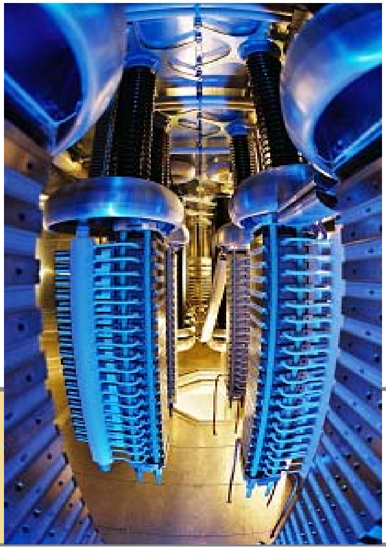
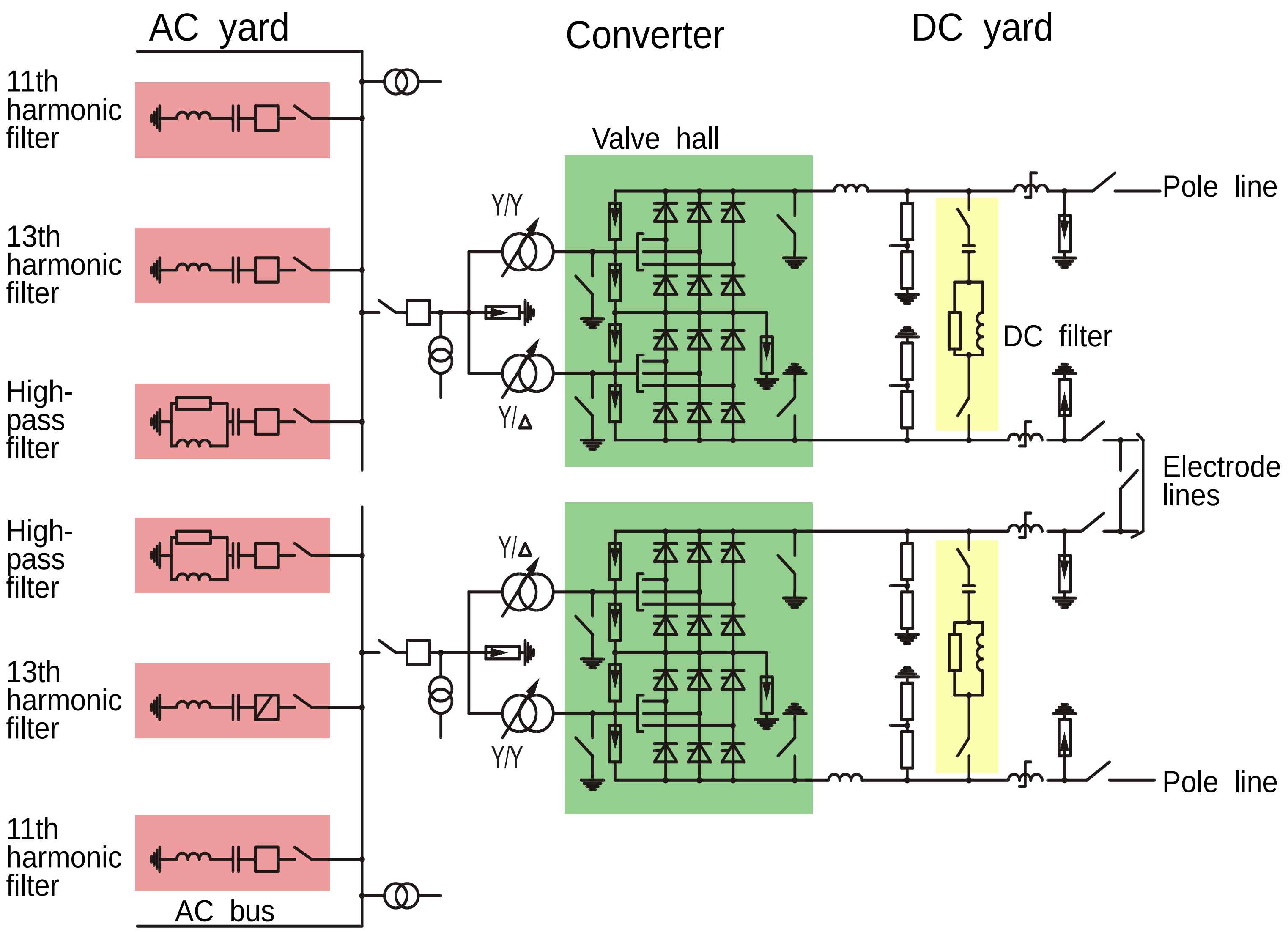
ERCOT
October 8, 2007
Don Martin

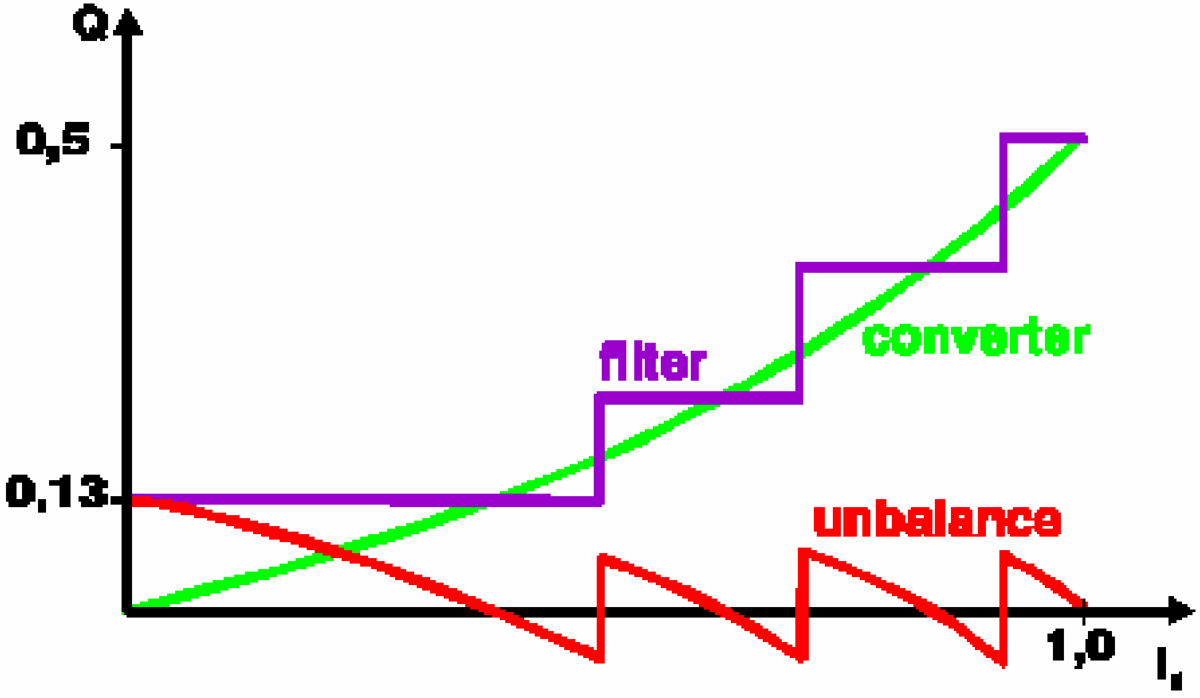


HVDC STUDIES AND APPLICATIONS

CLASSIC HVDC STATION COMPONENTS

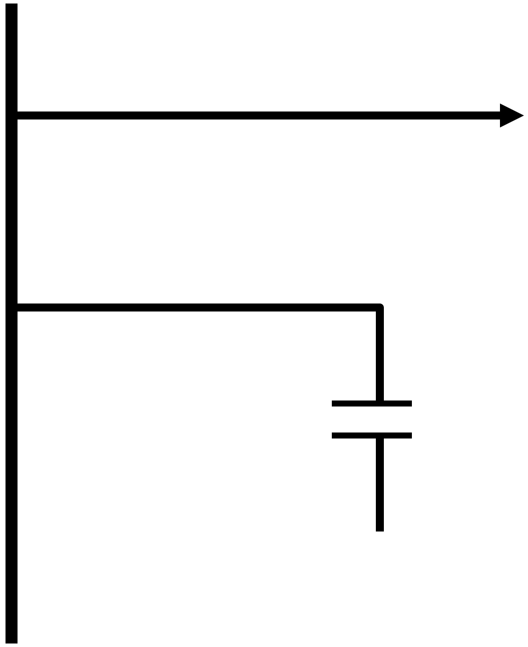


CLASSIC HVDC REACTIVE POWER BALANCE



HVDC Classic Steady-State Model

POWER FLOW MODELING

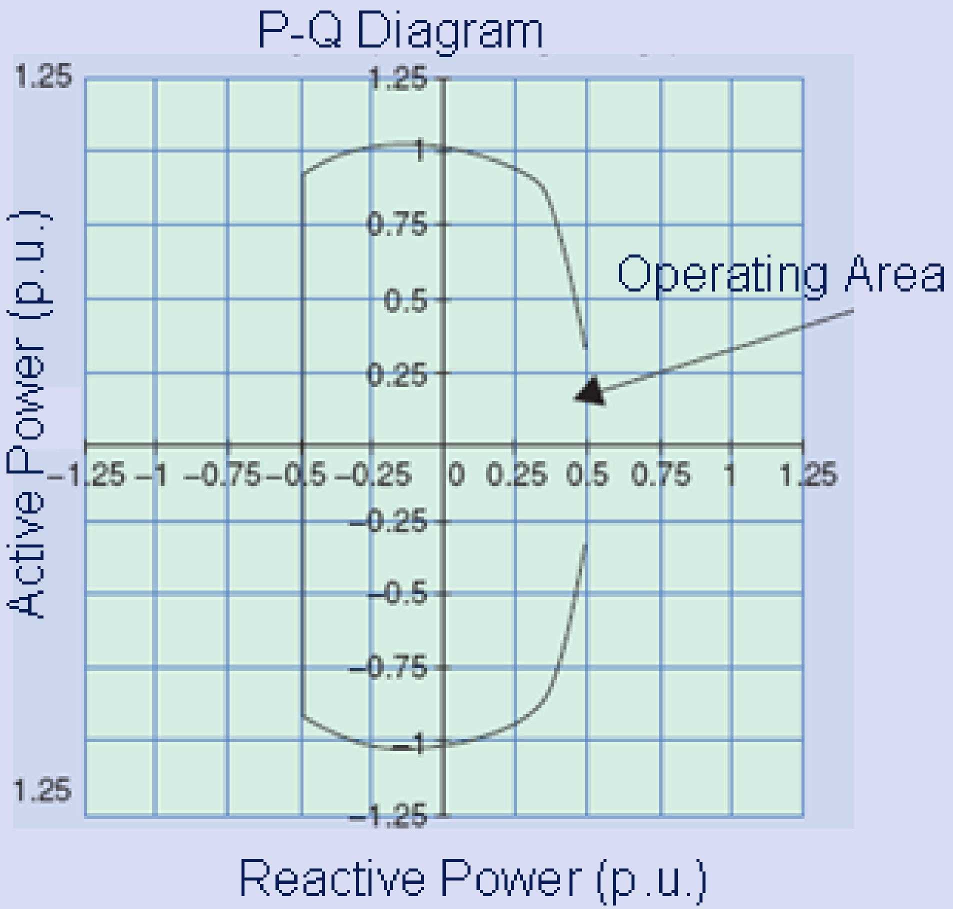


Pcon = +1.0 PU (-1.0 PU)

Qcon = -0.5 PU (-0.5 PU)

Qcap= +0.5 PU

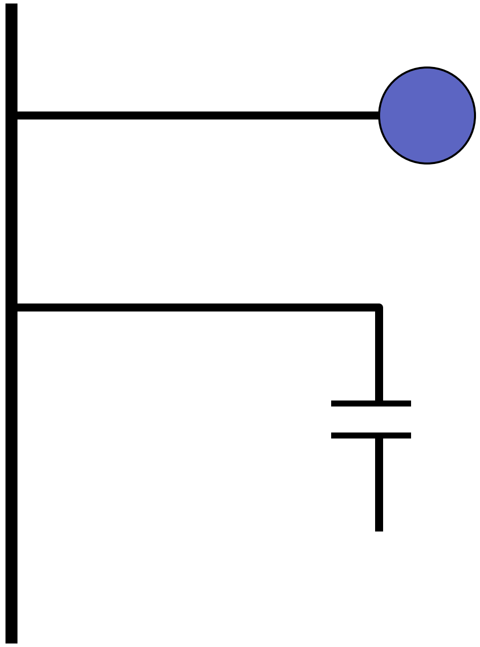
HVDC LIGHT STATION CHARACTERISTICS



HVDC VSC Operating Range

HVDC Light Steady-State Model

POWER FLOW MODELING



Pcon = +1.0 PU (-1.0 PU)

Qmax = +0.35 PU

Qmin = -0.50 PU

Qcap +0.15 PU

HVDC SIMPLIFIED STEADY-STATE MODELS

Investigate Typical Planning Study Requirements:

- **Thermal loading**
- **Reactive power requirements**
- **Power transfer limits and changes in the system power flow**
- **Voltage profiles**
- **System losses**

ABB HVDC Classic Calculations

$$U_{dr} = U_{dioR} \cdot \left[\cos(\alpha) - \left(d_x + d_r\right) \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dioR}} \right] - U_T$$

$$d_x = \frac{3}{\pi} \cdot \frac{X_t \cdot I_{dN}}{U_{dioN}}$$

$$U_{vN} = \frac{\pi}{3} \cdot \frac{U_{di0N}}{\sqrt{2}}$$

$$I_{vN} = \sqrt{\frac{2}{3}} \cdot I_{dN}$$

- Optimized design
- Typical estimate, Nominal conditions
  - α=15 degree
  - d_{xN}= 0.065
  - d_{rN}= 0.003
  - U_T=0.3/250 pu (0.12%) of U_{dN} /6-pulse bridge; i.e., negligible
- Equations per 6-pulse bridge
- Once the above definition of d_x is taken into account, and U_T is neglected, the equations are essentially the same as those in the PSS/E Manual.

HVDC DETAILED CLASSIC STEADY-STATE MODELS

Also Provide HVDC System Operating Parameters:

- **DC Voltages**
- **Converter P & Q**
- **DC Currents**
- **α, γ, μ (firing, extinction, and overlap angles)**
- **Converter Transformer Taps**
- **DC System Losses**

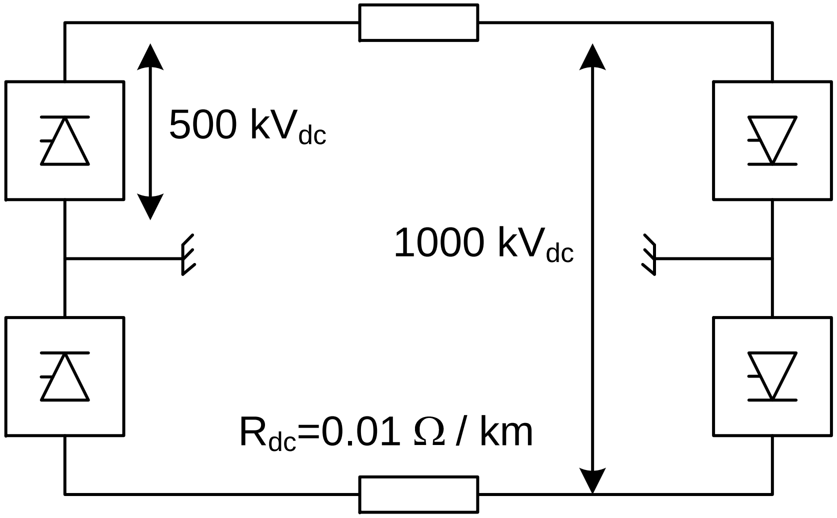
HVDC DETAILED CLASSIC STEADY-STATE MODELS

- A loadflow model of HVDC is necessary in order to be able to initialize its dynamic model.

- It is also useful for providing the approximate steady-state response of HVDC to changes in terminal voltage during loadflow studies.

HVDC Classic Configurations

- **Bipolar HVDC line, modeled as one dc line in PSS/E**
  - **VSCHD= 2*500 = 1000 kV**
  - **RDC= 2*0.01 = 0.02 Ω/km**
- Monopolar operation with ground return (one pole out or cable)
- Monopolar operation with metallic return
- Bipolar HVDC line, modeled as two dc lines in PSS/E



HVDC Classic Configurations

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  - **RDC= 0.01 Ω/km**
- Monopolar operation with metallic return
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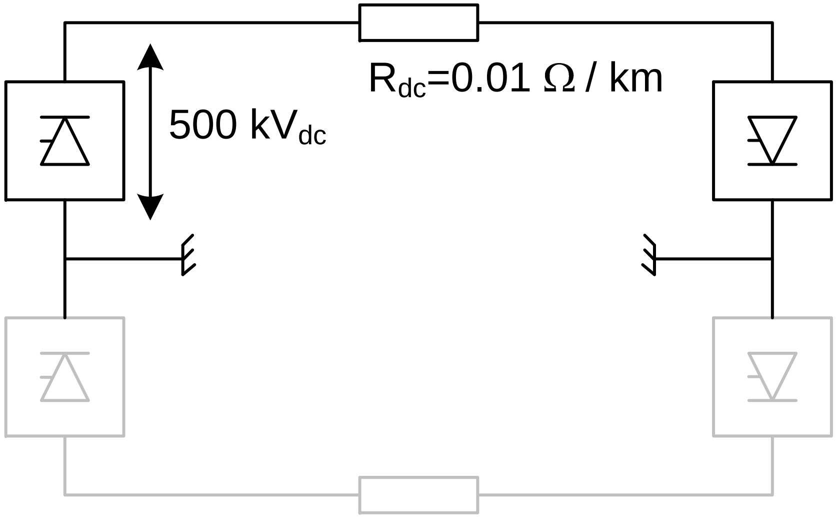

HVDC Classic Configurations

- Bipolar HVDC line, modeled as one dc line in PSS/E
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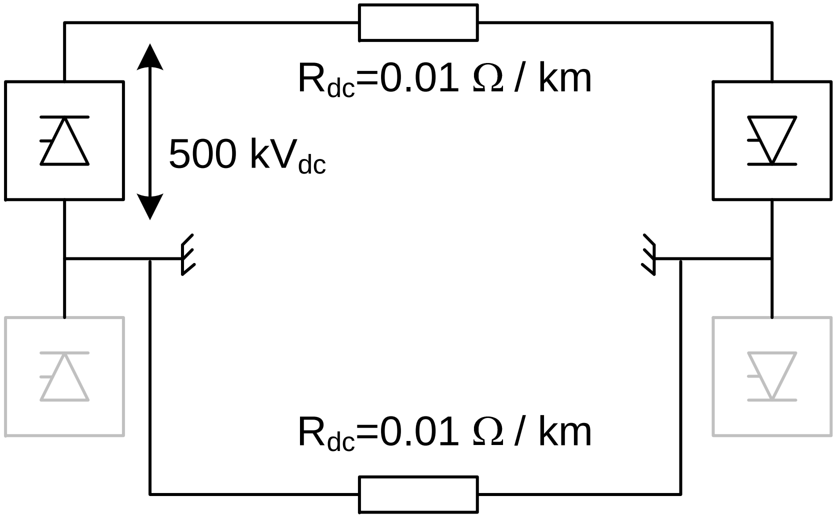
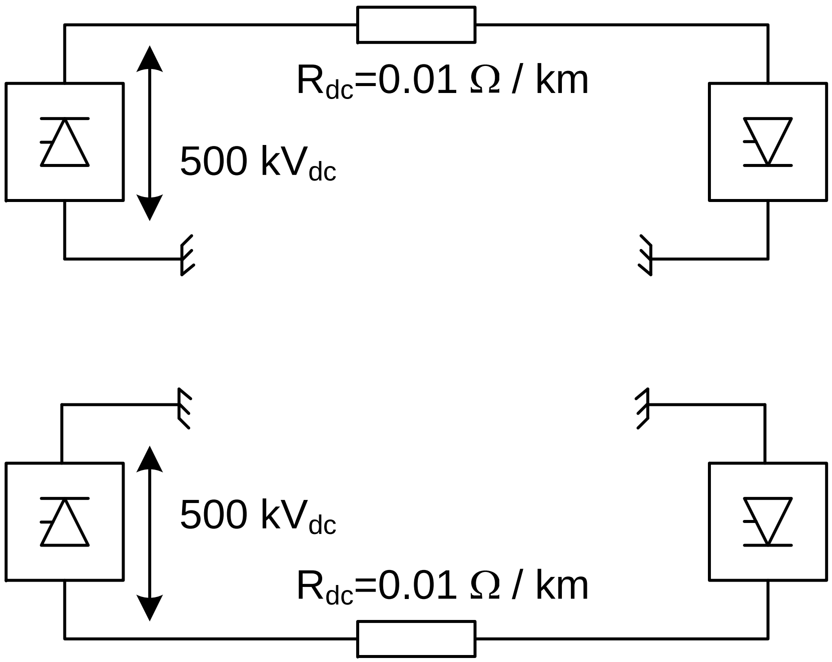
- Bipolar HVDC line, modeled as two dc lines in PSS/E

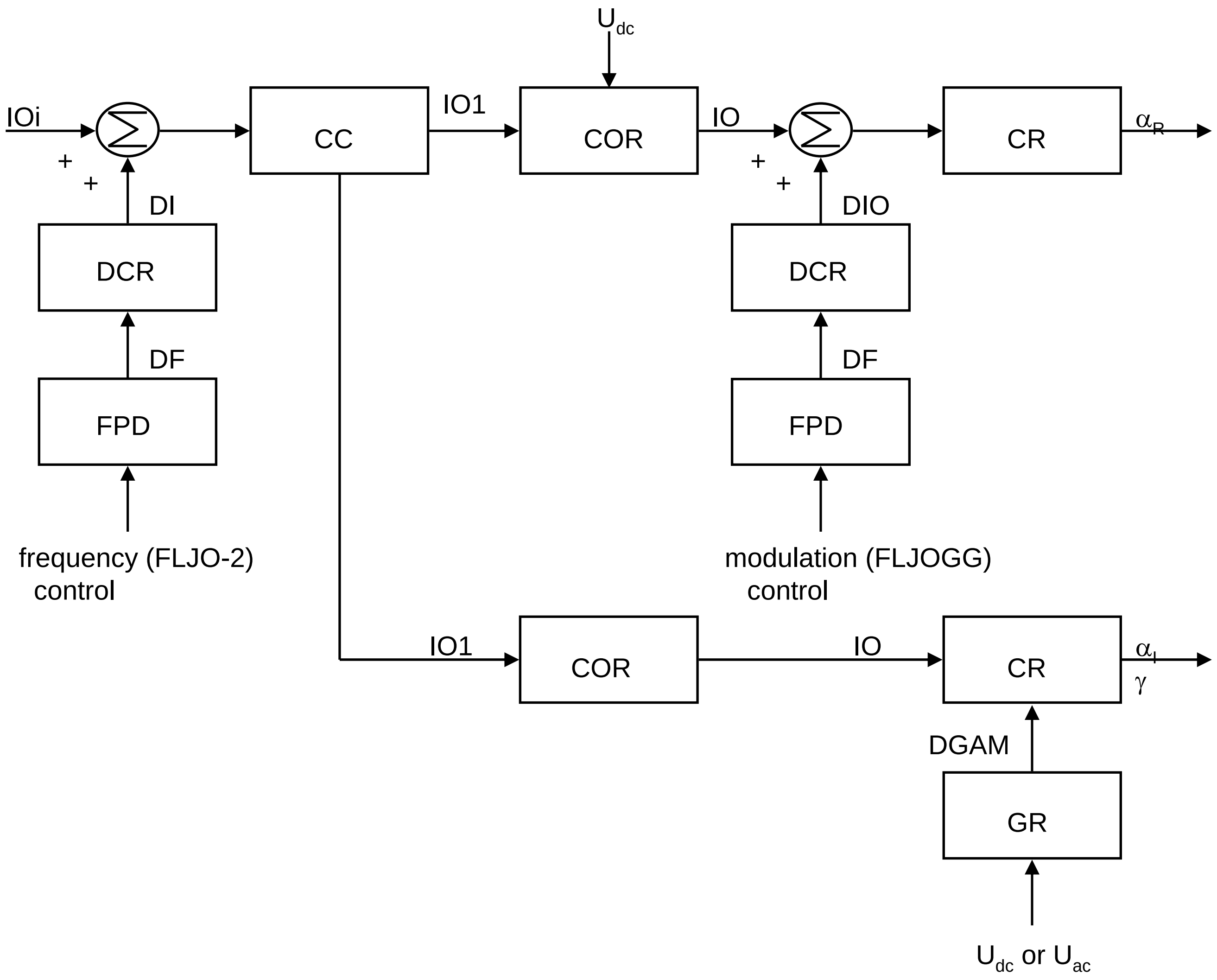


HVDC Classic Configurations

- Bipolar HVDC line, modeled as one dc line in PSS/E
- Monopolar operation with ground return
  (one pole out or cable)
- Monopolar operation with metallic return
- **Bipolar HVDC line, modeled as two dc lines in PSS/E**
- **Two entries**
  - **VSCHD= 500 kV**
  - **RDC= 0.01 Ω/km**

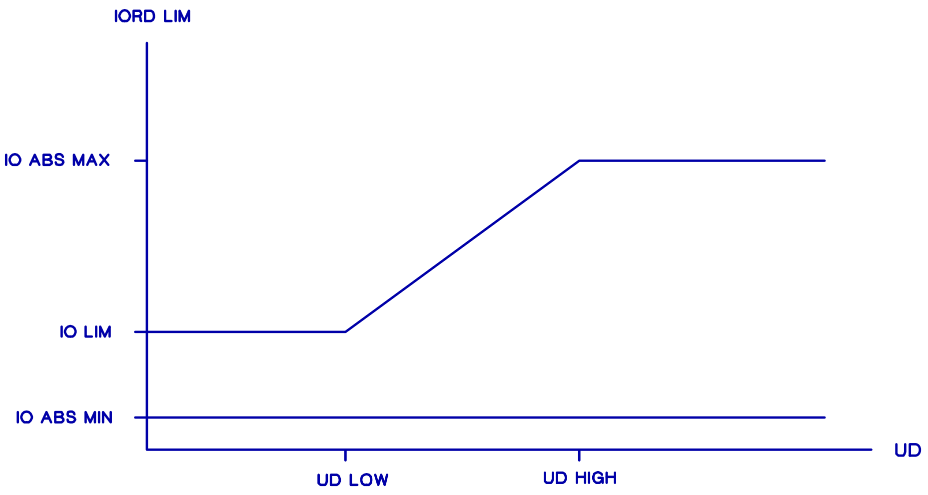


HVDC DYNAMIC MODELS

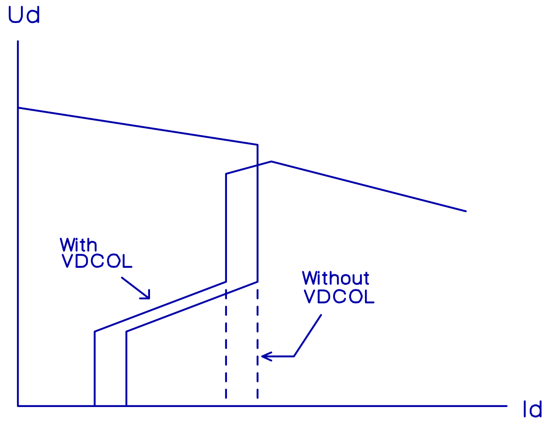


HVDC Classic Control

VDCOL function



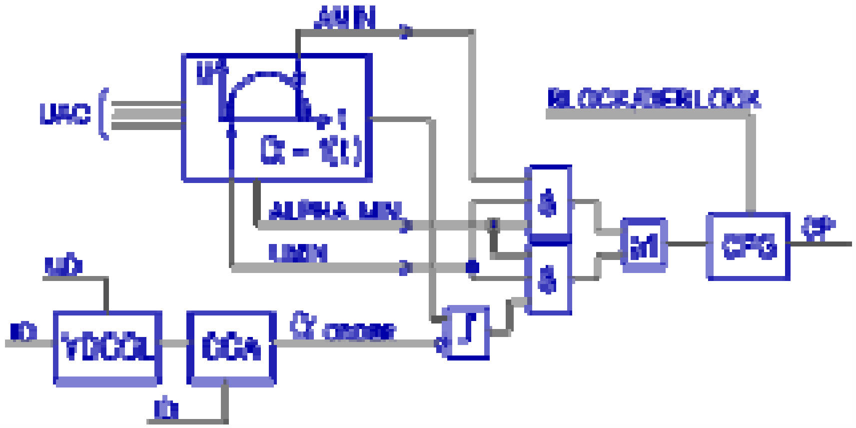
VDCOL characteristics

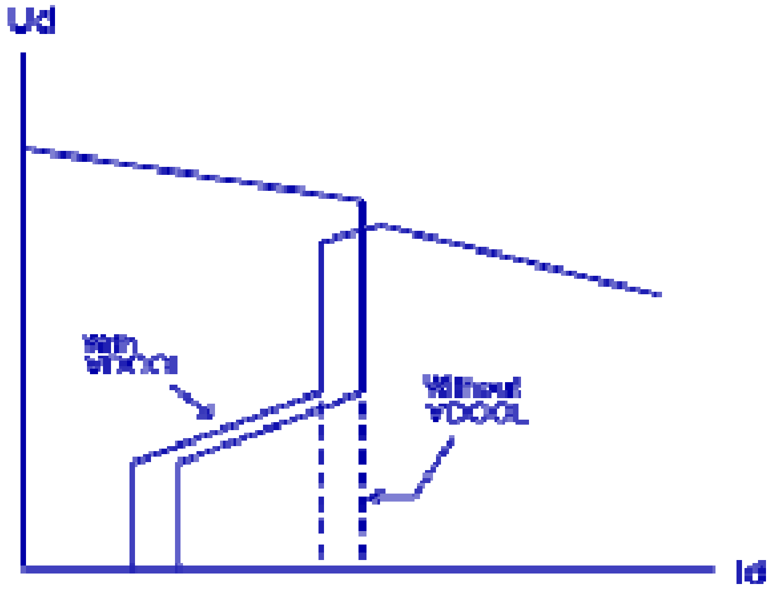


Main characteristics With/Without VDCOL

- avoid power instability during and after disturbances in the a.c. network
- define a fast and controlled restart after clearance of a.c. and d.c. faults
- avoid stresses on the thyristors at continuous commutation failure
- suppress the probability of consecutive commutation failures at recovery

Firing Angle Limits and VDCOL





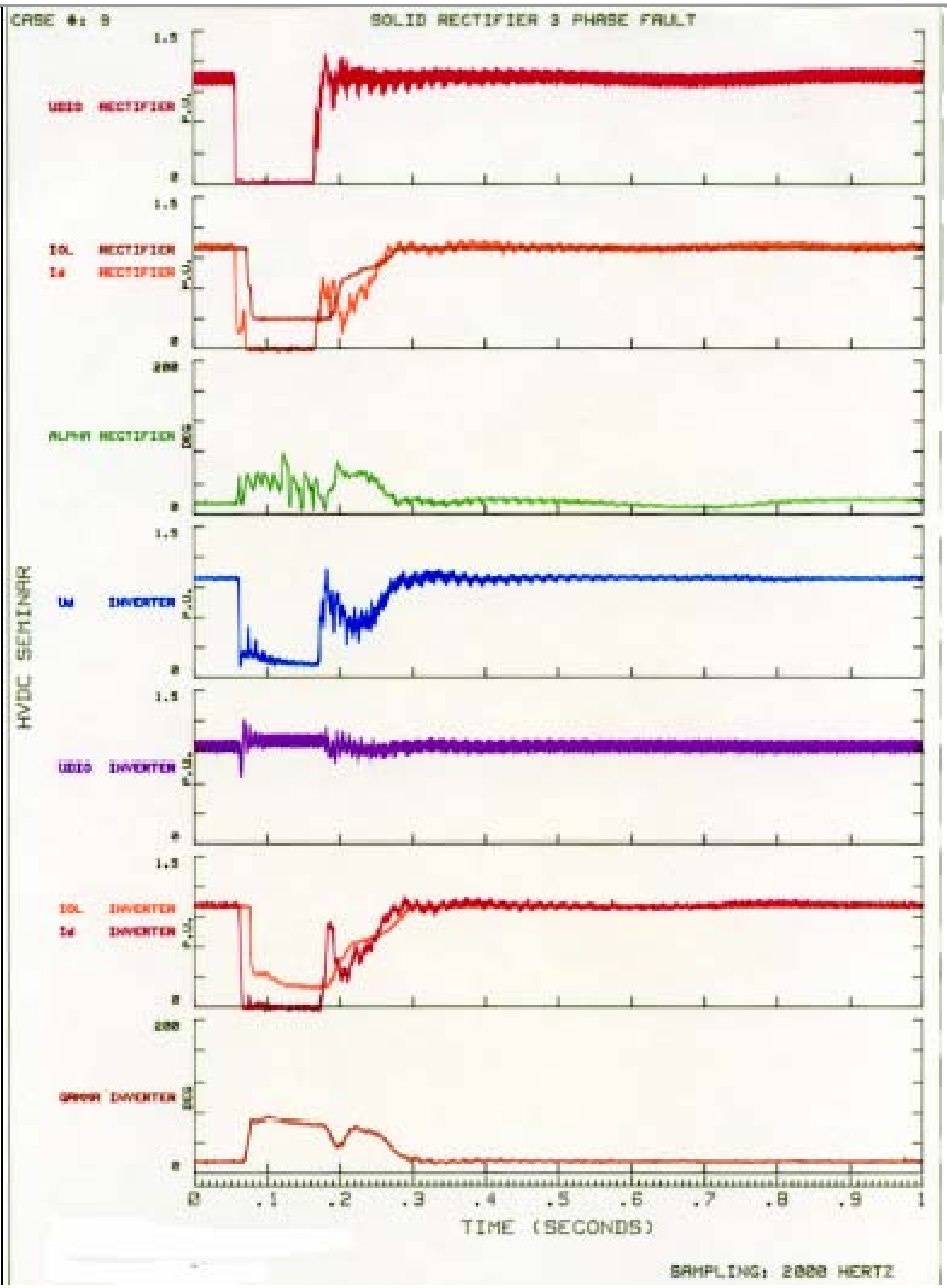
- Firing angle limits – alpha min for rectifier operation, minimum commutation margin for inverter operation
- Minimum firing voltage for rectifier operation for disturbances
- Voltage dependent current order limiter for controlling dynamic reactive power demand during start-up and disturbance recovery
- VDCOL time constants – fast for decreasing voltage, slower for increasing voltage
- VDCOL up time constant speed dependent on system strength

HVDC DETAILED DYNAMIC MODELS

HVDC CONTROLLABILTY CAN BE USED TO ENHANCE SYSTEM DYNAMIC PERFORMANCE:

- Frequency Control
- Modulation for System Stabilization
- System Oscillation Damping
- Reactive Power Control
- AC Voltage Control
- Fast Remedial Action Responses

Conventional HVDC – 3 ph rectifier ac fault



Vac Rectifier (rectified)

Io, Id Rectifier

Alpha Rectifier

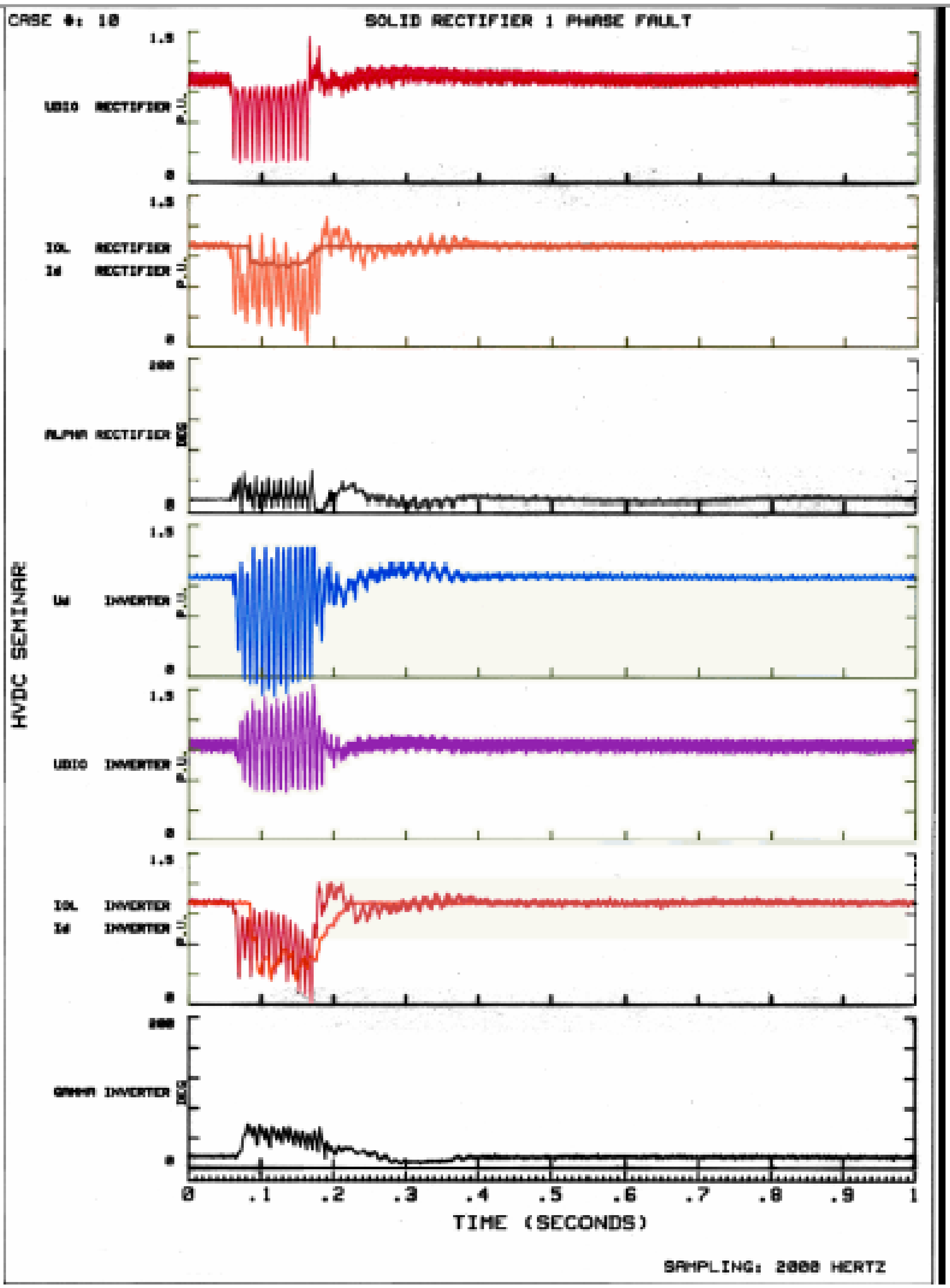
Vd Inverter

Vac Inv (rectified)

Io, Id Inverter

Gamma Inverter

Conventional HVDC – 1 ph rectifier ac fault



Vac Rectifier (rectified)

Io, Id Rectifier

Alpha Rectifier

Vd Inverter

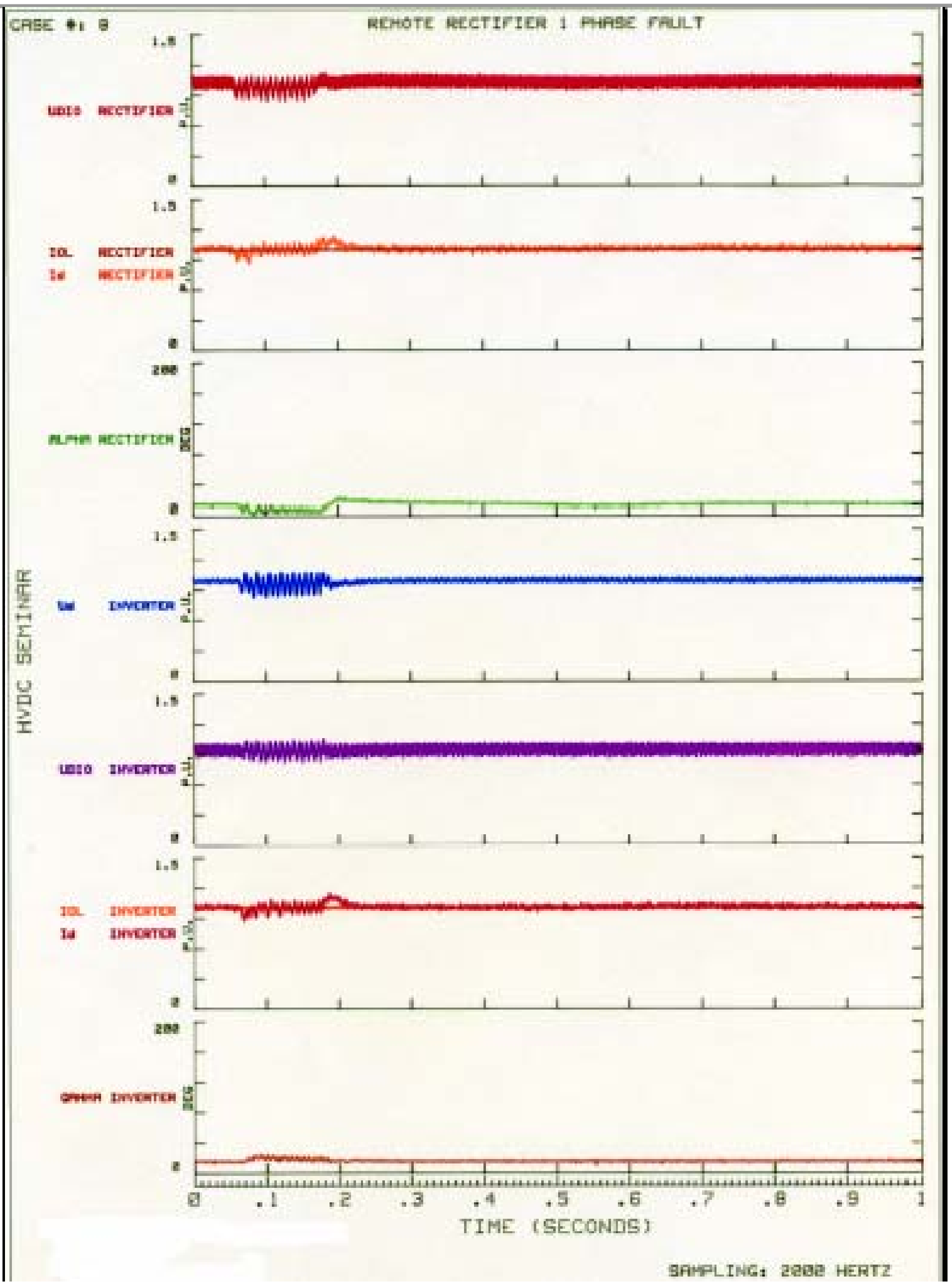
Vac Inv (rectified)

Io, Id Inverter

Gamma Inverter

Half power transmitted during fault

Conventional HVDC – 1 ph rectifier remote ac fault



Vac Rectifier (rectified)

Io, Id Rectifier

Alpha Rectifier

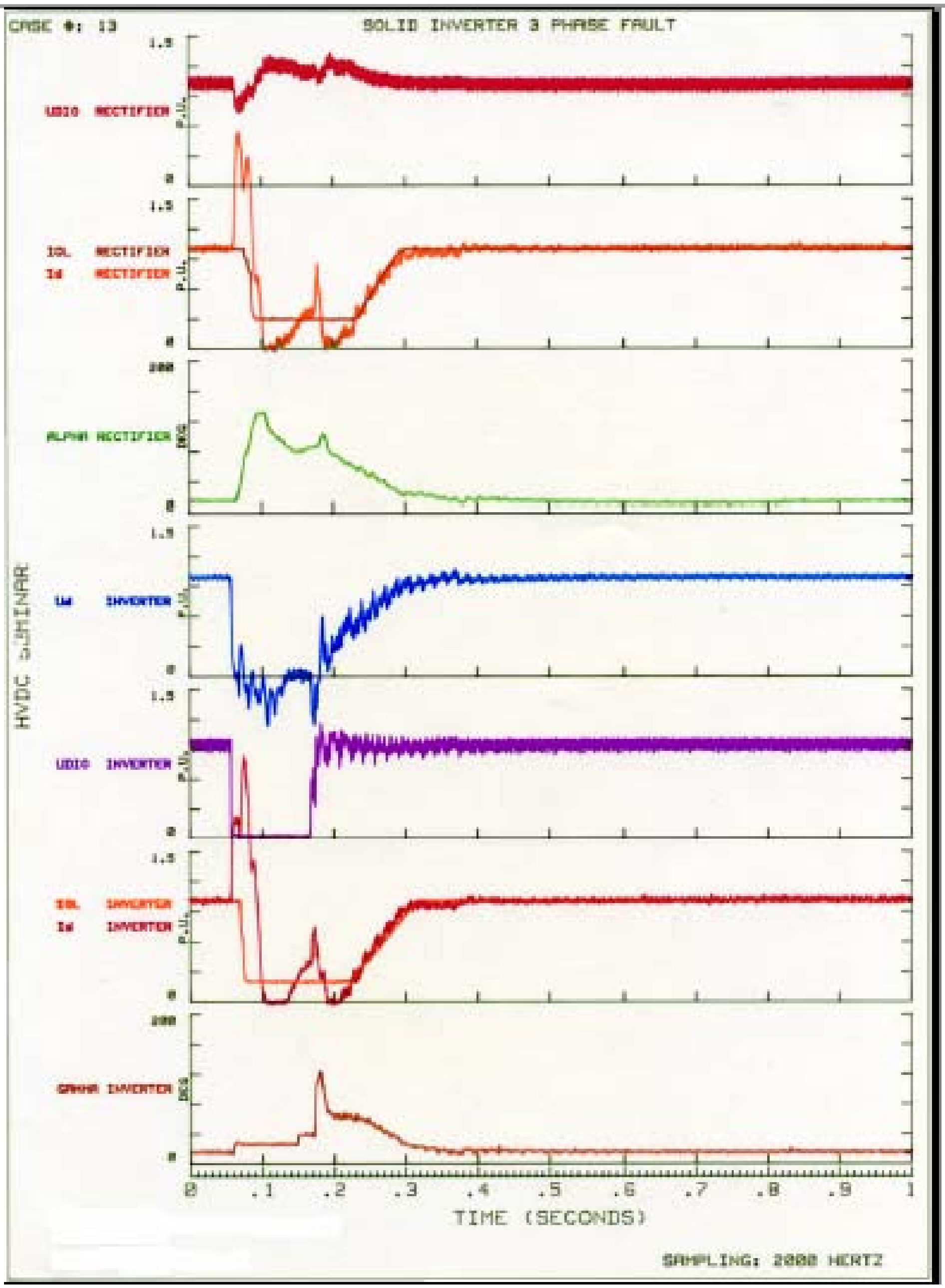
Vd Inverter

Vac Inv (rectified)

Io, Id Inverter

Gamma Inverter

Conventional HVDC – 3 ph inverter ac fault



Vac Rectifier (rectified)

Io, Id Rectifier

Alpha Rectifier

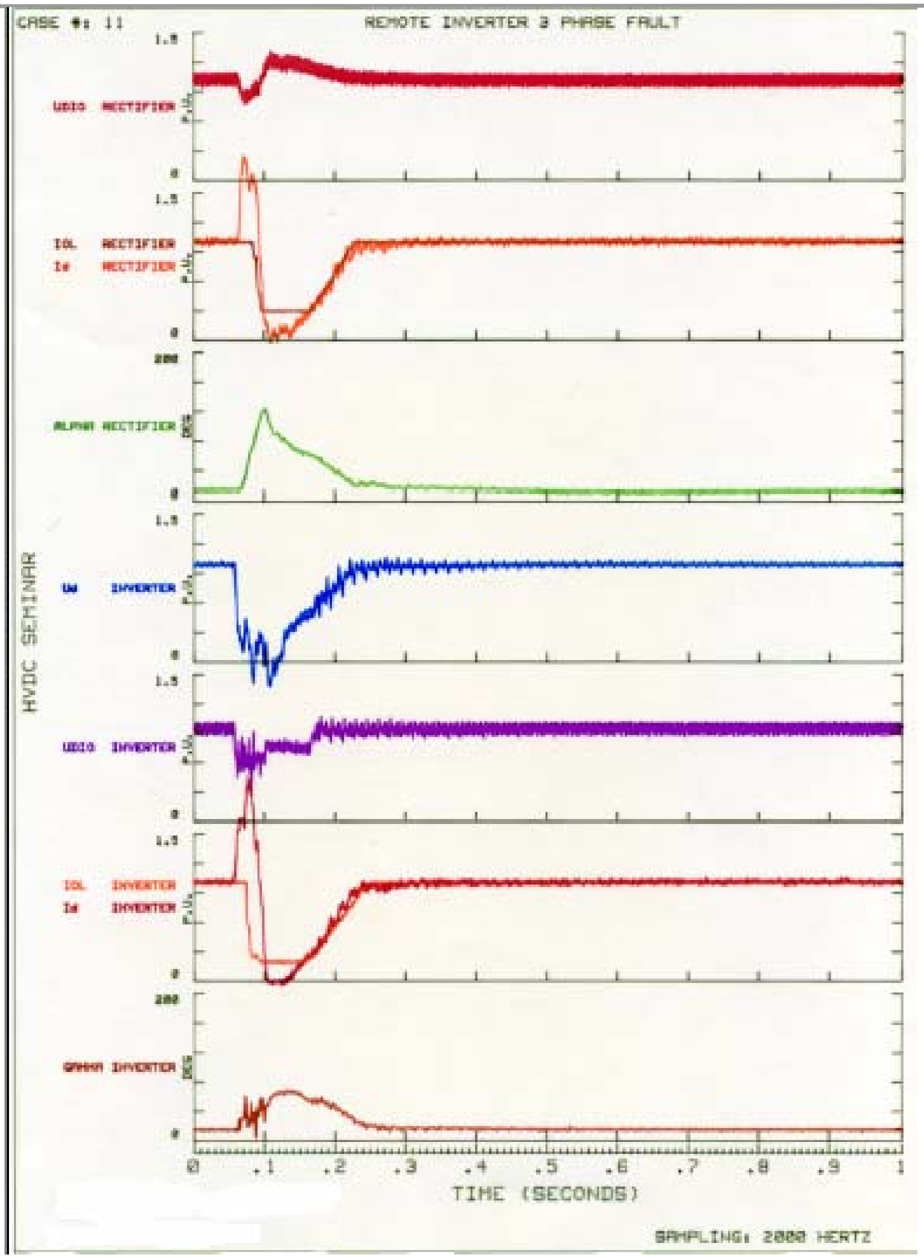
Vd Inverter

Vac Inv (rectified)

Io, Id Inverter

Gamma Inverter

Conventional HVDC – 3 ph remote inverter ac fault



Vac Rectifier (rectified)

Io, Id Rectifier

Alpha Rectifier

Vd Inverter

Vac Inv (rectified)

Io, Id Inverter

Gamma Inverter

Conventional HVDC – DC Pole Fault

Vac Rectifier (rectified)

Io, Id Rectifier

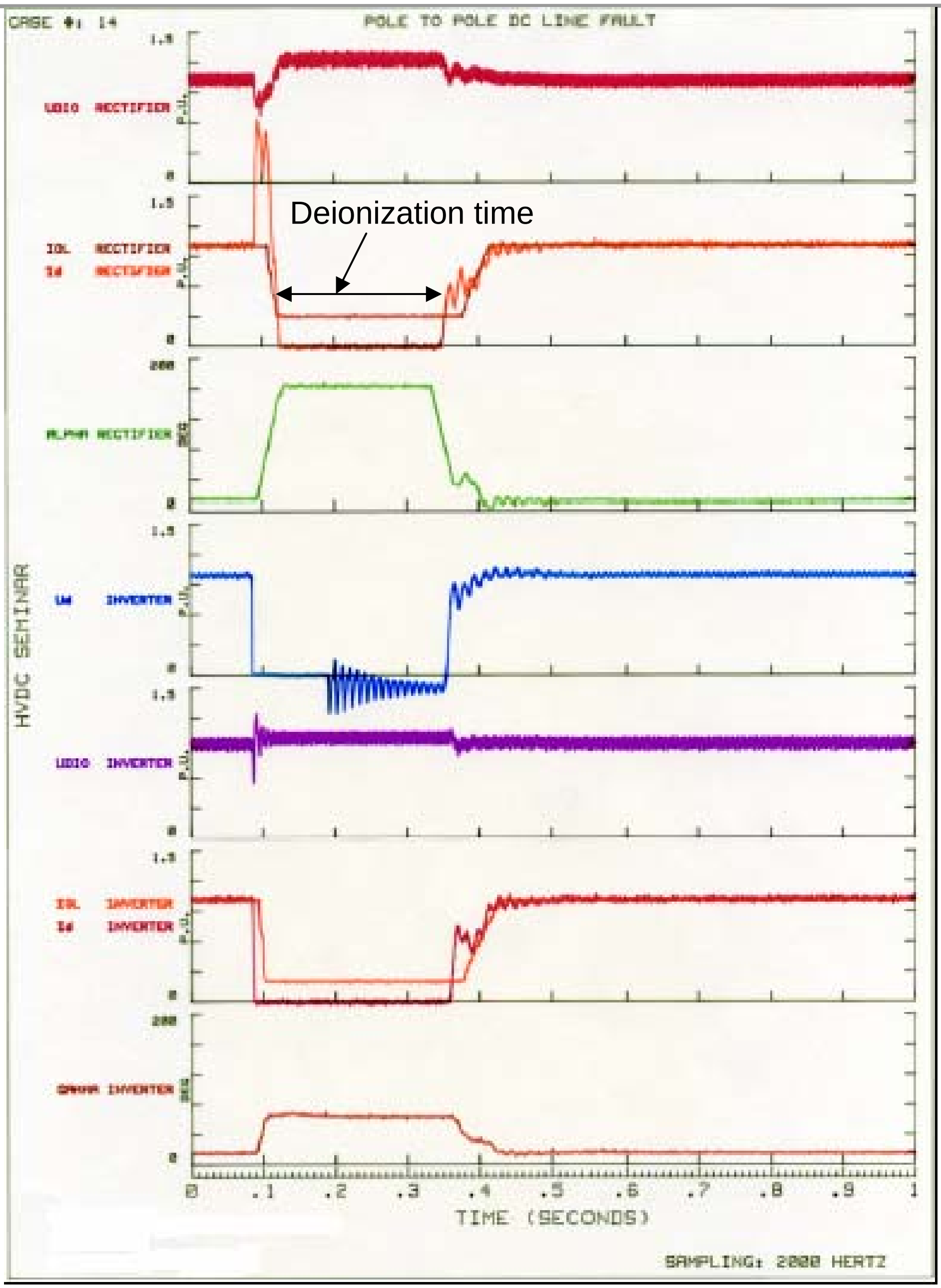
Alpha Rectifier

Vd Inverter

Vac Inv (rectified)

Io, Id Inverter

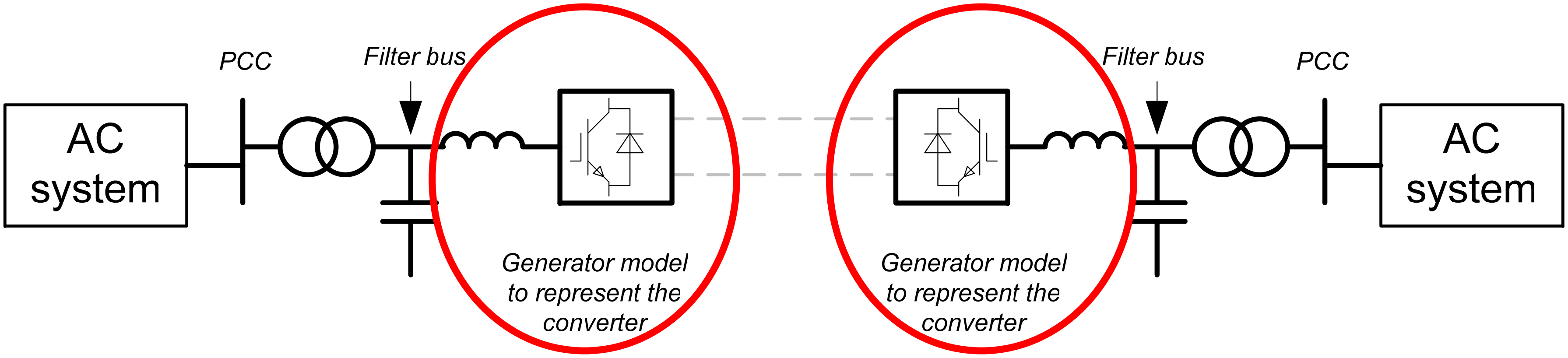
Gamma Inverter



Deionization time

Half power on other pole
Can compensate transiently

Power Flow Model for HVDC Light



Two Power Flow "Generators"

Load flow model

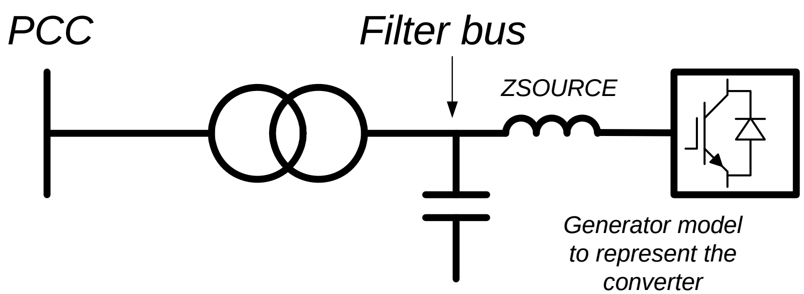
First converter

Second converter

Modular concept

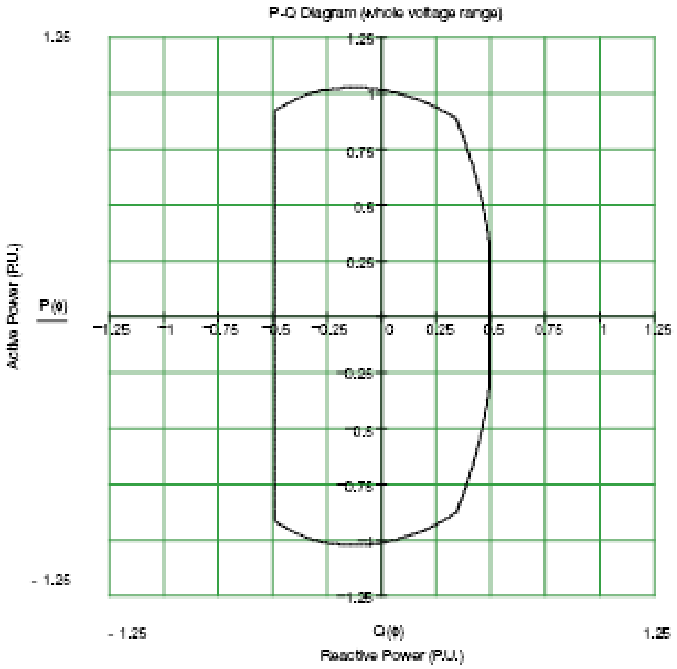
HVDC Light® modules		Currents		
		580A (2 sub)	1140A (4 sub)	1740A (6 sub)
Voltages	± 80 kV	**M1 =101 MVA**	**M2 =199 MVA**	**M3 =304 MVA**
	± 150 kV	**M4 =190 MVA**	**M5 =373 MVA**	**M6 =570 MVA**
	± 300 kV	**M7 =380 MVA**	**M8 =747 MVA**	**M9 =1140 MVA**

Load Flow data for HVDC Light®



Generator model
to represent the
converter

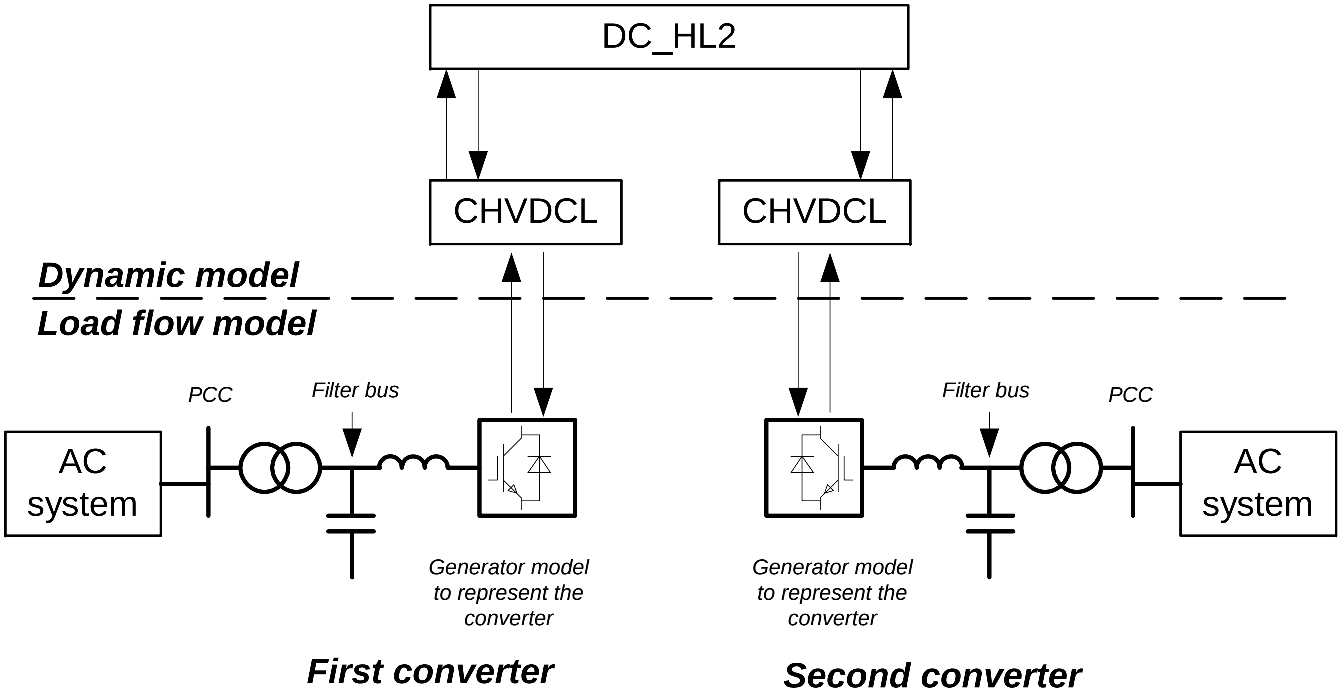
- The PQ-diagram (limitations)



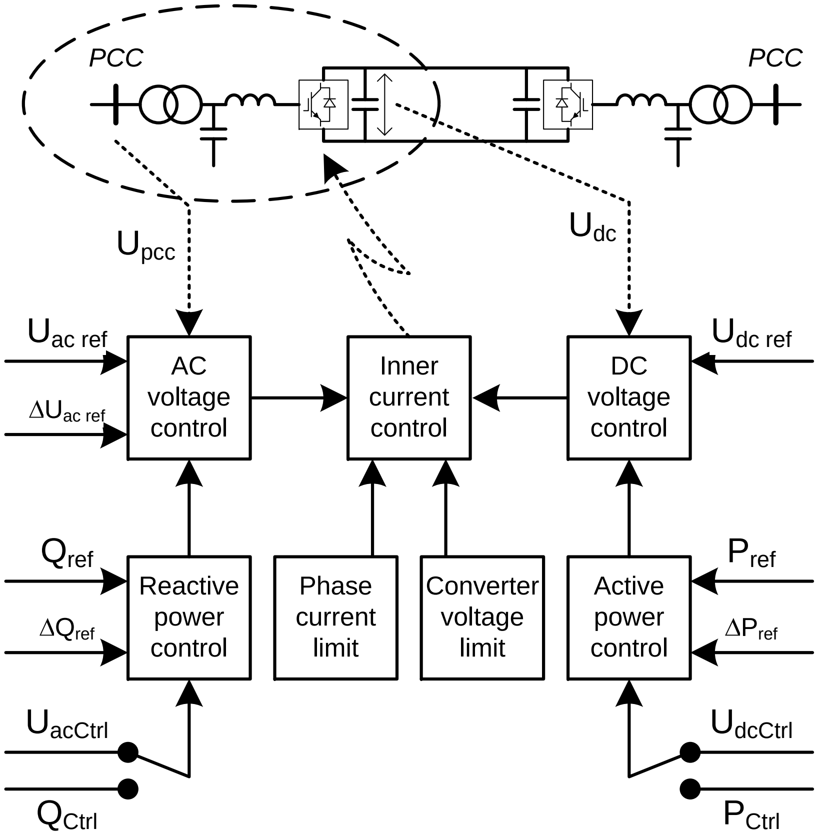
Typical P/Q diagram within the whole voltage range. Y-axis: Active power

Principals of the model - PSS/E

- First converter / Second converter
  - This naming is only to give the converters different references
  - There is no priority or differences in controls based on this naming
  - Either converter can operate in inverter or rectifier mode
  - One of the converters is in dc voltage control and the other is in active power control
  - Each of the converters can independently be set in ac voltage or reactive power control mode



Converter control - PSS/E



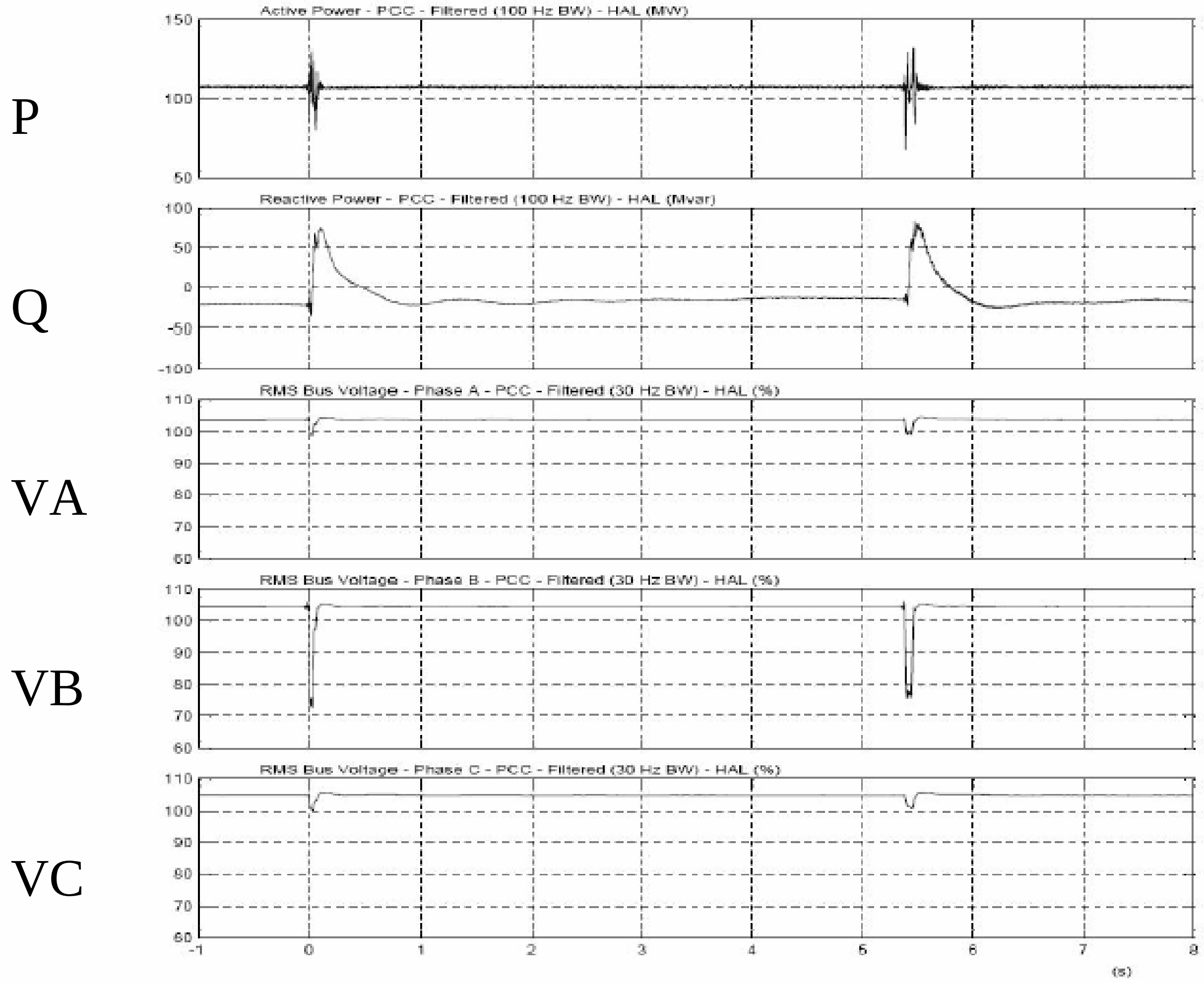
- The CHVDCL model represents the HVDC Light converter control
- Recognizes the following actions:
  - AC voltage control or reactive power control
  - Active power control or DC voltage control
  - Current output limitation
  - Internal converter voltage limitations

Converter control, user interaction

- Additionally, the HVDC Light model accommodates the following actions by the user:
  - Power ramping, by modifying the power order
  - Converter blocking
  - Modulation by an external control, separate auxiliary inputs for modulation
    - P_{order}
    - Q_{order}
    - $U_{acorder}$
  - Passive Net operation (optional)
    - Black start
    - Off shore applications (drilling, windfarms, etc.)

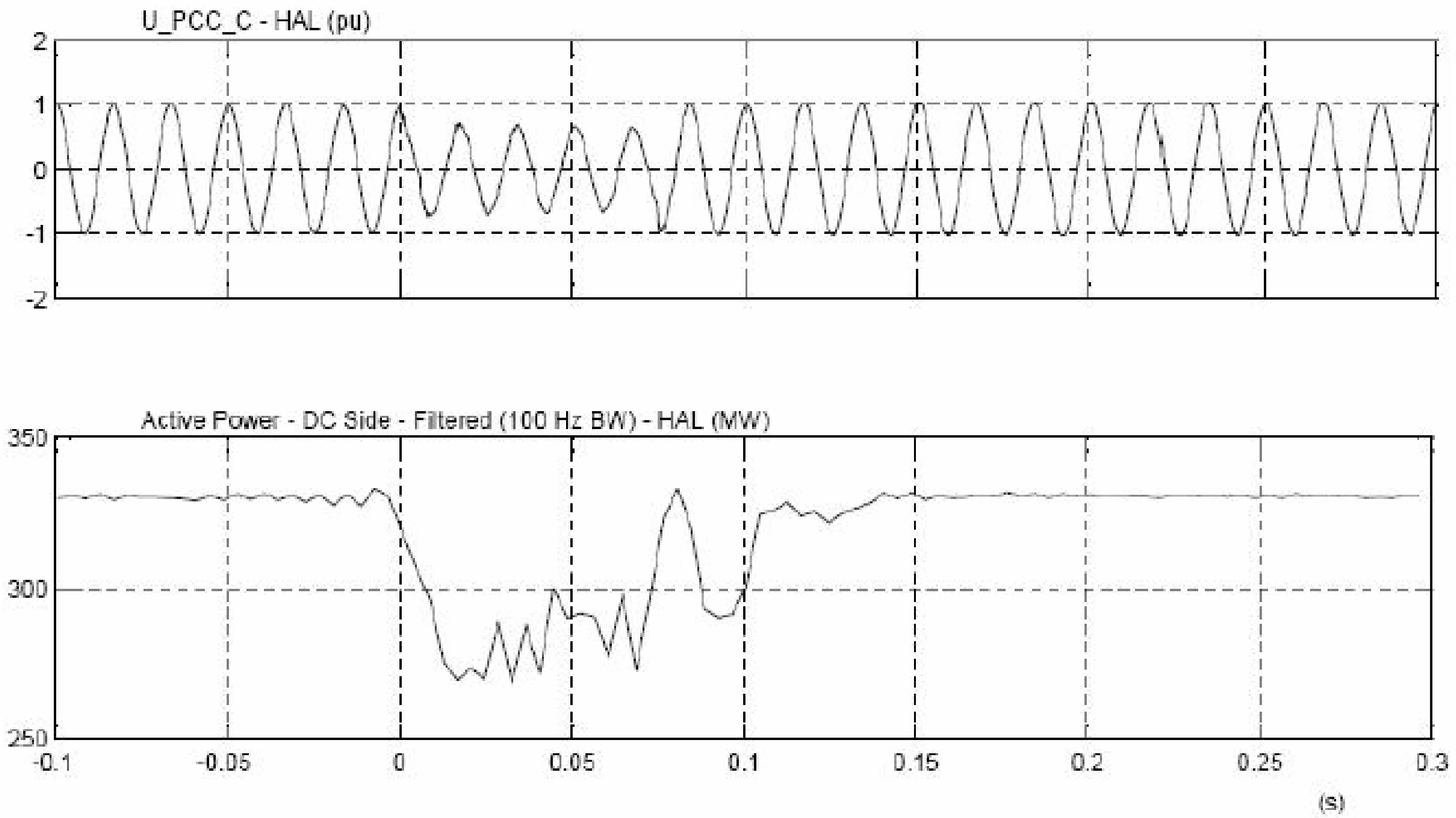
HVDC Light Dynamic Performance

Cross Sound Cable – Dynamic Response to Network Faults
June 6, 2005 – Fault on 310 Line (345 kV)

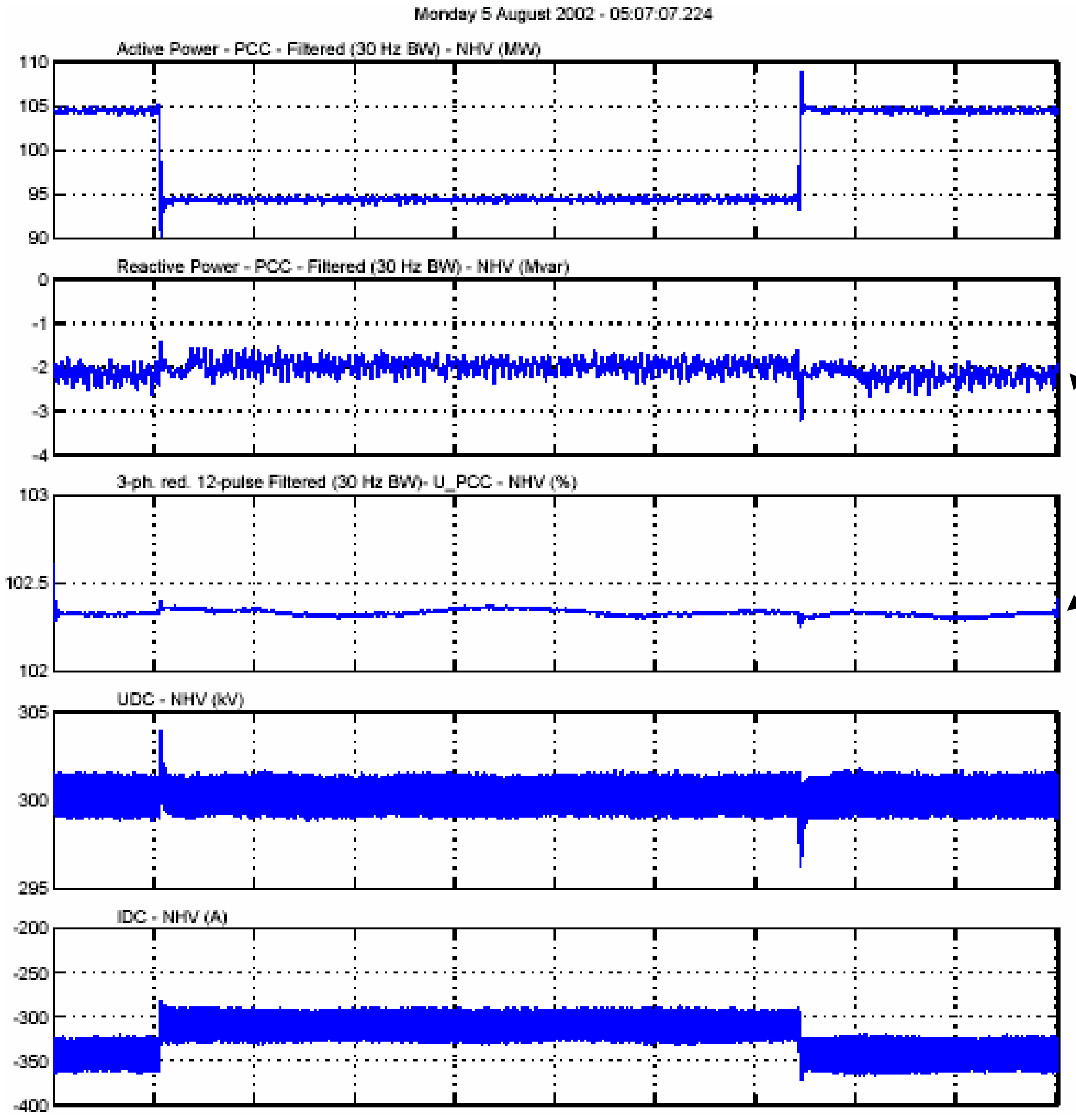


HVDC Light Dynamic Performance

Cross Sound Cable – Dynamic Response to Network Faults
March 17, 2005 – Cross arm fault on 353 Line (345kV)



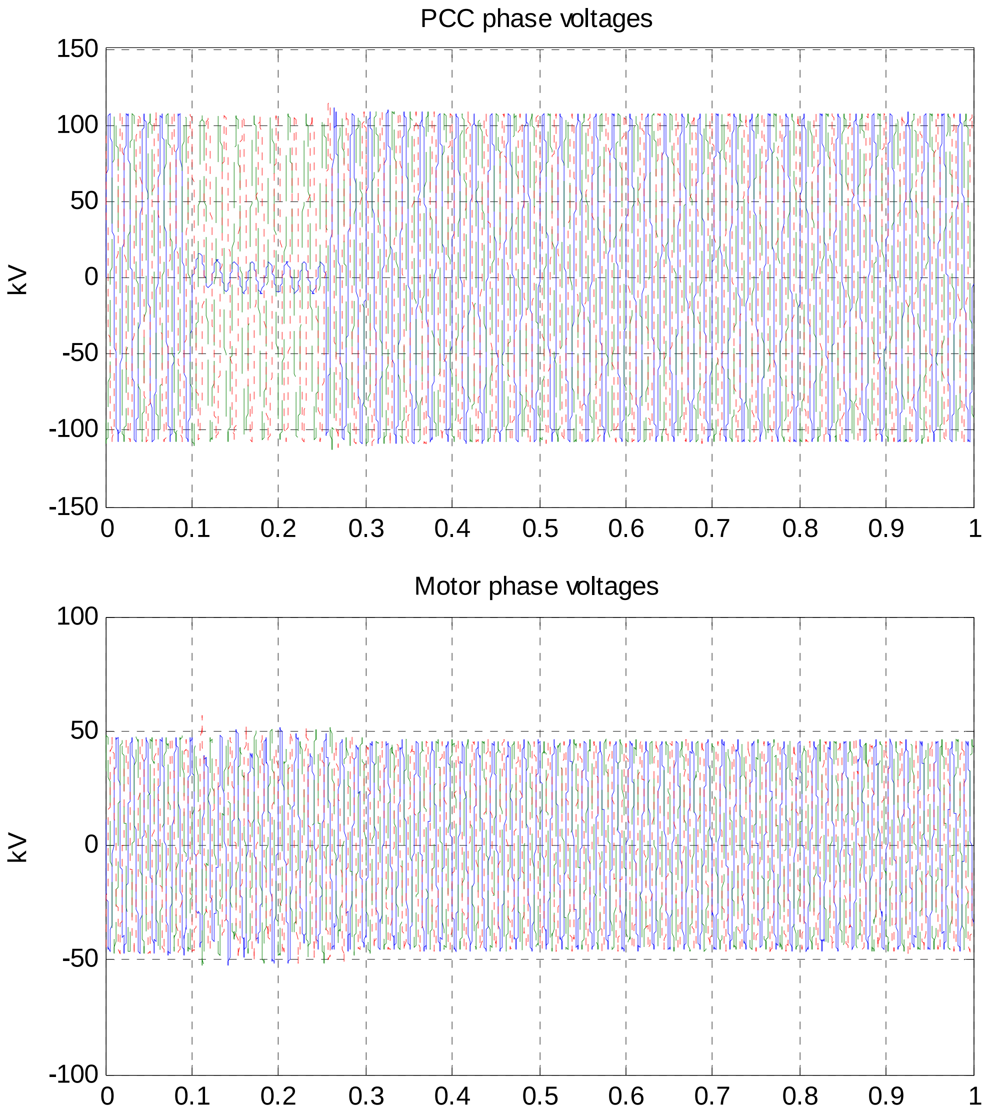
Cross Sound - Step Response Test



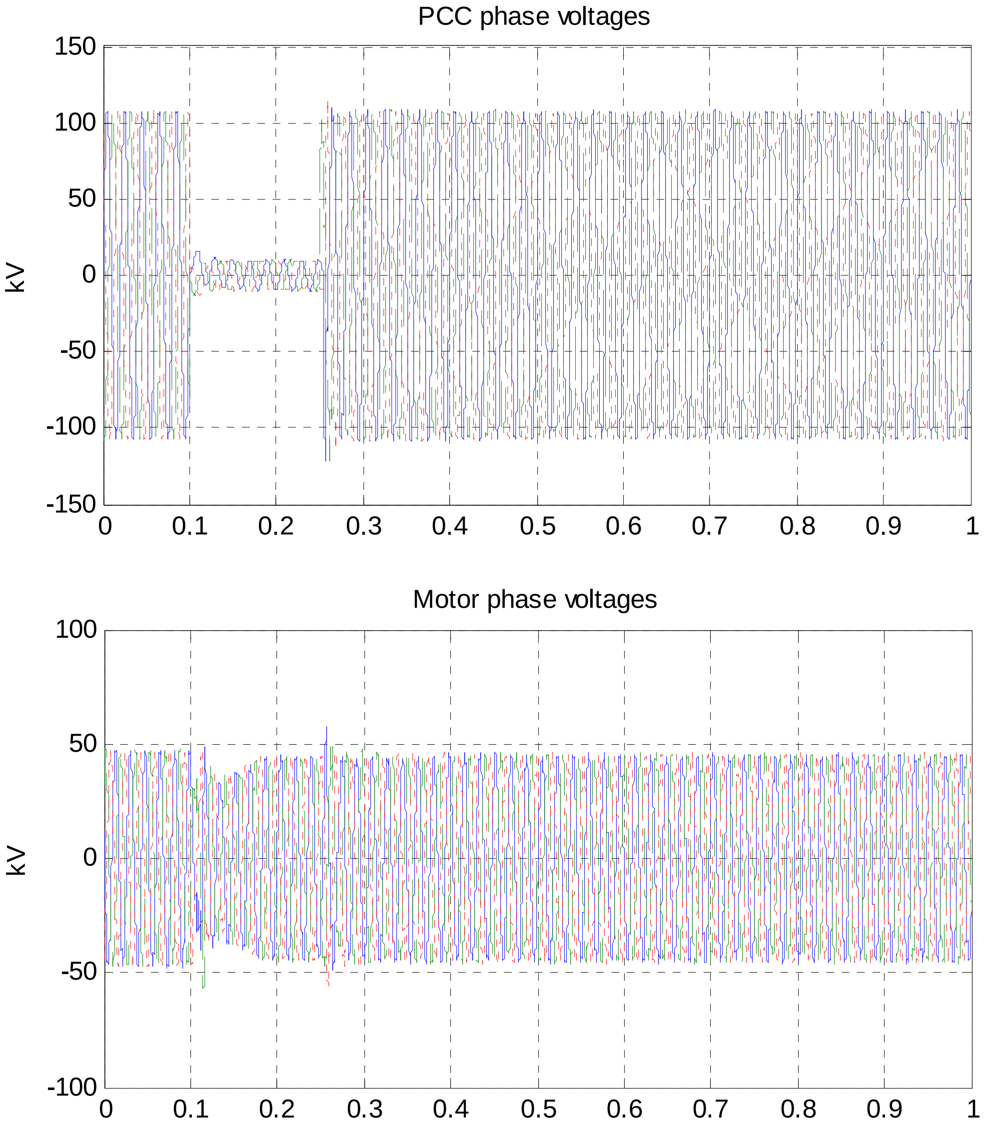
No Change in Reactive Power Demand or AC Voltage

First energized July 22, 2002
Heat-run test August 7, 2002
330 MW VSC Transmission

Troll A – Solid 1-phase fault in Kollsnes, 132-kV bus



Troll A – Solid 3-phase fault in Kollsnes, 132-kV bus



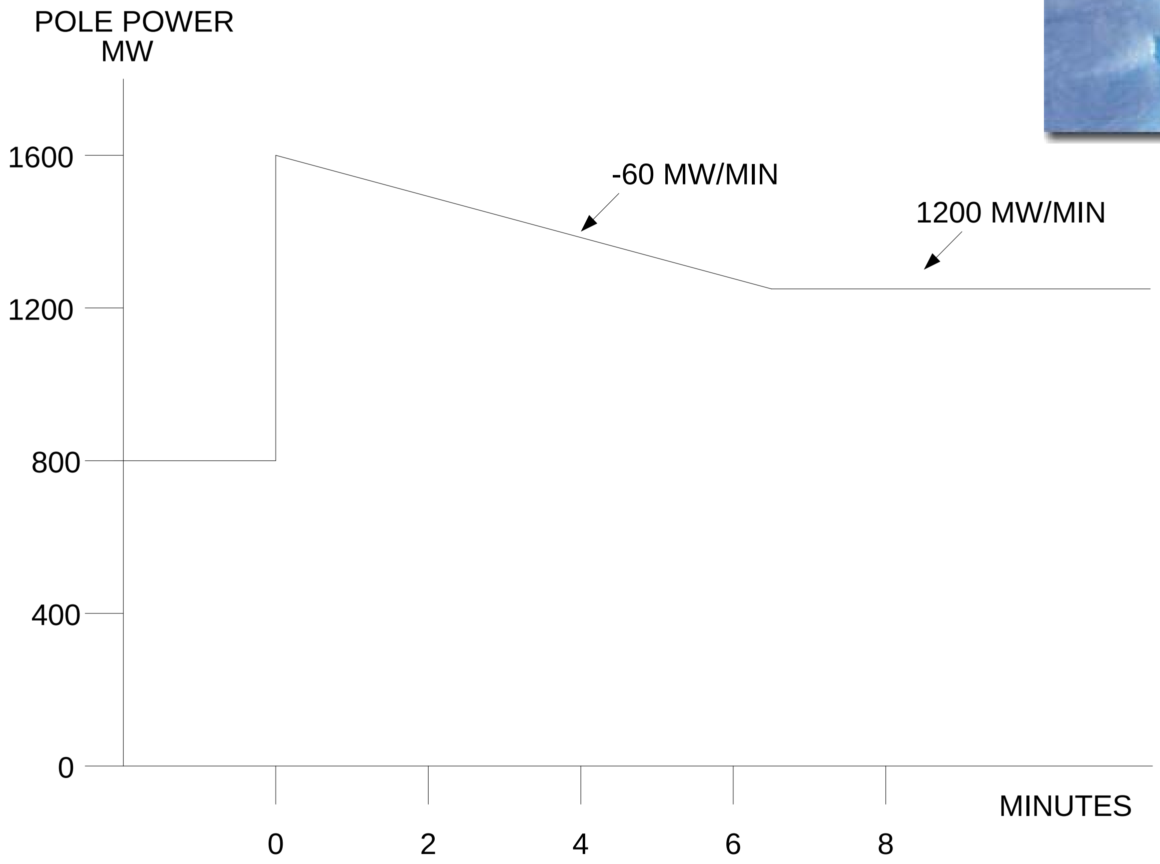
HVDC Model Availability

	PSS/E		PSLF	
	Available		Available	
HVDC Conventional	Yes		Yes	
HVDC Light - Reduced	Yes		Yes	
HVDC Light - Detailed	Yes		No	
Note: Detailed and Reduced Model generally require ABB to provide data to properly model the system				

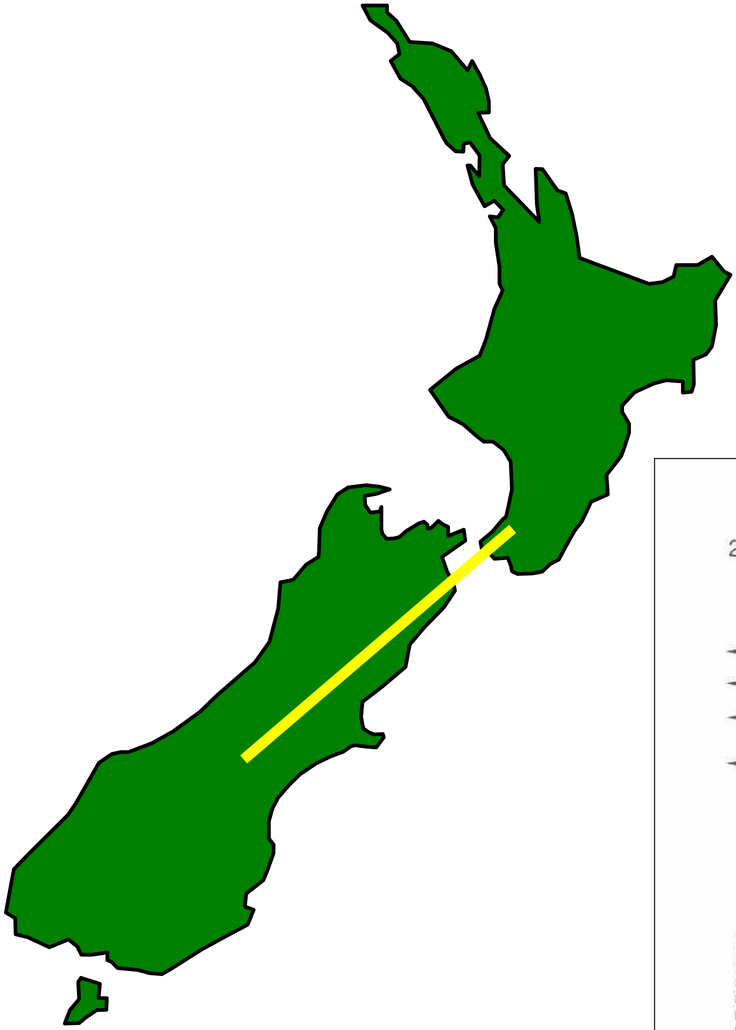
HVDC DETAILED DYNAMIC CAPABILITIES

EXAMPLES OF HVDC CONTROLLABILTY USED TO ENHANCE SYSTEM DYNAMIC PERFORMANCE:

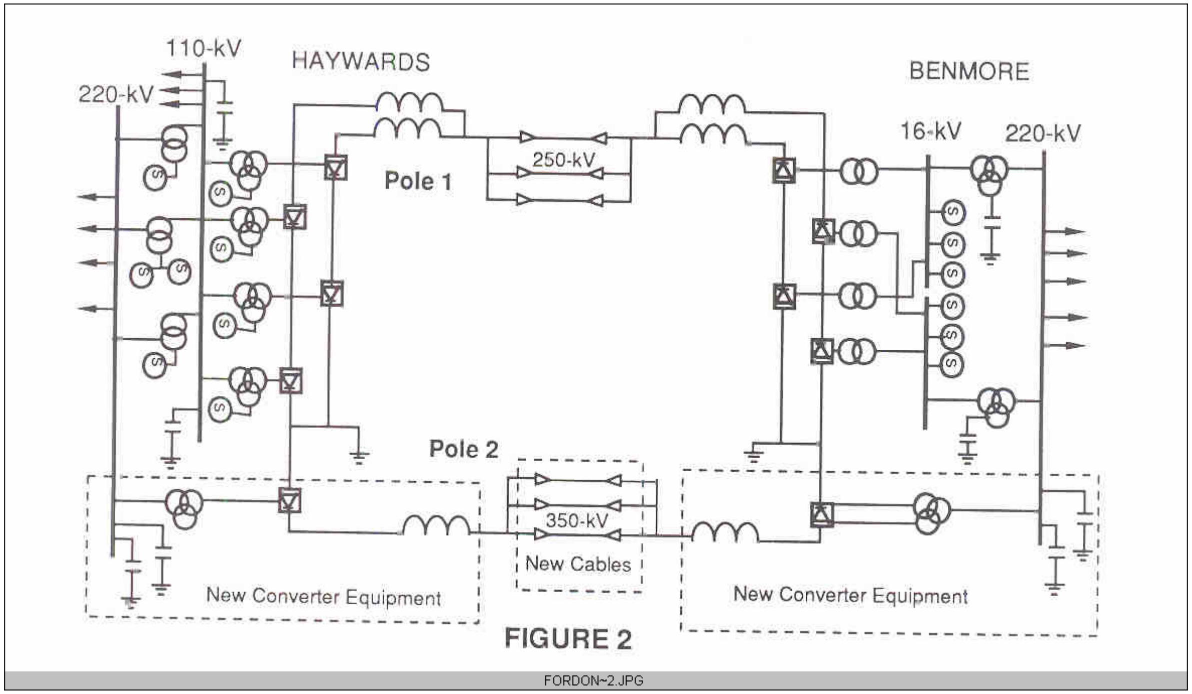
IPP HVDC POLE CAPABILITY



NEW ZEALAND HVDC UPGRADE LINK



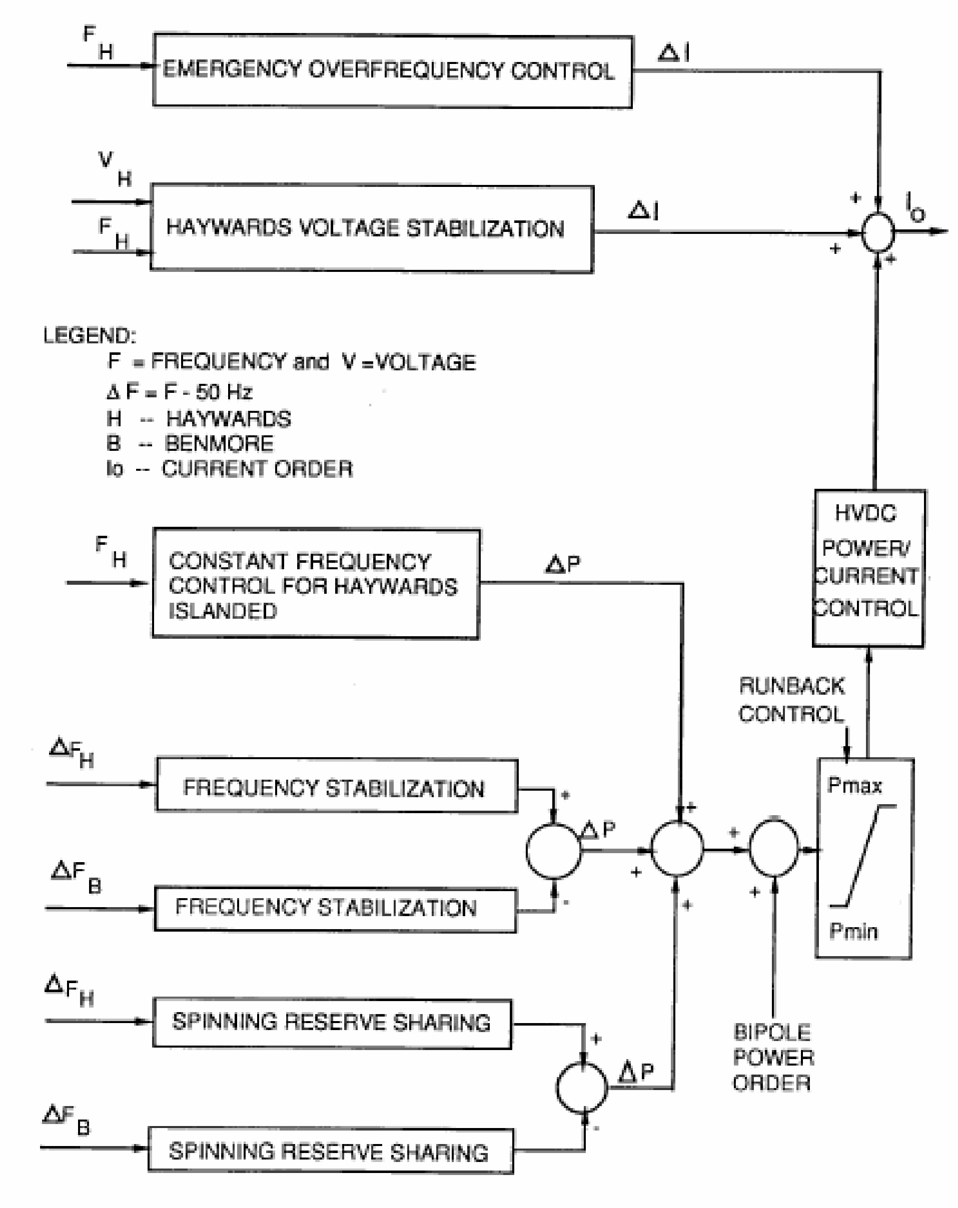
- Voltage Stabilization
- Constant Frequency Control
- Frequency Stabilization
- Spinning Reserve Sharing



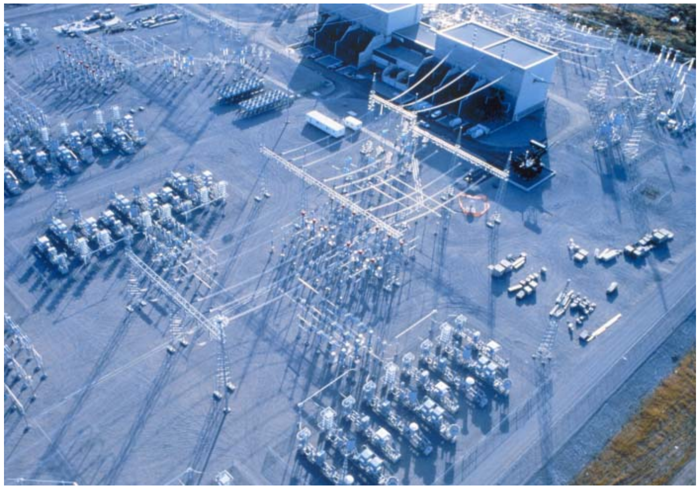
NEW ZEALAND HVDC UPGRADE LINK

New Zealand System Performance Enhancement with HVDC Control

Required Extensive Stability Studies



Q- NE HVDC Multiterminal Studies



- Radisson Frequency Control Study
- Power Modulation Control for Hydro-Quebec System
- Power Modulation Control for New England System
- Radisson Dynamic Overvoltage Study

HVDC PERFORMANCE

HVDC CONTROL HAS CAPABILITY FOR:

- No inadvertent or loop flow
- Improve AC system stability
- Improve AC system damping
- Optimize loss performance
- Participate in remedial action schemes
- Provide voltage support and control