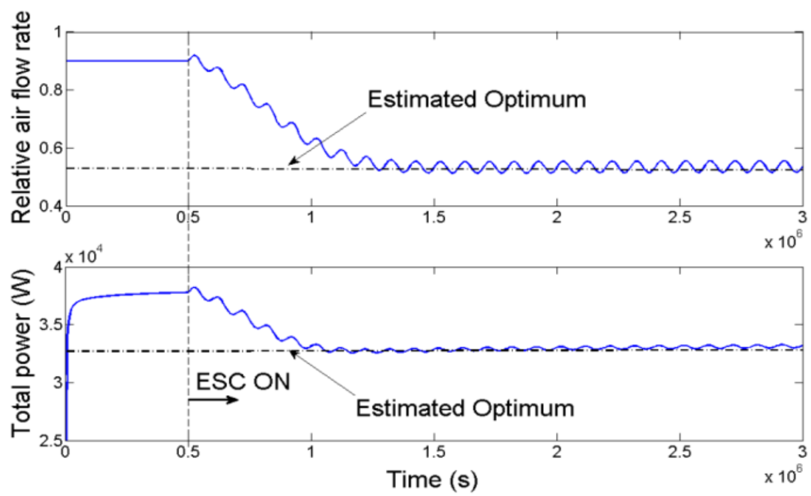
- The dither amplitude is selected as 0.02.

5. SIMULATION AND DISCUSSION

Static map under 80% cooling load



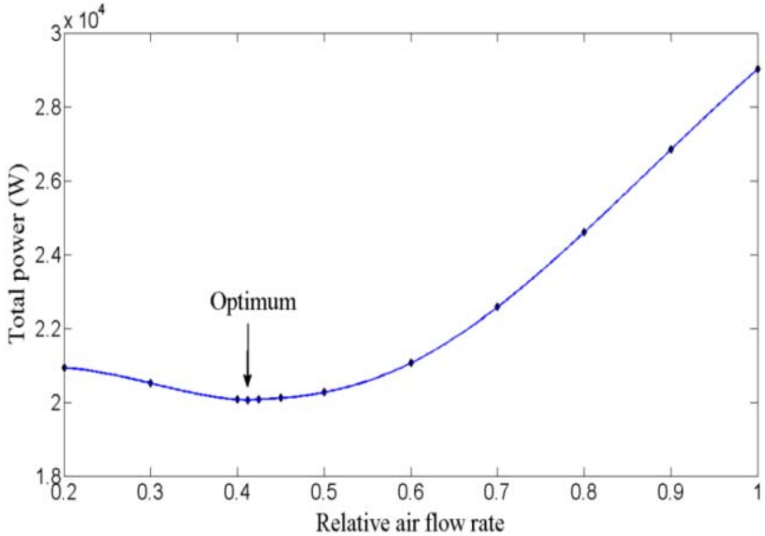
ESC simulation results for 80% cooling load



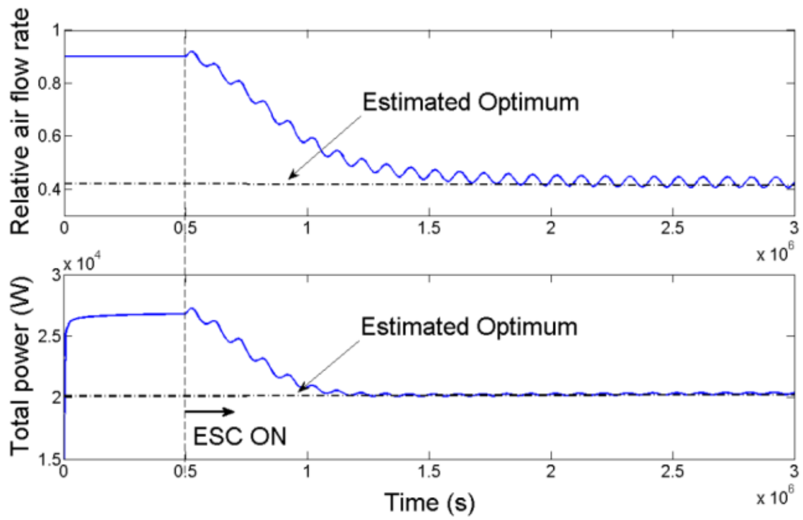
The ESC results are relative air flow rate of 0.53 and total power of 33.2kW. Compared to the static map, the steady-state error is about 3.1% and 1.5% for the relative air flow rate and the total power, respectively.

5. SIMULATION AND DISCUSSION

Static map under 50% cooling load



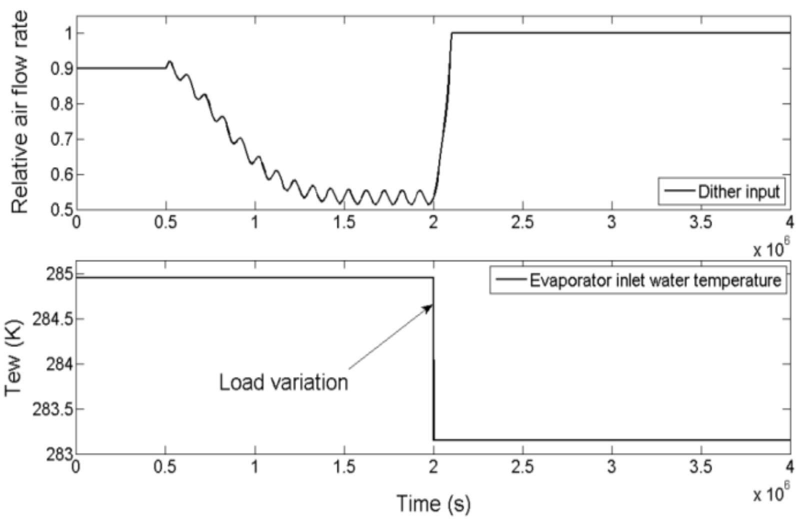
ESC simulation results for 50% cooling load



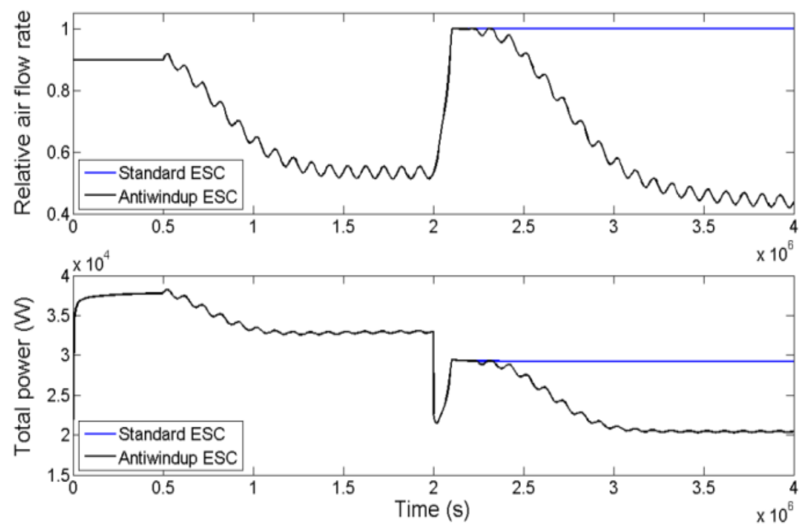
The ESC searched average steady-state relative air flow rate and the total power are about 0.425 and of 20.4kW, differing from the estimated optimum by only 2.9% and 1.6%, respectively. with power saving of 6.4kW (23.8%)

5. SIMULATION AND DISCUSSION

Standard ESC with actuator saturation



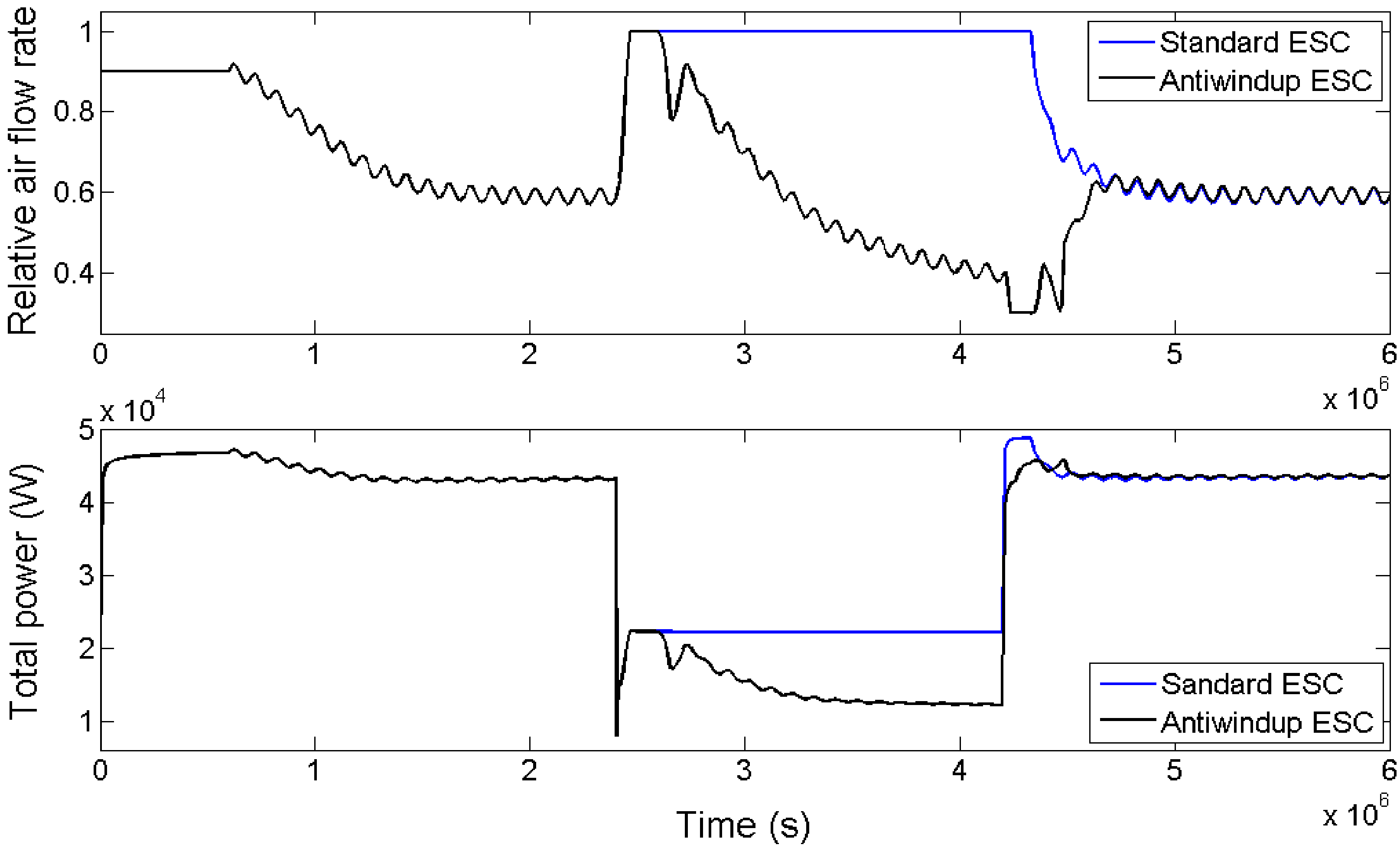
Anti-windup ESC with actuator saturation



Compared to standard ESC, the optimal searched relative air flow rate for anti-windup ESC is closed to static value. In this case, the system would consume 29.2kW, with power saving of 8.8kW (30.2%).

5. SIMULATION AND DISCUSSION

Comparison of standard and Anti-windup ESC

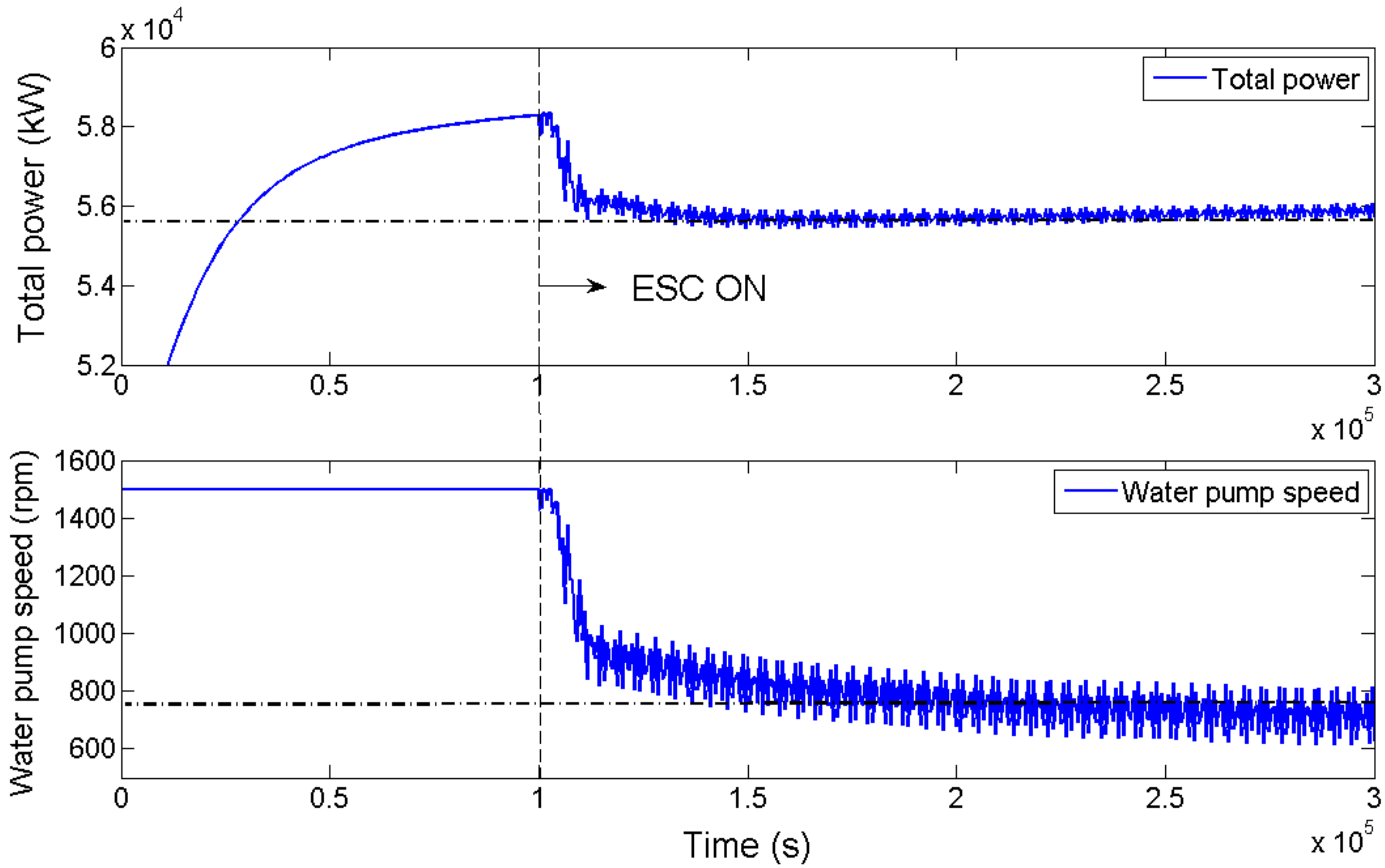


5. SIMULATION AND DISCUSSION

- The evaporator inlet water temperature is initially set at 286.15 K under full-load conditions. At 2,400,000 s, a ramp change is introduced to T_{EW}, bringing a decrease to 282.55K (25% load) in 60s. Then at 4,200,000 s, another 60s ramp change brings T_{EW} back to 286.15 K (full load).
- The simulation results show that the modified anti-windup ESC scheme could effectively solve the potential integral windup problem caused by system actuator saturation.

5. SIMULATION AND DISCUSSION

ESC with Water Flow Regulation



6. CONCLUSION & FUTURE WORK

- The proposed ESC is tested on a Modelica based dynamic simulation model of the hybrid GSHP system
- Transient heat conduction of vertical GHE is considered
- Simulation of fixed cooling load condition and varying cooling load conditions
- The power saving can be as large as 23.8% across the adjustable range of inputs
- Anti-windup ESC is validated by simulation under actuator saturation
- Work under way: ESC with both air and water flow control

Thank you for your attention !

Any Questions

The University of Texas at Dallas