

B01 — Data-center cooling system (staging)

FMU model and PLC guide · chiller + waterside economizer · chiller on/off staging

Version 2.0

Student exercise — Homa Virtual Plant (Model-in-the-Loop)

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Contents

1. Exercise objective

You are given an **FMU model** of a real data-center cooling system (chiller + waterside economizer) with **real hydraulics**. The task is, through **Homa Virtual Plant** to connect a PLC to the model and write a **PLC program that runs the whole process**.

This is a **Model-in-the-Loop (MIL)** setup: the model mimics the plant, and **all control, sequences, protections and fault detection are done by your PLC**. The model contains NO limits, alarms or switching logic — you design and implement all of that in the program, according to this functional description.

This variant (**B01 — staging**) controls the chiller via the signal `u_chiller_enable` (chiller staging (on/off)). There is also a related model: *B02 (continuous chiller-capacity control, `u_chiller` 0..1)* — the hydraulics and everything else are identical, only that one signal differs.

Important: the model provides only raw process values (flow, pressure, temperature...). All thresholds (e.g. minimum flow, maximum pressure), protections and interlocks **are defined by the programmer in the PLC**. An incorrect valve combination or operation without flow shows up in the model as physical behaviour (low flow, high pressure, rising temperature), and it is up to the PLC to recognize it.

2. Process description

The system cools the data-center IT equipment and is based on the example **Buildings.Examples.ChillerPlant** (LBNL). It consists of two water loops connected through the chiller and a free-cooling heat exchanger (WSE):

- **Chilled-water loop (CHW):** the CHW pump drives water that picks up the IT heat (`u_it_load`), and then passes in series through the WSE stage and the chiller stage, returning to the tank.
- **Condenser-water loop (CW):** the CW pump drives water through the cooling tower (cooling it toward the wet-bulb), and this cold water removes heat from the chiller condenser and/or the WSE.
- **Chiller** — mechanical cooling: the evaporator removes heat from the CHW, the condenser rejects it to the CW. Higher duty = higher consumption (`y_chiller_power`).
- **WSE (waterside economizer)** — “free cooling”: when the tower water is cold enough, the CHW is cooled directly through the exchanger, without the chiller. Its effectiveness (`y_wse_eps`) depends on the flow.
- **Cooling tower** — rejects heat to the environment; capacity rises with fan speed (`u_tower_fan`) and falls with a higher wet-bulb (`u_wet_bulb`).

Series (integrated) CHW-loop arrangement:

the chilled water flows **in series** through two stages (as in the LBNL original):

- **WSE stage:** after the IT load the water flows through `vWseCHW` → WSE exchanger or through `vEconByp` (`val1`) → WSE bypass.
- **Chiller stage:** then through `vChiCHW` → chiller (evaporator) or through `valByp` → chiller bypass, then back to the tank.

This way the WSE **pre-cools**, and the chiller **finish-cools the same stream** — so `y_chiller_power` actually drops when the WSE runs (a true integrated economizer). By combining the valves the water is routed through the chiller, the WSE or both — which selects the **three operating modes** (section 4).

HomaVP B01 — original scheme (LBNL Buildings ChillerPlant) with added FMU tags

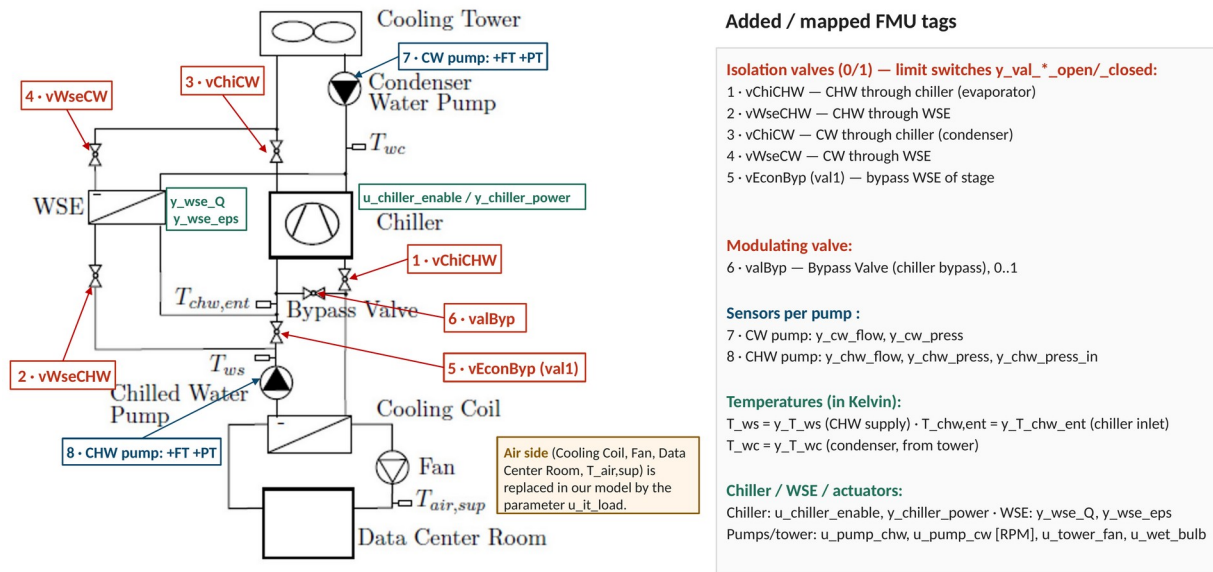


Figure 1. Process scheme of HomaVP B01 (based on the LBNL ChillerPlant). Red = valves (the PLC controls them via u_val_*), blue = per-pump sensors, teal = chiller/WSE.

New sensors (not on the original scheme): on **each pump** a flow and pressure sensor were added (y_chw_flow , y_chw_press , y_cw_flow , y_cw_press), and **limit switches** on every isolation valve (open/closed). These are key for the monitoring and fault detection you build in the PLC.

3. FMU interface — signals

Pay attention to the signal direction:

Signal direction: what is an **INPUT** for the FMU is an **OUTPUT** (command) for your PLC; what is an **OUTPUT** for the FMU, the PLC **reads** as a measurement.

Temperature units: all temperatures (y_T_ws , $y_T_chw_ent$, y_T_wc) are given by the model in **Kelvin [K]**. In the PLC convert to °C: $^{\circ}\text{C} = \text{K} - 273.15$. E.g. a supply target of 7 °C = 280.15 K. u_wet_bulb is an exception — it is set in °C.

3.1. FMU inputs

a) Actuators — controlled by your PLC (PLC outputs):

Variable (FMU)	Type	Unit	Range	Description
u_pump_chw	Real	RPM	0 – 1800	CHW (chilled-water) pump speed command
u_pump_cw	Real	RPM	0 – 1800	CW (condenser-water) pump speed command
$u_chiller_enable$	Real	–	0 / 1	Chiller enable (0 = off, 1 = on) — staging (on/off)
u_tower_fan	Real	–	0.0 – 1.0	Cooling-tower fan speed

Variable (FMU)	Type	Unit	Range	Description
u_val_chi_chw	Real	–	0 / 1	Isolation valve: CHW through chiller (evaporator)
u_val_wse_chw	Real	–	0 / 1	Isolation valve: CHW through WSE (exchanger)
u_val_econ_byp	Real	–	0 / 1	Isolation valve: WSE-stage bypass (val1)
u_val_chi_cw	Real	–	0 / 1	Isolation valve: CW through chiller (condenser)
u_val_wse_cw	Real	–	0 / 1	Isolation valve: CW through WSE
u_val_byp	Real	–	0.0 – 1.0	Modulating bypass around the chiller (CHW side)

b) Disturbances / scenario — the environment and operating conditions; set on the HMI, NOT controlled by the PLC:

Variable (FMU)	Type	Unit	Range	Description
u_it_load	Real	W	0 – 50000	IT-equipment heat load (heats the chilled water)
u_wet_bulb	Real	°C	~0 – 25	Wet-bulb temperature (input to the tower model)

3.2. FMU outputs (measurements the PLC reads)

Variable (FMU)	Type	Unit	Range	Description
y_chw_flow	Real	kg/s	~0 – 0.6	Chilled-water flow (after the CHW pump)
y_chw_press	Real	Pa	~1.0e5 – 2.2e5	Pressure on the discharge side of the CHW pump
y_chw_press_in	Real	Pa	~1.0e5 – 1.2e5	Pressure on the suction of the CHW pump
y_pump_chw_speed	Real	RPM	0 – 1800	Actual CHW pump speed
y_cw_flow	Real	kg/s	~0 – 0.6	Condenser-water flow (after the CW pump)
y_cw_press	Real	Pa	~1.0e5 – 2.2e5	Pressure on the discharge side of the CW pump
y_T_ws	Real	K	~278 – 295	Supply (mixed) CHW temperature from the tank — the main controlled variable
y_T_chw_ent	Real	K	~278 – 305	CHW temperature at the chiller-stage inlet (after WSE pre-cooling)
y_T_wc	Real	K	~276 – 300	Condenser-water temperature after the tower (cold supply)
y_chiller_power	Real	W	0 – ~4000	Chiller compressor electrical power
y_wse_Q	Real	W	0 – ~20000	WSE thermal duty (CHW → CW transfer)
y_wse_eps	Real	–	0 – 1	WSE effectiveness (decreases with flow)

Valves — position and limit switches (all 5 isolation valves have a finite travel; the switch is 1 when the valve is confirmed in its end position. valByp is modulating — it has only a position):

Valve	Position 0..1	Open 0/1	Closed 0/1
chiller CHW (vChiCHW)	y_val_chi_chw_pos	y_val_chi_chw_open	y_val_chi_chw_closed
WSE CHW (vWseCHW)	y_val_wse_chw_pos	y_val_wse_chw_open	y_val_wse_chw_closed
WSE bypass (vEconByp / val1)	y_val_econ_byp_pos	y_val_econ_byp_open	y_val_econ_byp_closed
chiller CW (vChiCW)	y_val_chi_cw_pos	y_val_chi_cw_open	y_val_chi_cw_closed
WSE CW (vWseCW)	y_val_wse_cw_pos	y_val_wse_cw_open	y_val_wse_cw_closed
chiller bypass (valByp)	y_val_byp_pos	— (modulating)	—

4. Operating modes and valve combinations

The process has **three cooling modes**, and the mode is selected **by the combination of valve positions and chiller control**. Your PLC must run this correctly:

Mode	vChiCHW	vWseCHW	vEconByp	vChiCW	vWseCW	valByp	u_chiller_enable	When it is used
Mechanical (chiller)	OPEN	closed	OPEN	OPEN	closed	modulates / 0	1	Warm; wet-bulb too high for free cooling. WSE bypassed.
Free (WSE)	closed	OPEN	closed	closed	OPEN	OPEN	0	Cold; T _{wc} sufficiently below the target — the chiller is not needed, the WSE cools alone.
Integrated	OPEN	OPEN	closed	OPEN	OPEN	modulates	1	Transitional; the WSE pre-cools, the chiller finish-cools the same stream to target.

Flow rule (series loop): in the **WSE stage** at least one path must always be open — vWseCHW OR vEconByp; in the **chiller stage** at least one — vChiCHW OR valByp. If both paths in a stage close, the CHW pump is left without an outlet (deadhead).

Key transition rules:

- The chiller (evaporator) requires **both CHW and CW flow**: in mechanical/integrated mode both vChiCHW and vChiCW must be open, and both pumps running. In the model a chiller without flow through both branches **physically does not cool** — so that is also a natural interlock.
- In free mode **disable the chiller** (u_chiller_enable=0) and bypass it (valByp open, vChiCHW closed); the WSE valves open, vEconByp closed. The WSE cools only if y_T_wc is sufficiently below y_T_chw_ent (otherwise y_wse_Q≈0).
- When switching modes **first open the new paths and confirm them with the limit switches, and only then close the old ones** — so a pump is never left without flow. valByp and vEconByp is used to secure flow during the transition.

5. What the PLC must achieve (control objectives)

Your PLC program must:

1. Hold the supply temperature y_T_ws around the target (e.g. 7–10 °C) with the lowest possible consumption.
2. Drive both pumps to the required flow and **monitor flow and pressure per pump** (min flow, max pressure).
3. Select the mode (mechanical / free / integrated) according to y_T_wc and u_wet_bulb ; use free/integrated cooling whenever possible.
4. Sequence the valves correctly with **monitoring of travel time and limit switches** (section 7).
5. Detect faults (section 6) and respond safely (alarm, stop the pump, close/open valves).
6. Avoid too-frequent chiller start/stop (anti-cycling, minimum times).

The objectives are given; **you design the control method yourself**.

6. Fault detection — recommended flow and pressure limits

The model reports no faults — **you build the limits and detection logic in the PLC**. Recommended procedure: in normal operation at the working pump speed, read the typical y_*_flow and y_*_press , then set the limits relative to those values (e.g. min flow = 30–40% of nominal).

Example limits (calibrate on your system): low flow < 0.15 kg/s while the pump runs; high pressure > $2.1 \cdot 10^5$ Pa (deadhead/blockage); low pressure < $1.1 \cdot 10^5$ Pa while the pump runs (rupture/trip); high flow > 0.6 kg/s (leak).

Fault	Symptom on the sensors	Recommended detection (logic)
Valve does not open (stuck)	Open command, but $_open$ stays 0; that branch flow low, pressure high	$_open \neq 1$ within travel time + margin → valve alarm
Valve does not close	Close command, but $_closed$ stays 0; flow runs through a branch that should be closed	$_closed \neq 1$ within travel time + margin → alarm
Deadhead (no outlet path)	Pump runs, but flow ~ 0 and pressure high	$y_flow < min_flow$ AND $y_press > max_press$ AND $speed > 0$
Pipe rupture / leak	Pressure low, flow unusually high, level dropping	$y_press < min_press$ AND $y_flow > max_flow$
Clogged pipe / dirty filter	Flow low with high pump pressure (partial deadhead)	$y_flow < min_flow$ AND $y_press > nominal$, at normal speed
Pump trip / fault	Speed command > 0, but actual speed/flow/pressure low	$u_pump > 0$ AND $y_pump_speed \ll command$ AND $y_flow < min_flow$

- **Combine conditions** (flow AND pressure AND valve/pump state) to distinguish similar faults — e.g. deadhead (both stage paths closed) from a blockage (partial).
- Use the **tank level / balance** and the trend (pressure drop + flow rise + level drop) as additional confirmation of a rupture.

7. Monitoring of valve travel time

The isolation valves have a **finite travel** — they do not open/close instantly. The PLC must track the time and the limit switches:

1. On every open/close command **start a timer** for that valve.
2. The valve must reach its end position within the allowed time: $y_val_open = 1$ (for opening) resp. $y_val_closed = 1$ (for closing), within $T_max = \text{travel time} + \text{margin}$.
3. If the switch does not arrive within $T_max \rightarrow$ **alarm “valve not responding”** and a safe response (e.g. stop the sequence, do not start the chiller, protect the pump).
4. In sequences **wait for the switch confirmation before the next step** — never assume the valve is already in position.

Travel time: in the model the travel time is a parameter (t_valve_iso, t_valve_mod). For faster testing it is set low (~5 s isolation, ~8 s modulating); **in reality it is 45–60 s (large valves up to 90–150 s)**. Align the T_max in the PLC with the value you use in the model.

8. Parameters the operator sets via the HMI

Recommended parameters and default values on your PLC HMI:

- **CHW supply temperature setpoint** (e.g. 7–10 °C) and the allowed band.
- **Free-cooling threshold:** the limit of y_T_wc / u_wet_bulb below which it switches to the WSE.
- **Protection limits:** min/max flow and pressure per loop (CHW and CW).
- **Maximum valve travel time** (T_max open/close) for fault annunciation.
- **Min flow and min pump speed** before starting the chiller; min chiller run/idle time (anti-cycling).
- **Operating conditions / scenario:** IT load (u_it_load) and wet-bulb (u_wet_bulb).
- **Mode selection** (auto/manual) and the thresholds for automatic switching.

9. What else to watch out for (interlocks and pitfalls)

- **The chiller starts only with flow:** do not enable $u_chiller_enable$ until y_chw_flow and y_cw_flow are above the minimum and the chiller valves are confirmed open.
- **Do not leave a pump in deadhead:** in each CHW-loop stage keep at least one path open; before closing all outlet valves, ramp down/stop the pump.
- **Transition sequencing:** open and confirm the new paths before closing the old ones.
- **The WSE makes sense only with a cold tower:** if y_T_wc is not below $y_T_chw_ent$, the WSE does not cool (or even heats) — then use the chiller.
- **Temperatures are in Kelvin** — convert to °C before comparing with setpoints.
- **Anti-cycling and staging:** avoid alternately starting the chiller around the threshold; use hysteresis and minimum times.

10. Suggested control structure (guideline)

Fast level (every cycle, ~1 s):

- Pump control: to the required flow / pressure (PI), with limit monitoring.
- Temperature control: according to y_T_ws drive $u_chiller_enable$ (chiller start/stop with hysteresis) and/or the tower fan u_tower_fan .

Slower level (staging / mode selection, 10–60 s):

- Mode selection according to y_T_wc and the load; valve sequences with switch confirmation; chiller anti-cycling.

Protection level (continuous):

- Fault detection (section 6), valve-travel-time monitoring (section 7), safe responses and alarms.

11. Recommended sample times

Layer	Recommended cycle
Control loops (pumps, temperature)	0.5 – 1 s
Valve monitoring / sequences	0.2 – 1 s
Mode selection / staging	10 – 60 s
FMU co-simulation communication step	~1 s

The model is configured for **StopTime 600 s** (Interval 1 s); this is only the final simulation time — in the closed loop the pace is driven by Homa VP, and the process runs to steady state.

12. Test scenarios and acceptance criteria

Scenario	How to trigger	Expected PLC behaviour	Pass criterion
Mechanical cooling	Pumps at working speed, chiller valves open, WSE bypassed ($u_chiller_enable$ active)	y_T_ws falls toward target, $y_chiller_power > 0$, $y_wse_Q \approx 0$	Temperature within band, flow/pressure within limits
Free cooling	WSE valves open, chiller bypassed ($valByp$ open, $u_chiller_enable = 0$), low u_wet_bulb	$y_wse_Q > 0$, y_T_ws falls without the chiller running	$y_chiller_power \approx 0$, target reached
Integrated mode	WSE in line + chiller running; watch $y_chiller_power$	WSE pre-cools → $y_chiller_power$ lower than in purely mechanical	Lower chiller power at the same target
Mode transition	Switch mechanical → free	Opens new paths and confirms with switches before closing the old ones	Pump always has flow; no deadhead
Valve not responding	Hold a valve command without switch confirmation (simulation)	Alarm after the travel time expires	Detection and safe response
IT-load step	u_it_load 10 → 40 kW	Increase cooling (capacity, pumps, tower)	y_T_ws returns to band
Deadhead test	Close all outlet CHW valves of one stage while the pump runs	Recognize low flow + high pressure, respond	Alarm; pump protected

General criteria: controlled variables within limits, correct mode selection, proper valve sequencing and reliable fault detection.

13. Integration into Homa Virtual Plant

1. Export the model as `DataCenterChillerStaging_600.fmu` (FMU 2.0, Co-Simulation) and load it into Homa VP.
2. Map the FMU variables: **actuators** (`u_*`) as PLC outputs, **measurements** (`y_*`) as inputs.
3. Disturbances (`u_it_load`, `u_wet_bulb`) are set on the HMI as operating conditions and tests.
4. Select a communication channel and run the closed loop (step ~1 s).

14. Notes on the model

Important: the model uses **reduced physics** (real hydraulics, but a simplified chiller/WSE/tower). The parameters are illustrative; the purpose is developing and testing PLC logic, not exact process analysis.

- **B01/B02 difference:** this is **B01 (staging)** — the chiller via `u_chiller_enable`. The related model is *B02 (continuous chiller-capacity control, `u_chiller` 0..1)*; the hydraulics and interface are otherwise identical.
- The model **does not simulate faults** nor does it contain limits/alarms — abnormal readings (deadhead, overheating) arise from the physics, and their interpretation is up to the PLC.
- Based on **Buildings.Examples.ChillerPlant** (the LBNL Modelica Buildings Library). The scheme is the original LBNL scheme, adapted to this model (per-pump sensors and valve limit switches added, FMU signal tags).
- Temperatures are in K; `y_wse_eps` and valve positions are dimensionless 0..1.