Part B

Electric systems

(15/03)

Electric systems - component models

same concept for others...

- Overview – models and control problems
- Generators – thermoelectric case ⇒ (explanatory case → generalizable)

  Controlled generators – still on the thermo case

  Generalising (a bit) to other generator types

  Lines and loads

Models and control problems

in the "traditional" *scenario*

- In traditional control of AC electric networks, two types of problems are encountered:
  - **power and cost control**, i.e., deliver the required power to all utilisers while
    - minimising costs (and possibly emissions) *globally* (general interest),
    - and/or maximising the economic revenue *for one or a set of generators* (particular interest),

    which are in general conflicting objectives;

    NOT split in general simple objectives... coupling obj
  - **energy quality control**, i.e., deliver electricity at the required voltage and frequency, which necessarily involves cooperation as all the generators (and loads) are coupled by the network, hence no particular interest makes sense.

    to deliver electricity @ ω_m, V_m there is coupling
- The above problems are clearly intertwined, in a way that however depends on the generator operation.
- Also, in the considered *scenario* only generators act to provide control: the power demand by loads is considered exogenous (i.e., a disturbance). (approx true)

Models and control problems

in the "traditional" *scenario*

distinguish

- In this respect, two generator types are in fact distinguished:
  - with rotating masses, i.e., with an alternator (e.g. thermo, nuclear, hydro, wind, tidal, thermal – or "thermodynamic" – solar), → heat up fluid an use it to have motion
  - and without rotating masses, i.e., with an inverter (e.g. photovoltaic solar). → NO mech inertia

inherently

- Rotating masses inherently couple power and frequency, as a power excess or deficiency accelerates or decelerates the masses, thereby altering frequency.

physical freq

- This does not hold true when no rotating mass is present.

- Other problems exist that do not fit in the space of this course, like e.g. reactive power control.
- Since we aim at system-level principles and models, we shall examine generators having the thermoelectric case as reference, and then generalise to a feasible extent. (power imbalance) how much spent for gen.
- Our KPIs will be power and frequency error, generation cost, revenue, and transmission losses.

how much gain

Models and control problems

in the “traditional” *scenario*

- When moving from generation to network control, another relevant problem is encountered:
  - **load flow**, i.e.,
    delivering power without overloading transmission lines, and possibly minimising line losses.

(check that feasible network set-up)

- Load flow can just provide constraints for power and quality control to avoid overloads (and we shall just say some words on this) or be part of the overall optimisation, leading to the (*optimal flow* problem) that we cannot treat here.

different models, depending on the problem!

- Finally, as we shall see soon, power and quality problems require to abstract different generator and network element interfaces.
- Let us now proceed to model generators: as anticipated, we start from the thermoelectric case and then extend the ideas.

Thermoelectric generators

Basics (in a view to power and frequency control)

- These generators include a rotating mass, whence the power/frequency coupling.
- Synthesis of operation:
  - fuel burns in a *furnace* and produces heat;
  - heat turns water into superheated steam;
  - steam moves a turbine;
  - the turbine moves the alternator,
- The generator has its internal controls, which we do not represent,
- and we also disregard the details about the water/steam path (free or forced circulation, once-through)... lots possible generator geometry of steam generators
- ...since the matter is treated in dedicated courses, and is not to be represented in our system-level models.

Thermoelectric generators

A system-level model – prime mover

→ (SIMPLE MODEL)

1ST/2ND ORD models

, on Network level I ORD, never of order higher than IV also on syst. level

Pc internal variab.

- We start from the *prime mover*, i.e., the system having fuel as inlet and mechanical power for the alternator as outlet. (shaft connected)
- For simplicity we take as exogenous input the combustion power P_c released to the *main energy storage* (steam); fuel consumption will come into play later on. (real input is a valve for fuel)
- In so doing we neglect heat storage in the combustion chamber and the flue gas path as they are very small w.r.t. those in the metal and water/steam path, which we assume thermally coherent.

  ↳ same m³ ≃ atm pressure negligible respect overall energy stored on gas path

  tones of steam and water steam respect air/gas m³... energy stored on steam's combustion chain/gas path energy!
- The stored energy balance is thus

combustion

$$\left(\dot{E} = P_c - P_{loss} - P_t \right)$$

where P_{loss} is the power lost to the external environment and P_t the power drawn by the turbine.

Thermoelectric generators

A system-level model – prime mover

water liquid, subcooled (below saturation enthalpy) which is, then heat up on SAT state ... thanks to evaporation → SATUR steam until superheated steam, more dense → more dense, dominant energy on evaporating section

- We simplistically assume that the main energy storage is composed of saturated steam and its mass is constant; we thus relate P_{loss} to the difference between the saturation temperature at the steam pressure p (which thereby comes to represent the stored energy) and the external temperature, as

we operate generator with constant op. point... (constant distribution of liquid, steam) change op point NOT on control

(By SATURATED steam..)

(exchange with external environm.)

$$P_{loss} = G_{loss}(T_{sat}(p) - T_{ext})$$

power lost related to

where G_{loss} is an equivalent thermal conductance.

- Even more simplistically, since in general $T_{sat}(p) \gg T_{ext}$, we write

(hundred degs of difference!)

(E/M) specific energy, depends on steam state

$$P_{loss} = K_{loss} E/M$$

specific energy content in generator

where K_{loss} is a parameter and the division by M represents the fact that P_{loss} depends on the steam *specific state*; K_{loss} is of course related to the dispersing surface.

once the liquid water ... reach superheated steam

in this condition, lower density than mixture / water

⇒ so the dominant energy stored is on the evaporating section

↓

we operate Gen. with constant distribution of MIXTURE, WATER, LIQUID, STEAM → changing a bit respect op. point !

⇓

- because, of main energy is given by SAT. STEAM ⟶ the temperature will be the SAT. temp @ operating pressure

so P loss to external environment.. $P_{loss} = G_{loss}\left(T_{sat}(p) - T_{ext}\right)$

Thermoelectric generators

A system-level model – prime mover

Water evaporate until reach turbine

assume turbine power...

- We now make another simplistic assumption by disregarding the superheating that steam undergoes prior to traversing the turbine valve, and assume P_t to depend on the steam pressure (that is, on E/M) and the turbine valve opening $\theta \in [0,1]$ as

$$\boxed{P_t = \theta K_{draw} E/M}$$

power taken @ the turbine

where K_{draw} is another parameter.

- The mechanical power to the alternator is then obtained by accounting for a mechanical efficiency, assumed constant and denoted by η_m, as

$$P_m = \eta_m P_t .$$

efficency mech.

power released to shaft

Thermoelectric generators

A system-level model – prime mover

- Putting it all together, we have

$$\begin{cases} \dot{E} = P_c - K_{loss}E/M - \theta K_{draw}E/M \\ P_m = \eta_m \theta K_{draw} E/M \end{cases}$$

(transient measure)

- Note that $[K_{loss}E/M] = [K_{draw}E/M] = [W]$ since θ and η_m are adimensional, thus

WATT dimension

$\Longrightarrow$ $[K_{loss}/M] = [K_{draw}/M] = [1/s]$ and we can write

$[W]=[J]/[s]$ so... therefore!

$$\frac{K_{loss}}{M} = \frac{1}{T_{loss}} \quad \text{speed at which you loss power}$$

$$\frac{K_{draw}}{M} = \frac{1}{T_{draw}} \quad \text{speed draw power with } \theta=1$$

{simple model near equilibrium}

(locally generator) behaviours well described so..

$$\begin{cases} \dot{E} = P_c - \left(\dfrac{1}{T_{loss}} + \dfrac{\theta}{T_{draw}}\right) E \\ P_m = \dfrac{\eta_m}{T_{draw}} E\theta \end{cases}$$

- In the state equation above, T_{loss} and T_{draw} are interpreted as the time constants with which energy is lost into the environment and drawn to the alternator at full throttling (turbine) valve opening. $(\theta = 1)$

Thermoelectric generators

A system-level model – prime mover

- Notice that the plant size, intuitively indicated e.g. by (some nominal value for) the contained water/steam mass M, in this formulation comes to be represented by the introduced time constants (larger plant, larger M, larger T_{loss} and T_{draw}).

- Of course models like this one are in the large *extremely* coarse, and for real-life uses they could only have local validity around an operating point.
- Treating such aspects strays from the course, however, and therefore we shall just use the model *as is* since this is more than enough for our purposes.

IF Gem has 0% power an we wanna restore it feeding at Pm.. how to reach 100% Em ? ↳(TREST !)

Thermoelectric generators

A system-level model – prime mover

further normalize...

combustion/mech power normalized by same power!

- We can furthermore introduce a generator nominal power P_n and denote by T_{rest} the time required to restore the generator from zero to its "nominal energy storage" E_n operating at nominal power, thereby defining E_n as $P_n T_{rest}$. Dividing the above equations by E_n we get

feeding ↳ energy from 0%. Trest told you the Δt to fill it at 100% of capability

(normalize)

"normalized energy" NOT specific respect mass!"

(adimensional number)

$$
\begin{cases}
\dot{e}_n = \dfrac{1}{T_{rest}} p_c - \left(\dfrac{1}{T_{loss}} + \dfrac{\theta}{T_{draw}}\right) e_n \\
p_m = \eta_m \dfrac{T_{rest}}{T_{draw}} e_n \theta \quad \text{(mech power)}
\end{cases}
$$

where $p_c = P_c/P_n$ and $p_m = P_m/P_n$ are respectively the normalised combustion and mechanical powers, while $e_n = E/E_n$ is the normalised energy storage (*not* the steam specific energy, beware).

We bring to normalized so we threat it easely in percentage to have a meaning respect absolute value

$E_m = P_m \cdot T_{REST}$

NOT [J/Kg], BUT adimensional!

Thermoelectric generators

A system-level model – prime mover

"e_m" [adimensional] normalized while "e_{spec}" is dimensional

- As such, indicating – for this discussion only – the steam specific energy $[J/kg]$ with e_{spec}, we could better rewrite the second model equation (mind the different meanings of e_{spec} and e_n) as

$$P_m = \eta_m K_{draw} e_{spec}\,\theta = \eta_m K_{draw} \frac{\overset{P_n \cdot T_{rest} \cdot e_n}{\overset{\|}{E}}}{M}\,\theta = \eta_m K_{draw} \frac{P_n T_{rest}}{M} e_n\,\theta$$

- Thus, normalising by P_n,

$\frac{P_m}{P_n} = p_m$ normalized $\Rightarrow$

$$p_m = \eta_m K_{draw} \frac{T_{rest}}{M} e_n\,\theta$$

- Overall, the quantity $k_\theta := K_{draw} T_{rest}/M$ acts as sort of a "valve gain" cascaded to the mechanical efficiency. Investigating its role would however require relating also the contained *mass* to the energy state, which we do not want to do for our purposes.

depends on energy level! $\rightarrow$ $K_{draw} \cdot T_{rest} = E_m$ $\rightarrow$ $\frac{E_m}{M} = e_{spec\,m}$:= nominal pressure

Thermoelectric generators

A system-level model – prime mover

- Thus, we shall simply write

simple model...

$$\begin{cases} \dot{e}_n &= \dfrac{1}{T_{rest}} p_c - \left(\underbrace{\dfrac{1}{T_{loss}}}_{\text{losses}} + \underbrace{\dfrac{\theta}{T_{draw}}}_{\text{extract by turbine}} \right) e_n \\ p_m &= \eta_m k_\theta \, e_n \, \theta \end{cases}$$

simple computation

and for simplicity (without didactic loss for this course) assume $k_\theta = 1$, hence omitting it hereinafter.

valve gain

- Summing up, we shall take as model for the generator prime mover the dynamic system

[Non linear I ORD model] ⇒

input

$$\begin{cases} \dot{e}_n &= \dfrac{1}{T_{rest}} p_c - \left(\dfrac{1}{T_{loss}} + \dfrac{\theta}{T_{draw}} \right) e_n \\ p_m &= \eta_m e_n \theta \end{cases}$$

state

Thermoelectric generators

A system-level model – prime mover

- We can now determine the equilibrium of the previous model for constant inputs $\overline{p}_c, \overline{\theta}$ (the overline denotes equilibrium values) using e.g. the Maxima script

derivative: $\dot{e}_m$

```
/* Model
*/
endot : pc/Trest-(1/Tloss+theta/Tdraw)*en;
pm    : etam*en*theta;

/* Equilibrium
*/
enbar : rhs(solve(subst([pc=pcbar,theta=thetabar],endot),en)[1]);
pmbar : ratsimp(etam*enbar*thetabar);
```

"solve" (... = 0)

- This produces

EQUILIBRIUM

$$\overline{e}_n = \boxed{\frac{T_{draw} T_{loss} \overline{p}_c}{T_{rest}\left(T_{draw} + T_{loss}\overline{\theta}\right)}}, \quad \overline{p}_m = \eta_m \overline{e}\,\overline{\theta}.$$

Thermoelectric generators

A system-level model – prime mover

(all on course library)

- We can also simulate the prime mover model in Modelica, starting at the equilibrium and applying steps to θ and p_c, with

system evolution from equilibrium

```
model SimpleThermoElecGenPM
  parameter Real Pn       = 100;
  parameter Real Trest    = 400;
  parameter Real Tdraw    = 500;
  parameter Real Tloss    = 1e4;
  parameter Real etam     = 0.95;
  parameter Real thetabar = 0.8;
  parameter Real pcbar    = 0.6;
  Real en(start=Tdraw*Tloss*pcbar/Trest/(Tdraw+Tloss*thetabar));
  Real pc,pm,theta;
equation
  der(en) = pc/Trest-(1/Tloss+theta/Tdraw)*en;
  pm      = etam*en*theta;
  theta   = if time<1000 then thetabar else thetabar+0.1;
  pc      = if time<5000 then pcbar    else pcbar+0.1;
end SimpleThermoElecGenPM;
```

definitions of parameters

initial equilibrium value

" $\bar{e}_m$ initially

0.1 @ $t^*=1000$

applied step on system

@ 5000 s (10% step)

(all normalized) → 0.1 = 10% step

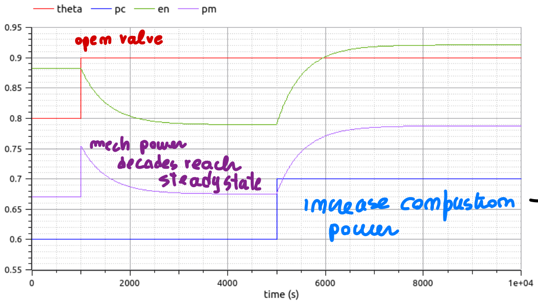
Thermoelectric generators

A system-level model – prime mover

running the model

- Simulating for 10000 s produces

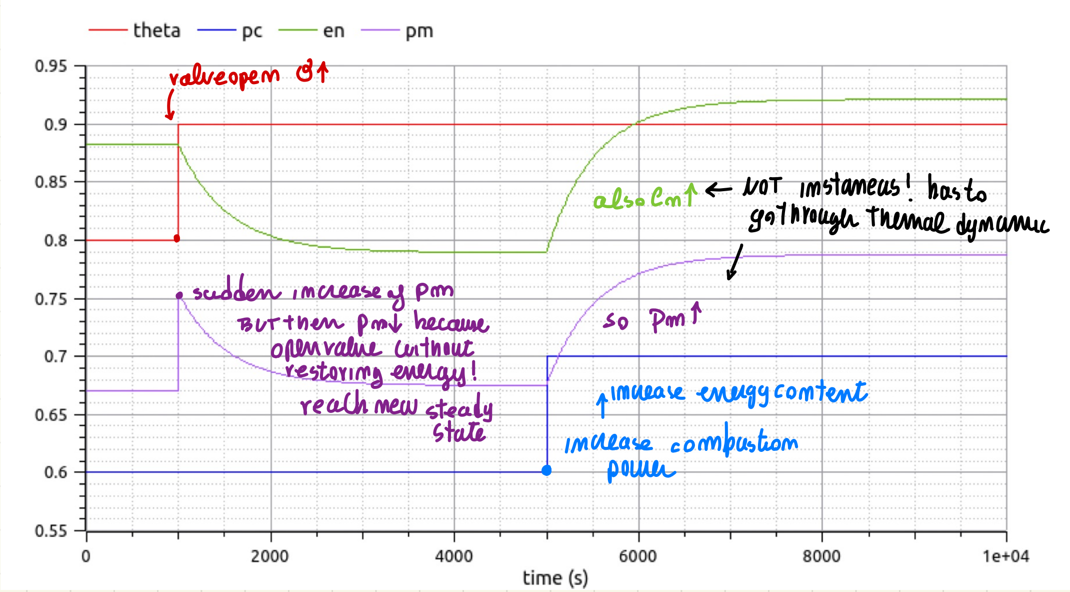
(Modellica) ↳



send in more power

- The θ step ($t = 1000\,s$) yields a sudden p_m response but then, as p_c is constant, p_m settles back while e_n decreases and settles as well, both transients being dominated by the storage time constant.
- The p_c step ($t = 5000\,s$) makes both p_m and e_n increase and settle, however with the storage time scale (no sudden p_m response).

↑ not istantaneus!


theta
pc
en
pm
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0
2000
4000
6000
8000
1e+04
time (s)
valveopen θ↑
also en↑
← NOT instaneus! has to go through thermal dynamic
sudden increase of pm
BUT then pm↓ because open valve without restoring energy!
reach new steady state
so pm↑
↑ increase energy content
increase combustion power

Thermoelectric generators

A system-level model – prime mover

- We can furthermore linearise the model in the vicinity of the equilibrium, setting $\Delta p_c = p_c - \overline{p}_c$, $\Delta\theta = \theta - \overline{\theta}$ and $\Delta e = e - \overline{e}$, $\Delta p_m = p_m - \overline{p}_m$, and taking as outputs both Δp_m and Δe:

```
/* Linearised model state space matrices
*/
A      : subst([pc=pcbar,theta=thetabar,en=enbar],jacobian([endot],[en]));
B      : subst([pc=pcbar,theta=thetabar,en=enbar],jacobian([endot],[theta,pc]));
C      : subst([pc=pcbar,theta=thetabar,en=enbar],jacobian([pm,en],[en]));
D      : subst([pc=pcbar,theta=thetabar,en=enbar],jacobian([pm,en],[theta,pc]));
```

- The result is LINEARIZED model linearized model asymp.stable

$$
\begin{cases}
\Delta\dot{e}_n = -\left(\dfrac{1}{T_{loss}} + \dfrac{\overline{\theta}}{T_{draw}}\right)\Delta e_n + \begin{bmatrix} -\dfrac{\overline{p}_c T_{loss}}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})} & \dfrac{1}{T_{rest}} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta p_c \end{bmatrix} \\[2ex]
\begin{bmatrix} \Delta p_m \\ \Delta e_n \end{bmatrix} = \begin{bmatrix} \eta_m\overline{\theta} \\ 1 \end{bmatrix}\Delta e_n + \begin{bmatrix} \dfrac{\eta_m \overline{p}_c T_{draw} T_{loss}}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta p_c \end{bmatrix}
\end{cases}
$$

even in open loop you can remain @ equilibrium

- Note that it is asymptotically stable, as T_{draw}, T_{loss} and $\overline{\theta}$ are all positive.

inherently

with (-) before → eig<0

Thermoelectric generators

(enough for prime mover description)

2 inputs $(p_c, \theta) \rightarrow$ 2 out (e_m, p_m)

A system-level model – prime mover

- We can finally compute the transfer matrix of the linearised model:

```
/* Linearised model transfer matrix. Note that here A is actually scalar;
   the syntax for the matrix-A case would be C.invert(s*ident(size_of_a)-A).B+D
*/
Gamma : factor(C.B*invert(s-A)+D);
```

(θ Rel 1 deg)

while all other response I ORD

(zero relative degree response

as seen on the response plot... a step on θ is a step on p_m only!

- We get

(compute T.F)

$$\Gamma(s) = \begin{bmatrix} \Gamma_{\theta m}(s) & \Gamma_{cm}(s) \\ \Gamma_{\theta e}(s) & \Gamma_{ce}(s) \end{bmatrix} = \begin{bmatrix} \frac{\Delta p_m(s)}{\Delta\theta(s)} & \frac{\Delta p_m(s)}{\Delta p_c(s)} \\ \frac{\Delta e_n(s)}{\Delta\theta(s)} & \frac{\Delta e_n(s)}{\Delta p_c(s)} \end{bmatrix} = \ldots$$

We only have one zero - from θ to p_m dynamic

denominator from same system

numbers

$$= \frac{1}{1+s\frac{T_{draw}T_{loss}}{T_{draw}+T_{loss}\overline{\theta}}} \begin{bmatrix} \frac{\eta_m T_{draw}^2 T_{loss}\overline{p}_c}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})^2}(1+sT_{loss}) & \frac{\eta_m T_{draw}T_{loss}\overline{\theta}}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})} \\ -\frac{T_{draw}T_{loss}^2\overline{p}_c}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})^2} & \frac{T_{draw}T_{loss}}{T_{rest}(T_{draw}+T_{loss}\overline{\theta})} \end{bmatrix}$$

- Note that all the elements have relative degree 1 except for $\Delta p_m/\Delta\theta$, which has 0; this is consistent with the simulated responses.

Thermoelectric generators

Pe powertaken is INPUT (INPUT for us)

A system-level model – balance at the alternator

- In *our scenario* the demanded active power P_e is exogenous for the generator, hence the energy equation for the rotating mass (turbine and alternator) reads

$K = \frac{1}{2}J\omega^2 \Rightarrow$ Kinetic energy $\left(\frac{\partial}{\partial\omega}K\right) :\Rightarrow$

$$\boxed{J\omega\dot{\omega} = P_m - P_e} \quad (*)$$

where J is the total inertia seen at the shaft, and ω the angular velocity (which we identify with the electric frequency, disregarding for simplicity the number of alternator polar expansions). normally the generator has np > 1 more poles than a couple.. so $\omega_e = n_p\omega_m$ higher electric velocity... here neglect

- The equation above yields possible equilibria at any ω, provided that the (constant) values $\overline{P}_m$ and $\overline{P}_e$ coincide. Linearising, therefore,

with $P_m \simeq P_e$ so $\dot{\omega} = 0 \ \forall \omega \rightarrow$ IF BALANCE you want

$P_m = P_e$

$$\Delta\dot{\omega} = -\cancel{\frac{\overline{P}_m - \overline{P}_e}{J\overline{\omega}^2}}\Delta\omega + \frac{1}{J\overline{\omega}}(\Delta P_m - \Delta P_e)$$

$(*)$ $\dot{\omega} = \frac{P_m - P_e}{J\omega}$

- Assuming ω regulated at its desired value ω_o (we shall guarantee this shortly) and recalling that at the equilibrium $P_m = P_e$, we have

$$\Delta\dot{\omega} = \boxed{\frac{1}{J\omega_o}(\Delta P_m - \Delta P_e)}$$

you can guarantee IF balance mech = elect $P_m = P_e \rightarrow \dot{\omega} = 0$, you want constant freq $\omega = \overline{\omega}$

Thermoelectric generators

A system-level model – balance at the alternator

(NOTATION)

$\frac{\Delta\dot{\omega}}{\omega_o} = \delta\dot{\omega}$ ....

mech, elect with nominal

- Normalising $P_{m,e}$ with P_n and ω with ω_o and using δ for the variations of normalised quantities, finally,

= nominal $\omega \simeq 50Hz$

divide all by $\omega_o P_m$

$$\frac{\Delta\dot{\omega}}{\omega_o P_n} = \frac{1}{J\omega_o}\left(\frac{\Delta P_m}{\omega_o P_n} - \frac{\Delta P_e}{\omega_o P_n}\right)$$

- which means, rearranging,

$$\boxed{\delta\dot{\omega} = \frac{P_n}{J\omega_o^2}(\delta P_m - \delta P_e)}$$

[J]

Note that $[P_m/J\omega_o^2] = [W/J] = [1/s]$; the quantity $\boxed{J\omega_o^2/P_m}$ is typically denoted by T_A.

characteristic time constant ...

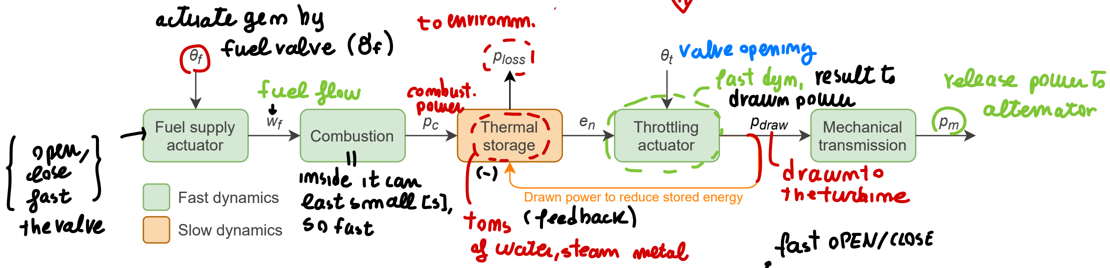
$T_A = \frac{J\omega_o^2}{P_m}$ time constant of alternator part of generator

Thermoelectric generators

BLOCK DIAGRAM

system level P.O.V (scheme)

A system-level model – synthetic scheme for the prime mover



- From the system-level viewpoint, acting on the fuel actuator (θ_f) or on the throttling one (θ_t) influences power p_{draw} through a dynamics that can be *decently* represented with a 2nd order system;
- θ_t acts rapidly but its effect need sustaining in the long run by p_c;
- on the contrary θ_t produces a sustained effect on p_{draw} via p_c, but has to traverse the far slower thermal dynamics.

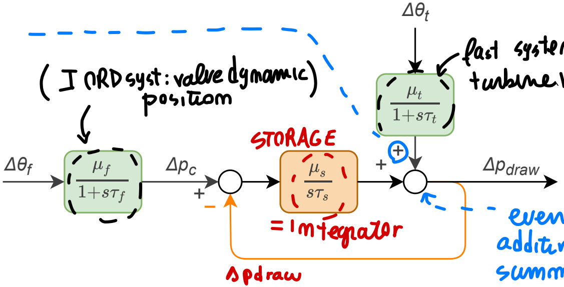
Thermoelectric generators

True block diagram:

A system-level model – synthetic scheme for the prime mover – QUALITATIVE interpretation

[IF: $y = a \cdot b$ → linearize
$\Delta y = \bar{a}\Delta b + \bar{b}\Delta a$]

contain steady state value, so added "+"



even if $\Delta\theta_t$ additive effect, here is as summ as linearized

- The effect of θ_t on draw as per the model is in fact multiplicative —yet additive (linearising) in the small.
- From the scheme above we get T.F.s

(to account for responce) zero on origin!

$\theta_f \to p_{draw}$

$$G_{pf}(s) = \frac{\Delta p_{draw}(s)}{\Delta\theta_f(s)} = \frac{\mu_f}{(1+s\tau_f)\left(1+s\frac{\tau_s}{\mu_s}\right)},$$

$$G_{pt}(s) = \frac{\Delta p_{draw}(s)}{\Delta\theta_t(s)} = \frac{s\mu_t\frac{\tau_s}{\mu_s}}{(1+s\tau_f)\left(1+s\frac{\tau_s}{\mu_s}\right)},$$

$\theta_t \to p_{draw}$

where the f, t and s subscripts stand for fuel, throttling, storage.

Thermoelectric generators

A system-level model – synthetic scheme for the prime mover – QUALITATIVE interpretation

- Let us simulate the responses of G_{pf} and G_{pt} in Scilab with ballpark numbers, just to see their aspect:

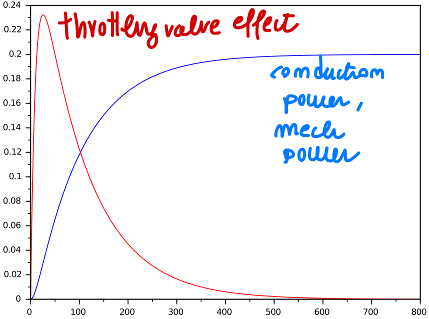
```
muf  = 0.2;
tauf = 10;
mut  = 0.3;
taut = 1;
mus  = 1;
taus = 100;
Gpf  = syslin('c',muf/(1+%s*tauf)/(1+%s*taus/mus));
Gpt  = syslin('c',%s*mut*taus/mus/(1+%s*tauf)/(1+%s*taus/mus));
t    = 0:0.1:800;
yf   = csim('step',t,Gpf);
yt   = csim('step',t,Gpt);
plot(t,yf,'b',t,yt,'r');
```

Thermoelectric generators

A system-level model – synthetic scheme for the prime mover – QUALITATIVE interpretation

↓ (shape of response!)

- Result:

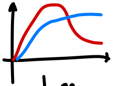


{ 2 actuators for same purpose on short run! }

[in real life you can use III, IV ORD syst...] → Just replace by higher order T.F!

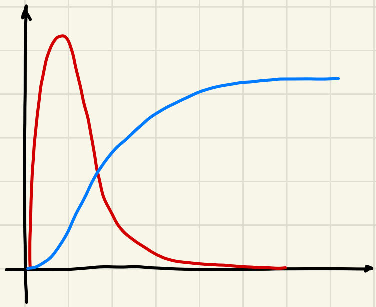
you manipulate the actuator to get fast responce and restore energy → or act directly on energy

If 2 time scales comparable...

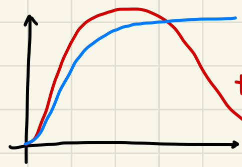


different possible behaviour → which help us to choose the best control variable

- As can be seen, the representation is "decent" in the sense suggested;
- in real-life cases higher order models can be used, but the dominant dynamics do resemble those we just saw.

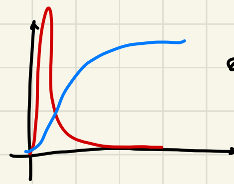


you can have a generator
where time scales are comparable



same τ more or less

OR you can have a GEN



take much
on short run
but different
restoring

this tells you
which is the
better control
variable to use as input!

Thermoelectric generators

A system-level model – synthetic scheme for the prime mover – QUALITATIVE interpretation

- Remark: the zero in the origin in G_{pt} comes from neglecting losses.
- This is consistent with our previous viewpoint as per the transfer matrix $\Gamma(s)$, since

goes to ZERO on origin

$$\underbrace{\lim_{T_{loss}\to\infty}}_{\text{NO LOSSES limit}} \Gamma(s) = \frac{1}{1+s\frac{T_{draw}}{\overline{\theta}}}\begin{bmatrix} s\frac{\eta_m T_{draw}^2 \overline{p}_c}{T_{rest}\overline{\theta}^2} & \frac{\eta_m T_{draw}}{T_{rest}} \\ -\frac{T_{draw}\overline{p}_c}{T_{rest}\overline{\theta}^2} & \frac{T_{draw}}{T_{rest}\overline{\theta}} \end{bmatrix}$$

(slow ZERO, NOT on origin if we consider loss)

where θ is playing the role now played by θ_t (if not for the cascaded dynamics of the throttling actuator).

- Note also that all the gains (for $\Gamma_{1,1}$, *lato sensu*) contain T_{draw}/T_{rest}, i.e., "how slow you restore over how slow you take".

↳ which characterize the gen

Controlled (thermo) generators

Generator CONTROL

Foreword

- We said that we would not represent the controls inside generators.
- True, but we now have to add a bit of additional information (still about the thermo case, before we generalise as anticipated).

(all assumptions...)

- After going through several coordinated viewpoints, we ended up with a (thermo) generator 2×2 linearised model

INPUTS

  - having as inputs the variations $\Delta\theta_f$ and $\Delta\theta_t$ of the fuel and throttling [0,1] commands,

OUTPUTS

  - and as outputs the variations Δp_m of the normalised mechanical power (i.e. for Δp_{draw}, as we assume η_m constant) and Δe_n of the normalised energy content (corresponding in practice to a normalised pressure).

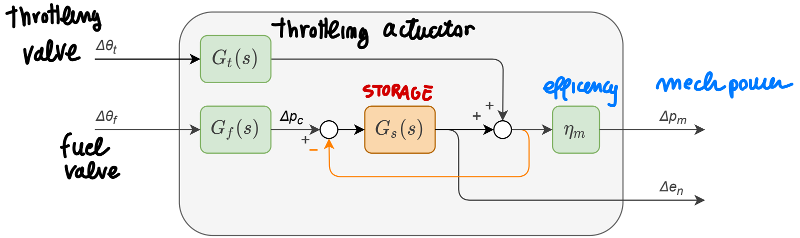
- (The generator internals are discussed in other courses,)
- but here, to get to out final representation, we need to spend a few words on how θ_f and θ_t can be coordinated. ?

fuel turbine

Controlled (thermo) generators

The 2×2 system to control

- Precisely, we got to model like this: ...



where the throttling, fuel/combustion and storage dynamics are

$$\boxed{G_t(s) = \frac{\mu_t}{1+s\tau_t}}, \quad \boxed{G_f(s) = \frac{\mu_f}{1+s\tau_f}}, \quad \boxed{G_s(s) = \frac{\mu_s}{s\tau_s}}.$$

Controlled (thermo) generators

Alternatives for coordinating θ_t and θ_f

We have 3 choices for control!

- We consider three alternatives:
  - using θ_t to control p_m and θ_f to control e_n, which is called boiler follows;
  - using θ_t to control e_n and θ_f to control p_m, which is called turbine follows;
  - setting the throttling valve to full open and use θ_f to control p_m, which is called variable or sliding pressure;

1 $\begin{cases} \theta_t \to p_m \\ \theta_f \to e_n \end{cases}$

2 $\begin{cases} \theta_t \to e_n \\ \theta_f \to p_m \end{cases}$

3 $\begin{cases} \theta_t = 1 \\ \theta_f \to p_m \end{cases}$

pressure able to vary → we don't control it!

Controlled (thermo) generators

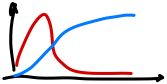
Boiler follows (BF) 1

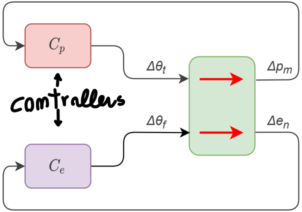
$\Downarrow \quad \left\{ \begin{array}{l} \theta_t \to p_m \\ \theta_f \to e_m \end{array} \right\}$

valve to control pm → FAST dynamic! responce

↑

valve with fast response!





- Power control (C_p) via θ_t, energy control (C_e) via θ_f:
  - ☺ fast power response as τ_t is tendentiously small (seconds or below);
  - ☹ transient pressure (energy) variations of potentially noticeable entity, hence mechanical stress that can be detrimental in the long run; $\Delta e \to \Delta p$ pressure var.

$\Rightarrow$ advisable when a plant has to take care of following fast load variations.

relay on fast draw of power... pressure go down transiently → $e \downarrow$ transiently restore gen

but e, p variation...

mech stress → reduce operating lifetime

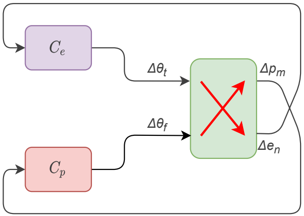
Controlled (thermo) generators

Turbine follows (TF)

$$\Downarrow \left\{ \begin{array}{l} \theta_t \rightarrow e_m \\ \theta_f \rightarrow p_m \end{array} \right\}$$

apparently PERFECT pressure control!

fast actuator to control pressure! Keep it still, little mech stress



- Power control (C_p) via θ_f, energy control (C_e) via θ_t:
  - ☺ almost ideal pressure (energy) control, hence little mechanical stress;
  - ☹ slow power response, as θ_f acts through the thermal dynamics (although energy control helps by its fast action on pressure);

small dynamic

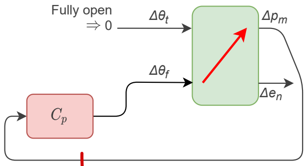
$\Rightarrow$ advisable when a plant has to take care only of quite slow load variations.

all dynamic traverse from $\theta_f \rightarrow p_m$, but close loop helps to keep pressure desired

Controlled (thermo) generators

Sliding pressure (SP)

$\Downarrow \left\{ \begin{array}{l} \Delta\theta_t = 0 \rightarrow \text{FULLY OPEN} \\ \theta_f \rightarrow p_m \end{array} \right\}$



use combustion power to control the power by θ_f

only slow δe

valve fully open

- Power control (C_p) via θ_f, $\theta_t = 1$:
  - ☺ minimum stress for the turbine as there is no control action on the throttling valve;
  - ☹ extremely slow power response, as θ_f acts through the thermal dynamics but this time there is no energy (pressure) loop to help;

slow power response, go through slow dynamics and → no pressure control!

⇒ advisable for base load plants (switching to BF/TF if pressure varies too much).

plant based on a load remain unchanged
IF needed switch to other control

Controlled (thermo) generators

Conclusions

- Blocks C_p and C_c are generally quite simple, such as PI/PID ones.
- As a consequence, the relationship between power request and produced power (p_m) is reasonably represented – *from our system-level viewpoint* – with a transfer function of quite low order, say three at most, with possibly slightly underdamped dynamics.
- As such, in the rest of this course we shall represent a (thermo) generator as a single block

  u = δt OR δs ... depending on type on control

  - with a [0,1] input that we shall denote by u to stay abstracted with respect to the BF/TF/SP/combined internal control policy
  - and an output that we shall denote by P_g (for "generated") power as in general this can be of other nature than "mechanical".

on Modelica course library there are example of it to check response shape etc..

Controlled (thermo) generators

Conclusions

- We shall however preserve a normalised power output, hence writing a generator block as

$$G(s) = \frac{\Delta P_g(s)}{\Delta u(s)} = P_n g(s)$$

where P_n is the nominal power and the transfer function $g(s)$, of unitary gain, outputs the normalised generated power $p_g = P_g/P_n$.

- Note: we have to always bear in mind that our transfer function models come from the linearisation of more complex ones not in the scope of this course, whence the Δ's; nonetheless, to lighten the notation, in the following we may sometimes drop the said Δ's (a simplification that must not be interpreted as altering in any sense the linearised and thus local nature of the used models, however).

Controlled (thermo) generators

Conclusions

(normalized generator T.F)

- As for $g(s)$, we shall use
  - simple first- or overdamped second-order models such as

$$g(s) = \frac{1}{1+sT_g}, \quad g(s) = \frac{1}{(1+sT_{g1})(1+sT_{g2})}$$

for exercises where the detailed form of $g(s)$ is not the point;
  - slightly more complex models like e.g.

$$g(s) = \frac{1}{(1+sT_g)\underbrace{\left(1+2\frac{\xi_g}{\omega_{ng}}s+\frac{s^2}{\omega_{ng}^2}\right)}_{\text{oscillating dynamic II ORD}}}$$

in some illustrative simulation examples.
- As we shall see, simple models like these can well reproduce the typical power/frequency transients of interest for network control and management.

↳ gen ≃ II ORD syst... as we see from physical considerations!

Solar plant

of the thermal type – traditional setup

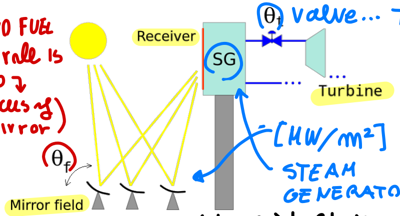
other types of generator... which one can be used, and their parts can play the same role of the model described!

- Heliostats (mirrors) point to receiver on the steam generator (SG):

θ_f → act on the INPUT energy through thermal dynamic!

{ take % of solar energy available } ← (focus of mirror)

here NO FUEL but θ_f role is to



θ_t valve... turbine valve as model seen
↳ act directly on turbine FAST!

[MW/m²] high power density!

STEAM GENERATOR

(tower) holds receiver

- The primary energy source (sun) is clearly uncontrollable.
- What is controllable, by focusing or de-focusing the mirrors, is the *amount* of the available power that the plant actually draws ⇒ the mirror focusing plays more or less the role of θ_f, but subject to the variability above (representable as a variable μ_f).
- Main problems: the said variability and the difficulty of introducing "large" energy storages (w.r.t. that provided by the SG alone).

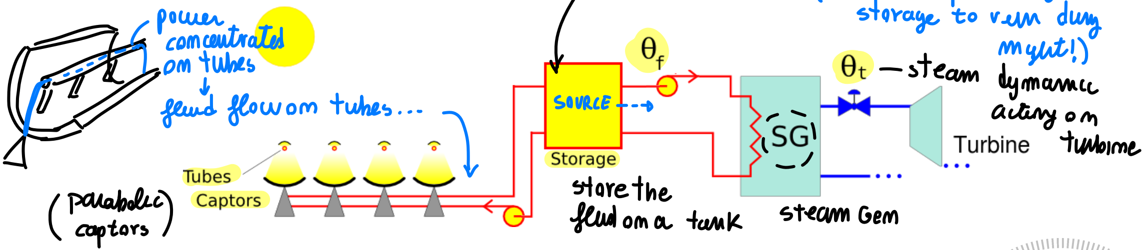
Solar plant

of the thermal (thermodynamic) type – alternative setup

to run continuous.. NOT ON/OFF

(to quench some radiation variation to the steam Generator)

- An example:



- The primary fluid (e.g., molten salt) allows for a significant heat storage, thereby smoothing the source variability seen by the SG $\Rightarrow$ the situation is more similar to the reference thermo case.
- Note: the figure is *highly* simplified as for the hot fluid storage management.

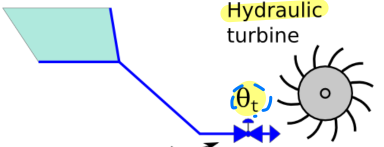
Hydro plant

hidro powers → for fast load variation (immediate open valve) → energy

@ gen time scale... unlimited energy in the lake

- Very simple scheme:

↳ { only θ_t control variable! }



↳ only θ_t

- At the generator control time scale, the energy reserve (basin) may be considered unlimited. Also, the piping height typically dominates that of the basin ⇒ constant pressure at the valve inlet.

↳ several [m] before reach turbine

- The mechanical power can be assumed to be an algebraic function of the turbine (throttling) valve command, i.e.,

like having ∞ energy available reserve

$$P_g = f(\theta_t),$$

depending on other parameters

although rigorously depending also on rotor and fluid speed (losses are due e.g. to residual jet kinetic energy).

- ...and so forth for other generator types.

Generators without rotating masses

(just a couple of words)

- Notable examples are photovoltaic generators and fuel cells.
- In both cases there is a primary source, either vastly exogenous (solar radiation) or well controllable (fuel).
- Then, there may or may not be a significant reserve (this is not the case e,g, for a photovoltaic generator without batteries).
- The process of generating electricity does not involve mechanics and is mostly solid-state, thus one can think that power can be commanded independently of frequency, while synchronisation with the network is always guaranteed. (remain synchronized, all electronic)
- In one word, these generators as well fall in our system-level model structure. Enough on the matter for this course.

Transmission lines

in AC networks

- A transmission line is readily represented as the series of a resistance and an inductance
  inductance should dominate, otherwise
- In general, the latter dominates. or loosing active power on R (by Joule effect)
- For problems requiring an explicit representation of voltages and currents (such as load flow) the natural modelling approach is in the phasor domain, as a complex (almost imaginary) impedance.
- For problems just requiring represent powers as signals, and in particular concentrating on active power as in frequency control, lines are in fact just losses, and can be represented (if necessary) by efficiencies conveniently located in the network.

active power enter

loss

active power out

Transmission lines

in AC networks

- As anticipated, for the type of problems we address, we are not representing transformers. (simplified)
- The matter is treated in specialised courses, as is reactive power control and network contingency management.
- When necessary, for the problems we face, one could just account for the inevitable losses across transformers, resort to an efficiency-based description here as well.

Generic loads

we can have 2 view points

(electrical POV)

- When representing voltages and currents, loads can be either
  - 1) impedances (obviously) variable ← electrical P.O.V → more / less power by impedence value
  - useful for control → 2) or devices drawing a specified active (and reactive) power thanks to some internal controls, as is more and more frequently the case with inverters. usefull POV for control
- When representing just power flows as signals, load are clerly just part of such signals, either exogenous or – when talking about "demand side control" – subjected to some management policy instead of just coming from requests (*) ⇒ on the part of the utilisers.

possible consumption reducing non visible to handle network management (can be done on high scale)

- We shall be more specific on the matter just sketched when it comes to control problems.

↳ CONTROL in electrical systems

(*) demand side control ~> by a small consumption reduction → you can aim to reduce all overall

decide for temporary reduction, obtaining BIG consumption reduction