Impact of excitation system on power system stability

1. INTRODUCTION
Impact of excitation system on power system stability

THE POWER STATION

HV SYSTEM
HV BREAKER

GOVERNOR

STEP UP TRANSFORMER

SYNCHRONIZING

Synchronous generator

TURBINE

STAR POINT CUBICLE

EXCITATION TRANSFORMER

PT’s & CT’s

PROTECTION

AUX. TRANSF

AC & DC AUXILIARY SYSTEMS

LV SWITCHGEAR

CONTROL SYSTEMS

CONTROL ROOM

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The automatic voltage control system
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Rotating exciter

Static excitation

1 a 200 A

100 a 10000 A
Basic Requirements

- Excitation Current up to 10’000 amps
- Input frequency range from 16 Hz to 400 Hz
- Adaptable to different redundancy requirements for controls and converters
- State of the art man machine interface
- Compatibility with most applied power plant control systems
- Remote diagnostics
- Comfortable commissioning tools
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Operational Application
Main Components of an UNITROL 5000 System
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Main Functions of the AVR with Field Current Controller

- AVR Setpoint
  - V/Hz limiter
  - Soft start
  - Iq Compensation
  - Ip Compensation

- Underexcit. limiter
  - Q= F(P, U, Ug)
  - Stator current lead
  - Min. field current

- Overexcit. limiter
  - Max field current
  - Stator current lag

- Power System Stabilizer PSS

- Man setpoint

- Measuring and A/D conversion

- To pulse generation

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2. IMPACT ON POWER SYSTEM STABILITY

- Voltage Control Dynamics (controller, power stage and power source)
- Limiters
- Power System Stabilizer
2.1 Voltage Control Dynamics (controller, power stage and power source)
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Computer representation of the AVR

- Parameter | Description                                      | Unit | Range          |
- ---------- | ------------------------------------------------- |------|----------------|
- TR        | Measuring filter time constant                    | s    | 0.020          |
- Ts        | Gate control unit and converter time constant     | s    | 0.004          |
- KIR       | Reactive power compensation factor                | p.u. | -0.20...+0.2   |
- KIA       | Active power compensation factor                  | p.u. | -0.20...+0.2   |
- KR        | Steady state gain                                 | p.u. | 10...1000      |
- Kc        | Voltage drop to commutations and impedances       | p.u. | Acc. Transf.   |
- TB1       | Controller first lag time constant                 | s    | TB1≥TB2        |
- TB2       | Controller second lag time constant                | s    | 0<TB2≤TC2      |
- TC1       | Controller first lead time constant               | s    | 0.01...10      |
- TC2       | Controller second lead time constant              | s    | 0.01...2       |
- Up+       | AVR output positive ceiling value                 | p.u. | Fixed          |
- Up-       | AVR output negative ceiling value                 | p.u. | Fixed          |
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Synchronous machine
three-phase representation
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d-q decomposition
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Torque

The characteristic Dynamic Equation

\[ TM = \frac{PM}{\text{speed}} \]

\[ TE = \frac{US \cdot Ep \cdot \sin \delta}{Xq + XT + XE} \]

Motion equation:

\[ TM - TE = 2 \cdot H \cdot \frac{d\omega}{dt} \]
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AVR - Voltage control dynamic

- **System type** (Static excitation, Brush-less, DC Exciter)
- **Settings of control algorithm**
- **Response time**
- **Ceiling capabilities**

“Excitation system nominal response”
IEEE 421.1

Abbreviation (NR):
\[ NR = \frac{ce - ao}{(ao)(oe)} \]
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### Comparison of Excitation System Types

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<tr>
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<tr>
<td><strong>Mechanical</strong></td>
<td></td>
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<tr>
<td>- Conversion of</td>
<td>yes</td>
<td>yes</td>
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<td>mech. to electr.</td>
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<tr>
<td>Energy</td>
<td></td>
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<td></td>
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<tr>
<td>- Size of exciter</td>
<td>power and speed</td>
<td>power and speed</td>
<td>power and speed</td>
<td>power</td>
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<tr>
<td>- Sliprings</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
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<tr>
<td><strong>Electrical</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>- Rectifier</td>
<td>not required</td>
<td>static external</td>
<td>static rotary</td>
<td>static</td>
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<tr>
<td>- Direct</td>
<td>possible</td>
<td>possible</td>
<td>not possible</td>
<td>possible</td>
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<tr>
<td>measuring of field</td>
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<tr>
<td>current</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>- Fast field</td>
<td>possible</td>
<td>possible</td>
<td>not possible</td>
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<td>suppression</td>
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#### Comparison of Exciter Characteristics

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<tr>
<td><strong>Dynamic Performance</strong></td>
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<td></td>
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<tr>
<td>- Major time constant of control circuit</td>
<td>Td’L+TE</td>
<td>Td’L+TE</td>
<td>Td’L+TE</td>
<td>Td’L</td>
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<tr>
<td>- Ceiling factor</td>
<td>limited</td>
<td>not limited</td>
<td>limited</td>
<td>not limited</td>
</tr>
<tr>
<td>- Negative field current</td>
<td>possible</td>
<td>not possible</td>
<td>not possible</td>
<td>possible</td>
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<tr>
<td><strong>Reliability (MTBF)</strong></td>
<td></td>
<td></td>
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<tr>
<td>- Machine, Transformer</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>better</td>
</tr>
<tr>
<td>- Converter</td>
<td>good</td>
<td>better</td>
<td>better</td>
<td>better</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>- Machine, Transf.</td>
<td>at standstill</td>
<td>at standstill</td>
<td>at standstill</td>
<td>at standstill</td>
</tr>
<tr>
<td>- Converter</td>
<td>at standstill</td>
<td>during operation</td>
<td>at standstill</td>
<td>during operation</td>
</tr>
</tbody>
</table>
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150 ms 3ph fault at HV system

Ceiling limit
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2.2 LIMITERS
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Setpoint building
Automatic channel

- Setpoint
- Soft start
- V/Hz limiter
- Q influence
- P influence

Follow up
Automatic

Ug
AC

Transducer and filter

Ug actual

Under excitation limiters (UEL)

Over excitation limiters (OEL)

Power system stabilizer (PSS)

Gain
DC Gain
HF gain

1/TA 1/TB

Ucmin
Ucmax

Follow up
Automatic

Manual set point

Follow up Manual

Follow up control

Uc AVR

Uc FCR

Uc FCR

AVR

IF

Transducer and filter

Gain
DC Gain
P gain

1/TA 1/TB

Ucmin
Ucmax

Ucmax

Ucmin

Uc
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The Power Chart of a solid pole synchronous machine

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Synchronous machine operation Limits

Max. field current limiter
Min. field current limiter
Stator current limiter
Under excitation P,Q limiter

Theoretical stability limit
Main duty of the limiters:

Keep the synchronous machine operating within the safe and stable operation limits, avoiding the action of protection devices that may trip the unit.
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THE OPERATING PHILOSOPHY OF I_{fmax} LIMITER

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Field current x IFN vs Time [s]

Ceiling limit
thermal limit
setpoint
switch time
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Machine frequency
$\mathbf{f_T}$ [p.u.]

Machine terminal voltage
$\mathbf{U_T}$ [p.u.]

Machine field current
$\mathbf{IF}$ [p.u.]

Setpoint 2 for IF max limiter
(cost)

Stator current limiter
$\mathbf{IT}$ [p.u.]

Min. field current limiter
$\mathbf{IF_{min}}$

P/Q limiter
$\mathbf{KPQ}$

Look-up Table
$\mathbf{y = f(x)}$

Generator reactive power
$\mathbf{Q_T}$ [p.u.]

Generator terminal voltage
$\mathbf{U_T}$ [p.u.]

Generator active power
$\mathbf{P_T}$ [p.u.]

Stator terminal voltage
$\mathbf{U_T}$ [p.u.]

Generator terminal voltage
$\mathbf{U_T}$ [p.u.]

Generator active power
$\mathbf{P_T}$ [p.u.]

Generator reactive power
$\mathbf{Q_T}$ [p.u.]

Stator terminal voltage
$\mathbf{U_T}$ [p.u.]

Generator terminal voltage
$\mathbf{U_T}$ [p.u.]

Generator active power
$\mathbf{P_T}$ [p.u.]

Generator reactive power
$\mathbf{Q_T}$ [p.u.]

Machine terminal voltage
$\mathbf{U_T}$ [p.u.]

Machine field current
$\mathbf{IF}$ [p.u.]

Setpoint 2 for IF max limiter
(cost)

Stator current limiter
$\mathbf{IT}$ [p.u.]

Min. field current limiter
$\mathbf{IF_{min}}$

P/Q limiter
$\mathbf{KPQ}$

Look-up Table
$\mathbf{y = f(x)}$
2.3 Power system Stabilizer
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Stationary and transient air gap voltages

\[ X_q(s) = X_q \cdot \frac{1 + s T q'}{1 + s T q o'} \cdot \frac{1 + s T q''}{1 + s T q o''} \]
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Transient behavior of $\Delta \omega$ and $\Delta PE$
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A)

\[ H \]

\[ XT + XE \]

Infinite Bus

B)

\[ H_1 \]

\[ XT + XE \]

\[ H_2 \]

Equivalent Inertia

\[ Heq = \frac{H_1 \cdot H_2}{H_1 + H_2} \]

taking

\[ TM - TE = 2 \cdot H \cdot \frac{d\omega}{dt} \]

\[ TM - TE = 2 \cdot H \cdot \frac{d^2\delta}{dt^2} \]

For small oscillations keeping the driving torque constant the dynamic equation linearized can be written as:

\[ \frac{2 \cdot H}{\omega n} \cdot \frac{d^2\delta}{dt^2} + \frac{D}{\omega n} \cdot \frac{d\delta}{dt} + K_1 \Delta\delta = 0 \]

Dynamic equation of synchronous machine+grid for small oscillations

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Phasor diagram of machine+grid for small oscillations (without AVR)

Oscillation frequency \( \Omega \)

\[
\Omega \approx \sqrt{\frac{K_1 \cdot \omega_n}{2 \cdot H}} \text{ rad/s}
\]

\( \delta \)

Torque

K1 = synchronizing coefficient

\[
K_1 = \text{slope} = \frac{\Delta T}{\Delta \delta} = \frac{E_p \cdot U_s}{X_q + X_E + X_T} \cdot \cos \delta^o'
\]
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\[
\frac{2 \cdot H}{\omega_n} \cdot \frac{d^2 \delta}{dt^2} + \frac{D}{\omega_n} \cdot \frac{d \delta}{dt} + K_1 \cdot \Delta \delta + K_2 \cdot \Delta E_p' = 0
\]


Phasor diagram of machine+grid+excitation system for small oscillations

Positive Damping (Stable Region)

Negative Damping (Unstable Region)

D/\omega_s^* \Delta \omega

\Delta \omega

\Delta U_G

\Delta U_G

\Delta E_p'

\Delta T_e = K_1 \Delta \delta

Synchronizing Axis

Resulting torque component without excitation system

Resulting torque component with excitation system

Phasor rotation
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**Fig3: PSS in the excitation system**
Main Target of PSS:

- It provides an additional torque component in order to get:

1) A positive resulting torque component on damping axis, even for the highest possible rotor oscillation frequency.

2) A positive torque component on synchronizing axis for partial compensation of generator terminal voltage variations even for the highest possible oscillation frequency.
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PSS2A acc. IEEE 421.5 1992

\[
\begin{align*}
\Delta PM &= \frac{\Delta PM}{1 + s \cdot 2 \cdot H} \\
\Delta PA &= \frac{\Delta PA}{1 + s \cdot 2 \cdot H} \\
\end{align*}
\]

\[
\begin{align*}
\Sigma &= \left[ \frac{(1 + s \cdot T8)^N}{(1 + s \cdot T9)^M} \right] \\
\end{align*}
\]

\[
\begin{align*}
\omega &= \frac{s.TW1}{1 + s.TW1} \\
s.TW2 &= \frac{s.TW2}{1 + s.TW2} \\
s.TW3 &= \frac{s.TW3}{1 + s.TW3} \\
s.TW4 &= \frac{s.TW4}{1 + s.TW4} \\
Ks2 &= \frac{Ks2}{1 + s.T7} \\
Ks3 &= \frac{Ks3}{1 + s.T7} \\
Ks1 &= \frac{Ks1}{1 + s.T1} \\
1+s.T1 &= \frac{1+s.T1}{1+s.T2} \\
1+s.T3 &= \frac{1+s.T3}{1+s.T4} \\
VSTmax &= \frac{VSTmax}{VSTmin} \\
VSTmin &= \frac{VSTmin}{VSTmin} \\
\Delta PE &= \frac{\Delta PE}{1 + s \cdot 2 \cdot H} \\
\end{align*}
\]
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Adaptive PSS (APSS) – Alternative to PSS2A

[Diagram of power system components including AVR, synchronous generator, measurement, grid, APSS, 3rd order system model, estimator, regulator, and white noise.]
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Multi Band PSS (MBPSS)

\[ \Delta \omega \]

\[ FB_1(s) \]
\[ FB_2(s) \]
\[ FI_1(s) \]
\[ FI_2(s) \]
\[ FH_1(s) \]
\[ FH_2(s) \]

\[ + \]
\[ \Sigma \]
\[ K_b \]

\[ + \]
\[ \Sigma \]
\[ K_i \]

\[ + \]
\[ \Sigma \]
\[ K_h \]

\[ \text{Output Limit} \]
To AVR

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