Automation of Energy Systems

(Modelling and Control of Energy Systems)

Alberto Leva

Academic year 2020/2021
Exam call of 29 June 2021

Family name ______________________

Given name(s) ______________________

Reg. code ______________________

Signature ______________________

- This booklet contains a total of **12 pages**, including this cover and the last page with the phase ruler to detach. **Check that the booklet is complete** and if this is not the case signal the problem immediately.
- **Fill in the space above with your personal data and signature; do this now, and in ink**. For the rest of the exam you can use a pencil.
- Answer the questions in the spaces provided, **following the instructions precisely** and writing legibly; **order and clarity are part of the evaluation**.
- During the exam **you are not allowed to consult books, notes or any other material**.
- **Hand in only this booklet**: nothing else will be accepted.
- The sections of the exam report **indicative** scores, so as to give an idea of their relative weights. Keep in mind that these are just indications, of course reliable but **not to be taken as rigid constraints**. Scoring is done considering the exam as a whole.

Foreword — read carefully

If you are taking Automation of Energy Systems (hereinafter AES) as a standalone exam, you must answer all the questions in the booklet.

If you are taking this test as part of the Modelling and Control of Energy Systems (hereinafter MCES) exam, you must **NOT** answer the questions marked with **"AES only"**.

If taking MCES, do not answer "AES only" questions in an attempt to compensate for other possibly missing ones: **no additional marks will be awarded** for that.

---

1 Multiple choice questions

This section is made of 30 questions for AES, 20 for MCES; only one of the proposed answers is correct. The total value of the section is **15 points**:

- each correct answer adds 0.5 points for AES, 0.75 for MCES,
- each incorrect answer subtracts 0.25 points for AES, 0.375 for MCES,
- answers not given have no effect.

Warning: answers must be provided by ticking the boxes on page 6, **not in the body of the questions**.

1 For "generator control" we mean

a. operating the generator as near as possible to its optimal efficiency condition, compatibly with the constraints in force.
?
b. switching the generator on and off timely with respect to the power generation plan.
c. coordinating the pool of generators that feed a particular utiliser, or set of utilisers.

2 For "generator mix control" we mean

a. distributing generation so as to be maximally efficient while properly fulfilling the demand.
b. blending the power from the active generation without provoking congestion.
c. activating generators according to an optimal sequence determined via some cost function minimisation.

3 A typical use of cascade controls in thermal energy systems is

a. to prevent pressure drops in a thermovector fluid supply from affecting utilisers in the short run.
b. to compensate for slow environmental disturbances on centralised heaters/chillers.
c. to reduce control efforts in multivariable cases with significant loop interaction.

4 An aspect to consider for the installation and maintenance of a cascade control structure is

a. the presence of an additional sensor with respect to a single loop.
b. the increased computational load for the host computing architem[fraction=-30] cture.
c. the necessity of autotuning capability for the inner loop.

5 A frequent goal of control with decoupling in thermal systems is

a. to prevent energy waste due to thermal zone interaction.
b. to equalise the energy expenditure of all the controllers.
c. to stabilise the system.

6 The scheme in which several actuators are used in sequence, each one starting to act when the previous one has reached its limit, is called

a. daisy chain.
b. split range.
c. cascade.

7 The scheme in which a single control signal activates one out of a set of actuators depending on its value, is called

a. split range.
b. time division output.
c. decoupling.

8 A generator can feed power to an AC grid through

a. an alternator or an inverter.
b. a turbine.
c. one or two wires.

9 In an electric generator, the presence of a rotating mass

a. inherently couples frequency and power.
b. makes it impossible to have any storage, even minimum.
c. requires kinetic energy level control.

10 A major impact of distributed generation in AC grids is

? **a.** to question the assumption of few "large" generators versus many "small" loads.
b. to increase the variability of loads over time.
c. to produce generation optimisation problem of larger dimension.

11 In classical approaches to the management of AC grids

a. control is exerted by generators and loads are viewed as disturbances.
b. control is exerted by loads while generators provide a base level of power.
c. loads and generators continuously exchange information to adapt the control policy.

12 The generator cost models used in the optimisation of generation distribution are

a. polynomial, most typically of the third order.
b. linear with an offset due to maintenance costs.
c. quadratic.

13 The "fuel to power ratio" function for a generator is

a. the power consumed as fuel over the generated power over.
b. the generated power over the power consumed as fuel.
c. the generated power over the lost power.

14 Concerning the load flow problem, a network is organised into generator busses, load busses and

- **a.** one slack bus.
- **b.** as many slack busses as there are external connections.
- **c.** control busses.

15 In a load flow problem, a load bus is also termed "PQ" bus because

- **a.** its active and reactive power are considered known.
- **b.** its admittance (hence power once the voltage is computed) is known.
- **c.** it takes either active or reactive power, not both.

16 A major goal of energy management in thermal systems for residential installations is

- **a.** to guarantee comfort with minimum expenditure.
- **b.** to keep strict temperature set points.
- **c.** to decide when heating or cooling is in order.

17 A relevant source of disturbances for ambient condition control in HVAC is connected with

?

- **a.** the necessity of air renovation.
- **b.** the presence of obstructions in air ducts.
- **c.** the variability of damper characteristics.

18 To optimise the use of differently energy-efficient actuators, a sensible strategy is

- **a.** based on a convenient daisy chaining.
- **b.** to set up a cascade control with an inner loop per actuator.
- **c.** to find an optimal distribution of the control actions among all the actuators.

19 The primary goal of a heat network is

- **a.** to centralise heat generation to the advantage of overall efficiency.
- **b.** to decouple thermal utilisers from one another.
- **c.** to distribute the burden of fulfilling the total thermal energy demand.

20 The main piping configurations for a heat network are

- **a.** ring and twin pipe.
- **b.** ring and star.
- **c.** star and tree.

21 **AES only.** A Smith predictor is advisable

- **a.** in the presence of a delay large enough to make response speed requirements not attainable.
- **b.** every time the controlled dynamics exhibits a delay.
- **c.** when the delay contained in the controlled process is significantly larger than the sampling time.

22 **AES only.** The main difference between daisy chain and split range actuation

- **a.** is that in daisy chain the "preceding" actuator stays on when the "following" is activated, while in split range just one is active.
- **b.** resides in fact not in the schemes themselves, but rather in the different way possible discrepancies in the actuator dynamics are addressed.
- **c.** does not exist: the schemes are in fact the same, the only point is that split range just concerns two actuators while in daisy chain there can be any number.

23 **AES only.** The power response of a thermoelectric generator to a throttling valve step

a. is practically instantaneous but then decays unless energy (pressure) is restored.
b. is practically instantaneous and then sustained.
c. cannot be instantaneous owing to the boiler dynamics.

24 **AES only.** The power response of a thermoelectric generator to a combustion power step

a. is in general dominantly first- or second-order as the boiler dynamics need traversing.
b. is practically instantaneous but then decays unless the throttling valve intervenes.
c. is the slowest possible.

25 **AES only.** In the management of AC grids, problems can be broadly classified into

a. "power/cost" and "energy quality" control.
b. primary and secondary control.
c. islanded and networked control.

26 **AES only.** In power control, two frequently conflicting objectives are

a. minimising costs/emissions globally versus maximising sold power for some generator pool.
b. achieving zero frequency error versus balancing generated and consumed power.
c. rejecting load disturbances versus keeping frequency as constant as possible.

27 **AES only.** The core of the generation optimisation problem is

a. determining the optimal distribution given the set of active generators.
b. determining in advance which generators to activate.
c. deciding which generators will be allowed to operate far from their optimal condition.

28 **AES only.** The result of generation optimisation is

a. a set of power request to be fed to the generators as tertiary control.
b. a set of coefficients to distribute the required total secondary control action.
c. a set of parameters for re-tuning the primary controllers and sometimes the secondary one.

29 **AES only.** When acting on a thermal system via two actuators (e.g., heater and cooler) the most energy-efficient strategy is

a. to employ two loops, one per actuator, exploiting controller saturation.
b. to set up a cascade control to equalise the actuator dynamics.
c. to use the two in a split range configuration with a wide dead zone.

30 **AES only.** In a ring heat network, temperature drops

a. are scattered along the entire piping.
b. are concentrated in the return line.
c. are inversely proportional to the load.

Answers to the multiple choice questions

	a	b	c		a	b	c	AES only	a	b	c
1				11				21			
2				12				22			
3				13				23			
4				14				24			
5				15				25			
6				16				26			
7				17				27			
8				18				28			
9				19				29			
10				20				30			

2 Open questions

The total **indicative** value of this section is **6 points**; partial values – indicative as well – are shown question by question.

?

Question 1 (AES 2 points, MCES 3 points)

List and synthetically describe the major use(s) of feedforward compensation in the context of energy systems.

Feed foreward compensation consists in the tuning of a control block $C_f(s)$ which take as input a measured disturbance (first cons, you need additional sensors) and compensate its effect on the controlled variable inverting the dynamic Y/d.
This can be used whenever we have a measurable disturbance.
Intuitively we can use it maybe in case of power disturbance on an electric Grid control or a pressure drop measurable on a Thermal system (if unmeas. usually we use cascade control).

Question 2 (AES 2 points, MCES 3 points)

Briefly comment on relative advantages and disadvantages of the "boiler follows" and the "turbine follows" policies for the control of thermoelectric generators.

boiler/turbine follows are two policies that depends on the coupling of control/controlled variable used.

- In "boiler follow" we use ϑ_t (trottling value) to control Pm (mech power) while ϑ_f (fuel value) to control em (internal energy ≃ related to pressure)
In this way we have almost an istantaneus response on power request in fact ϑ_t act directly on altenator using stored energy (if present)
BUT a long transient pressure, that can wear by mechanical stress reducing lifetime
- In "turbine follow" instead ϑ_t control em, ϑ_f for Pm. This cause a slow power responce respect load request (cons) but a perfect pressure control on the system, so reduce stress

Question 3 (2 points) — AES only

Illustrate how an on-off actuator can be made to behave (almost) equivalently to a modulating one.

sometimes is better to use an actuator exploiting its full power because it can be less efficent if modulated! => so we wanna achieve modulating actuation using an ON/OFF strategy, This can be done using a Time-division Output approach of actuation:
we define a small actuation interval Ta respect the process dyn. Use Ta as sampling time for digital control and on Ta mantain actuator on for a certain interval of Ta, off for the other, $u \in [0,1]$ define a duty cycle activation.

so you see an average effect of your on/off actuation

3 Exercises

The total **indicative** value of this section is **12 points**; partial values – indicative as well – are shown exercise by exercise.

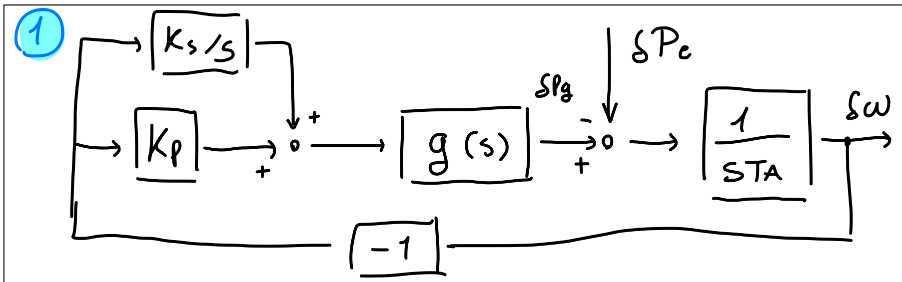
Exercise 1 (AES 5 points, MCES 12 points)

An islanded AC electric generator at frequency $f_o = 50Hz$ has nominal power $P_n = 50MW$ and a second-order dynamics, with time constants $\tau_1 = 20s$ and $\tau_2 = 5s$. Missing datum given during the exam: the total inertia produces an equivalent time constant T_A of $30s$.

1. Draw a block diagram representing the islanded AC systems with power and frequency control in primary plus secondary form, assuming the former and the latter to be purely proportional and integral, respectively.

2. Determine the primary and the secondary gain for a the closed-loop step response settling time t_a of $250s$ and a phase margin φ_m of $45°$; report the obtained open-loop frequency response magnitude, as well as the computations related to response speed and stability degree, on the semilogarithmic sheet of page 9.

1



with $g(s) = \dfrac{1}{(1+20s)(1+5s)}$

K_p, K_s primary, secondary gain to be tuned

(P_m is already included on T_A)

2 $t_{set} \simeq 250s \rightarrow \omega_c \simeq \dfrac{1}{t_{set}/5} \simeq 0.02\,rad/s$ $\qquad \varphi_m \simeq 45°$

we proceed working on semilog paper by loop shaping

computed phase loss on Bode

$\varphi_z = 45° + 21,5 + 5,5 \cong 72°$ of gain, let's put it in $0,006$ gaining $\simeq 74°$

$1/T = 0,006 \rightarrow T \cong 166$

$\tilde{\omega} \simeq 0,015 \rightarrow \mu = 0,000225$ openloop gain

so:

$$K \frac{\cancel{1+sT}}{\cancel{s}} \frac{1}{(1+\cancel{20s})(\cancel{1+5s})} \frac{1}{\cancel{s}T_A} = \mu \frac{1+\cancel{166s}}{(1+\cancel{20s})(\cancel{1+5s})\,s^{\cancel{2}}} \rightsquigarrow K = \mu T_A = 0,00675$$

in my formulation

$$C(s) = K_p + \frac{K_s}{s} = K_s \frac{1+(K_p/K_s)s}{s} \Rightarrow \begin{cases} K_s = 0,00675 \\ K_p = K_s T = 1,1205 \end{cases}$$

Exercise 2 (7 points) — AES only

Consider a thermal system in which a mass $M = 80kg$ of specific heat $c = 1.05kJ/kgK$ is connected to a heater with maximum power $P_{h,max} = 2kW$ and a first-order dynamics with time constant $\tau_h = 2min$; the mass disperses heat toward an exogenous ambient temperature T_a through a surface $S = 20m^2$ with a transfer coefficient $\gamma = 15W/m^2K$.

1. Draw an electric equivalent for the system.

2. Draw and tune a cascade scheme with two PI controllers to regulate the temperature T of the mass acting on the heater command – in the range $[0, 1]$ – having the heater power P_h as the inner variable; assume that the inner (closed) loop cannot achieve a response speed greater than twice that of the heater, so aim for that maximum and for a one-decade band separation between inner and outer loop is required. Once the scheme is tuned, provide an estimate of the temperature loop settling time.

$C = cM = 84\ kJ/K$

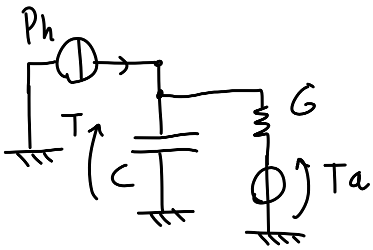
$\tau_H = 120 sec$

$A_H = \frac{2000}{1+120s}$

$G = S\gamma = 300\ W/K$

1 from system dynamic description

$C\dot{T} = P_h - G(T - T_a)$ electric equivalent



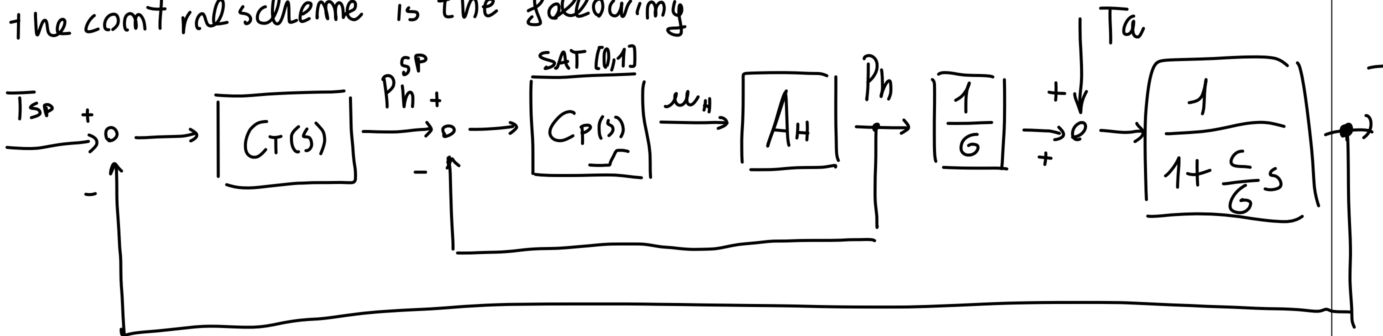
$CTs = P_h - GT + GT_a$

$T(s) = \frac{P_h}{G(1+\frac{C}{G}s)} + \frac{T_a}{(1+\frac{C}{G}s)}$

2 cascade scheme PI

$\tau_{in} \le \frac{1}{2}\tau_H$

the control scheme is the following



we achieve to a $\tau_{IN} = \frac{1}{2}\tau_H = 60 sec \Rightarrow$ so we want $\omega_{cIN} \cong 0{,}01\bar{6} \simeq 0{,}016\ \frac{rad}{s}$

while $\omega_{cOUT} = \frac{1}{10}\omega_{cIN} = 0{,}0016$

tuning $C_P(s)$ on $A_H(s)$ IF we wanna achieve an $L(s) = \frac{1}{60s}$

we set $C_P(s) = \frac{L(s)}{A_H(s)} = \frac{1+120s}{120000s} = \frac{1}{120000}\frac{1+120s}{s}$ (PI)

while we can set up the outer loop consider as first approx

$C_P A_H$ closed loop $\simeq 1$

and so tune $C_T(s)$ on $\frac{1}{G}\cdot\frac{1}{1+\frac{C}{G}s} = \frac{1}{300}\frac{1}{1+280s} = P(s)$

objective $L(s) = \frac{1}{600s} \rightarrow C_T(s) = \frac{L}{P} = 0{,}50\ \frac{1+280s}{s}$ PI

If we wanna be more accurate on the tuning of G_T we should consider as process to control

$$P(s)\cdot\frac{1}{1+120s} = \frac{1}{300(1+120s)(1+280s)}$$

so we must approx the dym. leading to:

$$C_P(s) = \frac{L(s)}{P(s)} = \frac{1}{600s}\cdot 300\,(1+\cancel{120s})(1+280s) \simeq \frac{0{,}5}{s}(1+280s)$$

and because $\frac{1}{120} > \frac{1}{600}$ we should neglect it!

same result!

overall the system is characterized by a loop settling time T given by outer loop time constant

$$\downarrow \quad \omega_{cOUT} \simeq \frac{1}{600} \rightarrow \tau_T = \frac{1}{\omega_{cOUT}} = 600s$$

$$t_{set_T} = 5\tau_T = 50\,\text{min}$$