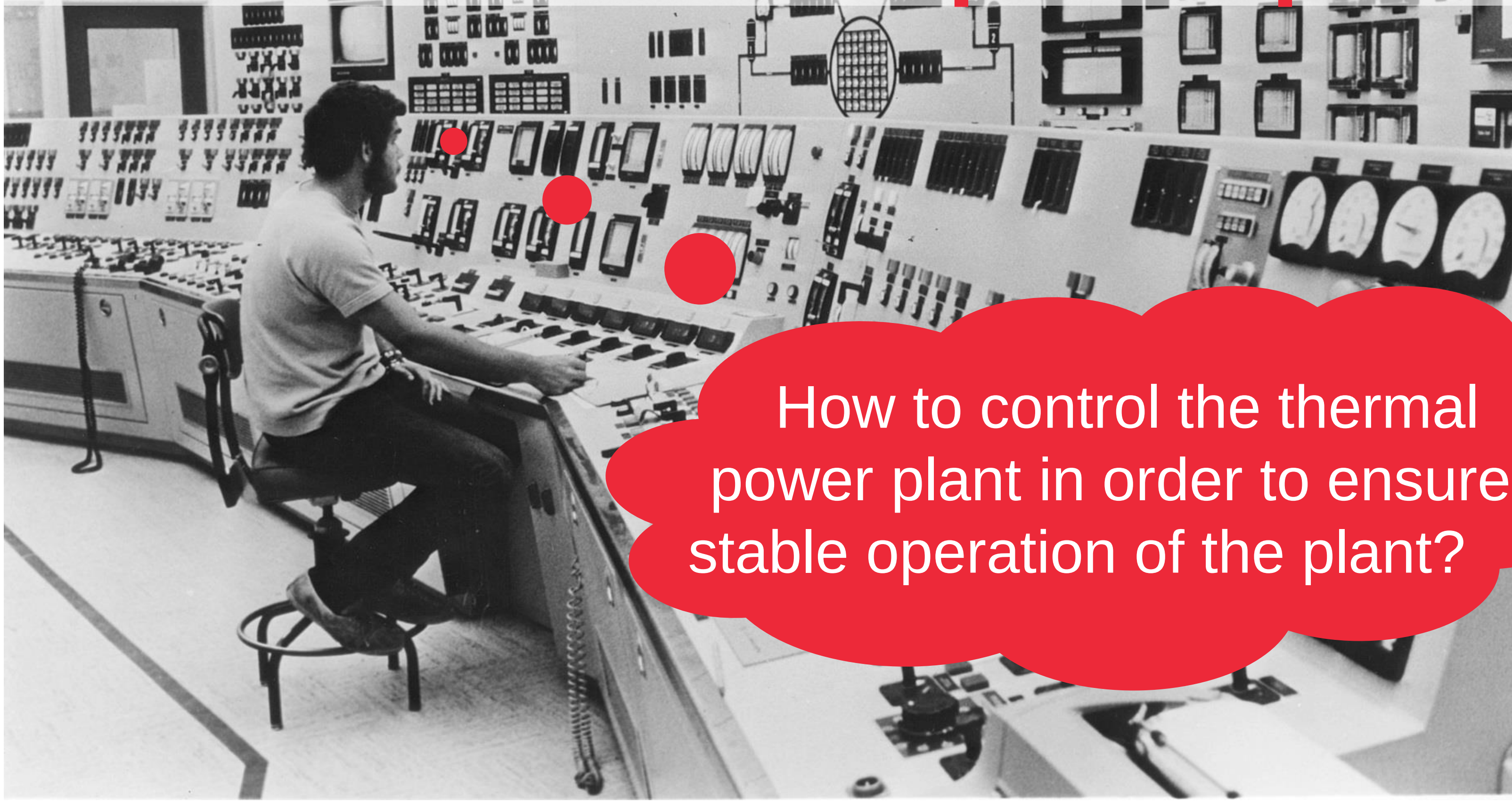
MS-E2132 Laboratory Assignments in Operations Research II

Assignment 2

Control of thermal power plant



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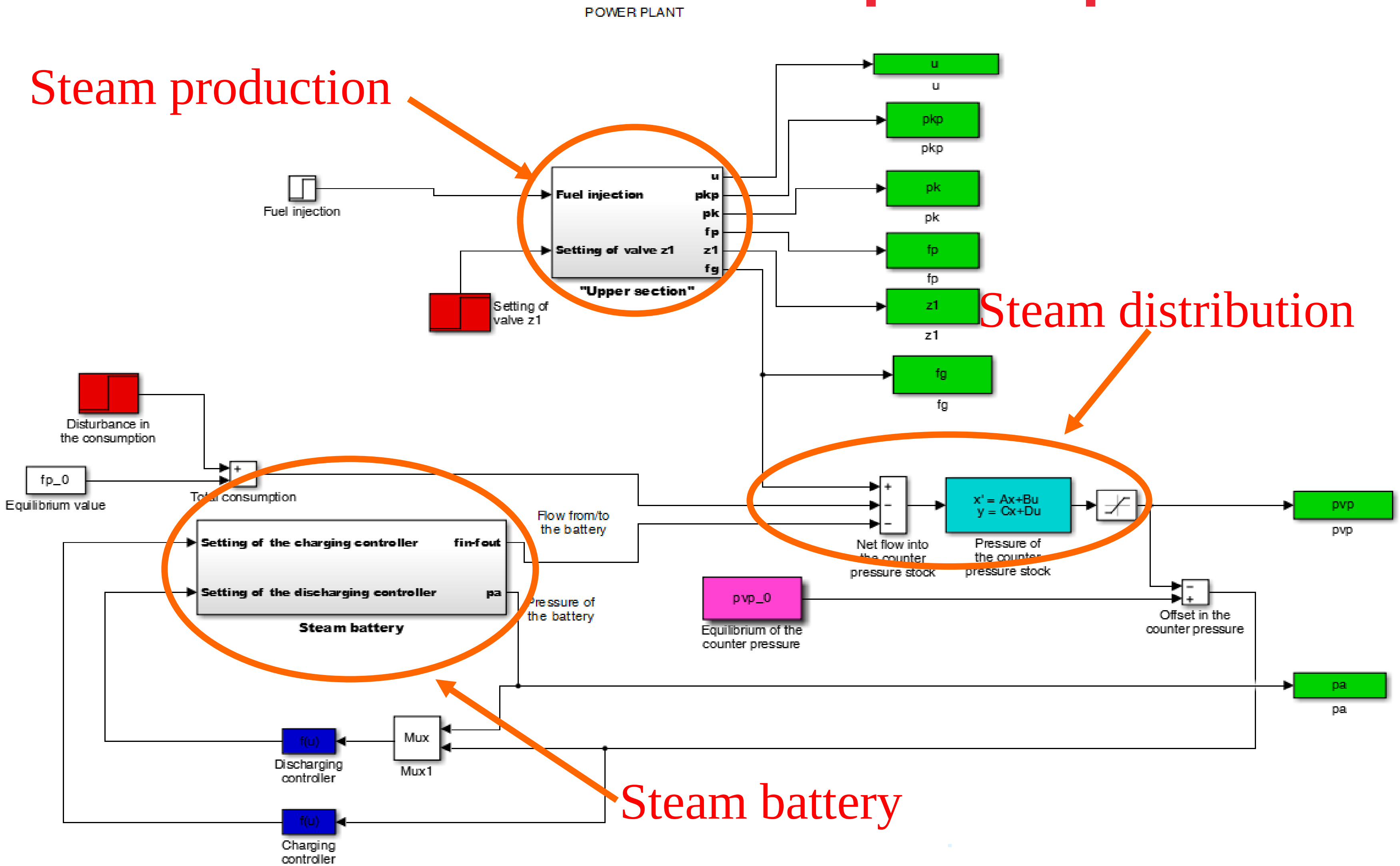
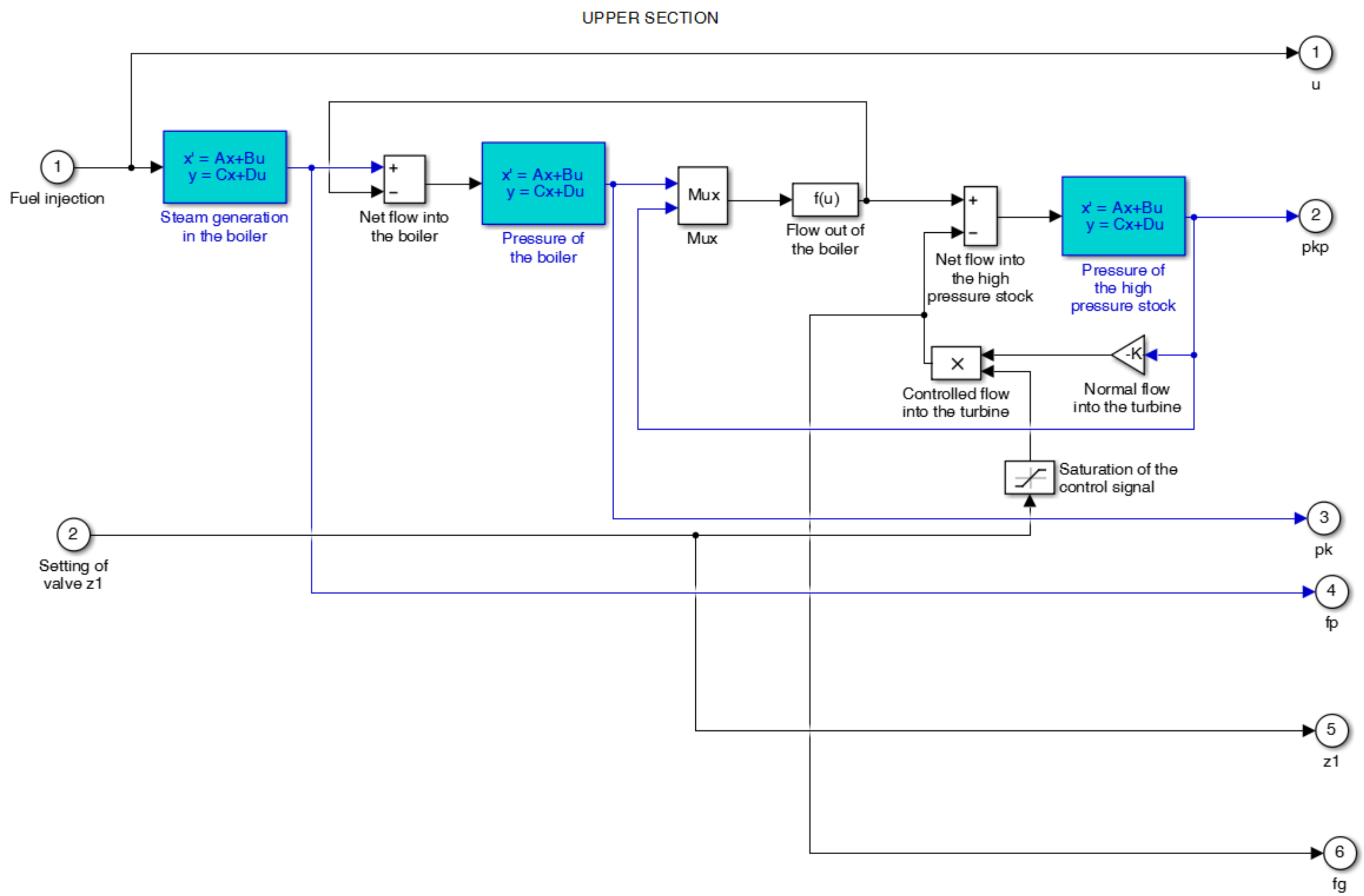
In the assignment…

- Production of steam in a thermal power plant is analyzed
  - Burning process of fuel => Steam generation in a boiler => Production of high pressure steam => (Turbine) => Distribution of counter pressure steam => Steam battery => Consumption of steam
  - Steam used by, e.g., a paper mill
- Steam production affected by ”disturbance”: Steam consumption (also steam flow through the turbine)
- Steam production stabilized by
  - Controlling fuel injection
  - Controlling steam flow through the turbine
  - Charging and discharging the steam battery
- PID controller and state feedback controller are used
- Three sections of the power plant
  1. Steam production; upper section of the plant
  2. Steam distribution; turbine flow & counter pressure stock
  3. Steam battery
- Analysis and control of a large scale system (in principle)

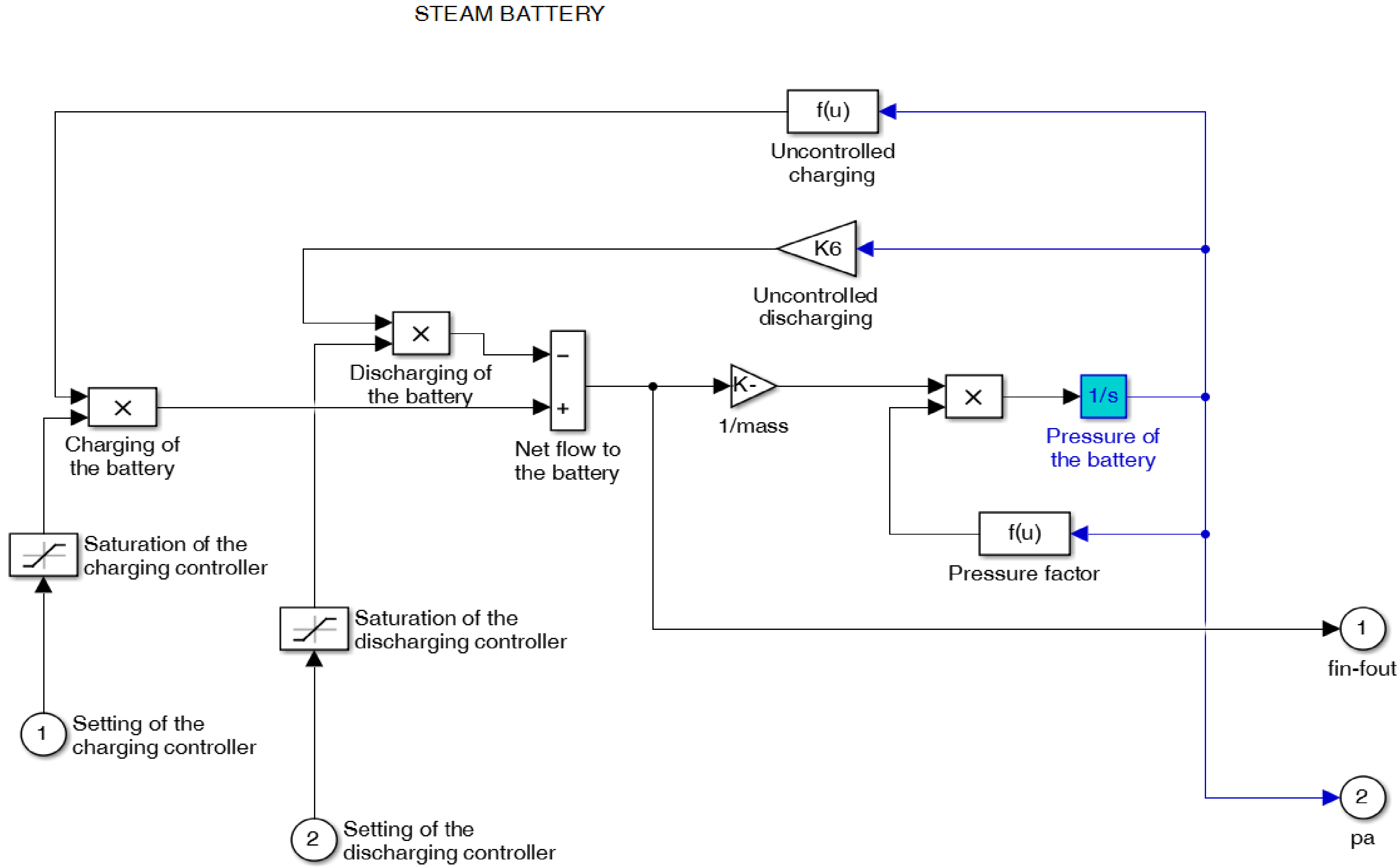
Simulink model of the power plant



Steam production (”upper section”)



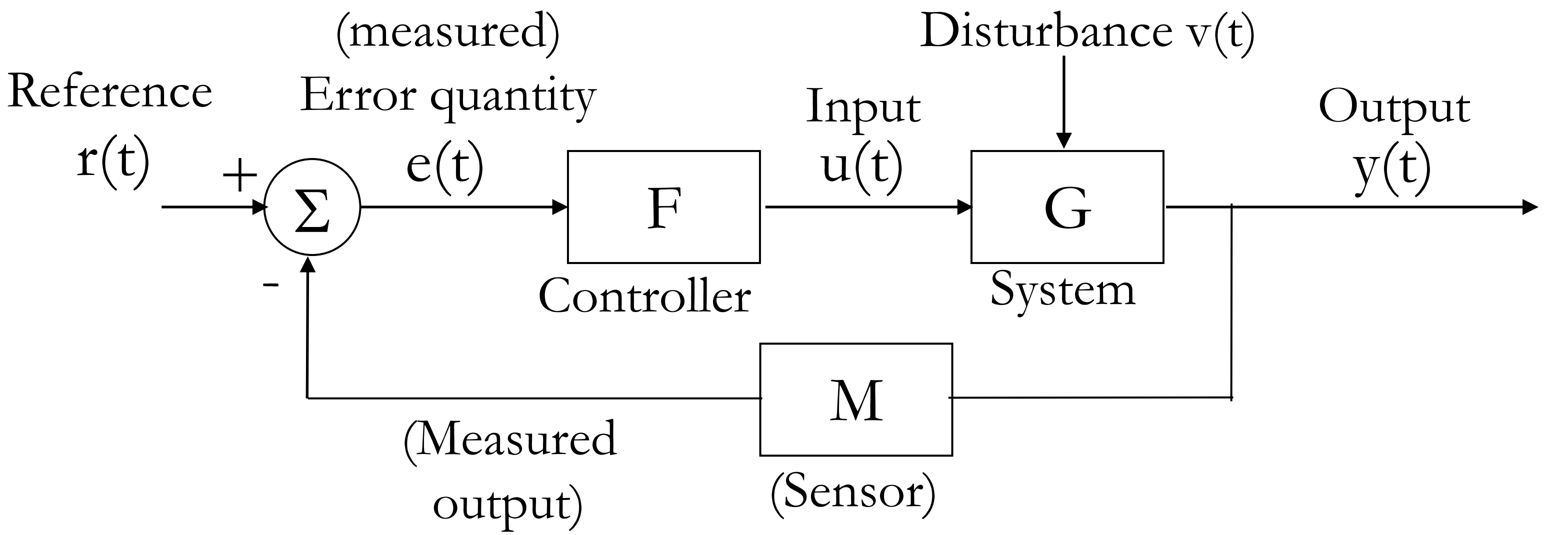
Steam battery



On control theory
(e.g., Åström & Murray, Chapter 1)

- Feedback:
  - The control (= the input) of a system depends on the output / the state of the system
- Basic problems:
  - Tracking: The output should follow the external reference signal as accurate as possible (focus is to compensate the dynamics of the system)
  - Stabilization: The output should be constant (focus is to compensate disturbances)
- The assignment deals with stabilization

Idea of feedback



- r(t) is the external reference signal
- Feedback from the output using the error quantity e(t)=r(t)-y(t)
  - e(t)=0 => OK! Otherwise: Adjust u(t) until e(t)=0
- Control problem: Construct the controller
  - Structure
  - Gains, i.e., parameters

PID-controller

(e.g., Åström & Murray, Chapter 10)

- P = Proportional, I = Integral, D = Derivative
  - P-term: The input depends on the current value of the error quantity
    - Insufficient for steady/constant disturbance
  - I-term: The input depends on the time integral of the error quantity
    - Destabilizes the system; relying on old information
  - D-term: The input depends on the time derivative of the error quantity
    - Stabilizes the system; issues on amplification of high frequency measurement or process noise
- Each term has a gain - tuning parameters K_P, K_I and K_D of the controller
  - Select the parameters in an appropriate way => Stability of the system

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{d}{dt} e(t)$$

State feedback controller

(e.g., Åström & Murray, Chapter 6)

- Linear dynamic system $dx/dt=Ax+Bu$
  - External reference signal = 0
  - Control the system such that $x = 0$
- Controls = Linear combinations of states: $u=-Kx$
  - Closed loop system: $dx/dt=(A-BK)x$
- System matrix of the closed loop system: $A-BK$
- The open loop system is controllable (see, e.g., Åström & Murray, Chapter 6) => Arbitrary dynamics for the closed loop system
- The problem: Select gain K
- The state feedback controller does not have necessarily integrating feature
  - Integration should be augmented if needed (step disturbances)

Optimal state feedback controller

(e.g., Kirk, Chapter 5.2)

- Select u such that the functional

$$J[u] = \frac{1}{2}\int_0^T x(t)^T R x(t) + u(t)^T Q u(t) dt + \frac{1}{2} x(T)^T P x(T)$$

is minimized (linear-quadratic (LQ) problem)

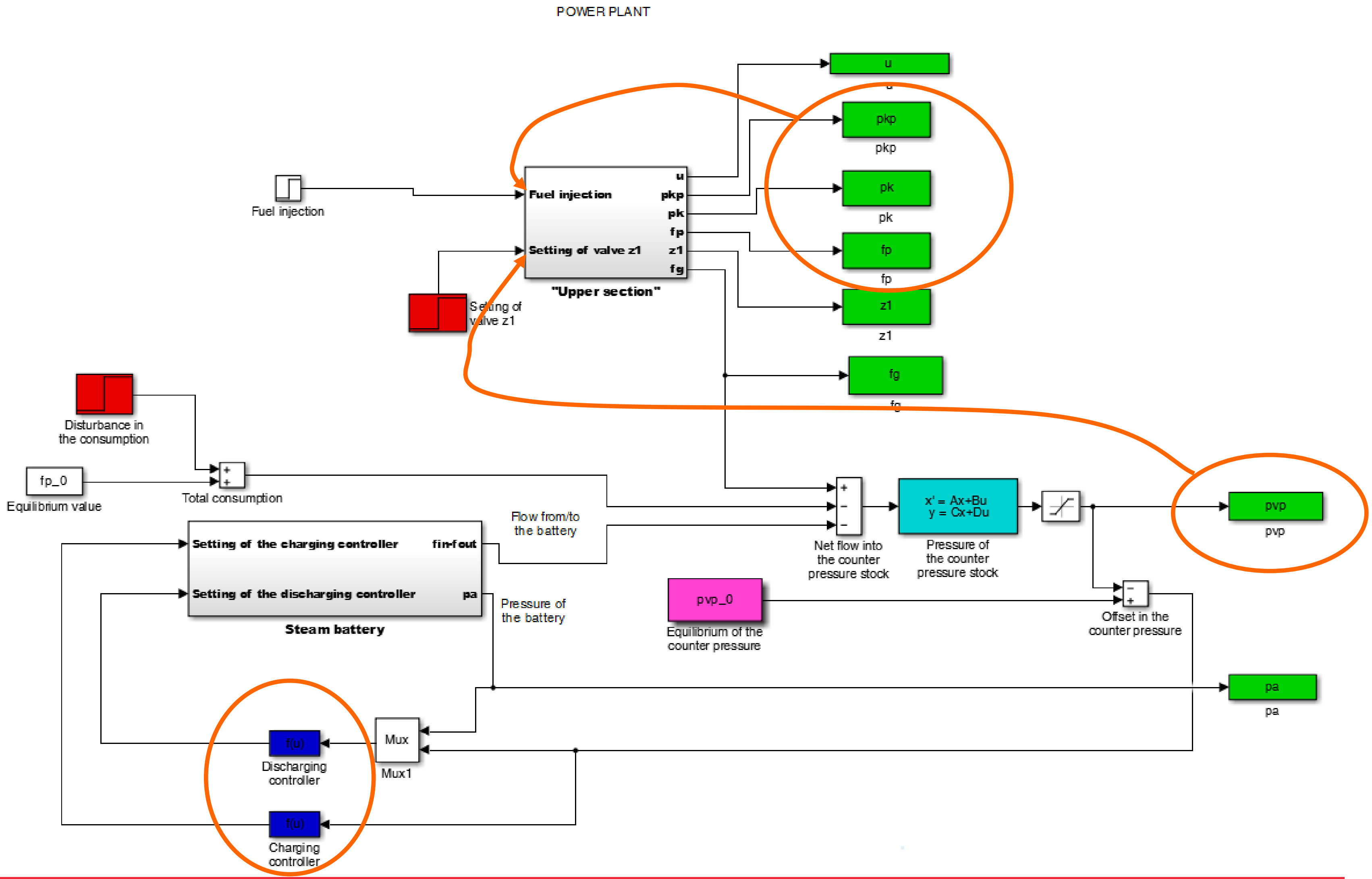
- Weights R => penalty related to large states, weights Q => penalty related to large controls, weights P => penalty related to large terminal states
- Feedback solution obtained by deriving and solving the necessary conditions for the optimal control
  - State equation, co-state equation, optimal control (see the material of the MS-E2148 course)

- Assume that the co-state is of form S(t)x(t)
=> Riccati equation for S
  - The optimal control is the time variant linear combination of the states: u*=-K*(t)x(t)

$\Rightarrow$ Solution: Integrate Riccati equation backward => S(t) => the optimal feedback gain K*(t) => Employ the control u(t)=-K*(t)x(t)

- S typically stabilized quickly => Time invariant (but suboptimal) gain K* obtained by solving algebraic Riccati equation (derivatives of S are set to be zeros)
  - (Matlab: lqr/lqr2)

Feedbacks in the assignment



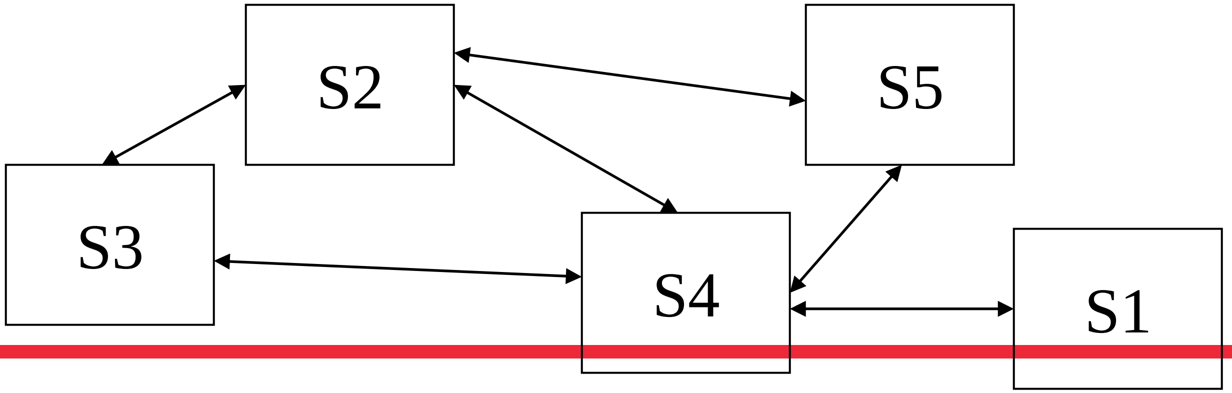
Linearization (e.g., Åström & Murray, Chapter 5.4)

- Controllers can be used (cautiously) with nonlinear systems
  - PID-controller can be tuned by using a real-life system – a system model is not needed but can be used
- Tuning of a State feedback controller – also PID if a model is used - requires a linear system model => Nonlinear systems must be linearized
- Nonlinear system $dx/dt=f(x(t),u(t))$, $y(t)=g(x(t),u(t))$
  - Analyze the stationary/equilibrium point (x_0,u_0) (and the corresponding y_0) and small differences $\Delta x=x-x_0$, $\Delta u=u-u_0$, $\Delta y=y-y_0$
  - It holds
    $d\Delta x(t)/dt= \partial f/\partial x \Delta x(t)+\partial f/\partial u \Delta u(t)$
    $\Delta y(t)=\partial g/\partial x \Delta x(t)+\partial g/\partial u \Delta u(t)$
  - Jacobians evaluated at (x_0,u_0,y_0)
- Note: Valid domain of linearization?

On large scale systems

- Large-scale system = System consists of several subsystems connected each other loosely
  - thousands of variables
  - analysis and synthesis using direct methods challenging or impossible
- ”Theory” of large-scale systems: Approaches, methods and techniques for tackling such systems
  - ”divide and conquer”
- Typical applications areas: optimization and simulation
- More esoteric themes dealing with large-scale systems:
  - decentralized control, coordination, autonomous agents, agent simulation, self-organization, artificial life,...

- Basic idea: subsystems treated separately by taking into account interactions and dependences between the subsystems
- Interactions and dependences treated in an iterative way
  - Subsystems treated with wrong (but hopefully converging) assumptions on interactions and dependences
- Typically two level algorithms
  - Upper level: Updating interactions and dependences with fixed subsystems
  - Lower level: Updating subsystems with fixed interactions and dependences



Structural versus mathematical large-scale system

- Often subsystems interacting identifiable wholes
  - For example, multi-part mechanical systems: Parts and subsystems interact through different articulations; interactions due to supporting forces
- ”Large-scale system” can also be originated from mathematical analysis
  - For example, discretization of a continuous time dynamic optimization problem: each discretization point depends only on proximate points – points far away from each other loosely coupled
- Regardless of origin of a large-scale system, mathematical description of the system has utilizable structure
  - For example, the Jacobian of the constraints of a discretized dynamic optimization almost block diagonal

Important solution paradigms

- Analysis of large-scale systems using decentralizing methods enables parallel and distributed computation
  – A single processor for each single subsystem (lower level)
  – One processor coordinates computation (upper level)

- Algorithms and data structures for sparse matrices
  – Decentralization on algorithm level

How do large-scale systems relate to the assingment?

- The thermal power plant is a large-scale system
  - Three subsystems connected each other loosely: Steam production, Steam distribution, Steam battery
- First: Each subsystem is tuned separately
- Second: Interactions between the subsystems are taken into account and the tuning is updated
- Iterative process

Comments / hints, Exercises 1-2

- Exercise 1:
  - Read the work instructions!
  - Familiarize yourself with the Simulink model of a power plant
  - The system is initially in a steady/equilibrium state – the steady state values of the variables are given in the work instructions
- Exercise 2:
  - Control variables of the upper section: fuel injection u, setting of the valve of the turbine flow z1
  - Turbine flow increases (=”disturbence”) => How much the setting of the valve change? => What happens to the pressure of the high pressure stock?

Comments / hints, Exercise 3

Exercise 3:

- Operation of the upper section of the plant is only analyzed!
- Offset of the pressure of the high pressure stock from the steady state pressure must be below 2%
- Rapid changes in the fuel injection is not preferable (such ”control” fuels are expensive)

  => Multiple objective optimization problem (stable pressure of the high pressure stock is more important!)
- ***Control of the fuel injection (u) using feedback from the pressure of the high pressure stock (pkp)***
- Modify the Simulink model
- Tune P-controller with the step response experiment (u=+1kg/s) => How the controller works when turbine flow is changed? => No good! => Tune PI => How it works? => Tune PID => How it works?
- Tuning of PID (e.g., Åström & Murray, Chapter 10)
- Maximum value of the derivative of the response using, e.g., difference approximation

Comments / hints, Exercise 4

- Exercise 4:
  - State feedback controller for the upper section
  - ***Control, i.e., the fuel injection (u) is the linear combination of the steam generation in the boiler (fp), the pressure of the boiler (pk) and the pressure of the high pressure stock (pkp)***
  - The model of the upper section must be linearized! A linear open loop system is controllable => arbitrary dynamics for the closed loop system => stabilization possible
  - Modify the simulink model
  - Tune the gains of the controller such that the eigenvalues of the system matrix of the closed loop system are on the left-half complex plane
  - Linear quadratic dynamic optimization problem => Riccati differential equation => algebraic Riccati equation (Matlab's functions lqr, lqr2)
  - Select the weight matrices of the criterion appropriately; compare different matrices; study eigenvalues of A-BK (should be on the left-half complex plane)
  - Other means for defining appropriate eigenvalues laborious!!!

Comments / hints, Exercises 5-6

- Exercise 5:
  - Issue on the state feedback controller – fixed offset in the output from the steady state output, cf. P-controller
  - Extend the system by taking into account a new state variable
  - Time derivative of the new state variable is the error quantity, i.e., the variable is the integral of the error quantity

$$\tilde{x} = \int_0^t (pkp_0 - pkp)\,dt \;\Rightarrow\; \dot{\tilde{x}} = pkp_0 - pkp$$

  - Tune the controller using the solution of the LQ problem – selection of the weight matrices of the criterion – comparisons
  - How the controller works?
- Exercise 6:
  - Compare and discuss the application of the PID-controller and the state feedback controller – Which one is better?
  - Go with PID

Comments / hints, Exercises 7-8

- Exercise 7:
  - The upper section of the plant works fantastically (after exercise 6)
  - Consumption flow of steam (=”disturbance”) suddenly changes => How does this affect the pressure of the counter pressure stock? (Should be within 10% of the equilibrium value)
- Exercise 8:
  - ***Control of the turbine flow (z1) using feedback from the pressure of the counter pressure stock (pvp)***
  - Modify the Simulink model
  - P, PI, I, ID, PID controllers – tune such that the counter pressure within acceptable limits, i.e., close to the equilibrium value
  - How different controllers work? Only experiments - e.g., tuning of the controllers based on the step response is not required!
  - Controls of the turbine flow and the fuel injection take care of low frequency and large amplitude disturbances in steam consumption

Comments / hints, Exercise 9

- Exercise 9:
  - The steam battery is included in the analysis
  - ***Control of the input and output flow of the steam battery (charge and discharge valves z2 and z3) using feedback from the pressure of the counter pressure stock (pvp)***
  - Ready made P-controllers in the Simulink model; saturation limits for Z2 and Z3 have so far been zero => modify them to appropriate values given in the work instructions
  - Find appropriate gains (Kin ja Kout) such that the controllers of the steam battery and the turbine flow provide jointly the good behaviour of the plant – try & test alternative disturbances in steam consumption
  - The steam battery takes care of large frequency disturbances in steam consumption => compensate sudden consumption changes => no variations in the fuel injection

Comments / hints, Exercise 10-11

- Exercise 10:
  - Adjust the gains of all the controllers such that
    - The counter pressure stays within the given limits
    - Fluctuations in the pressure of the high pressure stock as small as possible
    - Use of expensive ”control” fuel in the heating of the boiler minimized
  - Test the operation of the plant as a whole
  - Different step and ramp disturbances in the steam consumption – also frequency responses (high frequencies, low frequencies)
  - Give a general recommendation to the consumer of steam regarding
    - The amplitudes of disturbances allowed at high and low frequencies
    - The size of step disturbances allowed with the given limits of the counter pressure
- Exercise 11:
  - Write the report – see the work instructions

References

- Feedback Systems; Åström K.J. & Murray R.M., Princeton University Press, 2008
- Optimal Control Theory; Kirk D.E., Prentice-Hall, 2004