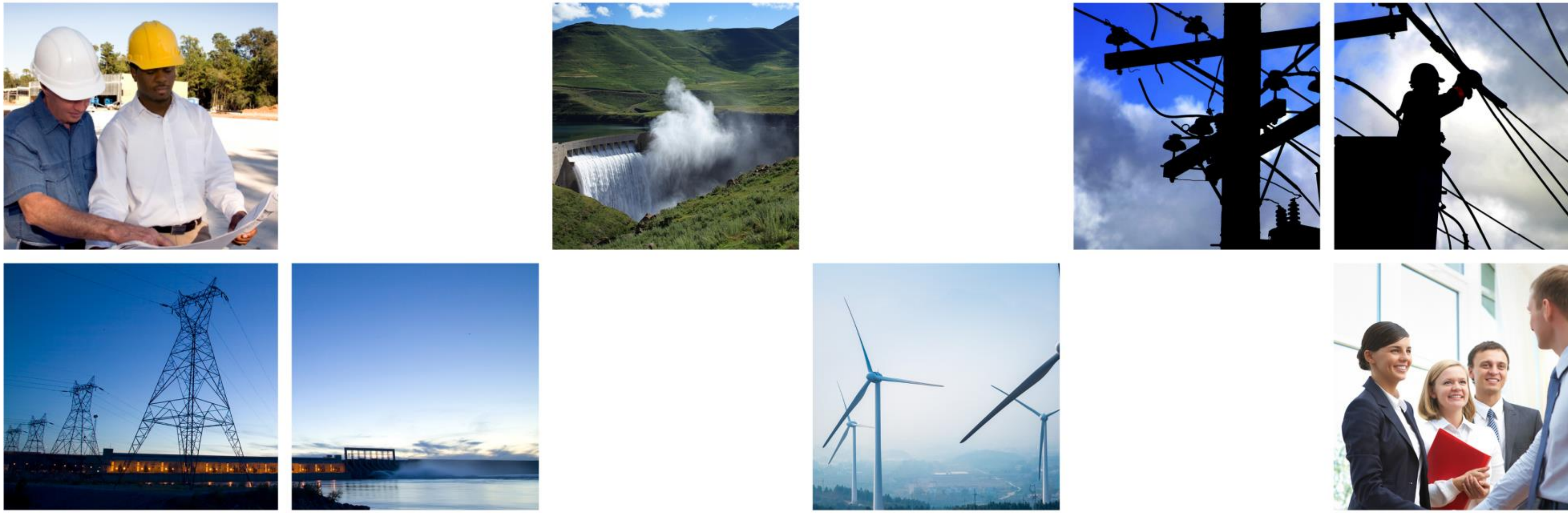


PSCAD

Machine Modeling and Power System Study Applications

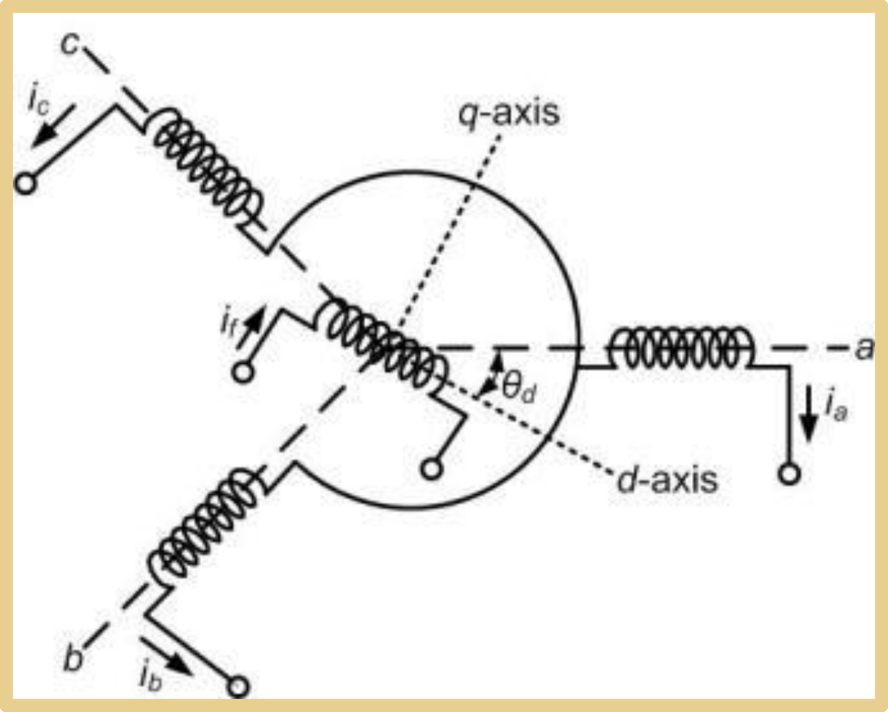
Presented by: Dharshana Muthumuni

Manitoba HYDRO INTERNATIONAL

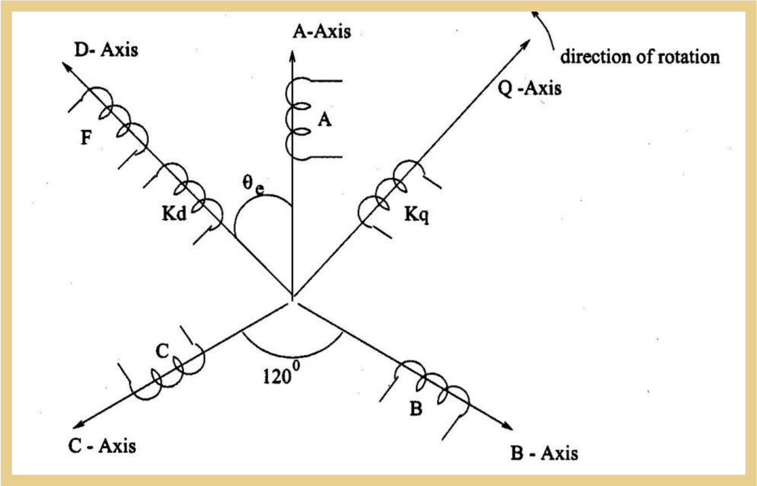
Outline - Machine Modeling and Applications

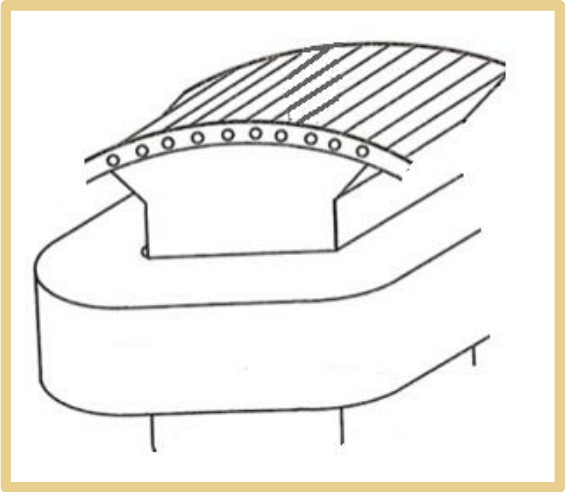
- Mathematical representation of machine windings and rotor dynamics
- Machine models and controls models available in PSCAD
- Setting up a PSCAD simulation case
    - Synchronous machine (initialization of machine and control models)
    - Induction machine (starting example)
- Illustration of Simulation examples
    - Model setup and data entry and model response
    - Model Benchmarking
    - Black start restoration studies
    - Voltage flicker due to compressor load driven by a synchronous machine
    - Sub synchronous resonance and torsional interactions
    - Voltage dips due to induction motor starting and mitigation options
    - Applications in wind generation (DFIG)

Machine windings and the mathematical representation

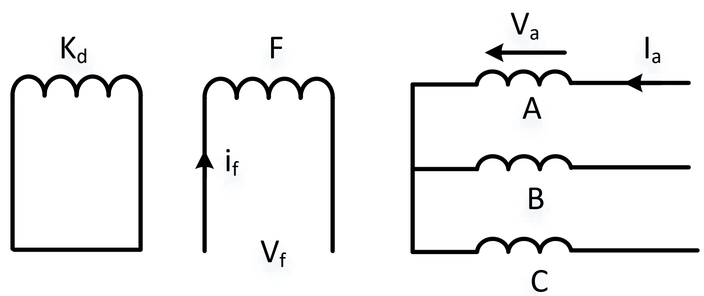


Representation of the machine coils and the direction of their magnetic axes

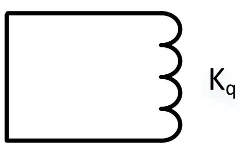




$$[V] = [R][i] + \frac{d}{dt}([L][i])$$



$$[\boldsymbol{V}] = [\boldsymbol{R}][\boldsymbol{i}] + \frac{\boldsymbol{d}}{\boldsymbol{dt}}([\boldsymbol{L}][\boldsymbol{i}])$$



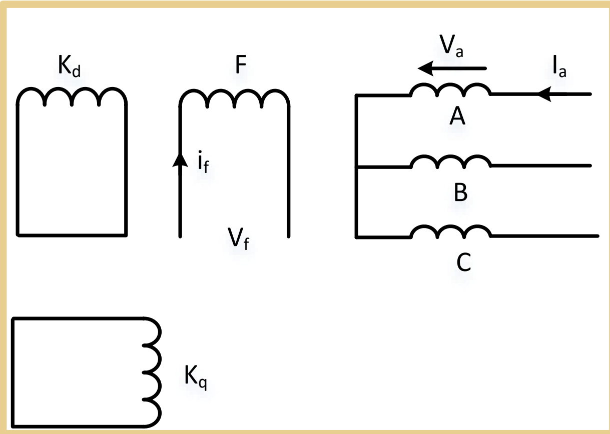
$$R := \begin{bmatrix} Rs & 0 & 0 & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 & 0 & 0 \\ 0 & 0 & Rs & 0 & 0 & 0 \\ 0 & 0 & 0 & Rf & 0 & 0 \\ 0 & 0 & 0 & 0 & Rkd & 0 \\ 0 & 0 & 0 & 0 & 0 & Rkq \end{bmatrix}$$

$$L := \begin{bmatrix} La & Mab & Mac & Maf & Makd & Makq \\ Mab & Lb & Mbc & Mbf & Mbkd & Mbkq \\ Mac & Mbc & Lc & Mcf & Mckd & Mckq \\ Maf & Mbf & Mcf & Lf & Mfkd & Mfkq \\ Makd & Mbkd & Mckd & Mfkd & Lkd & 0 \\ Makq & Mbkq & Mckq & 0 & 0 & Lkq \end{bmatrix}$$

Position dependent (time dependent) elements.

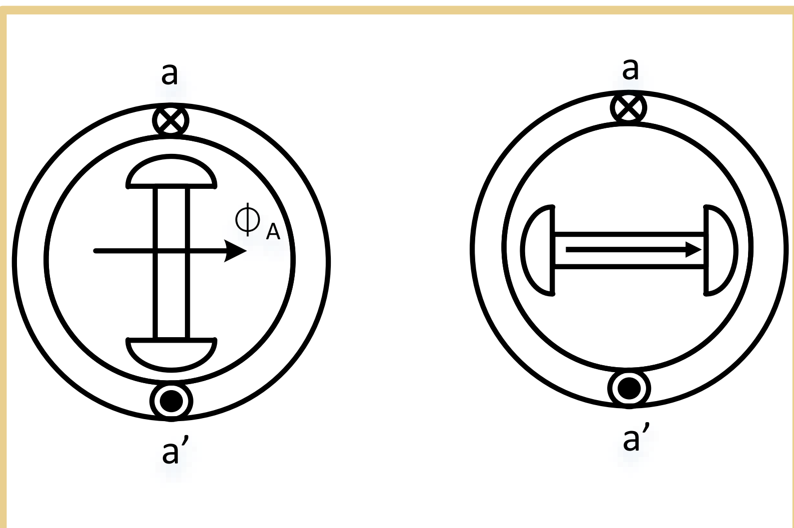
$$\boldsymbol{L_a} = (\boldsymbol{L_1} + \boldsymbol{L_2}) + \boldsymbol{L_3 Cos}(\boldsymbol{2\theta})$$

$$\boldsymbol{M_{af}} = \boldsymbol{M_f Cos}(\boldsymbol{2\theta})$$



$$[V] = [R][i] + \frac{d}{dt}([L][i])$$

$$L := \begin{bmatrix} La & Mab & Mac & Maf & Makd & Makq \\ Mab & Lb & Mbc & Mbf & Mbkd & Mbkq \\ Mac & Mbc & Lc & Mcf & Mckd & Mckq \\ Maf & Mbf & Mcf & Lf & Mfkd & Mfkq \\ Makd & Mbkd & Mckd & Mfkd & Lkd & 0 \\ Makq & Mbkq & Mckq & 0 & 0 & Lkq \end{bmatrix}$$



Position dependent (time dependent) elements of Inductance matrix

$$L_a = (L_1 + L_2) + L_3 Cos(2\theta)$$

$$M_{af} = M_f Cos(2\theta)$$

Synchronous Machine Equations in d-q reference frame

Stator Side

$$V_d = R_s . i_d + \frac{d}{dt}\lambda_d(t) - \lambda_q(t).w_r$$

$$V_q = R_s . i_q + \frac{d}{dt}\lambda_q(t) + \lambda_d(t).w_r$$

$$V_0 = R_0 . i_0 + \frac{d}{dt}\lambda_0(t)$$

Rotor Side

$$E_f = R_f . i_f + \frac{d}{dt}\lambda_f(t)$$

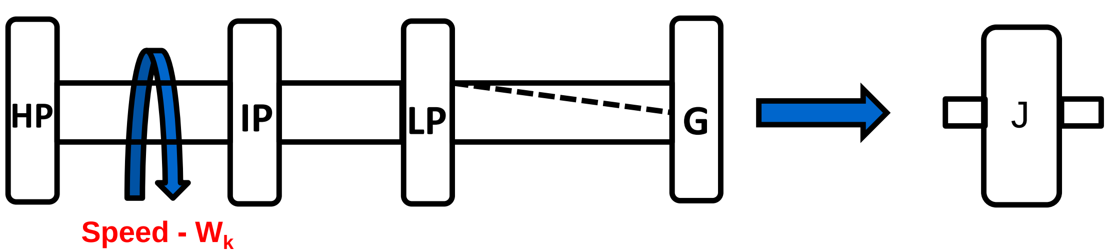
$$0 = R_{kd} . i_{kd} + \frac{d}{dt}\lambda_{kd}(t)$$

$$0 = R_{kq1} . i_{kq1} + \frac{d}{dt}\lambda_{kq1}(t)$$

$$0 = R_{kq2} . i_{kq2} + \frac{d}{dt}\lambda_{kq2}(t)$$

Dampers – 2 on Q-axis

Mechanical rotation



$$T_m - Te = J\frac{d\omega}{dt} + B\omega$$

Synchronous Machine Equations in d-q reference frame

Parameter	
Stator leakage Inductance	X_l
Synchronous Reactance	X_d
	X_q
Transient Reactance	X'_d
	X'_q
Sub transient Reactance	X''_d
	X''_q
Transient OC Time Constant	T'_{do}
	T'_{qo}
Sub transient OC Time Constant	T''_{do}
	T''_{qo}

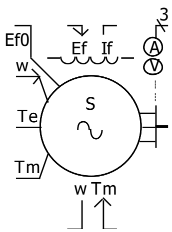
[ABC] → [dq0]

Direct linear relationship

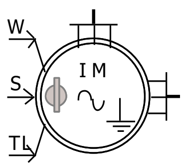
→ $L_a, L_b .. M_{ab}, .. L_f, M_{af}, L_{kd} .....$

Examples:

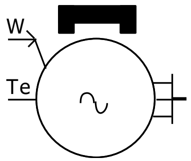
Field open time constant: $\boldsymbol{T_{d0}{}' = \frac{L_f}{R_f}}$



Synchronous Machine



Induction Machine



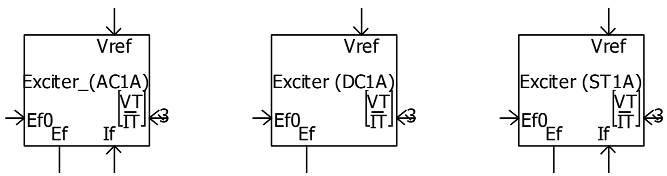
Permanent Magnet Machine

PSCAD Machine models are accurate and reliable.

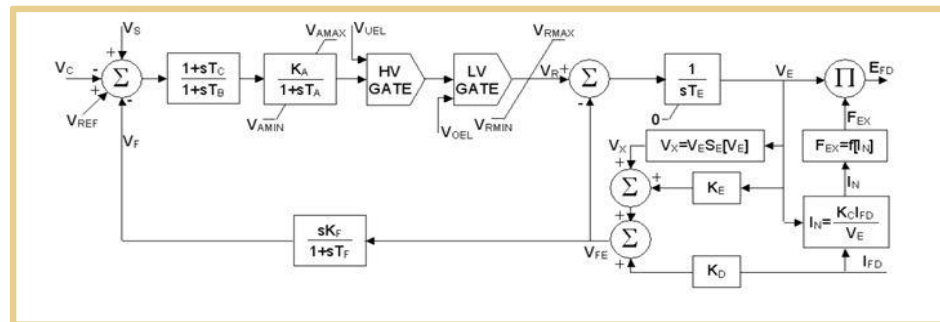
- In use for over 30 years
- Almost all major power system projects (HVDC, large generation) were studied using these models
- In recent times, the wind turbine models of all vendors use PSCAD machine models

Machine control models

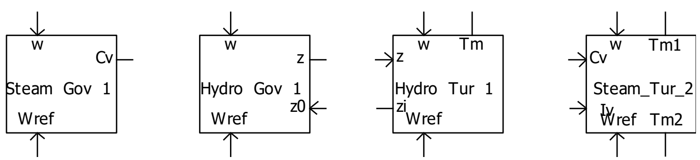
Exciter models



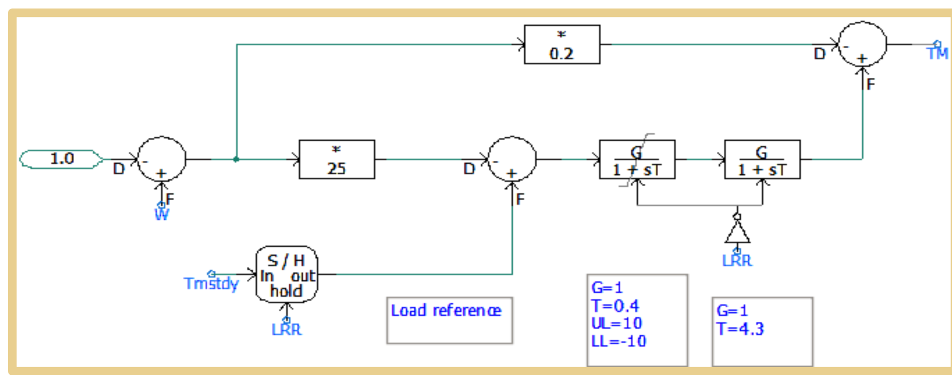
IEEE Standard exciter type AC1A



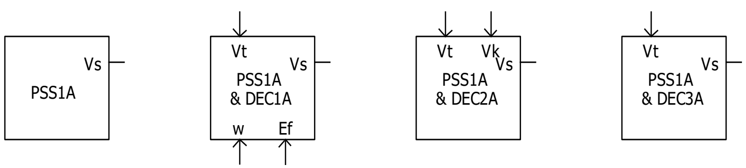
Governor/Turbine models



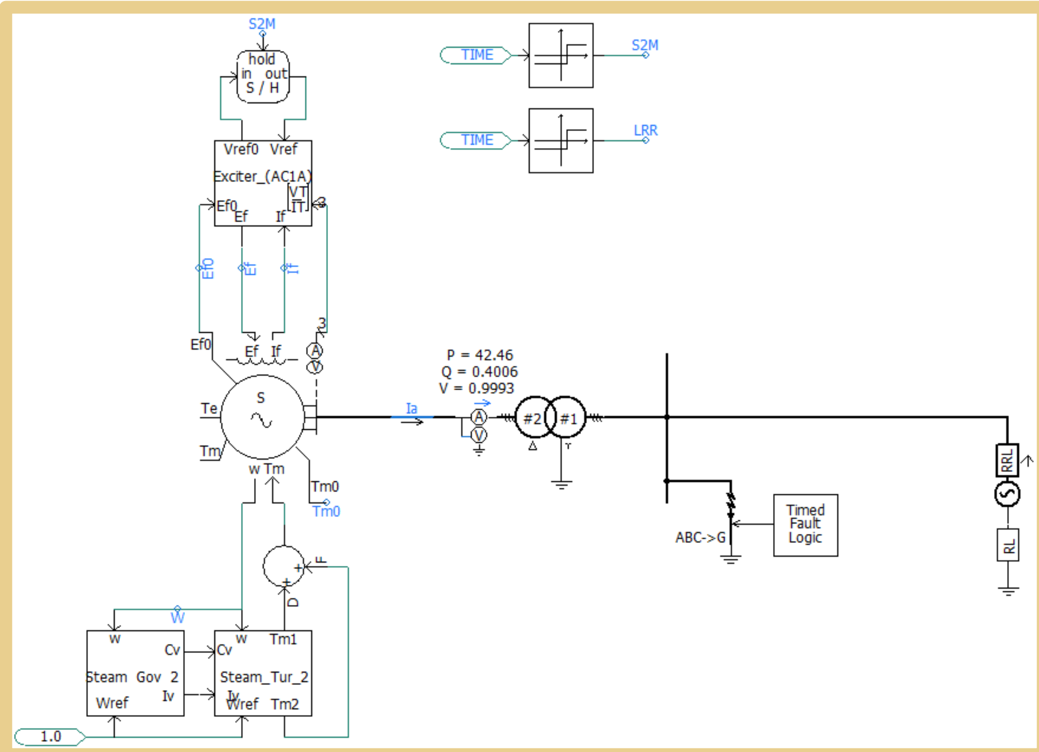
Non standard generator control systems



PSS models

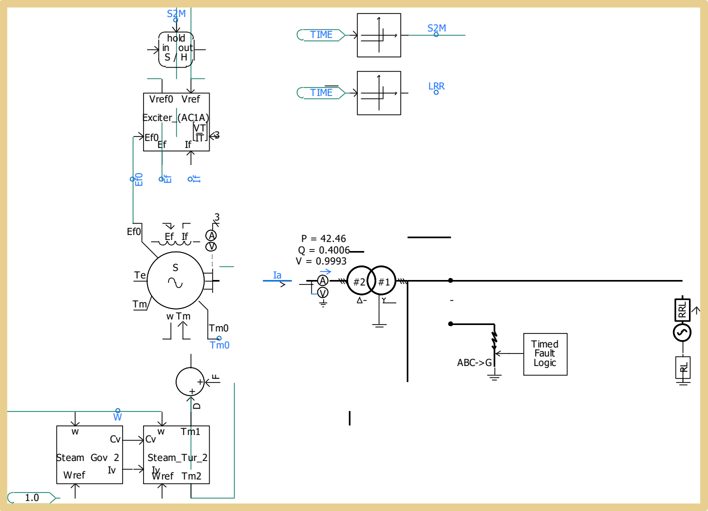


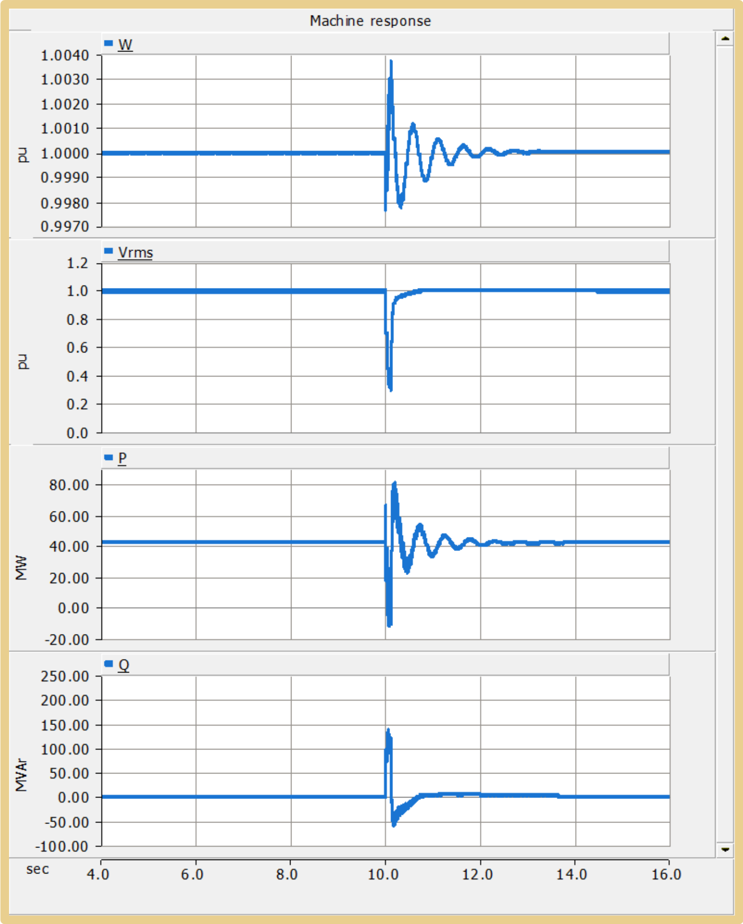
Simulation setup – Synchronous machine



Parameter		Thermal Units (Typical values)
Stator leakage Inductance	x_l	0.1-0.2
Synchronous reactance	X_d	1.0-2.3
	X_q	1.0-2.3
Transient Reactance	X'_d	0.15-0.4
	X'_q	0.3-1.0
Subtransient Reactance	X''_d	0.12-0.25
	X''_q	0.12-0.25
Transinet OC time constant	T'_{do}	3.0-10.0 s
	T'_{qo}	0.5-2.0 s
Subtransient OC Time constant	T''_{do}	0.02-0.05 s
	T''_{qo}	0.02-0.05 s

Simulation setup – Synchronous machine

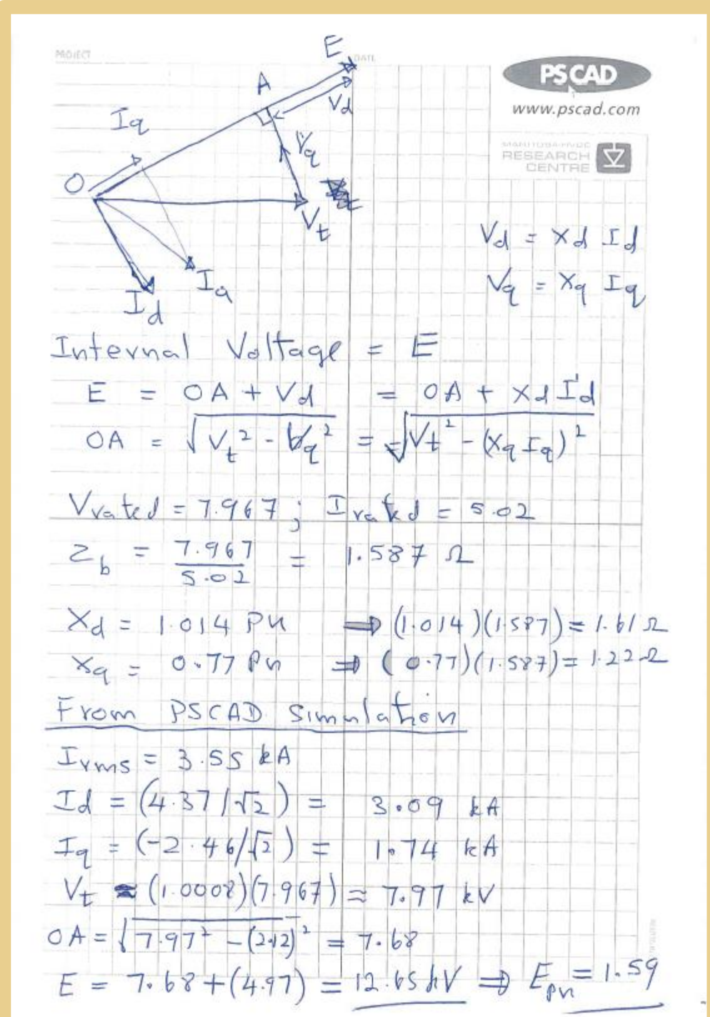




Technical note available on how to set up the machine model and controls.

Steady state operation:

Hand calculations confirm PSCAD model response



$V_d = X_d I_d$

$V_q = X_q I_q$

Internal Voltage = E

$E = OA + V_d = OA + X_d I_d$

$OA = \sqrt{V_t^2 - V_q^2} = \sqrt{V_t^2 - (X_q I_q)^2}$

$V_{rated} = 7.967$; $I_{rated} = 5.02$

$Z_b = \frac{7.967}{5.02} = 1.587\ \Omega$

$X_d = 1.014$ pu $\Rightarrow (1.014)(1.587) = 1.61\ \Omega$

$X_q = 0.77$ pu $\Rightarrow (0.77)(1.587) = 1.22\ \Omega$

From PSCAD Simulation

$I_{rms} = 3.55$ kA

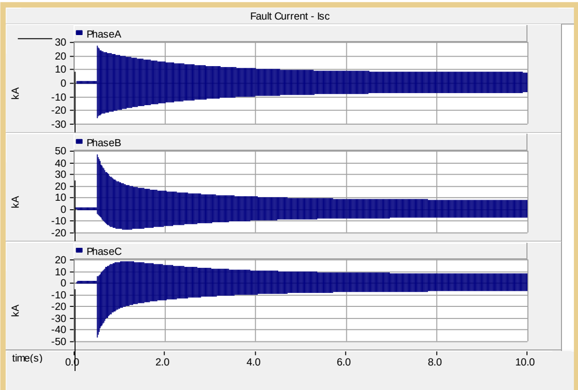
$I_d = (4.37/\sqrt{2}) = 3.09$ kA

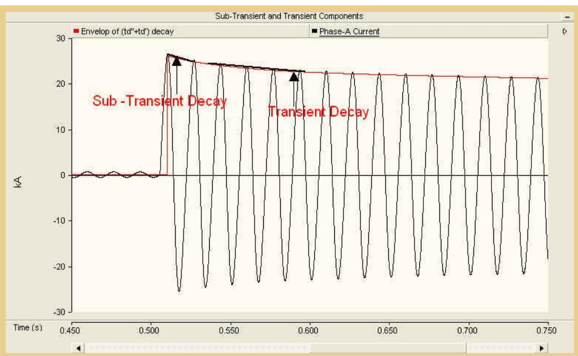
$I_q = (-2.46/\sqrt{2}) = 1.74$ kA

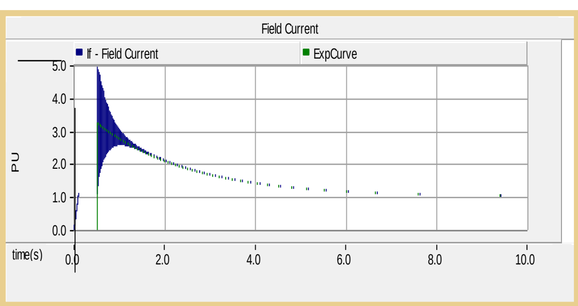
$V_t \approx (1.0008)(7.967) \approx 7.97$ kV

$OA = \sqrt{7.97^2 - (2.12)^2} = 7.68$

$E = 7.68 + (4.97) = 12.65$ kV $\Rightarrow E_{pu} = 1.59$







Transient response: PSCAD model follows expected response (see technical note)

Transient response

$$Td^{'} = \left(\frac{Xd\_}{Xd}\right)\cdot Tdo\_ = \left(\frac{0.314}{1.014}\right)\cdot 6.55 = 2.03\,s$$

Sub Transient response

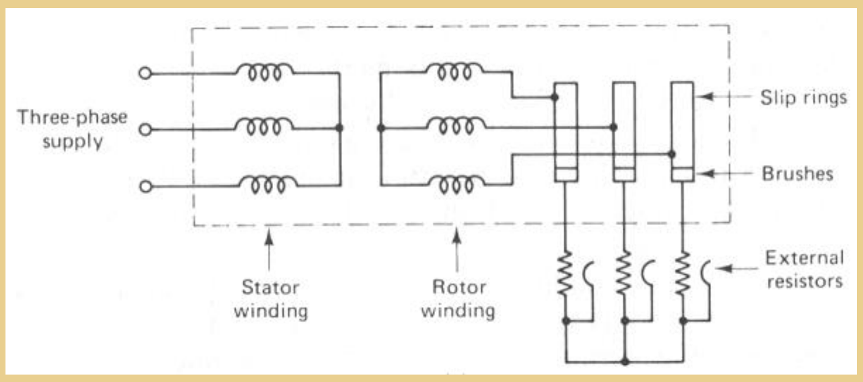
$$Td^{''} = \left(\frac{Xd\_\_}{Xd\_}\right)\cdot Tdo\_\_ = \left(\frac{0.280}{0.314}\right)\cdot 0.039 = 34.7\,ms$$

Field current decay time constant

$$I^{'}_{fo} = \left(\frac{Xd}{Xd\_}\right)\cdot I_{fo} = \left(\frac{1.014}{0.314}\right)\cdot 1 = 3.23PU$$

$$I^{'}_{f} = I_{fo} + \left(I^{'}_{fo} - I_{fo}\right)\cdot e^{-t/T_d^{'}} \quad = \quad 1 + (3.23-1)\cdot e^{-t/T_d^{'}}$$

Induction machine



Machine response can be represented in the form of six mutually coupled winding

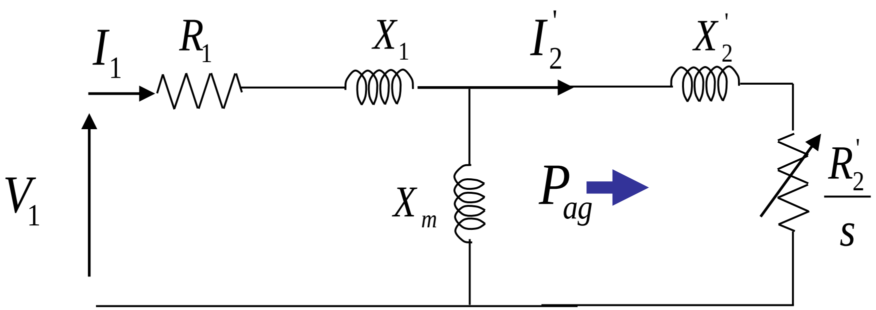
$$L_s = \begin{bmatrix} L_{ls} + L_{ms} & -.5L_{ms} & -.5L_{ms} \\ -.5L_{ms} & L_{ls} + L_{ms} & -.5L_{ms} \\ -.5L_{ms} & -.5L_{ms} & L_{ls} + L_{ms} \end{bmatrix},$$

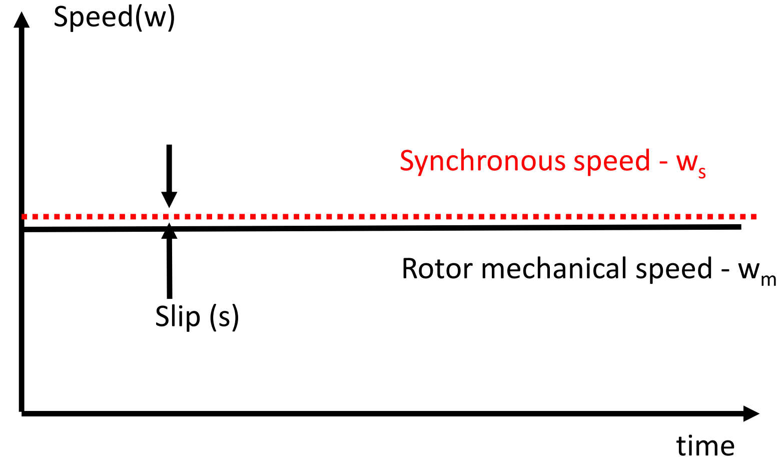
$$L_r = \begin{bmatrix} L_{lr} + L_{mr} & -.5L_{mr} & -.5L_{mr} \\ -.5L_{mr} & L_{lr} + L_{mr} & -.5L_{mr} \\ -.5L_{mr} & -.5L_{mr} & L_{lr} + L_{mr} \end{bmatrix}$$

and

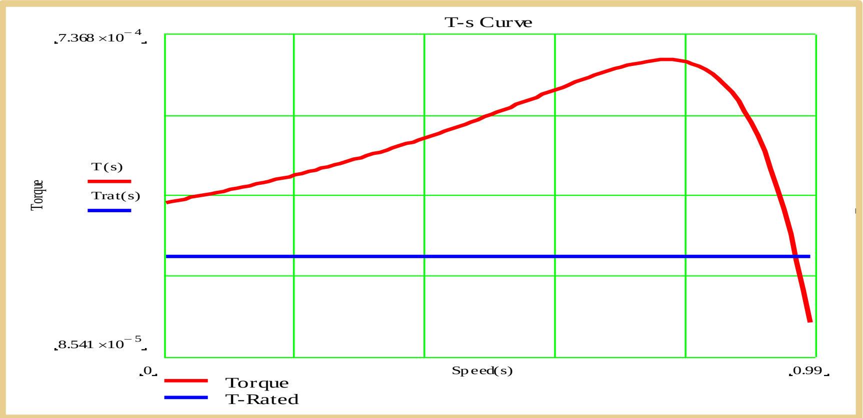
$$L_{sr} = l_{sr} \begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r) \end{bmatrix}.$$

Steady state equivalent circuit and torque-slip characteristics



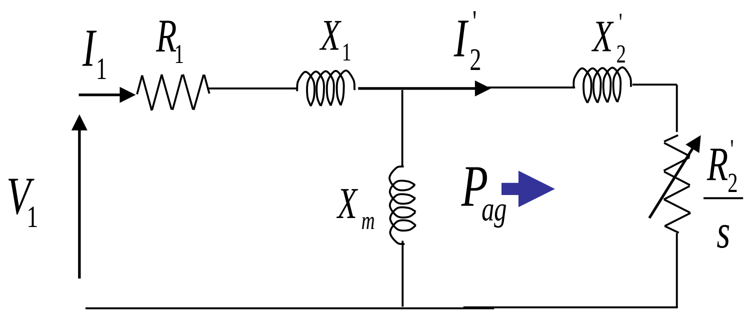


$$T(s) := \frac{3 \cdot V^2 \cdot R_2}{s \cdot w_0 \cdot \left[\left(R_1 + \frac{R_2}{s} \right)^2 + (Xeq)^2 \right]}$$



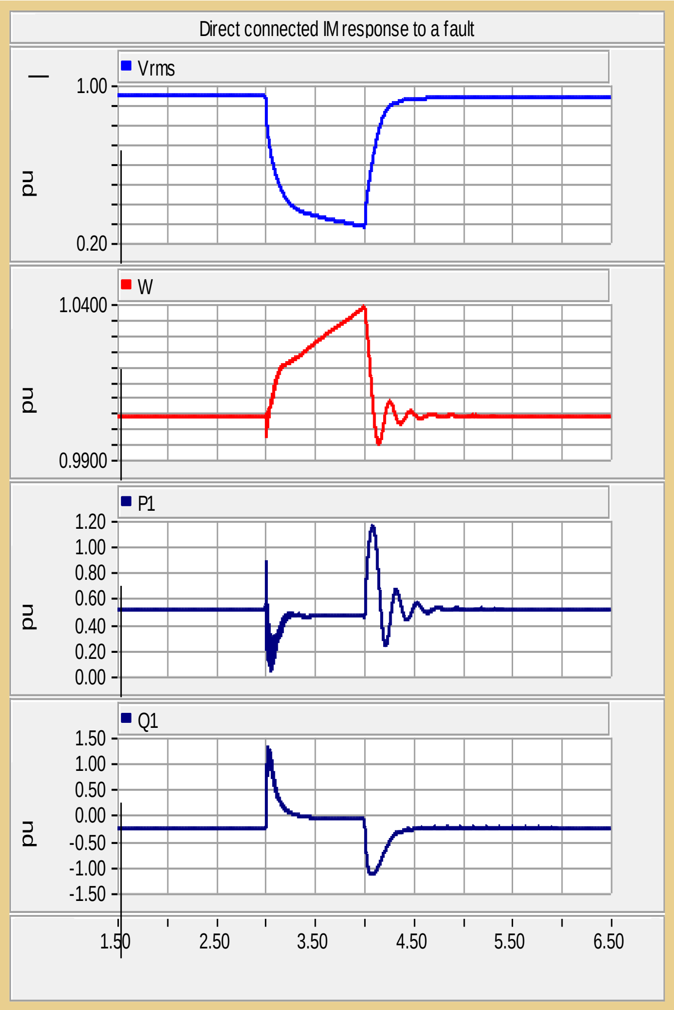
Induction machine

Induction machine response during fault recovery – High reactive power absorption can lead to voltage stability concerns

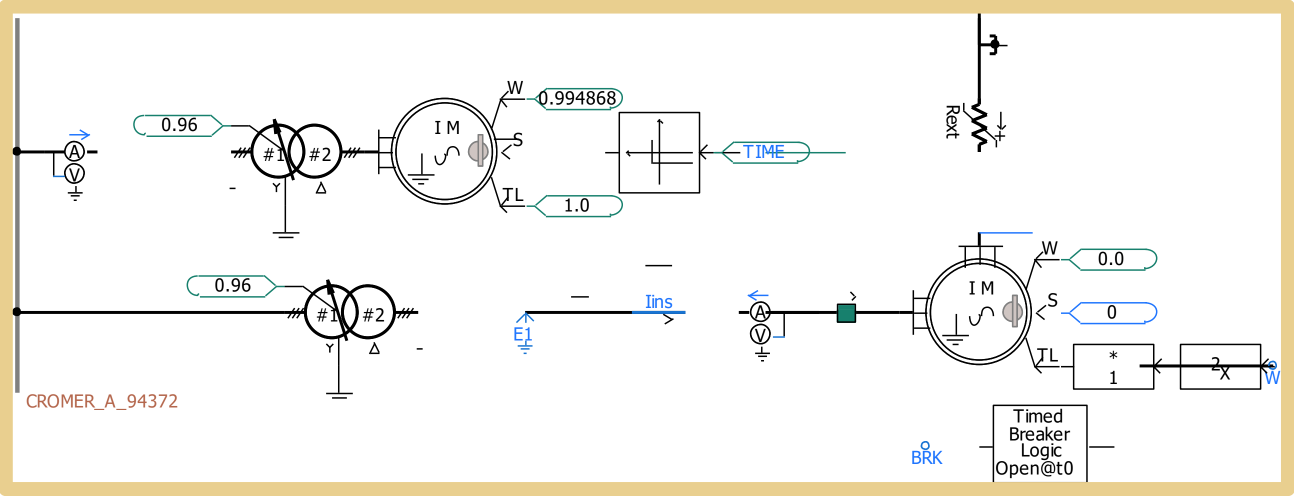


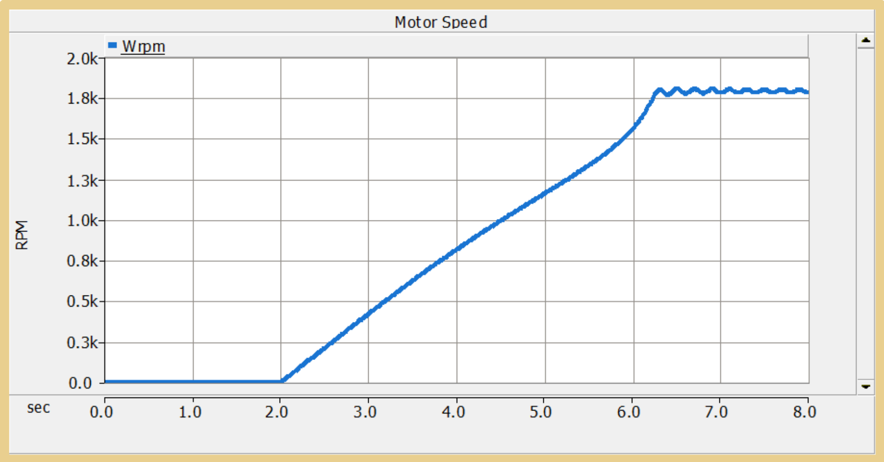
Machine speeds up (assume a Type 1 wind unit) during the fault

- At fault clearance, slip is larger (compared to normal operation)
- Stator and rotor current will be high as a result of high slip
- Increased reactive power absorption in leakage fields



Simulation setup – Induction machine





Technical note available on how to set up the machine model and controls

Simulation examples

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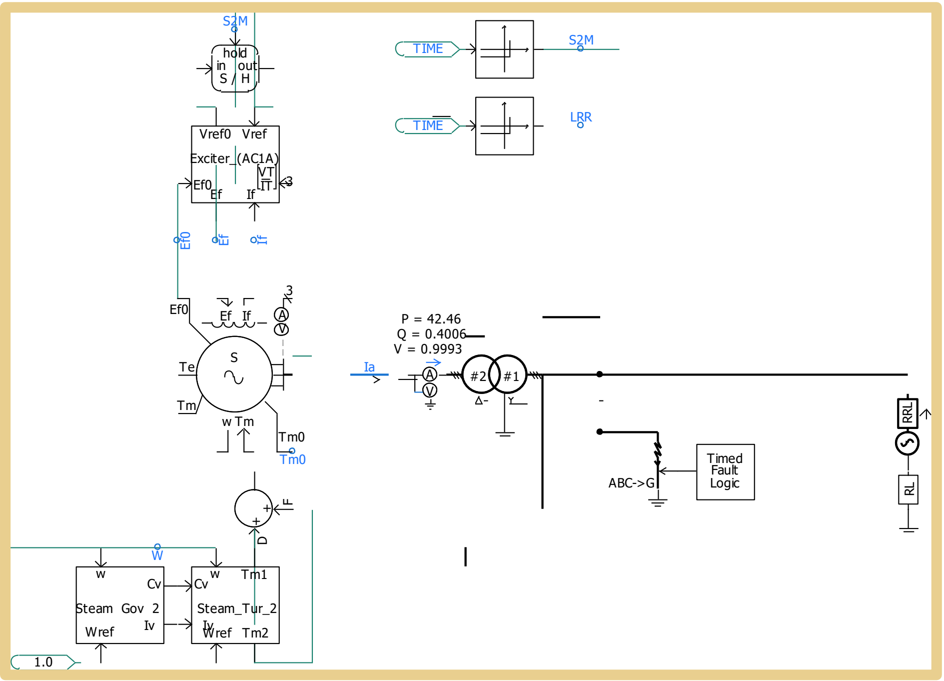
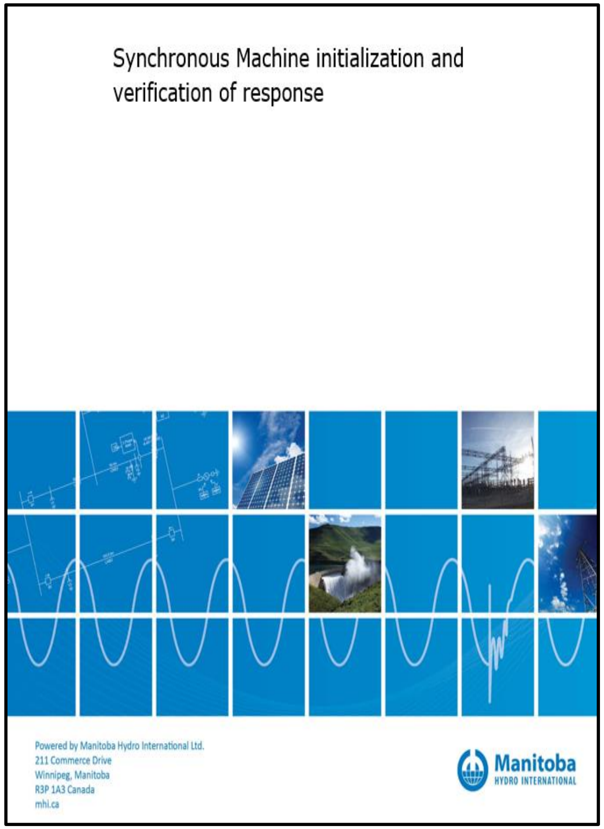
- Illustration of Simulation examples
  - Model setup and data entry
  - Model Benchmarking
  - Black start restoration studies
  - Voltage flicker due to compressor load driven by a synchronous machine
  - Sub synchronous resonance and torsional interactions
  - Voltage dips due to induction motor starting and mitigation options
  - Applications in wind generation (DFIG)

Simulation setup – Synchronous Machine





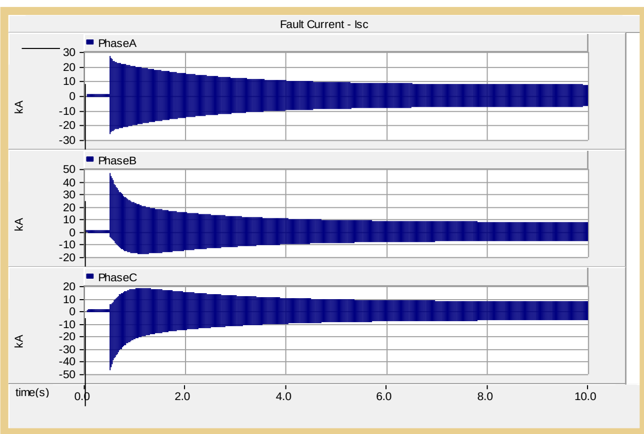
Transient response: PSCAD model follows expected response (see technical note)

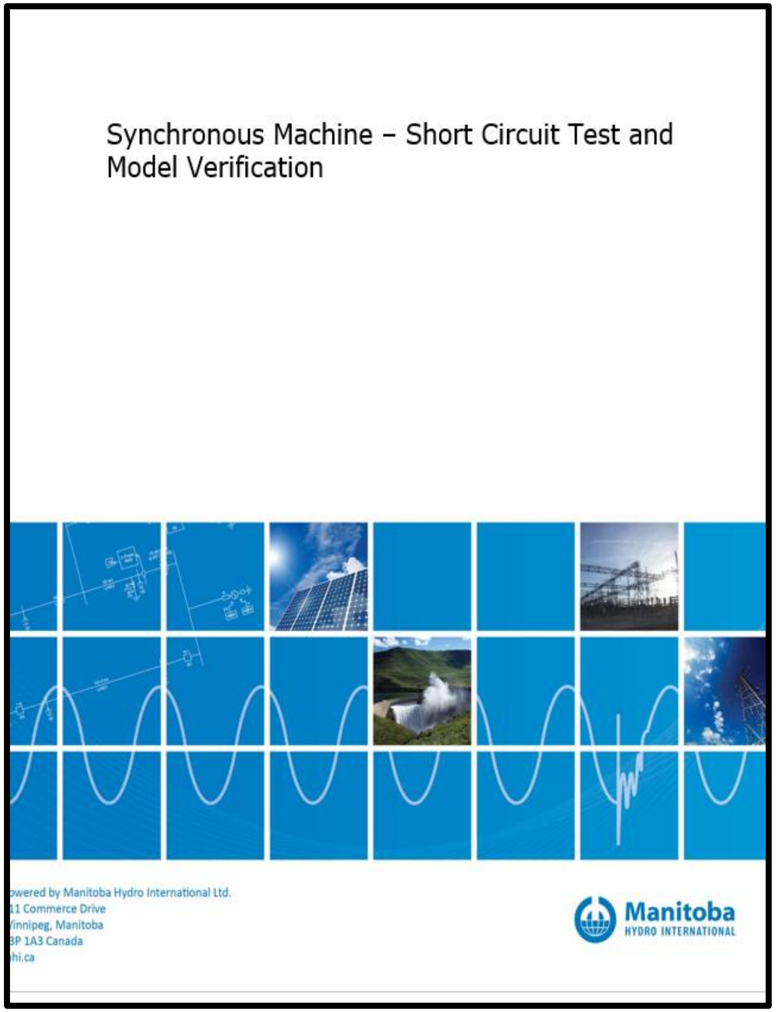
Transient response

$$Td' = \left(\frac{Xd\_}{Xd}\right)\cdot Tdo\_ = \left(\frac{0.314}{1.014}\right)\cdot 6.55 = 2.03\,s$$

Sub Transient response

$$Td'' = \left(\frac{Xd\_\_}{Xd\_}\right)\cdot Tdo\_\_ = \left(\frac{0.280}{0.314}\right)\cdot 0.039 = 34.7\,ms$$

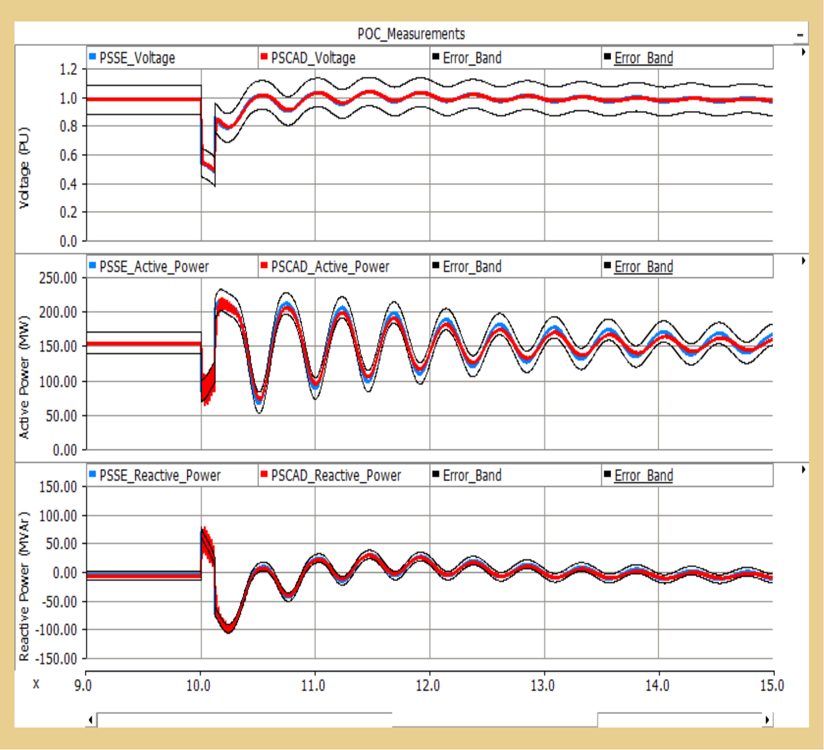




Comparing response with RMS simulation results

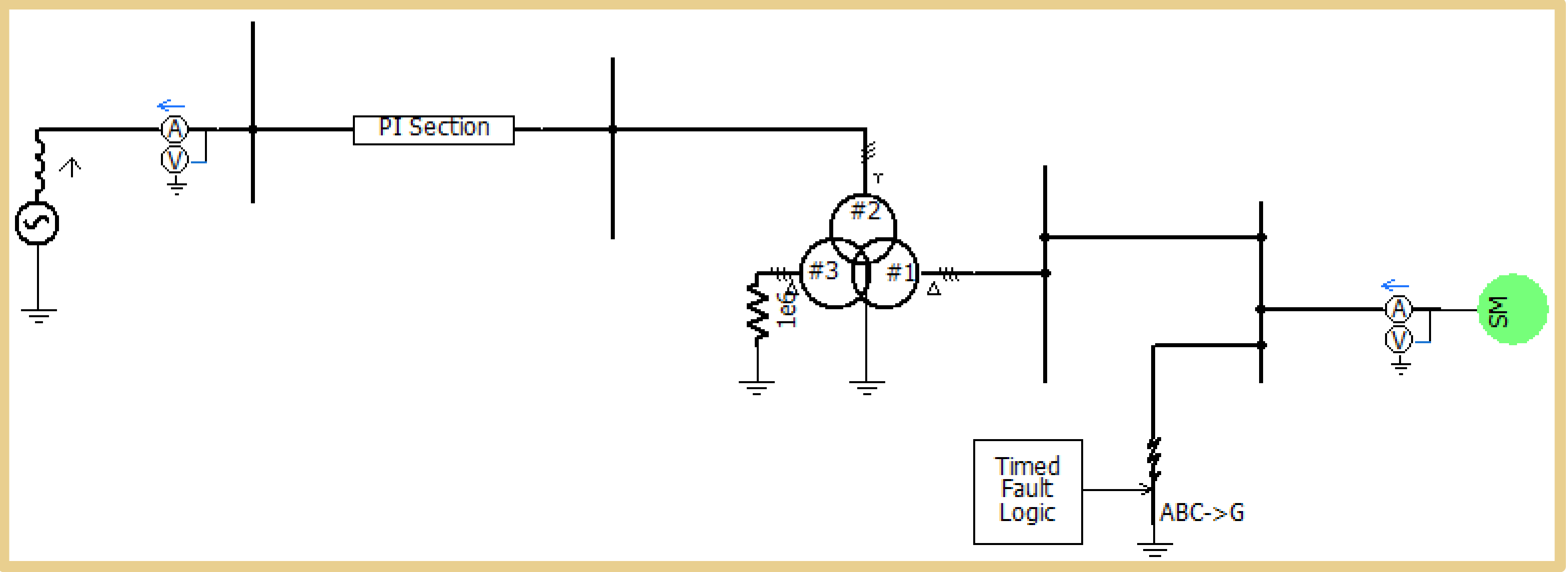
The results (even RMS quantities) are derived from two different methods of mathematical circuit solution techniques – There can be minor differences

Synchronous generator fault ride through

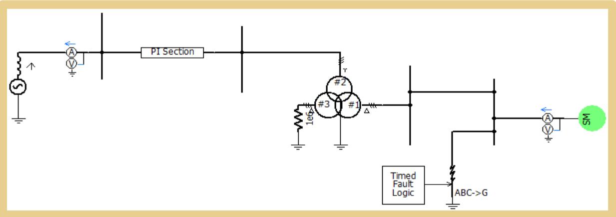


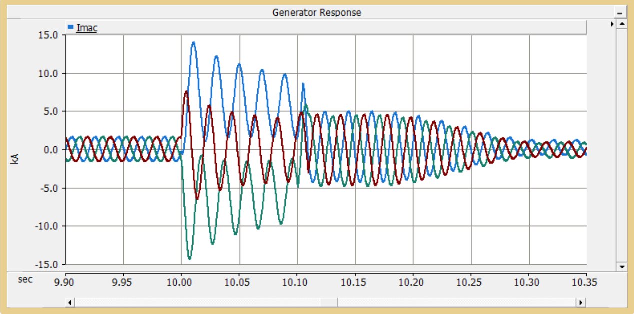
The results (even RMS quantities) are derived from two different methods of mathematical circuit solution techniques

- The test circuits are simplified (ideal like)
- Note network dynamics such as DC offset in fault current
- In EMT, currents are interrupted at ‘zero crossings’

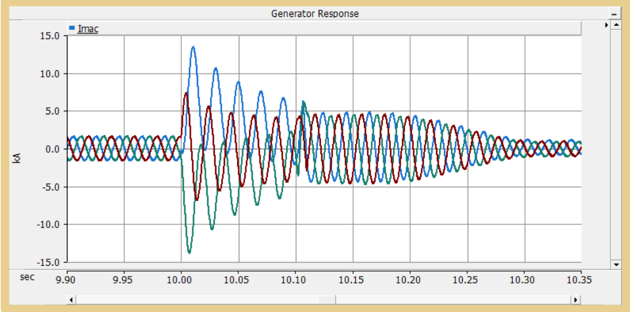


The results (even RMS quantities) are derived from two different methods of mathematical circuit solution techniques

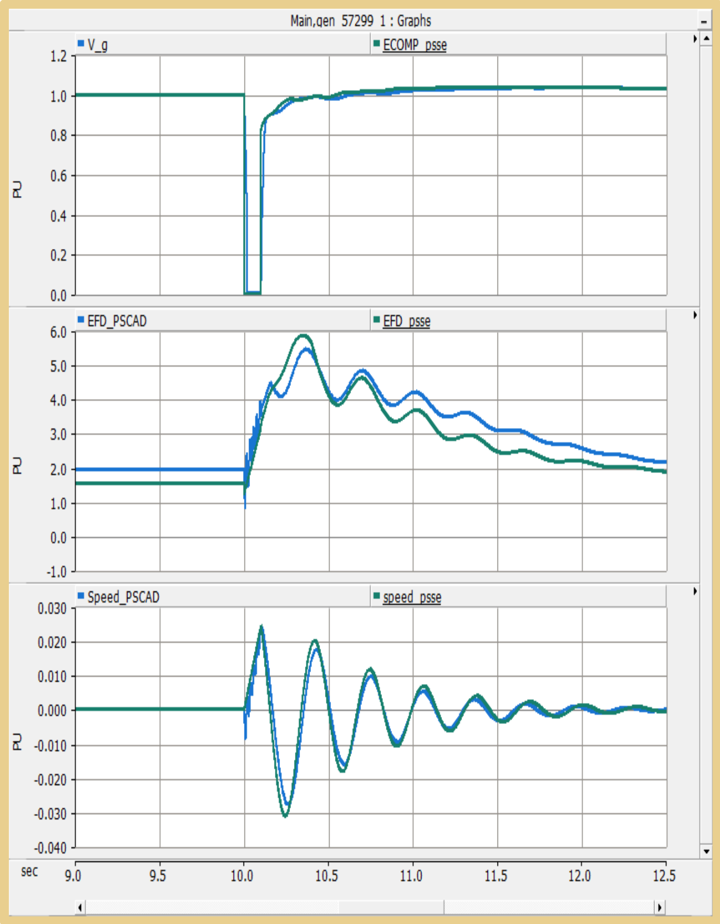




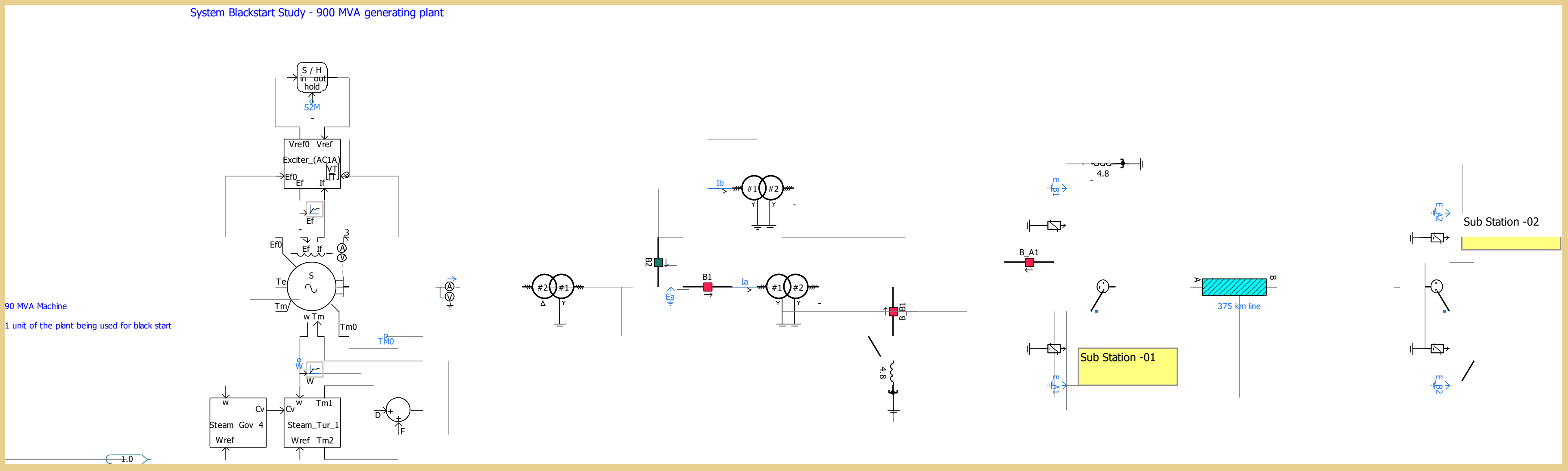
Zero fault resistance



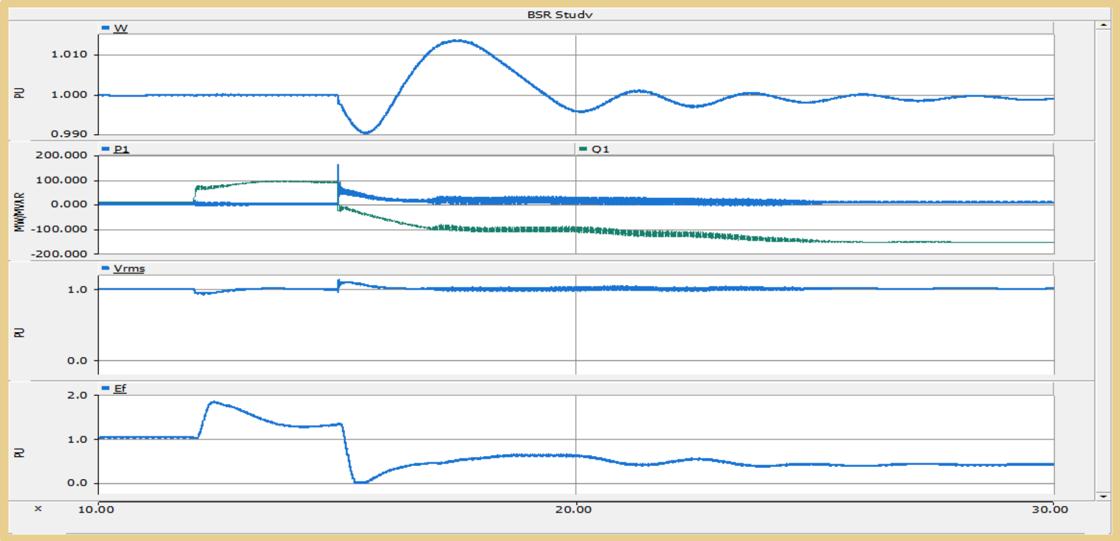
Low fault resistance



Black Start Restoration Example

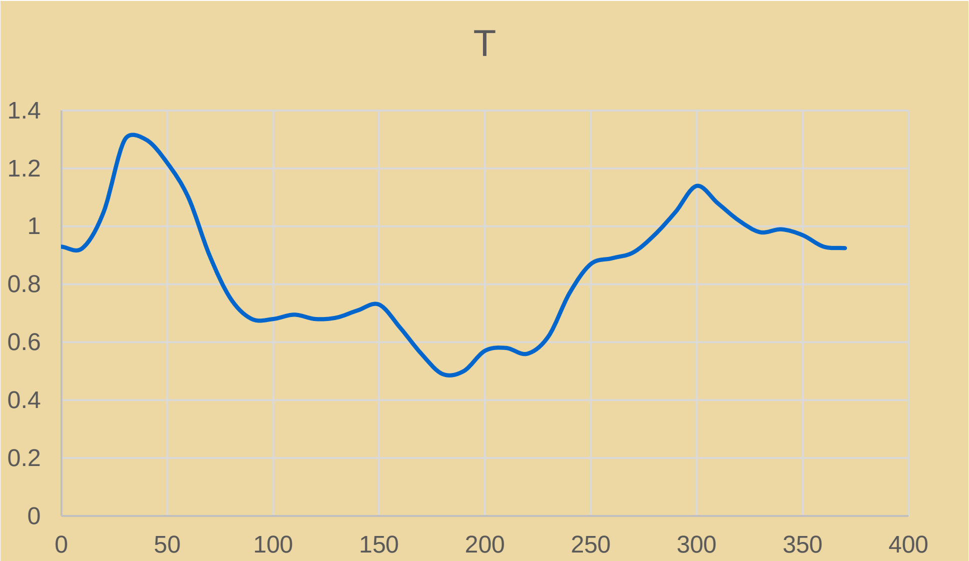


Example: Self Excitation when energizing a long line

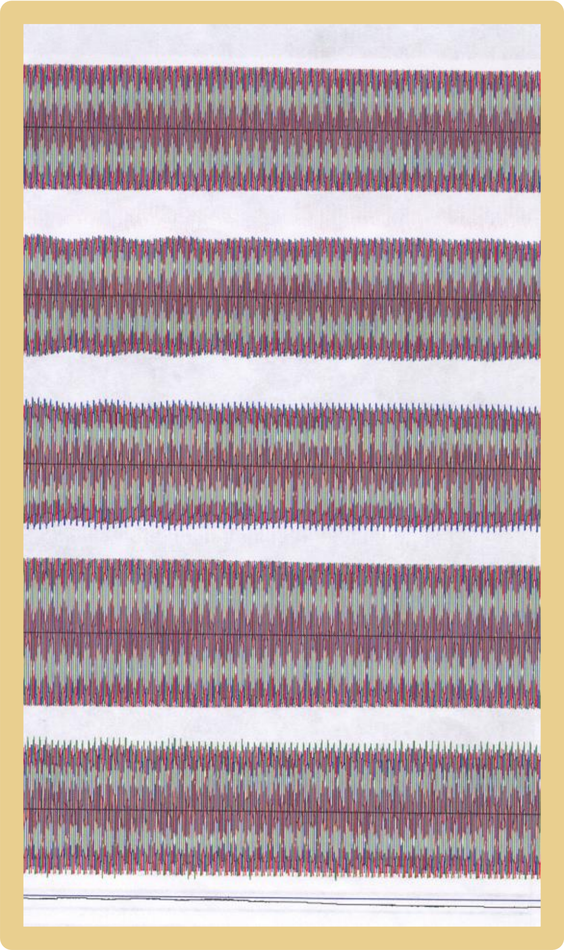


Example: Flicker due to a synchronous motor driven compressor

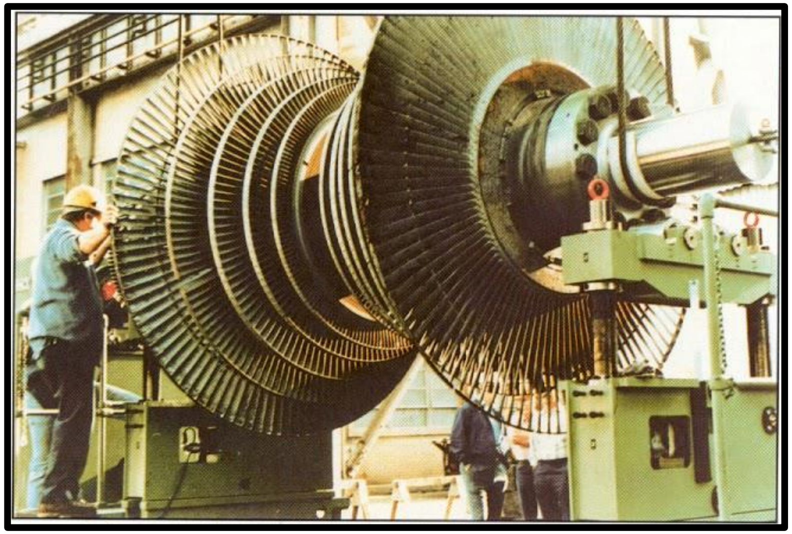
Compressor load torque characteristics



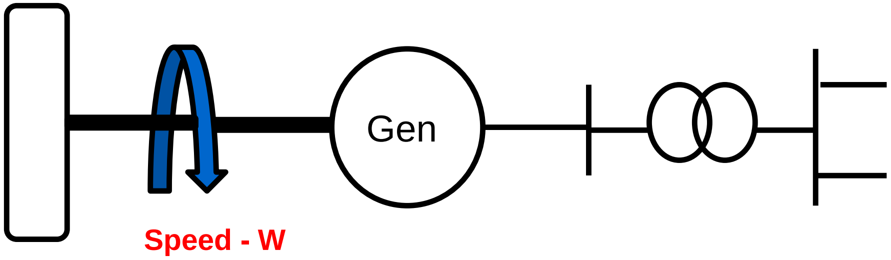
Voltage flicker measured at transmission level

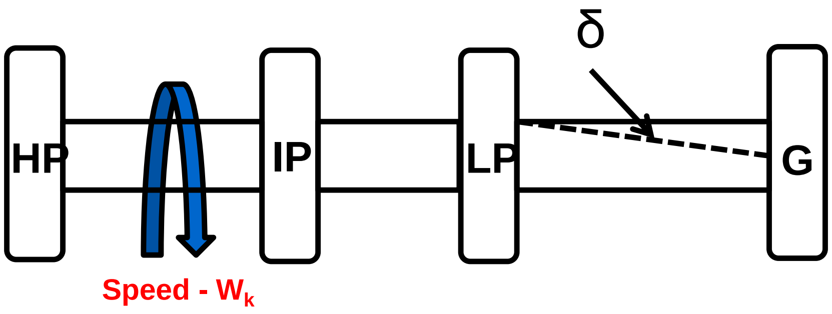


Example: SSTI studies - Mechanical shaft-mass system



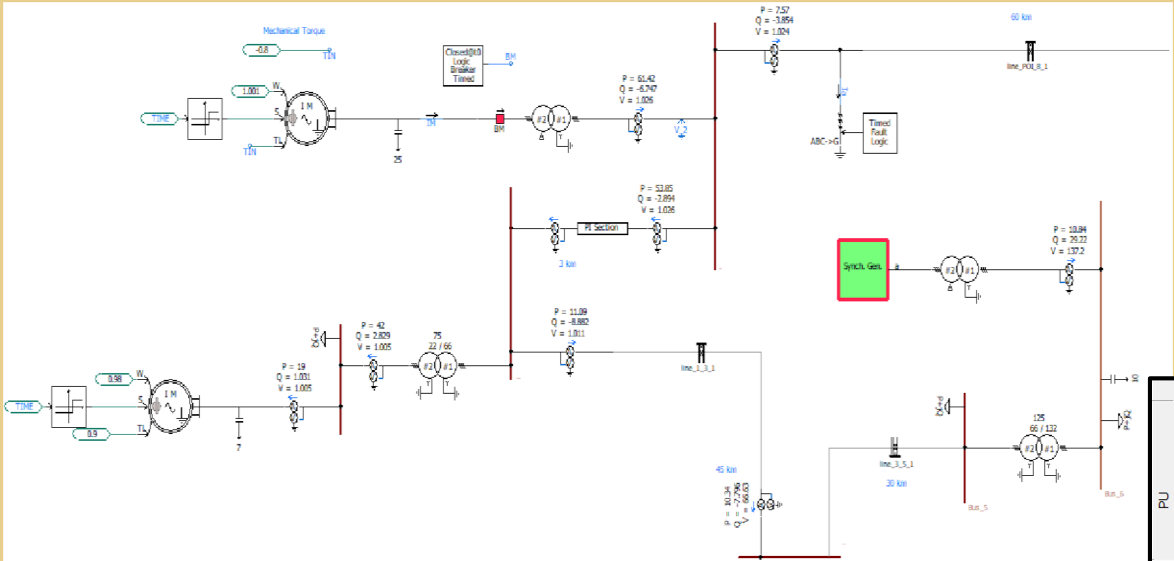
- Rotor of a Turbine Generator is a complex system of masses connected by shaft sections
- The total length can be as much as 50 m.
- A single lumped inertia representation is typically considered in system transient stability studies
  - Assumption: Rigid shafts

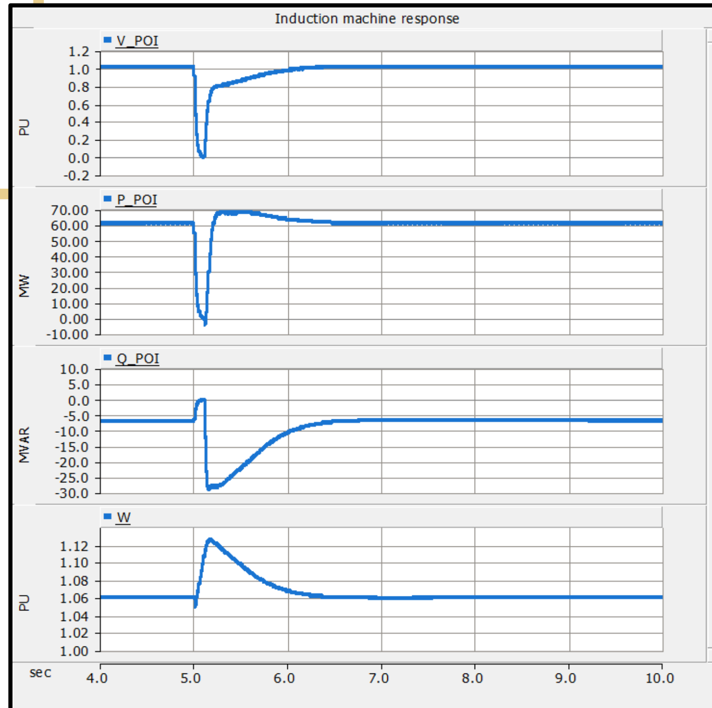




- Torsional Interaction studies require a more detailed representation of the shaft (compared to lumped mass representation)
  - A Multi-Mass representation
    - Main rotor components represented as separate (rigid) masses
    - The masses are connected to each other with 'elastic' shaft sections

Induction Machine Response





Thank you