# Dynamic Modeling and Analysis of a Synchronous Generator in a Nuclear Power Plant

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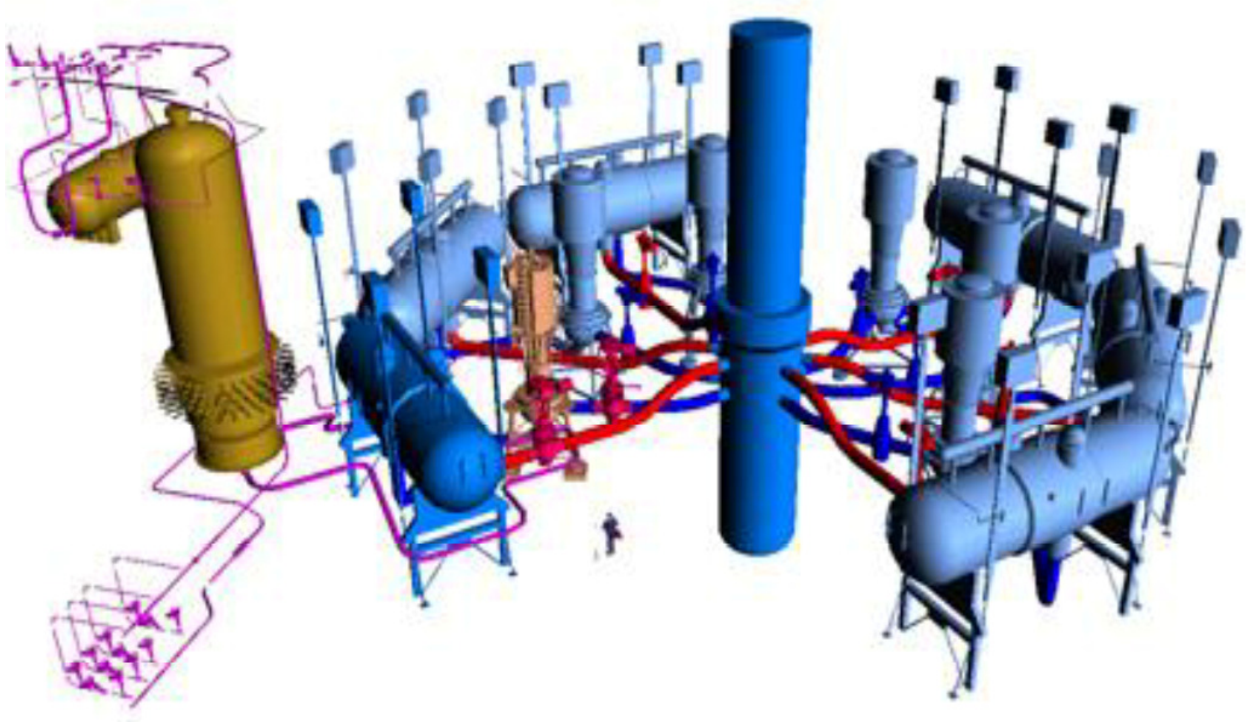
# Contents

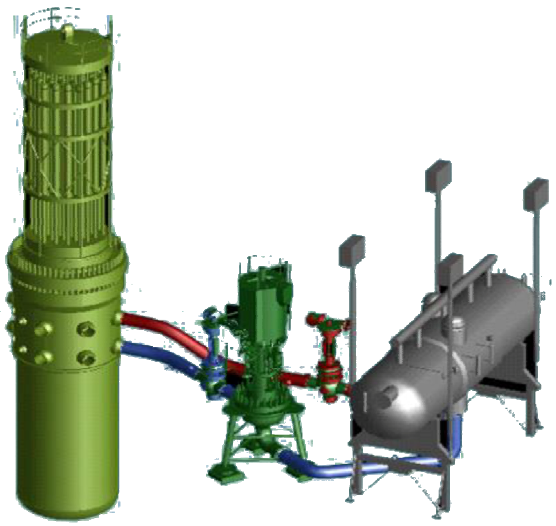
# The research plan

- **Modeling of synchronous machine (electrical and mathematical)**
- **Model analysis (e.g. stability)**
- Generator model parameter identification
- Generator model validation (partially controlled case)
- Design of synchronous generator control structure
- Controller design and validation by simulation

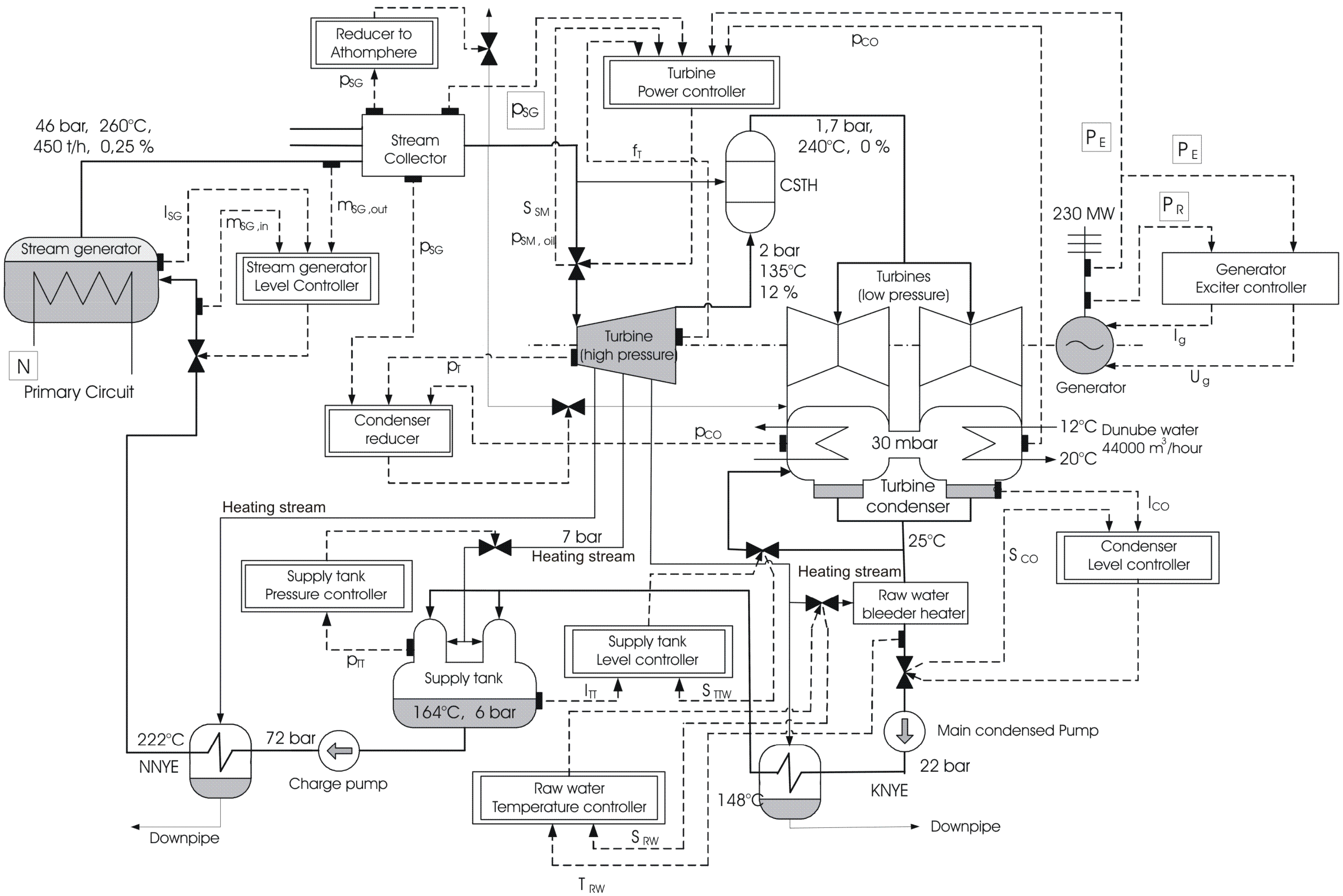
# *The primary circuit of Paks NPP*

- Pressurized water reactor (VVER 440/213)
- 6 stream generators



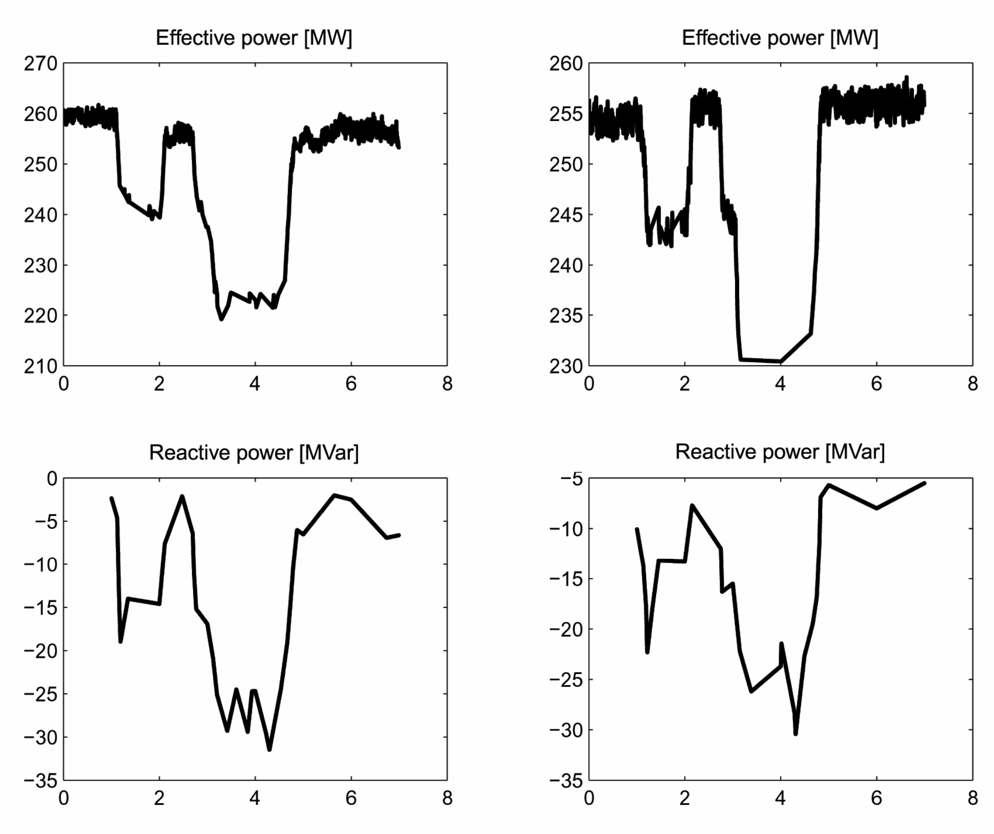


# The secondary circuit of Paks NPP

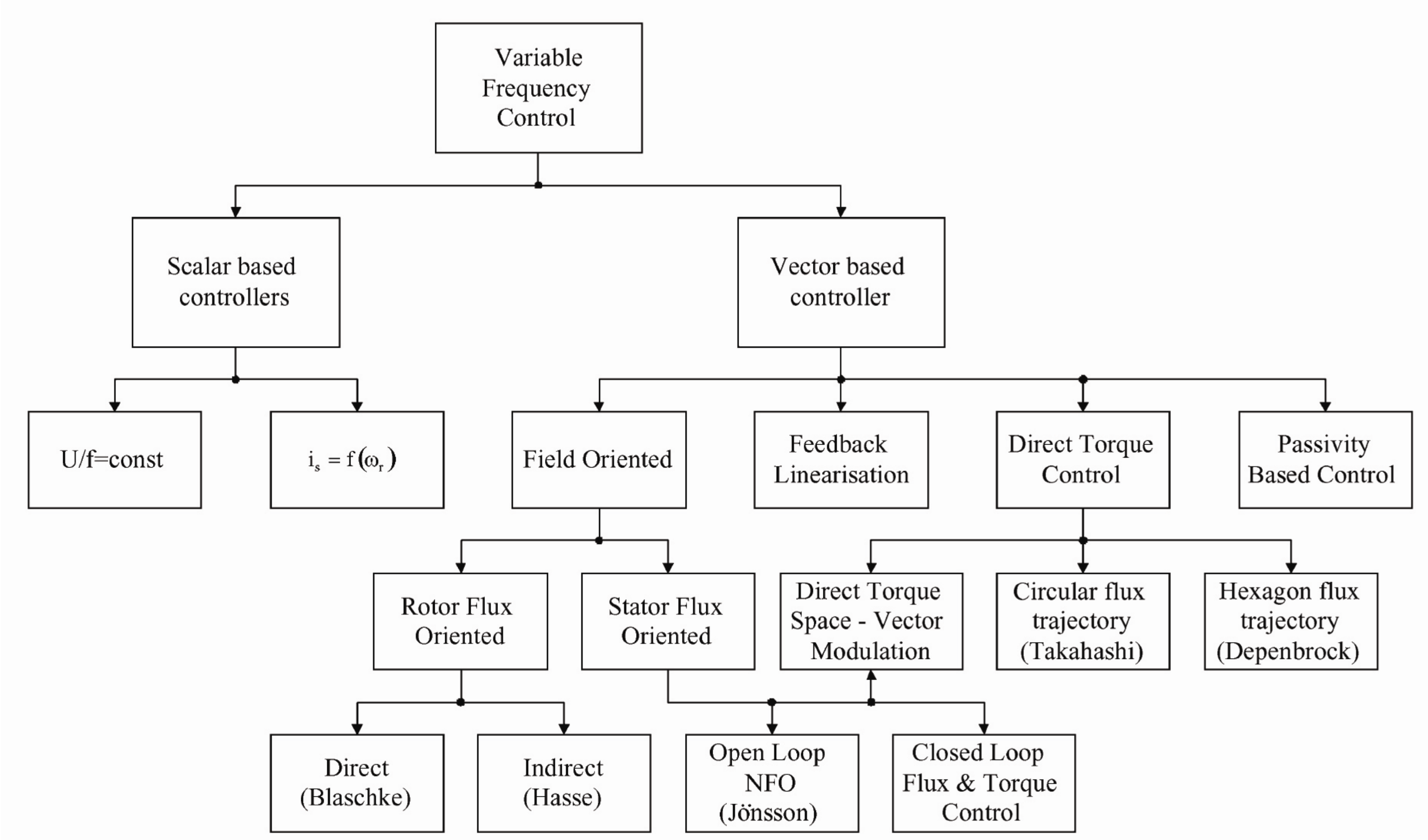


# *Introduction, problem statement*

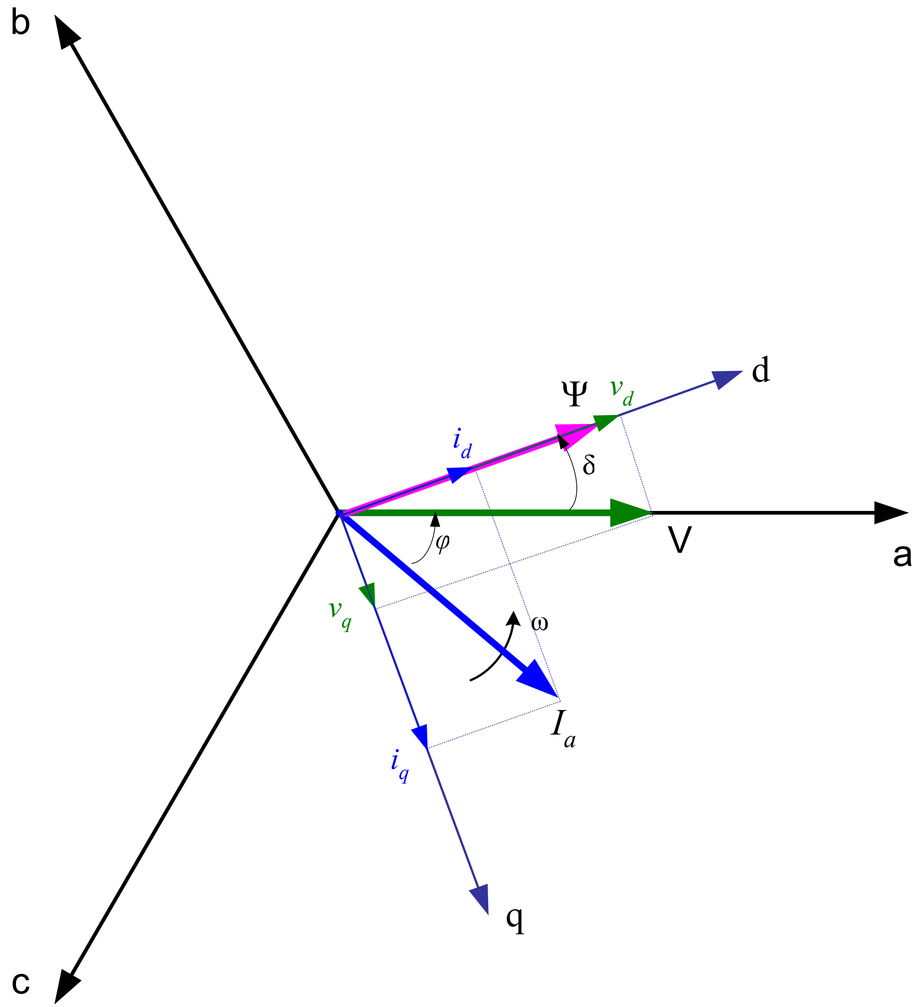
- There is no joint effective and reactive power control in the Paks NPP
- The reactive depends on the control effective power



# Classic types of the rotating machine controls



# *Vector control for a Synchronous Generator*




a,b,c: The 3 phases coordinate system

V: The „a" phase voltage vector

$I_a$: The „a" phase current vector

d: The direct axis

q: The quadratic axis

$v_q$: The quadratic component of the voltage of the SG

$v_d$: The direct component of the voltage of the SG

$i_q$: The quadratic component of the current of the SG

$i_d$: The direct component of the current of the SG

# The Flux Equations of the SG

- The equations in natural coordinate system

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \\ \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & L_{FQ} \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & L_{DQ} \\ L_{Qa} & L_{Qb} & L_{Qc} & L_{QF} & L_{QD} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_F \\ i_D \\ i_Q \end{bmatrix}$$

- The equations in d-q coordinate system

$$\begin{bmatrix} \lambda_0 \\ \lambda_d \\ \lambda_q \\ \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_Q \\ 0 & kM_F & 0 & L_F & M_R & 0 \\ 0 & kM_D & 0 & M_R & L_D & 0 \\ 0 & 0 & kM_Q & 0 & 0 & L_Q \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_Q \end{bmatrix}$$

# *State-Space model of the SG*

- The nonlinear state-space model of the SG

$$\begin{bmatrix} \dot{\lambda}_d \\ \dot{\lambda}_F \\ \dot{\lambda}_D \\ \dot{\lambda}_q \\ \dot{\lambda}_Q \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{r}{l_d}(1-\frac{L_{MD}}{l_d}) & \frac{r}{l_d}\frac{L_{MD}}{l_F} & \frac{r}{l_d}\frac{L_{MD}}{l_D} & -\omega & 0 & 0 \\ \frac{r_F}{l_F}\frac{L_{MD}}{l_F} & -\frac{r_F}{l_F}(1-\frac{L_{MD}}{l_F}) & \frac{r_F}{l_F}\frac{L_{MD}}{l_D} & 0 & 0 & 0 \\ \frac{r_D}{l_D}\frac{L_{MD}}{l_d} & \frac{r_D}{l_D}\frac{L_{MD}}{l_F} & -\frac{r_D}{l_D}(1-\frac{L_{MD}}{l_D}) & 0 & 0 & 0 \\ \omega & 0 & 0 & -\frac{r}{l_q}(1-\frac{L_{MQ}}{l_q}) & \frac{r}{l_q}\frac{L_{MQ}}{l_Q} & 0 \\ 0 & 0 & 0 & \frac{r_Q}{l_Q}\frac{L_{MQ}}{l_q} & -\frac{r_Q}{l_q}(1-\frac{L_{MQ}}{l_Q}) & 0 \\ -\frac{L_{MD}}{3\tau_j l_d^2}\lambda_q & -\frac{L_{MD}}{3\tau_j l_d l_F}\lambda_q & -\frac{L_{MD}}{3\tau_j l_d l_D}\lambda_q & \frac{L_{MD}}{3\tau_j l_q^2}\lambda_d & \frac{L_{MD}}{3\tau_j l_d l_Q}\lambda_d & \frac{D}{\tau_j} \end{bmatrix} \begin{bmatrix} \lambda_d \\ \lambda_F \\ \lambda_D \\ \lambda_q \\ \lambda_Q \\ \omega \end{bmatrix} + \begin{bmatrix} -v_d \\ v_F \\ 0 \\ -v_q \\ 0 \\ \frac{T_m}{\tau_j} \end{bmatrix}$$

$$\begin{aligned} p_{out} &= v_d \frac{1}{l_d}(\lambda_d - \lambda_D) + v_q \frac{1}{l_q}\lambda_q \\ q_{out} &= v_d \frac{1}{l_q}\lambda_q - v_q \frac{1}{l_d}(\lambda_d - \lambda_D) \end{aligned}$$

$$x = \left[\ \lambda_d\ \lambda_F\ \lambda_D\ \lambda_q\ \lambda_Q\ \omega\ \right]^T,\ y = [p_{out}\ q_{out}]^T,\ u = [v_d\ v_F\ v_q\ T_m]^T$$

- The steady-state values (in p.u. units)

$$\lambda_d = 1.345,\ \lambda_q = 1.934,\ \lambda_F = 1.633,\ \lambda_D = 1.094,\ \lambda_Q = 0.994$$

# Simplified State-Space Model and Stability Analysis

- The bilinear state-space model of the SG ($\dot{\omega} = 0$)

$$\begin{bmatrix} \dot{\lambda}_d \\ \dot{\lambda}_F \\ \dot{\lambda}_D \\ \dot{\lambda}_q \\ \dot{\lambda}_Q \end{bmatrix} = \begin{bmatrix} -\frac{r}{l_d}(1-\frac{L_{MD}}{l_d}) & \frac{r}{l_d}\frac{L_{MD}}{l_F} & \frac{r}{l_d}\frac{L_{MD}}{l_D} & -1 & 0 \\ \frac{r_F}{l_F}\frac{L_{MD}}{l_F} & -\frac{r_F}{l_F}(1-\frac{L_{MD}}{l_F}) & \frac{r_F}{l_F}\frac{L_{MD}}{l_D} & 0 & 0 \\ \frac{r_D}{l_D}\frac{L_{MD}}{l_d} & \frac{r_D}{l_D}\frac{L_{MD}}{l_F} & -\frac{r_D}{l_D}(1-\frac{L_{MD}}{l_D}) & 0 & 0 \\ 1 & 0 & 0 & -\frac{r}{l_q}(1-\frac{L_{MQ}}{l_q}) & \frac{r}{l_q}\frac{L_{MQ}}{l_Q} \\ 0 & 0 & 0 & \frac{r_Q}{l_Q}\frac{L_{MQ}}{l_q} & -\frac{r_Q}{l_q}(1-\frac{L_{MQ}}{l_Q}) \end{bmatrix} \begin{bmatrix} \lambda_d \\ \lambda_F \\ \lambda_D \\ \lambda_q \\ \lambda_Q \end{bmatrix} + \begin{bmatrix} -v_d \\ v_F \\ 0 \\ -v_q \\ 0 \end{bmatrix}$$

$$\begin{aligned} p_{out} &= v_d \frac{1}{l_d}(\lambda_d - \lambda_D) + v_q \frac{1}{l_q}\lambda_q \\ q_{out} &= v_d \frac{1}{l_q}\lambda_q - v_q \frac{1}{l_d}(\lambda_d - \lambda_D) \end{aligned}$$

$$x = \left[\ \lambda_d\ \lambda_F\ \lambda_D\ \lambda_q\ \lambda_Q\ \right]^T,\ y = [p_{out}\ q_{out}]^T,\ u = [v_d\ v_F\ v_q]^T$$

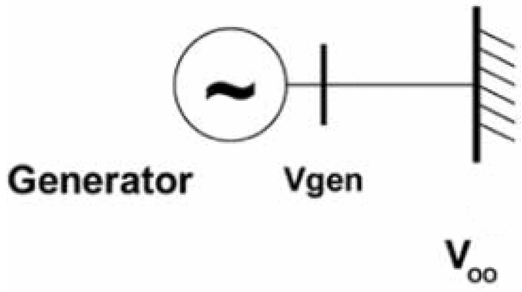
- The eigenvalues of the model (Linear State-Space Eq.)

$$\begin{aligned} \lambda_1 &= -5.686 \cdot 10^{-3} + i0.999 \qquad & \lambda_4 &= -0.117 \\ \lambda_2 &= -5.687 \cdot 10^{-3} - i0.999 \qquad & \lambda_5 &= -3.061 \cdot 10^{-3} \\ \lambda_3 &= -0.313 \end{aligned}$$

- Asymptotically stable, near the boundary, oscillating

# The simulated controller

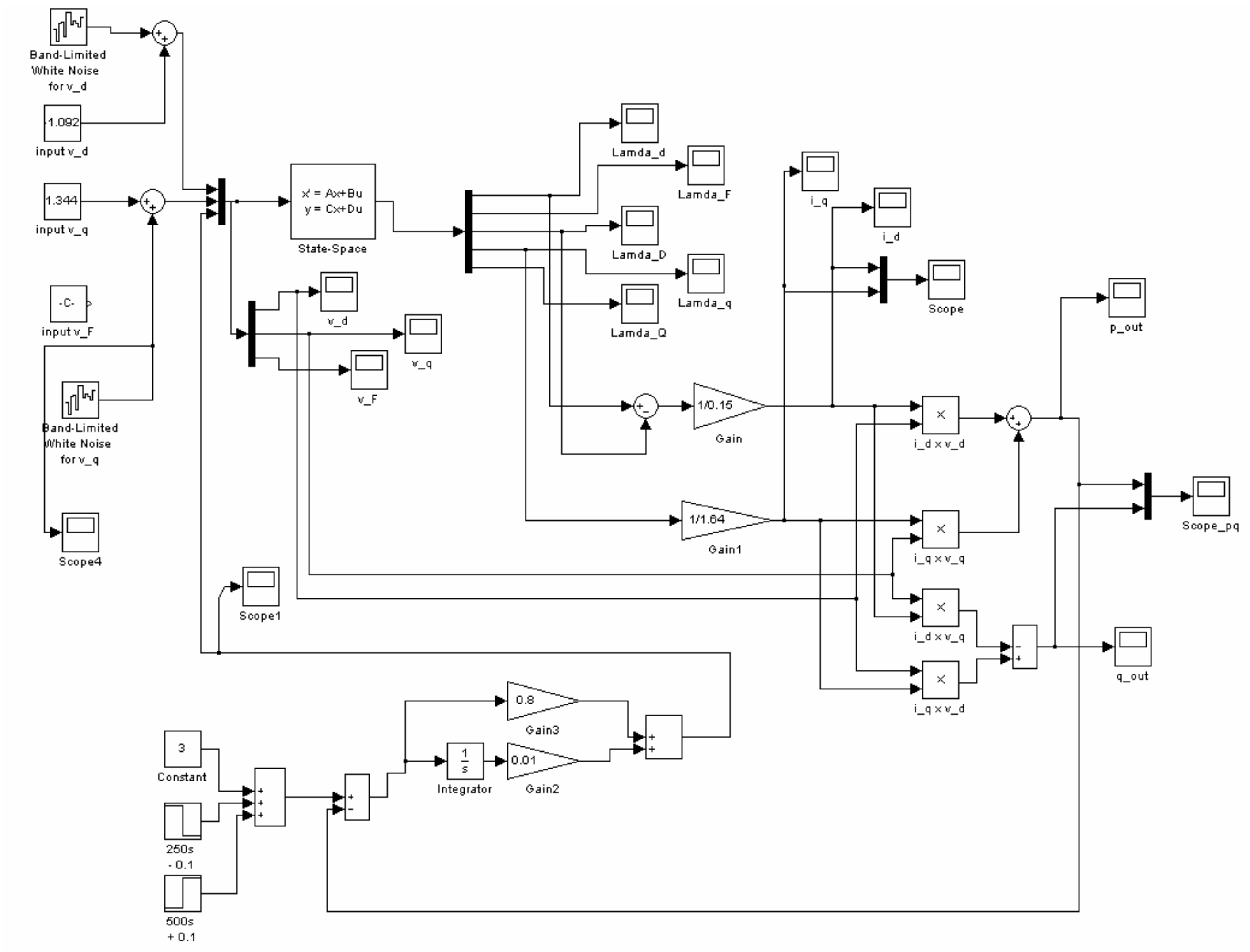
- The SG is connected to an infinite electrical network



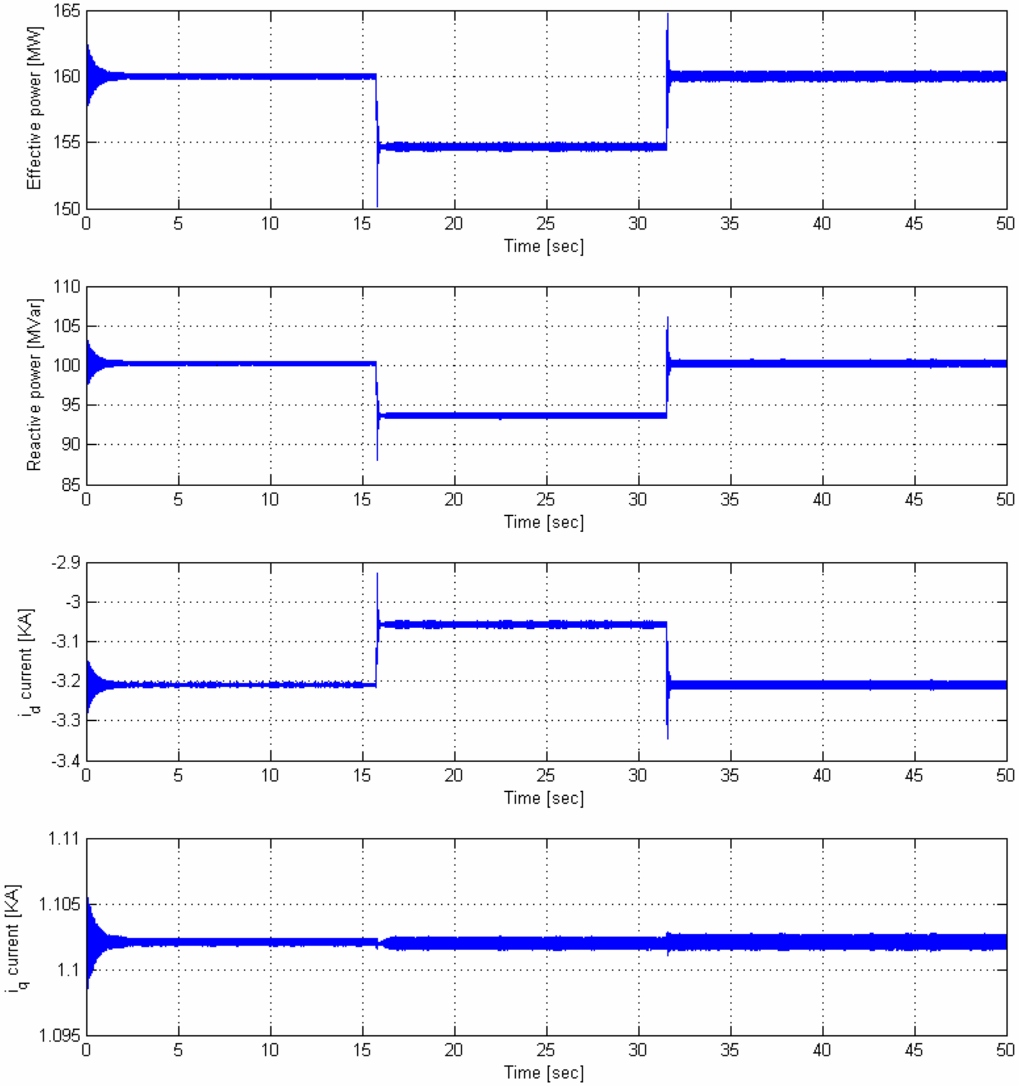

- Currently simulated controller (presently controlled case)
  - PI controller (P=0.8, I=100)
  - Controlled value: effective power ($p_{out}$)
  - Manipulated value: the exciter voltage ($v_F$)

- Generator parameters
  - P.M. Anderson and A.A. Fouad: Power-Systems-Control and Stability, The IOWA State University Press, Ames Iowa, 1977.

# *Changing the Effective Power of the SG*



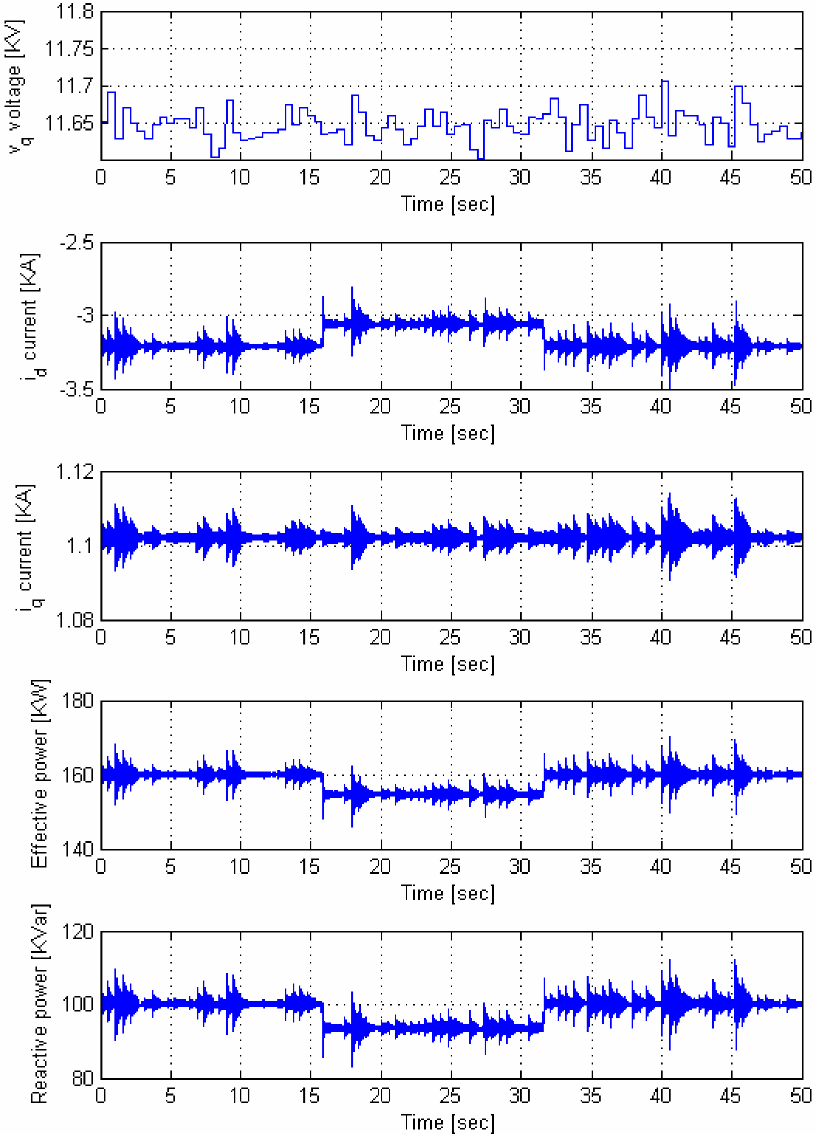
# *Changing the Effective Power of the SG*




$i_q$: The quadratic component of the current of the SG

$i_d$: The direct component of the current of the SG

# *The effect of Disturbances from the Network*




Vq: The quadratic component of the voltage of the electrical network

iq: The quadratic component of the current of the SG

id: The direct component of the current of the SG

# Conclusion and Future work

- Conclusion
  - Modeling of the SG based on engineering principles
  - A linear-bilinear state-space model is constructed for the SG
  - The model of the SG is implemented in MATLAB/Simulink
  - The set-point tracking at disturbance rejective properties were investigated by simulation

- Future work:
  - Model parameter estimation
  - Controller design
    - Linear(ised) case
    - Non-linear case