Automation of Energy Systems

(Modelling and Control of Energy Systems)

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Exam call of 22 July 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 answers: **no marks will be awarded** for that.

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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 "primary" energy we mean in general

a. energy devoted to uses that cannot be discontinued.
b. energy as found in nature.
c. energy used to quench short-run power imbalances in electric networks.

2 For "renewable" energy we mean energy

a. from practically inexhaustible sources.
b. that when used is contextually restored to its original repository.
c. to be saved when taken and used later on.

3 In cascade controls within thermal systems, the inner loop is frequently closed around

a. a centralised heater.
b. a chiller.
c. a valve.

? 4 A decoupler-controller unit is frequently realised as a monolithic block owing to the need for a thorough management of

a. sampling.
b. antiwindup and tracking.
c. proportional action, when present.

5 The scheme in which a control signal becomes the duty cycle for a periodic logic signal to command an on-off actuator, is called

a. time division output.
b. daisy chain.
c. delayed activation.

6 A major reason to employ daisy chain actuation is

a. allowing a controller to exert a signed action although actuators cannot.
b. alternating the actuators so as to distribute wear.
c. having less "desirable" actuators intervene only when necessary.

7 The fundamental components of a generator with rotating masses are

a. boiler and turbine.
b. prime mover and alternator.
c. prime mover and secondary mover.

8 In system-level models for thermoelectric generators, the control inputs are

a. power and frequency.
b. fuel valve and mechanical power.
c. turbine throttling valve and combustion power.

9 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.

10 In power control, two frequently conflicting objectives are

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

11 In AC grids, for “energy quality” we essentially mean

?

a. the distance of all generators from their optimal operating point.
b. the required voltage and frequency.
c. the correct generation/demand balance.

12 In electric AC networks, the secondary control is

a. integral.
b. proportional.
c. derivative.

13 A primary plus secondary control system for an AC grid can be viewed as

a. a PI controller with centralised I and decentralised P.
b. a PI controller with centralised P and decentralised I.
c. a totally decentrialsed PI controller with an offset from a central network manager.

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

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

15 In a load flow problem, a generator bus prescribes

a. reactive power and voltage amplitude.
b. active power and voltage amplitude.
c. active and reactive power.

16 The network admittance matrix

a. comes from applying voltage balances at busses.
b. comes from applying current balances at busses.
c. is determined once the admissible load is known.

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

a. to allow a flow control loop to respond more promptly when required.
b. to increase stability and robustness in general.
c. to quench the difficulties posed by valve nonlinearities via inner flow loops.

18 To help ambient condition control systems use less energy, set points are in general

?

a. kept constant whenever possible so as to minimise transients.
b. adapted on line so that no control signal hits the maximum-power saturation limit too often.
c. scheduled based on a periodic (e.g., daily) estimate/forecast of thermal loads.

19 When operating two actuators with opposite or complementary action, a major advantage of a two-loop saturation-based scheme over a mere split range structure is

a. that setting two extremal set points governs the controlled varible swings better than a control dead zone.
b. that the two controllers are led to always use actuators at the minimum possible level.
c. that the tuning of the two controllers can be made equal (i.e., only one in fact needs tuning).

20 As for sizing, a major advantage of a twin pipe heat network over a ring one is

a. that pumps can be smaller as there is practically no total hydraulic impedance variation.
b. that the heater outlet temperature can be made lower as there is virtually no drop on the forward line.
c. that the two pipes are smaller than a single one.

21 **AES only.** For "energy intensity" we mean

a. the amount of energy per "unit" (in the broadest sense) of the intended result.
b. the energy spent for the intended result in the unit of time.
X **c.** the instantaneous rate at which energy is released for the intended purpose.

22 **AES only.** In a 2×2 decoupler-controller structure, if antiwindup is applied upstream the decoupler and one of the physical control variables hits a saturation limit,

a. the affected loop ceases to function, the other operates normally.
b. in general both loops are lost.
c. nothing critical happens.

23 **AES only.** In a hydroelectric generator the role of prime mover is played by

a. a hydraulic turbine. alternator ?
b. a boiler-turbine compound.
c. the turbine valve controller.

24 **AES only.** The two main control loops aboard a thermoelectric generator, from a system-centric viewpoint, concern

a. primary and secondary control.
b. promari and tertiary control (the secondary one is centralised).
c. mechanical power and energy (pressure) level.

25 **AES only.** In electric AC networks, the reason why secondary control is centralised resides in

a. observability.
b. controllability.
c. stability.

26 **AES only.** Denoting by $\underline{y}_{ij}$ the line admittance between busses i and j, the i-th diagonal element of the admittance matrix for a network with n_B busses is

a. $\underline{Y}_{ij} = -\underline{y}_{ij}$
b. $\underline{Y}_{ii} = \underline{y}_{ii} + \sum_{j=1,j\neq i}^{n_B} \underline{y}_{ij}$.
c. $\underline{Y}_{ii} = \underline{y}_{ii} - \sum_{j=1,j\neq i}^{n_B} \underline{y}_{ij}$.

27 **AES only.** Thermal systems composed of controlled volumes and containments typically exhibit

a. oscillatory dynamics, though in general quite well damped.
b. highly nonlinear dynamics.
c. dynamics with multiple time scales, often quite widely separated.

28 **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.

29 **AES only.** In a generic heat network, the temperature of the working fluid

?

a. should be be as high as possible so as to reduce pumping power to the minimum.
b. should be as low as possible compatibly with load requirements and optimal flow, to minimise losses.
c. has no influence on efficiency, it is just a matter of desired temperatures to serve.

30 **AES only.** In a ring heat network, disturbances propagate to downstream utilisers as

a. working fluid temperature variations.
b. working fluid flow variations.
c. shock waves.

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 decoupling control in the context of energy systems.

Decoupleing is used when you have to deal with a MIMO system (for example 2x2) and you want to design separate controllers for your controlled variables. So Approach system in a decentralized easyer approach instead of using compeex MIMO system control tuning. The decoupler (for example backward) take the control var $v_1, v_2, ...$ as imput and give you u_1, u_2 such that the resulting system is diagonal. This can beusefull for example on the modelling of generators where you deal with more imputs (fuel, throttling valve ecc..) and you want to control more outputs with independent controllers (mech power, energy).

Question 2 (AES 2 points, MCES 3 points)

Illustrate the role of tertiary control in AC grids, briefly explaining the main objectives pursued in its computation.

When designing an AC Grid control structure, I, II control have to deal with power and freq control. But when we have a complex network composed of more generators, another main Goal could be to use the proper combination of Generators (assuming they can always switch ON/OFF) Each generator will have a cost rate $C(P_g)$, and we want to minimize the overall $\sum_i C(P_g)$ respecting each gen contrain $P_{g\,MIN/MAX}$ and guarantee the overall Net request P_e. So tertiary control is a top optimization layer, centralized which compute Tertiary BIAS to give as input to each generator to minimize overall cost

Question 3 (2 points) — AES only

Illustrate how KKT-based optimisation is typically used to determine tertiary control contributions in an AC grid, assuming that the objective is to minimise the total generation cost.

KKT optimisation is a mathematical procedure to solve continuous multivariable constrained optimization problems. In our case if we have an AC grid of N generators $G_1 \ldots G_N$, each with its cost rate $C_i(P_{g_i})$ $i=1,\ldots,N$ and constrained power $P_{g_i\,MIN}$, $P_{g_i\,MAX}$. We can write Tertiary control as an optimization problem

$$\min_{P_{g_i}} \left\{ \sum_{i=1}^{N} C_i(P_{g_i}) \right\} \sim\!\!>$$

$$\text{s.t} \quad \sum_{i=1}^{N} P_{g_i} = P_e$$

$$P_{g_i\,MIN} \leq P_{g_i} \leq P_{g_i\,MAX} \quad \forall i=1,\ldots,N$$

and from here we find the equivalent KKT formulation writing the Lagrangian and derivate on the control var and additional variable of optimization

3 Exercises

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

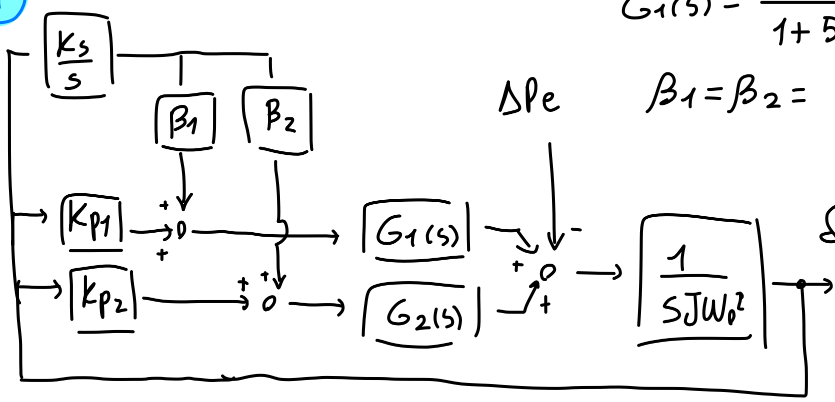
Exercise 1 (AES 5 points, MCES 12 points)

An AC grid at frequency $f_o = 50Hz$ contains two generators G1 and G2, of nominal power $P_{n1} = 10MW$ and $P_{n2} = 30MW$ respectively, both characterised by a first-order dynamics with time constant $\tau = 5s$. The total inertia J is such that *with only G1 active*, the equivalent time constant T_A amounts to $10s$.

1. Draw a block diagram representing the above AC grid with power and frequency control in primary plus secondary form, assuming these to be purely proportional and integral, respectively, and the secondary distribution coefficients to be equal and summing to the unity.

2. Determine the primary and the secondary gain for a the closed-loop dominant time constant of $25s$ and a phase margin φ_m of $50°$; 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



$G_1(s) = \frac{10}{1+5s}$ $G_2(s) = \frac{30}{1+5s}$

$\beta_1 = \beta_2 = 0.5$

$\omega_0 = 2\pi f_0 = 314,16$ rad/s

compute J considering that

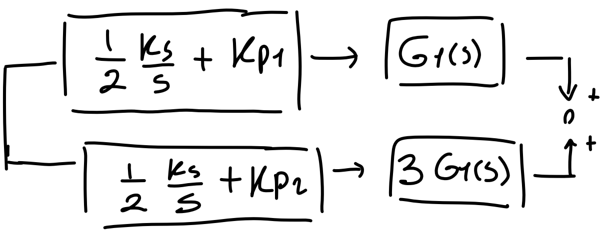
$$\frac{1}{T_A} = \frac{P_{n1}}{J\omega_0^2}$$

$$\hookrightarrow J = \frac{P_{n1}}{T_A\omega_0^2} = 3,18 \frac{kJ}{(r/s)^2}$$

2 $\tau_c = 25s \rightarrow \omega_c = 0.04$ rad/s

$\varphi m = 50°$

considering the parallel of the controllers + Gen



We can set $K_{p2} = 3K_{p1}$ to partition control action properly, obtaining

$$\left(\frac{1}{2}\frac{K_s}{s} + K_{p1} + \frac{3}{2}\frac{K_s}{s} + 3K_{p1}\right) G_1(s)$$

$$\simeq \left(2\frac{K_s}{s} + 4K_{p1}\right) G_1(s)$$

so we have to tune a PI controller

$2\frac{K_s}{s} + 4K_{p1} \simeq \frac{1+sT}{s} K$ on $G_1(s)$

we can proceed with usual tuning procedure:

by loop shaping loosing 11° for the pole, we place PI zero in $\frac{1}{T} = 0,02$

$T = 50$, obtaining $\tilde{\omega} \simeq 0,03 \rightarrow \mu = 0,0009$

$$L(s) = 0,0009 \cdot \frac{\cancel{(1+sT)}}{\cancel{(1+5T)}\cancel{s^2}} = K\,\frac{\cancel{(1+sT)}}{\cancel{s}} \cdot \frac{10\times10^6}{\cancel{1+5s}}\,\frac{1}{\cancel{s}J\omega_0^2} \rightsquigarrow K = \frac{0,0009 \cdot J \cdot \omega_0^2}{10^6} = 0,282$$

$T = 50,\ k = 0.282 \longrightarrow \quad \frac{1+50s}{s} \cdot 0{,}282 = 2\frac{K_s}{s} + 4K_{p1} = 2K_s \frac{\left(1 + 2K_{p1}/K_s\right)}{s}$

$$\ldots \begin{cases} 2K_s = 0{,}282 \longrightarrow K_s = 0{,}141 \\ 50 = \frac{2K_{p1}}{K_s} \longrightarrow K_{p1} = 25 \cdot K_s = 3.525 \end{cases}$$

$K_{p2} = 3K_{p1} = 10.575$

Exercise 2 (7 points) — AES only

Consider a transport system taking an incompressible fluid with density $\rho = 800kg/m^3$ at pressure $p_i = 5bar$ and discharging at $p_o = 2bar$. The system is composed of the series of a valve and a pipe. The valve is described by the flow relation

$$w_V = C_v \Phi(x) \sqrt{\rho \Delta p_V}$$

where Δp_V is the pressure drop across the valve, w_V the mass flowrate through it, and $x \in [0, 1]$ the opening command. The pipe is conversely ruled by

$$\frac{\Delta p_P}{\rho} = K_P w_P^2$$

where Δp_P is the pressure drop across the pipe, w_P the mass flowrate through it, and the constant coefficient K_P – *when expressed in SI units* – equals 20.

1. Determine C_v so that with the valve fully open, the mass flowrate w through the system equals $2.5kg/s$.
2. Assuming the valve intrinsic characteristic $\Phi(x)$ to be linear – i.e., $\Phi(x) = x$ – determine the installed characteristic $w(x)$.
3. Still assuming $\Phi(x) = x$ and setting $x = 0.5$, how different is the resulting flowrate from the one that would be obtained with a linear *installed* characteristic?

$1bar = 10^5 Pa$

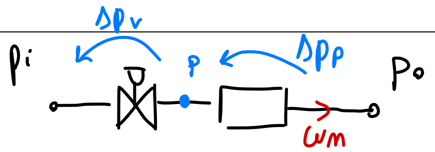
① $\rho = 800 kg/m^3$

$p_i = 5 bar$, $p_o = 2bar$

$w_V = C_v \phi(x) \sqrt{\rho \Delta p_V}$

$\Delta p_P = K_P w_P^2 \rho$

$K_P = 20$



$w_m = 2.5 \ kg/s \rightsquigarrow C_{vm}$? ↑ with w_m flow rate

to properly dimension the valve, consider that

$p = p_o + \Delta p_P = p_o + w_m^2 K_P \rho$ $\quad \phi(x=1) = 1$ fully open

and $\quad w_{Vm} = C_{vm} \cdot 1 \cdot \sqrt{\rho (p_i - p_o - w_m^2 K_P \rho)}$

↓

$w_m^2 = C_v^2 \rho (p_i - p_o - w_m^2 K_P \cdot \rho)$ using proper SI units:

$$C_{vm} = \frac{w_m}{\sqrt{\rho (p_i - p_o - w_m^2 \rho K_P)}} = 0{,}0002 \text{ (in SI)}$$

② $\phi(x) = x \to$ installed charact? from :

$w(x) = C_v \cdot \phi(x) \sqrt{\rho (p_i - p_o - w^2(x) \rho K_P)} \rightsquigarrow w^2(x) = C_v^2 \phi^2(x) \rho (p_i - p_o - w^2(x) \rho K_P)$

$$w(x) = \frac{C_{vm}\, x \sqrt{\rho (p_i - p_o)}}{\sqrt{1 + \rho^2 K_P C_{vm}^2 x^2}}$$ non linear characteristic

3 for $\phi(x) = x = 0.5$ $\omega(x) = 1.458$ m/s
while, we can find the equivalent linear installed characteristic imposing that

$\omega(x=0) = \omega_0 = 0$ $\omega(x=1) = \omega_x = 2.519$ m/s

$\omega(x) = \omega_{max}\, x = 2.519\, x \rightsquigarrow \omega(x=0.5) = 1.259$ m/s

$\Delta\omega \cong 0.2$ which is an error NOT so negligible...
(14% of error)