ELEC0047 - Power system dynamics, control and stability

Excitation systems and automatic voltage regulators

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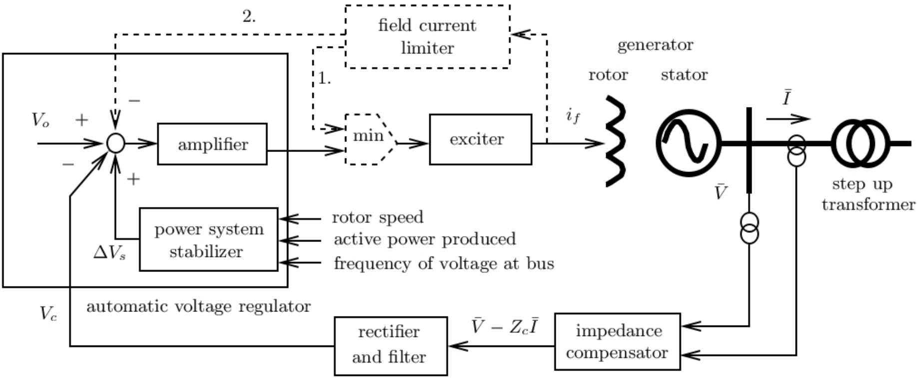
Overview


2.
field current
limiter
1.
generator
rotor
stator
V_o
+
−
−
+
amplifier
min
exciter
i_f
$\bar{I}$
$\bar{V}$
step up
transformer
power system
stabilizer
ΔV_s
rotor speed
active power produced
frequency of voltage at bus
V_c
automatic voltage regulator
rectifier
and filter
$\bar{V} - Z_c\bar{I}$
impedance
compensator

Description of main excitation systems

Purposes of excitation system:

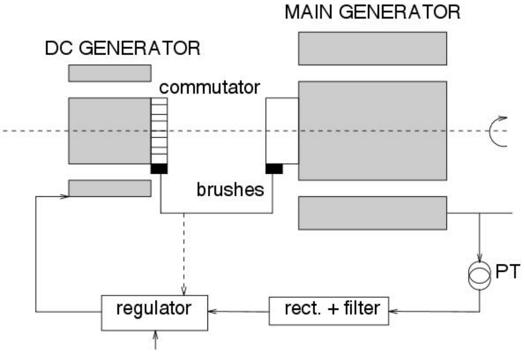
- provide the power required by the field winding of generator
- make the field voltage v_f quickly vary in response to network disturbances.

Two main categories:

1. rotating machine: excitation power taken from mechanical power of turbine $\Rightarrow$ mounted on the same shaft as turbine and generator
    - Direct Current (DC) machine
    - Alternating Current (AC) machine with rectifier
2. static excitation system: excitation power taken from network through a transformer and a rectifier.

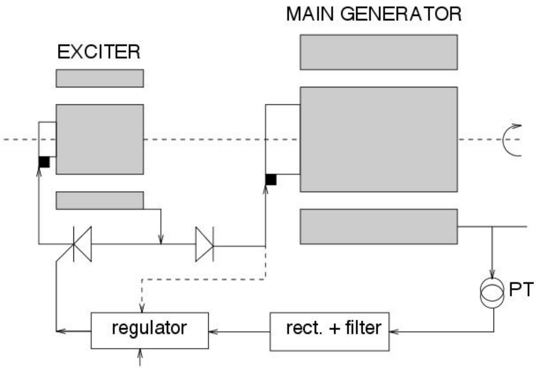
- There is a wide range of systems
    - each manufacturer has its own equipment and know-how
- We limit ourselves to a short description of the main systems without going into details

DC generator



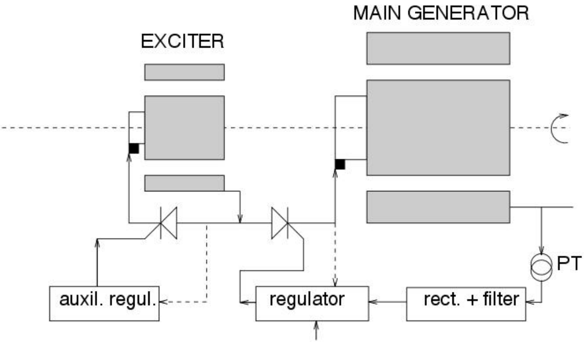
- Non negligible time constant of exciter
- the DC generator can be:
  - self-excited or
  - separately excited: requires a "pilot" exciter = separate permanent magnet DC machine
- not suited to large units: collector speed below brushes and current too large
- has been replaced by power electronics.

Alternator with non-controlled rectifier



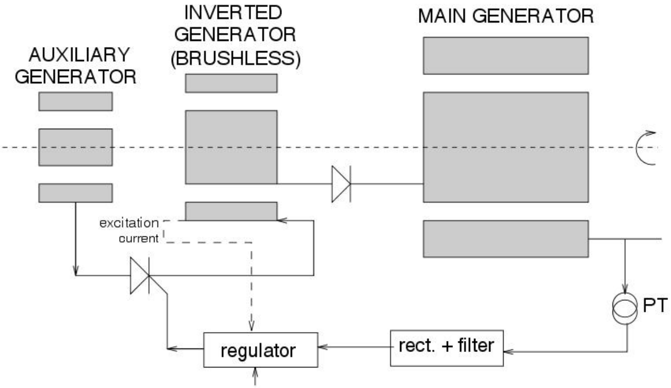
- The diode rectifier does not introduce any delay
- the firing of the thyristors can be adjusted very rapidly
- the exciter still introduces a time constant
- the diodes do not allow applying a negative field voltage (if needed during large transients)

Alternator with controlled rectifier



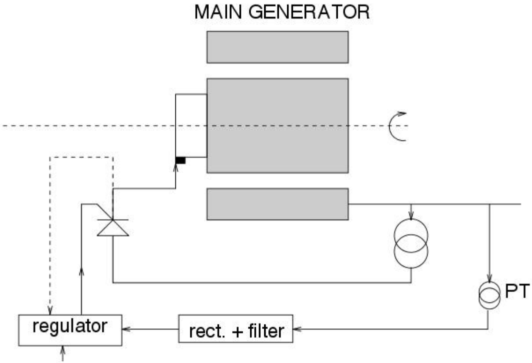
- The field voltage v_f is varied by changing the firing angle of the thyristors, which involves a very short delay
- the auxiliary regulator maintains the terminal voltage of the exciter constant
- to avoid delays, the exciter alternator operates at full voltage; hence, it is dimensioned to operate permanently at ceiling field voltage
- the thyristors allow applying a negative field voltage (if needed during large transients).

Rotating diodes or "brushless" system



- Very widespread system
- no contact between stator and rotor (no brushes, no slip rings)
- the rate of change of the field voltage v_f is limited by the response time of the inverted generator
- no access to the field current i_f of the main generator; the excitation current of the inverted generator is used as an "image" of i_f.

Potential-source controlled-rectifier or “static” exc. system



- A very fast excitation system
- the excitation power is drawn from the main generator bus or from an auxiliary bus
- in case of short-circuit close to the main generator, the voltage of the transformer feeding the excitation system drops; this limits the ceiling field voltage.

Modelling of excitation systems, regulators and limiters

IEEE

421.5™

IEEE Recommended Practice for Excitation System Models for Power System Stability Studies

IEEE Power Engineering Society

Sponsored by the
Energy Development and Power Generation Committee

IEEE
3 Park Avenue
New York, NY 10016-5997, USA

21 April 2006

IEEE Std 421.5™-2005
(Revision of
IEEE Std 421.5-1992)

Per unit system

The following base is usually considered :

- V_{fB}: the field voltage that produces the nominal voltage V_B at the terminal of the open-circuited generator rotating at the nominal speed
- I_{fB}: the field current that produces the nominal voltage V_B at the terminal of the open-circuited generator rotating at the nominal speed.

In steady state, in Volt:

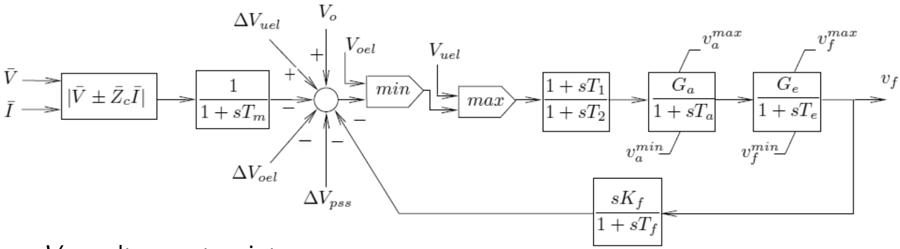
$$v_f = R_f \, i_f$$

and in per unit:

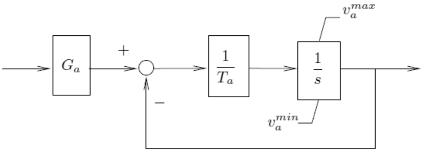
$$v_{fpu} = \frac{v_f}{V_{fB}} = \frac{R_f \, i_f}{R_f \, I_{fB}} = i_{fpu} \quad \Leftrightarrow \quad R_{fpu} = 1$$

This base is different from the one used for the synchronous generator. A change of base is thus necessary.

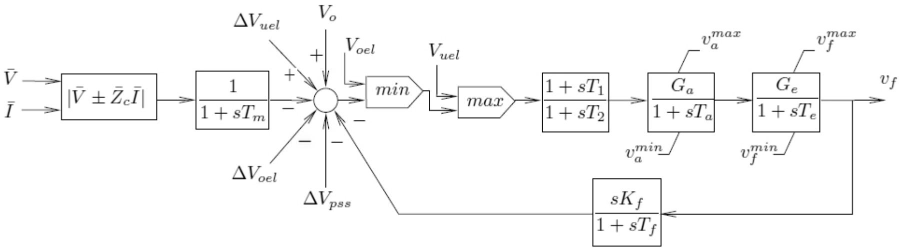
Simple generic model of automatic voltage regulator and excitation system



- V_o: voltage set-point
- Z_c: compensation impedance; see course ELEC0014
- ΔV_{pss}: output of power system stabilizer[1] (zero in steady state)
- $1/(1+sT_m)$ relates to rectification and filtering of AC voltage; $T_m \simeq 0.05$ s
- $G_a/(1+sT_a)$ relates to an amplifier; $T_a \simeq 0.05$ s. Non-windup limit:



[1] see lecture on small-disturbance angle stability

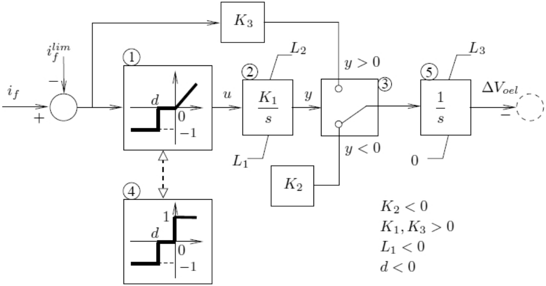


- $G_e/(1+sT_e)$ relates to the excitation system; wide variety of values: $T_e \simeq$ from a few 0.01 s to 1 s
- internal compensation of the Automatic Voltage Regulator (AVR):
  - provides desired dynamic response (settling time, overshoot, etc.) usually specified for the generator with stator open
  - either by lead-lag filter $(1+sT_1)/(1+sT_2)$ in the direct path, or by derivative feedback $sK_f/(1+sT_f)$ in the feedback path
  - *transient gain reduction* : $T_1 < T_2$
- the *OverExcitation Limiter* (OEL) acts either through the *min* gate or through the correction signal ΔV_{oel} (see slides 14 and 15)
- the *UnderExcitation Limiter* (UEL) acts either through the *max* gate or through the correction signal ΔV_{uel} (see slide 16)

Various items that can be added to the above generic model:

- for a diode rectifier: the (rectified) v_f voltage decreases when the field current i_f increases
- brushless system: internal compensation does not use the (unavailable) v_f voltage
- $v_f^{min} = 0$ for the diode rectifier, $v_f^{min} < 0$ for the thyristor rectifier
- v_f^{max} sensitive to generator terminal voltage in the static excitation system
- magnetic saturation of exciter
- etc.

Overexcitation limiter acting on summation point of AVR ("non-takeover"):



model initialized with:

- $y = L_1 < 0$
- switch of block 3 in lower position
- $\Delta V_{oel} = 0$

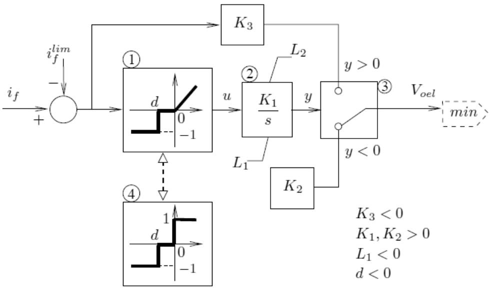
$$
\text{Bloc 1:} \quad u = \begin{cases} -1 & \text{if } i_f - i_f^{lim} \leq d < 0 \\ 0 & \text{if } d < i_f - i_f^{lim} \leq 0 \\ i_f - i_f^{lim} & \text{if } i_f - i_f^{lim} > 0 \end{cases}
$$

A value $i_f^* > i_f^{lim}$ is tolerated during a time τ such that:

$$
\left(i_f^* - i_f^{lim}\right)\tau = \frac{|L_1|}{K_1} \quad \Rightarrow \quad \tau = \frac{|L_1|}{K_1}\frac{1}{i_f^* - i_f^{lim}}
$$

inverse-time characteristic. Fixed-time obtained with block 4 instead of 1.

Overexcitation limiter acting through min gate of AVR ("takeover"):



model initialized with:

- $y = L_1 < 0$
- switch of block 3 in lower position
- $V_{oel} = K_2 >> 0$

In steady state, after OEL action:

$$v_f = G_a G_e K_3 (i_f - i_f^{lim}) \quad \Rightarrow \quad i_f = v_f = \frac{-G_a G_e\, K_3}{1 - \; G_a G_e\, K_3} i_f^{lim} = \frac{G_a G_e\, |K_3|}{1 + \; G_a G_e\, |K_3|} i_f^{lim}$$

and, since $G_a G_e \gg 1$ and $|K_3| > 1$:

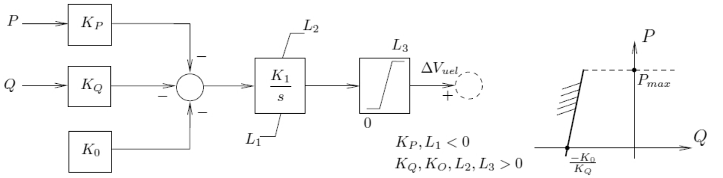
$$i_f \simeq i_f^{lim}$$

Underexcitation limiter

Aimed at preventing:

- i_f from becoming lower than a minimum, or
- reactive power Q from becoming lower than a minimum (which depends on active power P).

Example: limiter of second category, acting on summation point of AVR



The integrator output is initially at $L_1 < 0$.
If the operating point (P, Q) enters the forbidden zone where :

$$K_P\, P + K_Q\, Q + K_o < 0$$

after a delay dictated by L_1, the integrator starts acting and eventually forces :

$$K_P\, P + K_Q\, Q + K_o = 0$$