MANITOBA·HVDC RESEARCH CENTRE

# Voltage Source Converter (VSC) IEEE PES Winnipeg Tutorial

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# Acknowledgements:

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MHRC Staff

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Cigre DC Grid Working Groups

B4-55, 56 57 58 59 and 60 ..

ABB Siemens and Alstom Grid

# VSC Tutorial

VSC Converter Theory Basics

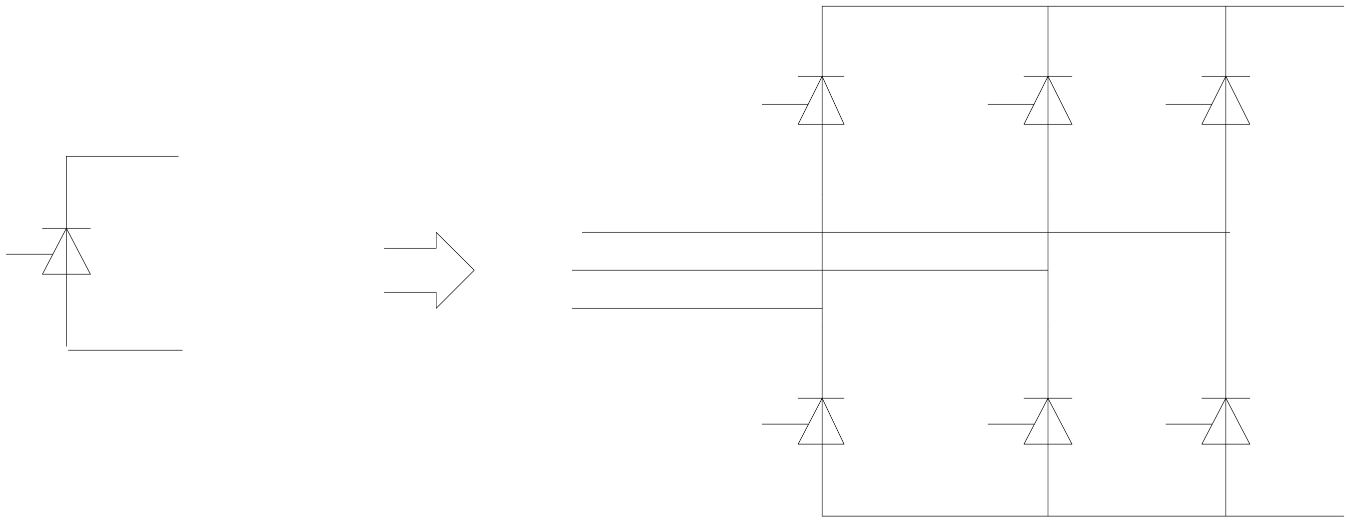
VSC Control and Modelling

VSC system simulations

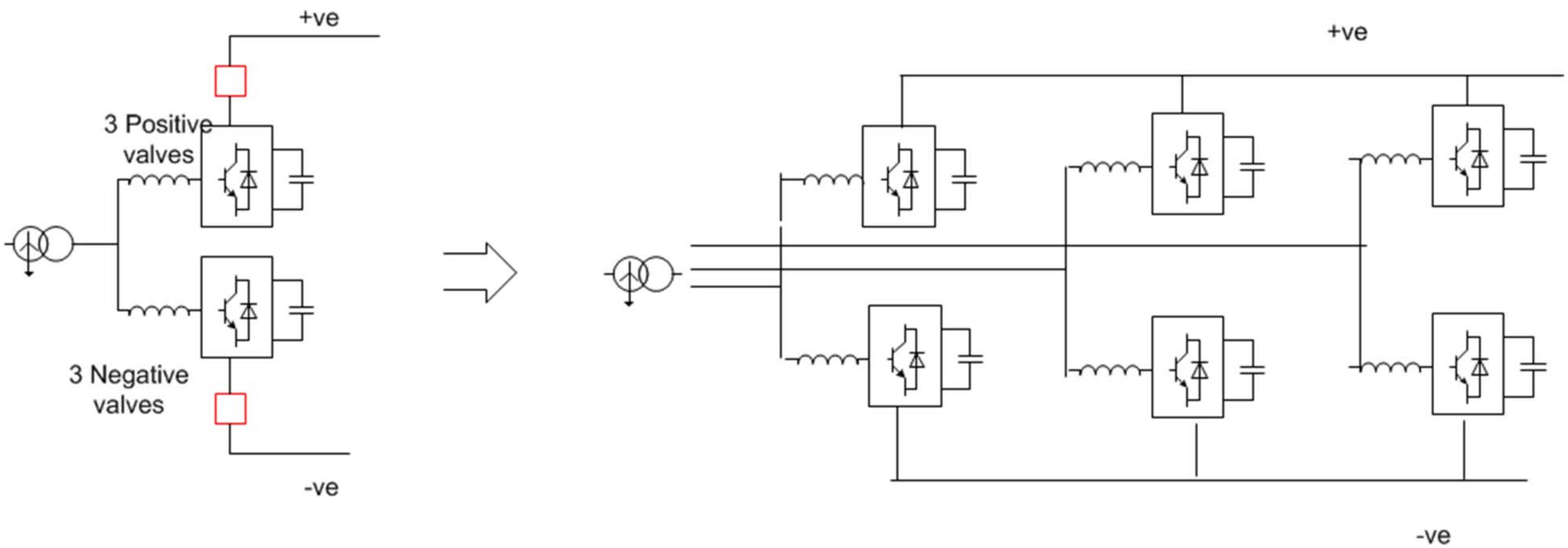
Start –up; DC Fault

DC Grid Test Case Cigre B4-57/58

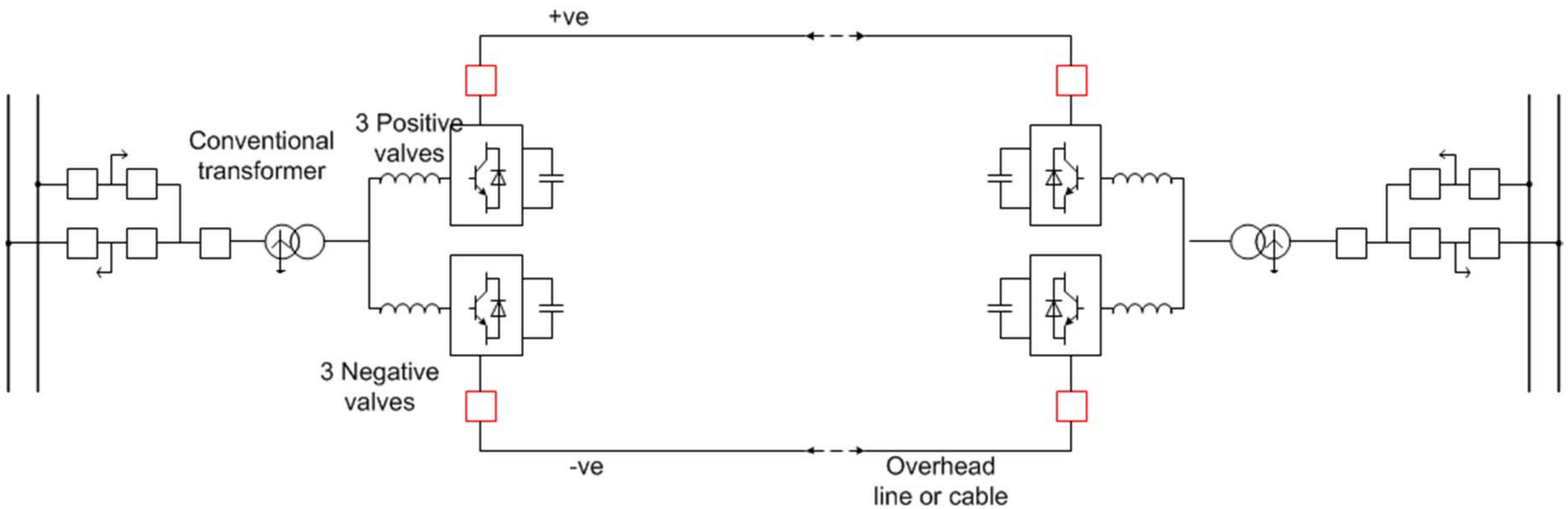
# Introductory Basics: LCC Single line



# VSC: Single Line Diagram Format



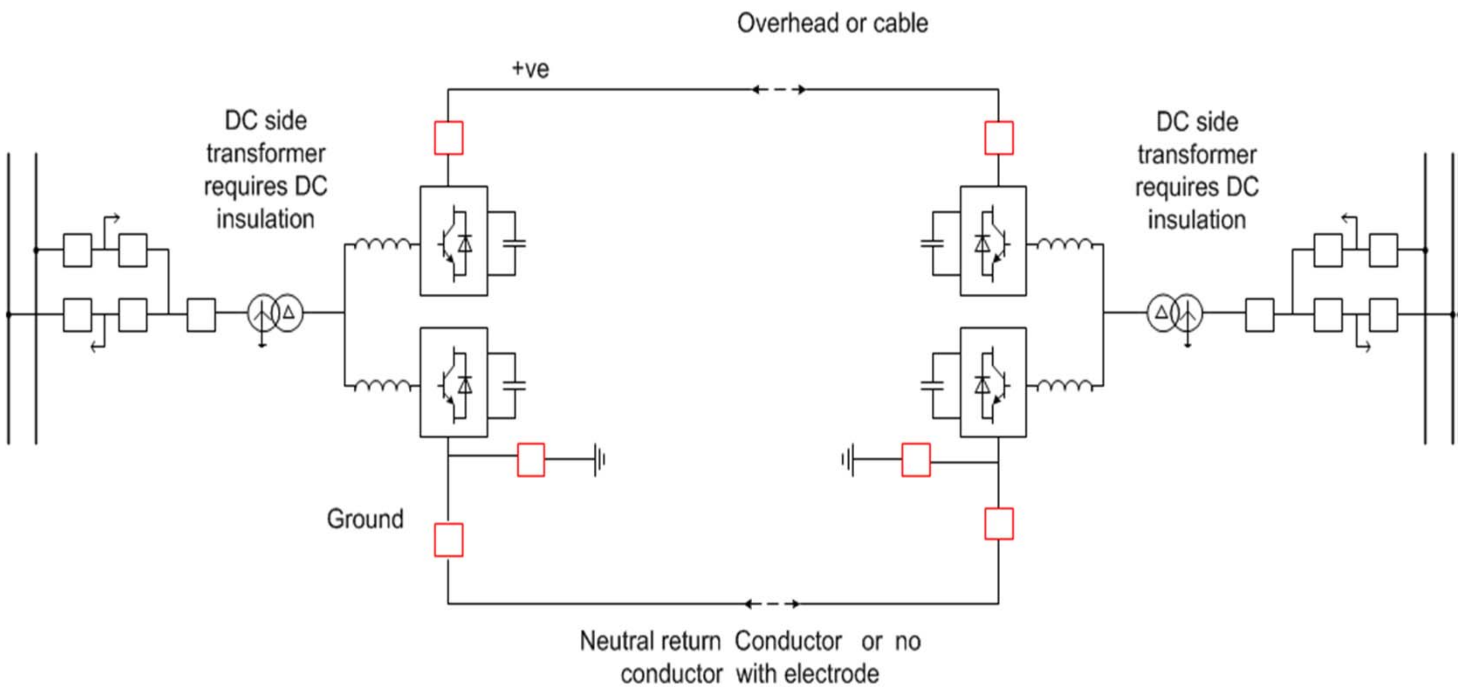
# Symmetrical HVDC Monopole




**Symmetrical Monopole**

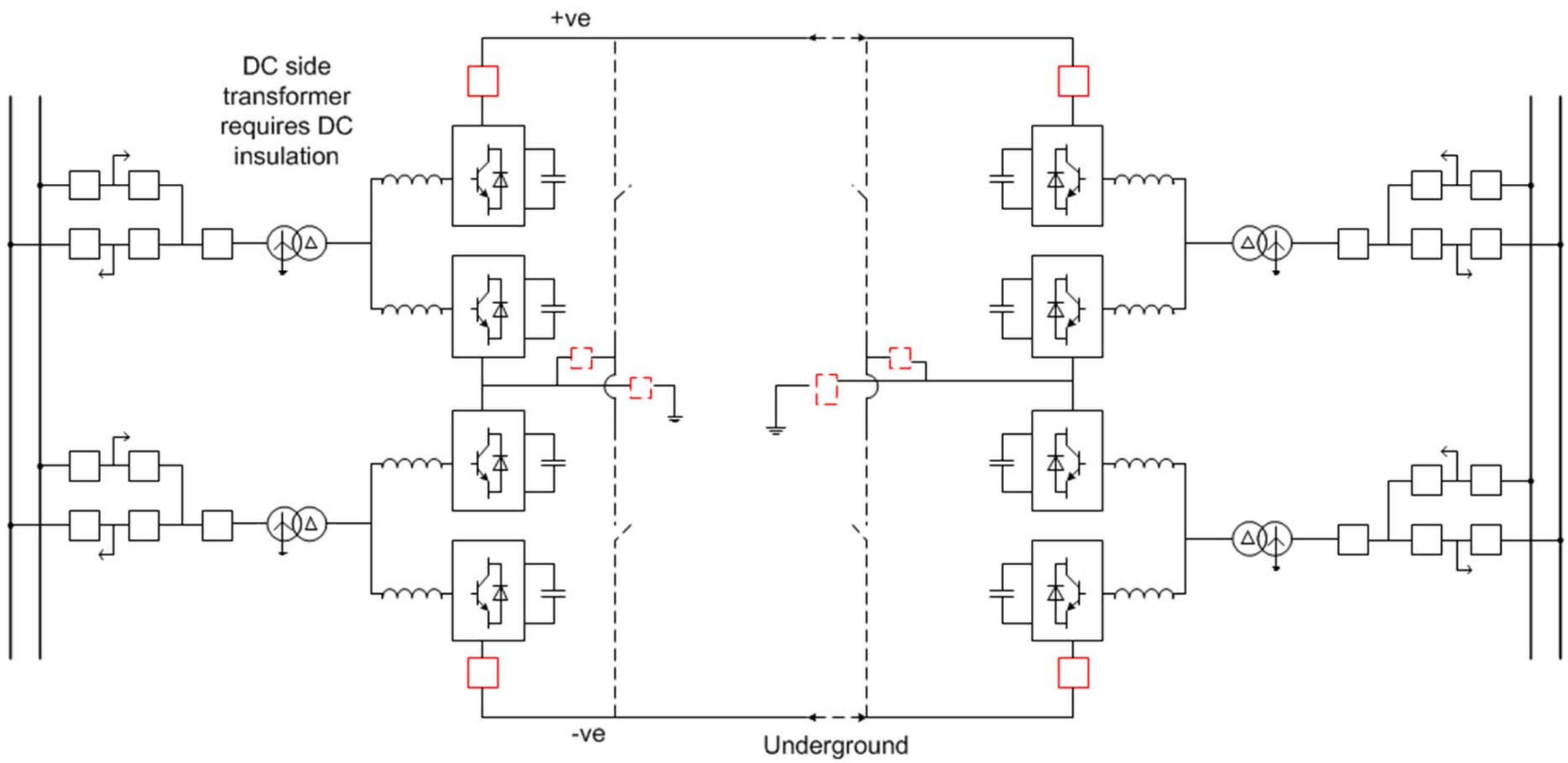
(Not A Bipole)

# VSC: Unsymmetrical Monopole




**Unsymmetrical Monopole**

# VSC: Bipole Configuration




VSC Bipole

# LCC - VSC Comparison

| LCC HVDC | VSC HVDC |
| --- | --- |
| Mature Technology | Rapid growth |
| “Requires” strong ac system | Helps ac system<br>Control real and reactive power independently |
| Lower losses 0.8% per converter | Losses reducing 1.1- 1.2% per converter |
| Requires 60% reactive power | No Commutation failure |
| AC-DC system interactions | Less Special Transformers |
| Harmonics | Flexible Dispatch |
| Commutations failure | Harmonics with MMC no issue |
| Special Transformers | DC Grid (multi-terminal) possible |
| Multi terminal operation possible but hard | DC voltage is a constant polarity |
| Controlled DC Current to zero (Idref=0) | DC Line faults are problematic |
| Dc voltage + to - as alpha changes rectifier to inverter | |

# Multi Terminal

**For LCC:**

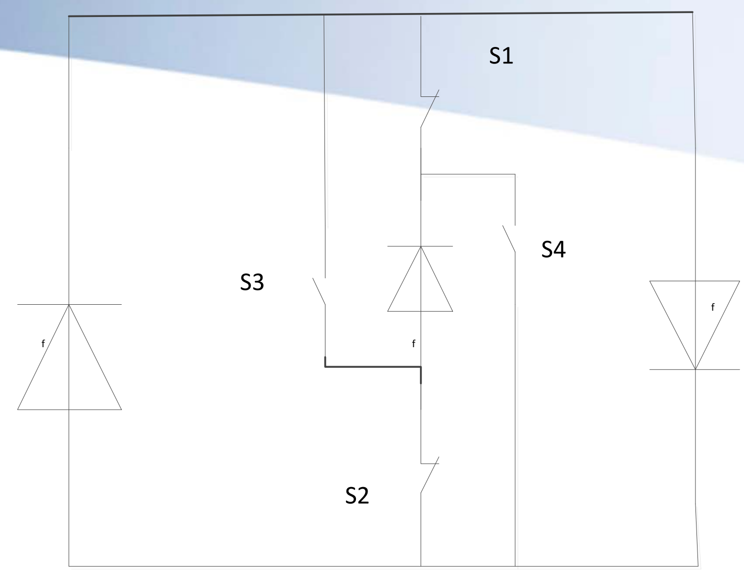
Rect α < 90 Vdc +ve

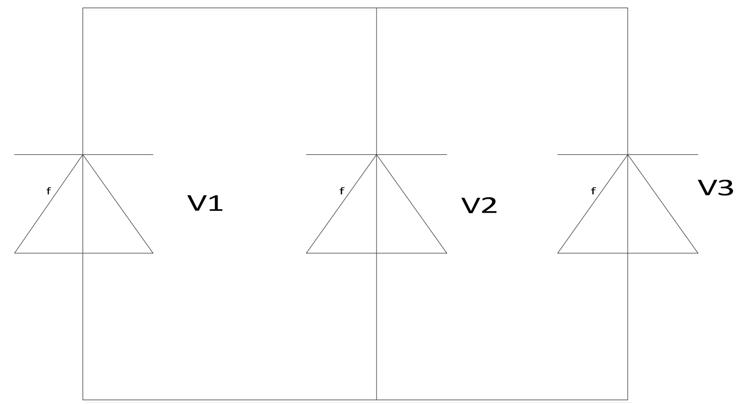
INV α > 90 Vdc -ve

To change Conv 2 from Rect to Inv you must flip the thyristor

**For VSC:**

Power Flow is controlled by control signals only



# VSC Technology is very flexible

VSC technology can control two variables together

real power and reactive power

VSC can generate an AC Waveform….

Black start or island mode possible

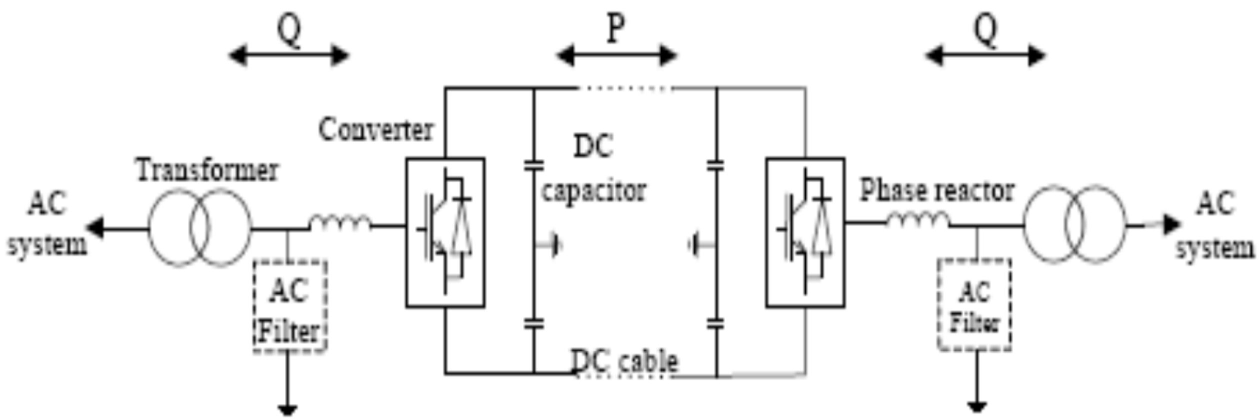
Many dispatch options available

- Real Power set point in or out + or -
- Use power to control DC voltage Vdc
- In island mode : use power to control frequency

- Reactive Power Q set point in or out + or –
- Use Q to control Vac magnitude Grid or islanded Mode…

- Other control targets are possible..

# VSC Operation



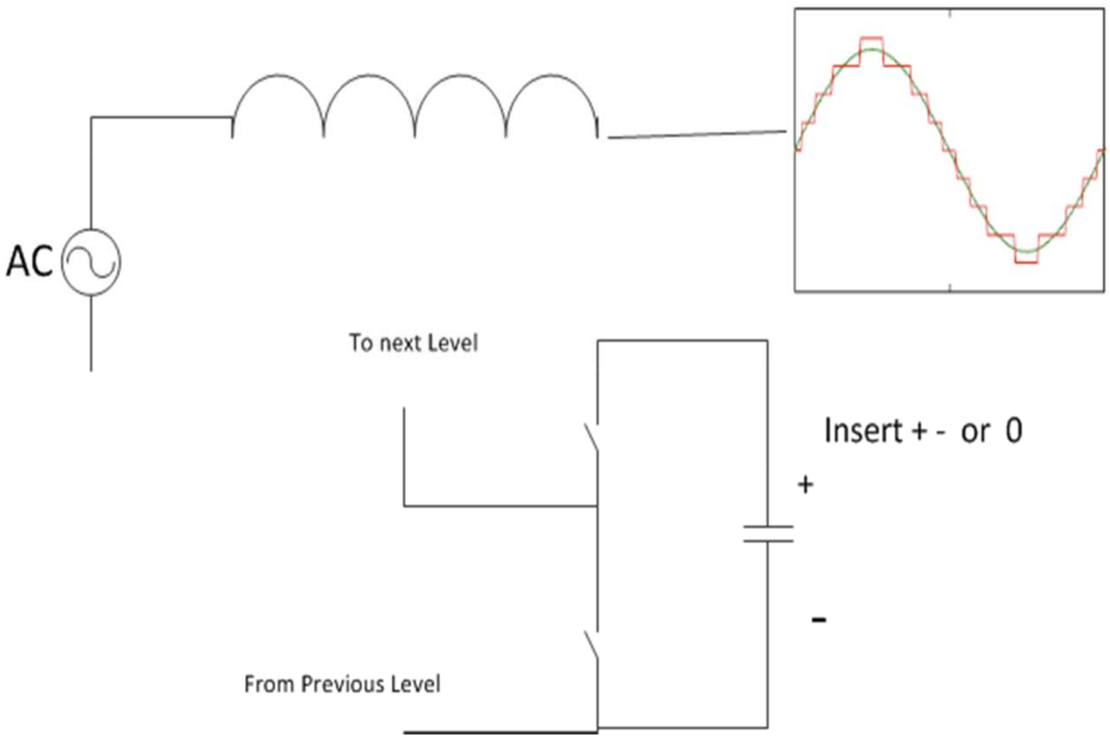

$$P = \frac{U_F \times U_C \times \sin\delta}{\omega L}$$

$$Q = \frac{U_F \times (U_F - U_C) \times \cos\delta}{\omega L}$$

We tend to think of LCC from AC side to rectifier and generate Dc voltage

For VSC ; think from the DC side.. Assume DC Capacitors are charged
The capacitor voltages are used to piecewise build ac voltage
We the ac voltage waveform and the ac system voltage
now we can transfer energy to charge Dc capacitor(s)

# Transfer P & Q across Reactor




Use DC capacitor voltage (Ud) to build an ac Voltage waveform Uc

Exchange P based on δ
- ↑ δ P into Converter Ud ↑
- ↓ δ P from Converter Ud ↓

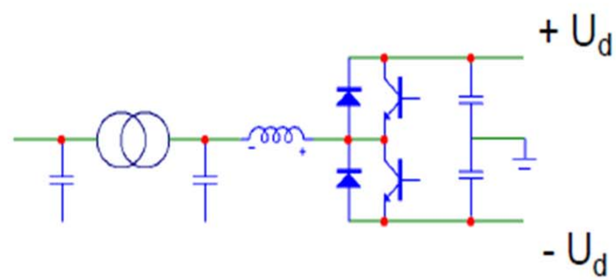
Exchange Q based on |Uc|
- ↑ |Uc| Q flows into system
- ↓ |Uc| Q flows from system

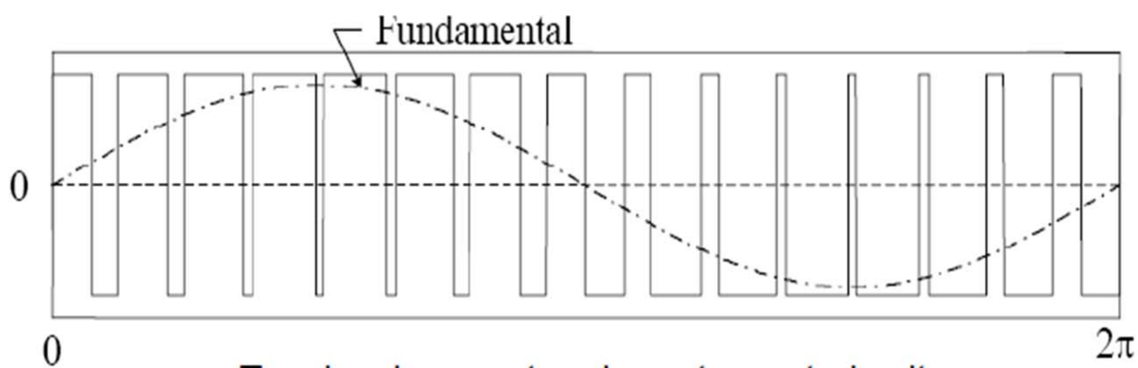
# History of VSC Development: ABB, Siemens and Alstom Grid

- VSC Rapid Growth and continue to change
- Many projects but few projects have the same design
- An MMC type configuration appears to be the “winner” but many marketplace has variations
  - Not unlike LCC technology 25 years ago
- The Final VSC configuration is not decided
  - and may never occur.

# HVDC Light
## Historical review, 1997-2001

- **Two-level Converter, Generation 1**
  - Converter losses 3 %
  - High switching frequency
  - Filters required

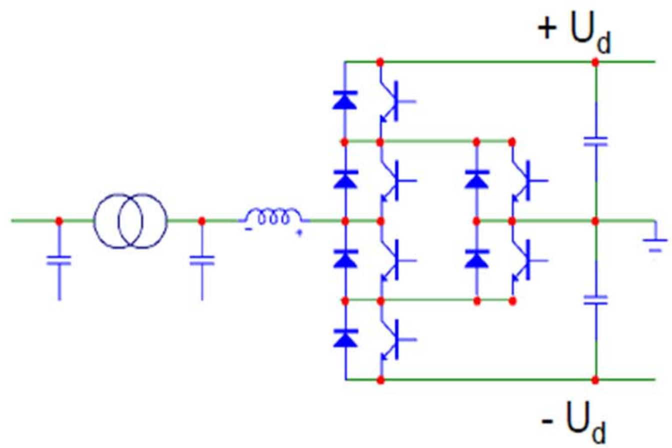


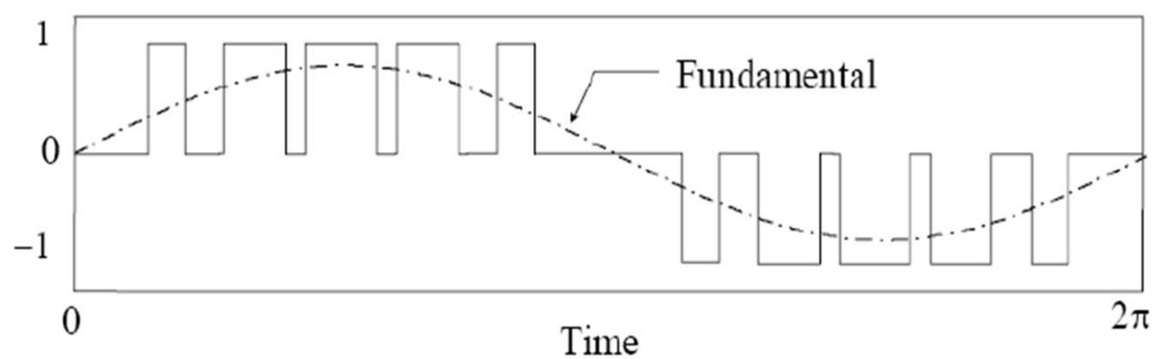




Two-level converter phase-to-neutral voltage

# HVDC Light
## Historical review, 2002-2004

- **Three-level Converter, Generation 2**
  - Converter losses 1.7 %
  - Switching frequency reduced
  - Harmonic generation improved



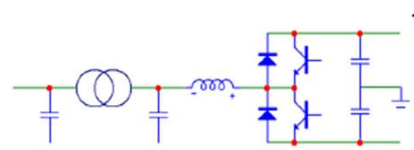



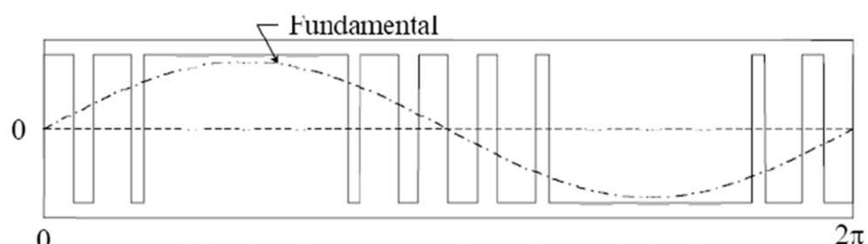

Three-level converter phase-to-neutral voltage

# PWM Based VSC

## HVDC Light
## Historical review, 2005-2009

- **Two-level Converter, Generation 3**
- Converter losses 1.7 %
  By optimized IGBT and drive
- Lower switching frequency
- Harmonic generation maintained

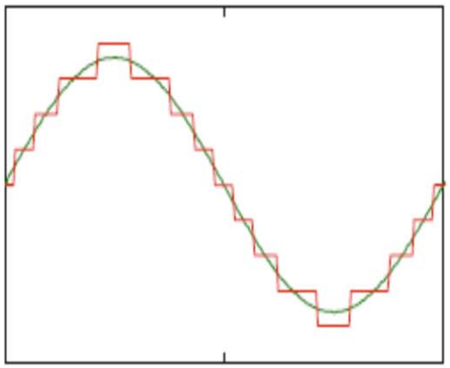


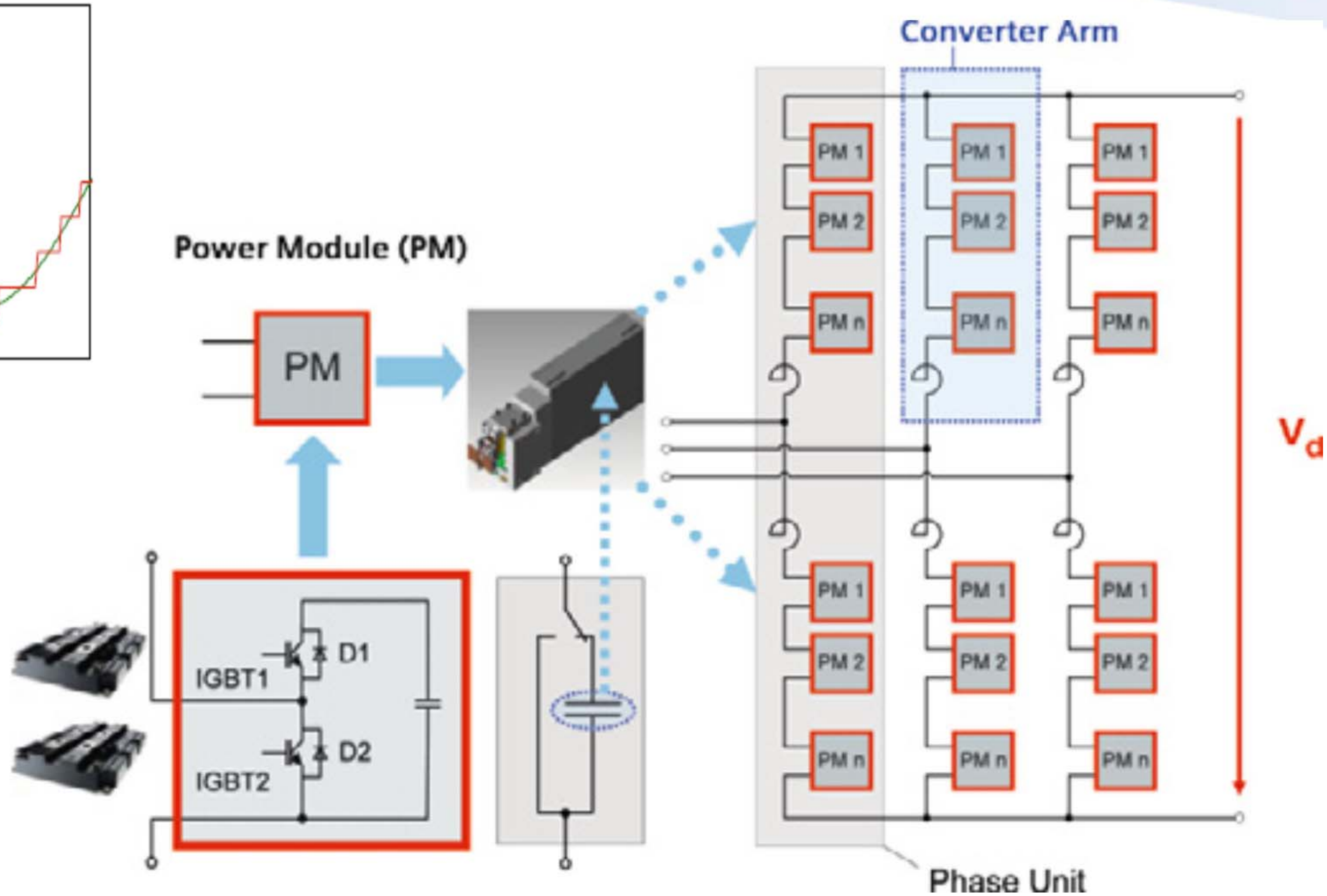




Two-level converter phase-to-neutral voltage

ABB slide

# ½ Bridge Multi Module Converter MMC

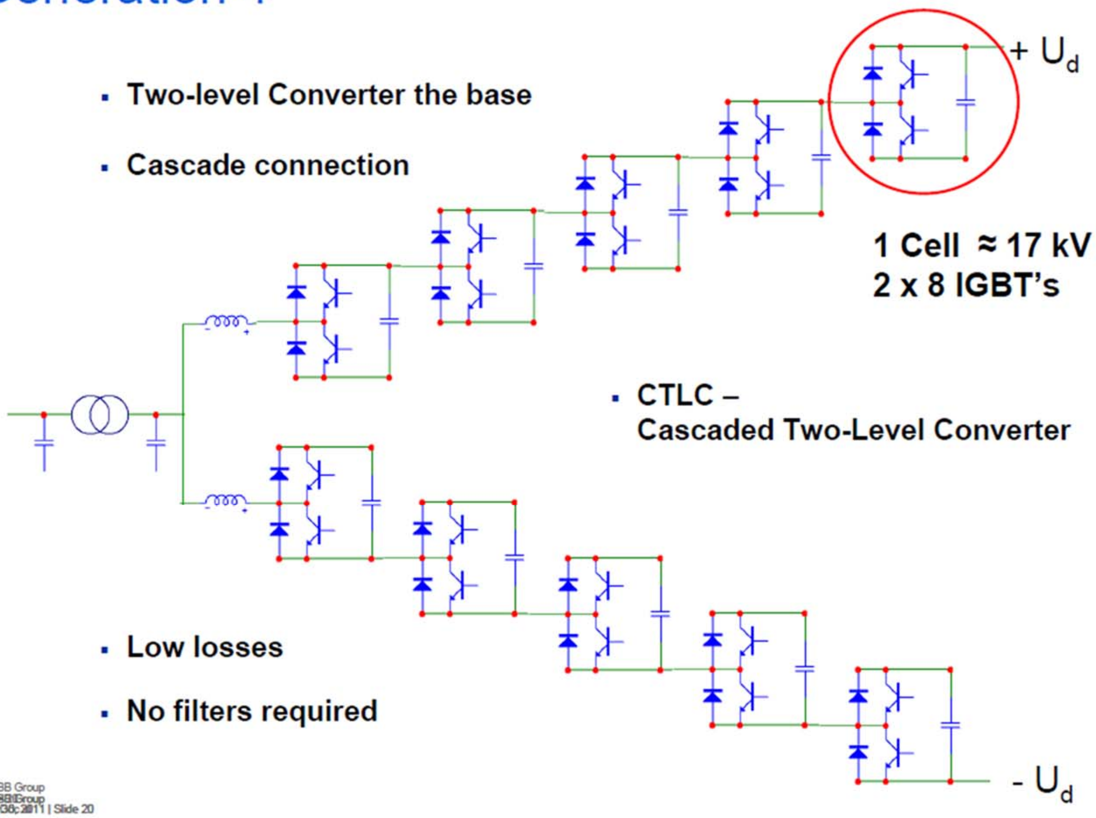





Siemens Slide

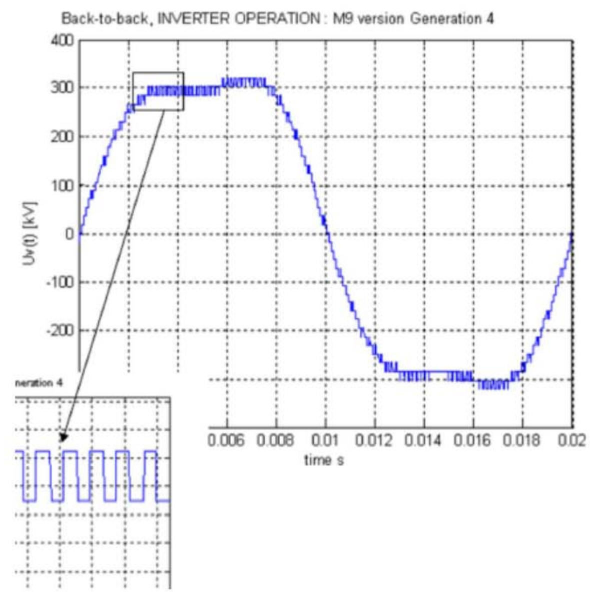
# HVDC Light
## Generation 4

- Two-level Converter the base
- Cascade connection




1 Cell ≈ 17 kV
2 x 8 IGBT's

- CTLC –
  Cascaded Two-Level Converter

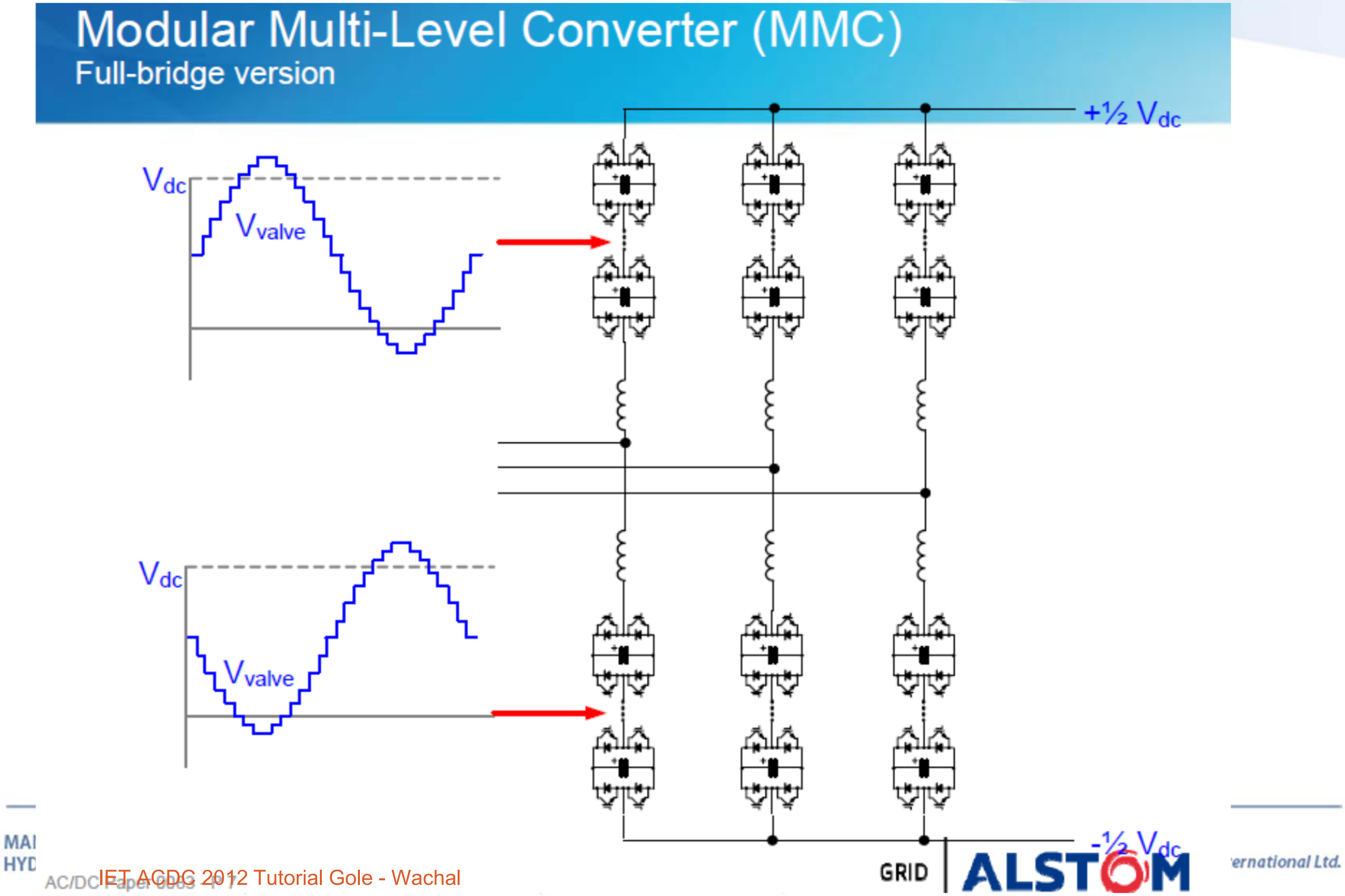



- Low losses
- No filters required

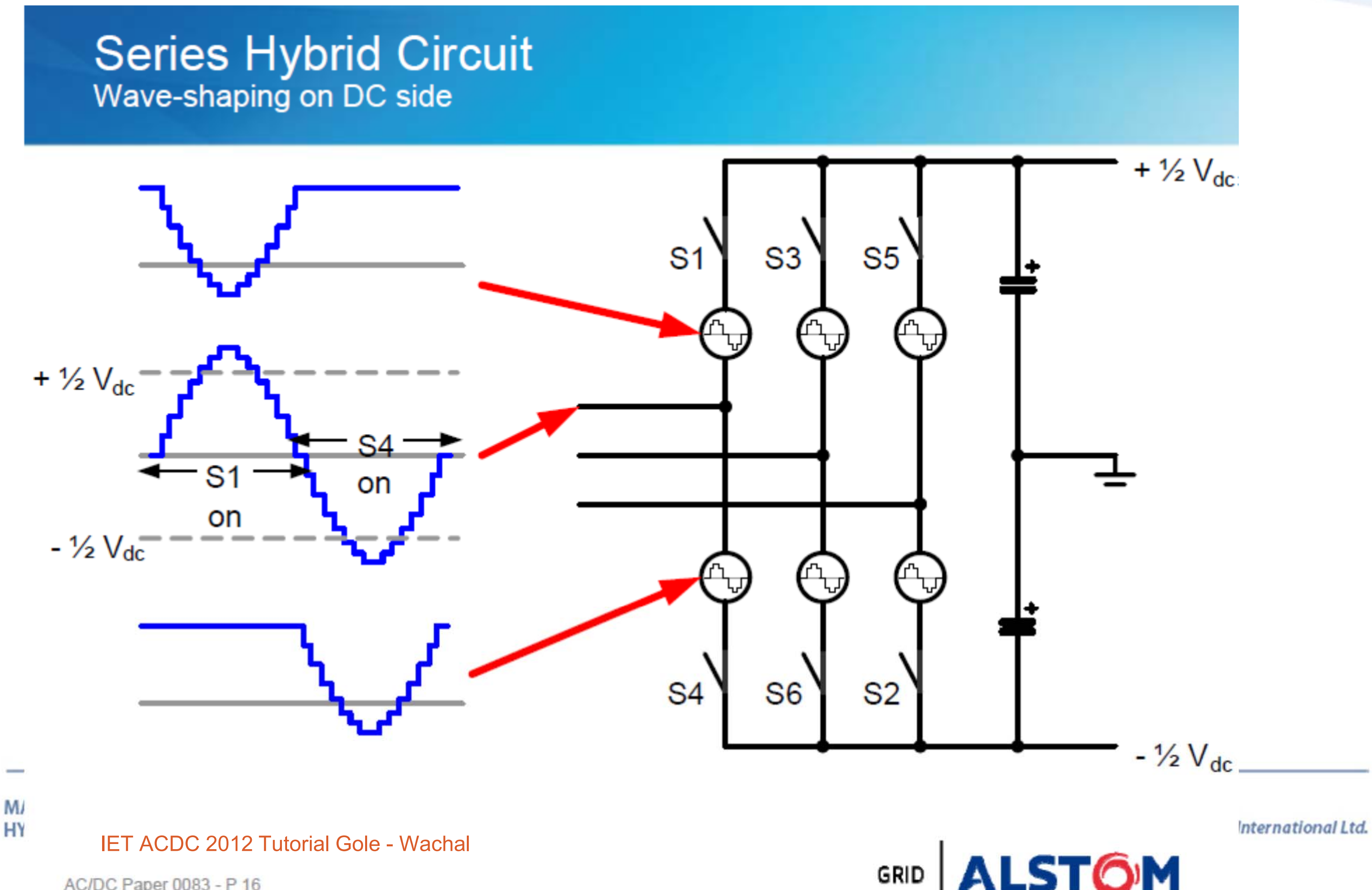


ABB

# Full Bridge MMC



# One possible Hybrid Configuration



# VSC Control and Modelling

- Control system organization
- Look at impact of diode in configuration
- High Level Control

  D Q controller development

  Development of Voltage reference signals based on dispatched orders

Lower level control

  Valve fire pulses (IGBT firing pulses)

  Capacitor energy balancing

# Models For VSC MMC system

EMT and RMS transient (Dynamic and loadflow) type models are required

Lots of VSC configurations to consider

- PWM based (all series devices in Valve switch together)
- ½ bridge MMC
- ½ bridge MMC with PWM (cascaded two level converter CTLC)
- Full bridge MMC
- Hybrid mixtures of series valves, ½ and full bridges

# Traditional ‘emt’ solution methods not effective

Emt simulation speed is dependent on number of electrical nodes (size of simulation matrix)

MMC configurations increase electrical nodes exponentially

- LCC and PWM VSC
  - **6 nodes per 3 phase valve**
  - **entire valve arm (xx series devices) switch together**
- MMC
  - **Valve may have 400 levels (each switching independent)**
  - **400*6 = 2400 nodes for 1 converter**

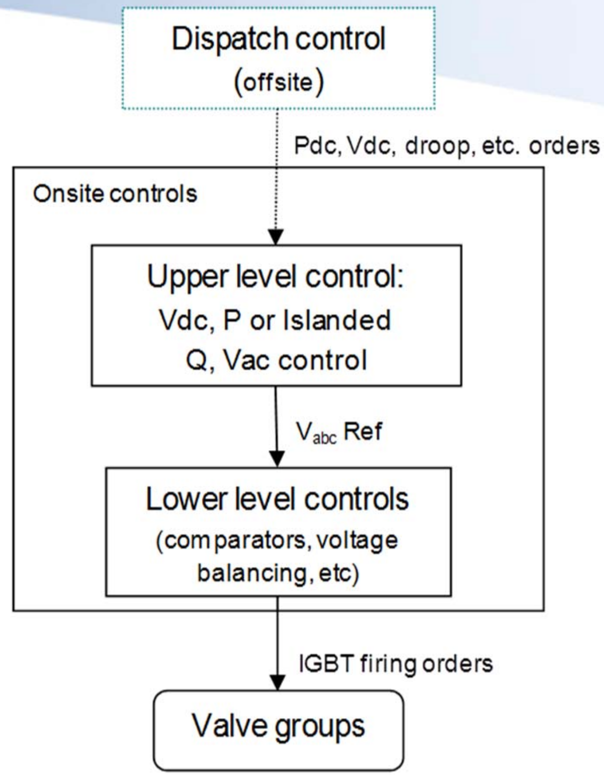
Compare 6 to 2400 ……

simulation issue is evident …

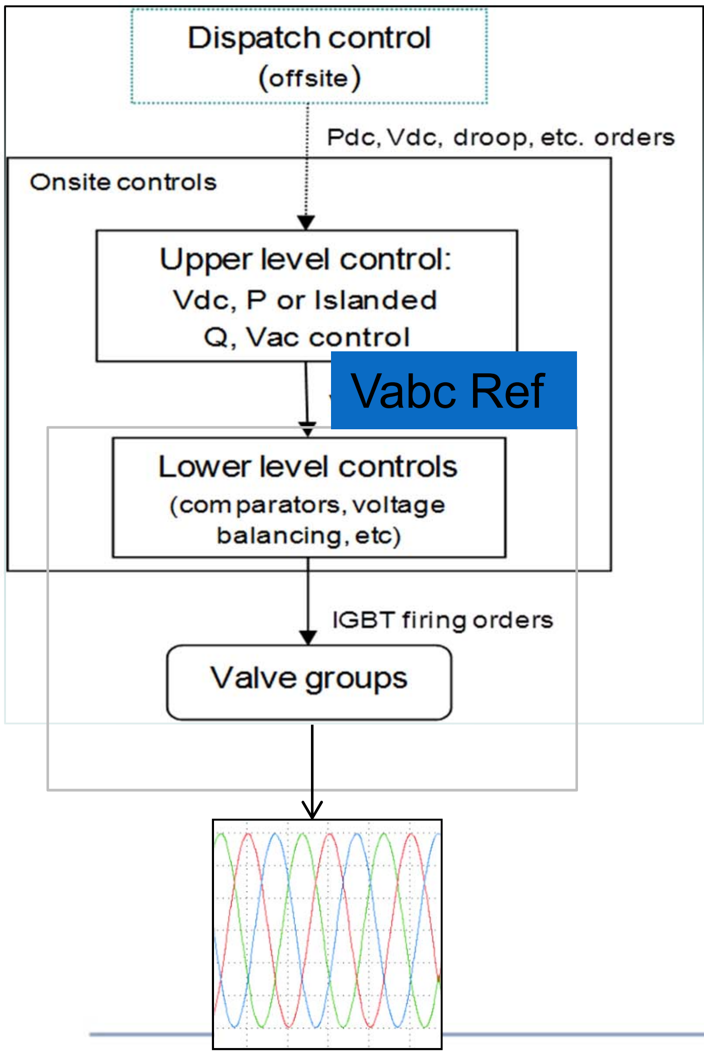
# VSC System Control Model & Levels

- **Dispatch  What is the target of Converter ?**
  - Power Set or Dc voltage (grid mode)
  - Ac voltage reference or MVar set (grid mode)
  - Frequency reference (P) and Ac Voltage (Q) (island mode)
  - Other P& Q strategy
- **High Level Controls**
  - Based on dispatch set points (Inputs)
  - Droop setting to allow autonomous control
  - d-q control will generate **Vref a, b and c** (outputs)
  - Voltage and current limits applied
- **Lower Level Controls**
  - Inputs Vref signals
  - Valve specific configurations

(½ bridge MMC, ½ bridge MMC with PWM, full bridge, etc.)
  - Capacitor balancing algorithm(s)
  - Circulating current suppression algorithm(s)
  - Generates gate pulses and the ac waveforms



# Control Hierarchy




Natural separation occurs Higher Lower level Controls

Regardless of Dispatch Orders Higher Level controls develop

Vref A Vref B and Vref C outputs

Regardless of converter valve implementation Lower Level controls use the VREF inputs to generate the gate pulses to produce

Va Vb and Vc

Lower level controls are unique for valve topology and will have ancillary control
- Capacitor balance
- Circulating current suppression

# Impact for VSC System Models

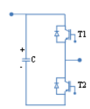
- Dispatch and Higher Levels Controls remain same regardless of Converter implementation
  - Generic or public domain models
  - Vendor specific (IP) models
- Lower Level Controls unique for different types of converter
  - Different Power electronics and control algorithm
  - Different Capacitor balance algorithm
  - Different Circulation Current suppression algorithm
  - Generic or public domain models
  - Vendor specific (IP) models
  - Different level of details for each lower level models
    - Full emt , detailed equivalent, firing pulse RMS

**From a Simulation Study Point View**

**Choose the appropriate Lower Level Model for your study … How ???**

# New  Model Techniques required

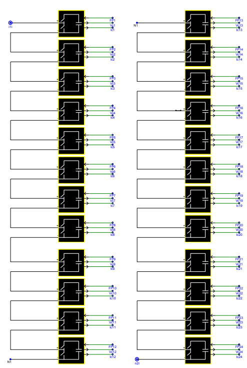
Computationally efficient model developed by Simulation Chair University of Manitoba



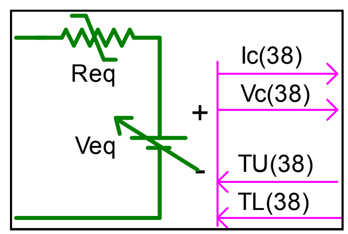

Thevenin equivalent

$$R_{eq} = R_1 \left[ 1 - \frac{R_1}{R_1 + R_2 + R_C} \right]$$

$$V_{eq} = \frac{R_1}{R_1 + R_2 + R_C} V_C$$



100's of nodes into 2 nodes




It makes possible the simulation of Multilevel converters with only a PC

U. N. Gnanarathna, A. M. Gole, and R. P.Jayasinghe, "Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs," IEEE Transactions on Power Delivery, vol.26, no.1, pp.316-324, Jan. 2011

# Start up Concerns

Initial Energization

- Transformer
- MMC Capacitors (Precharge capacitors to 1.41*ELL via diodes)
- DC Line or DC Cable

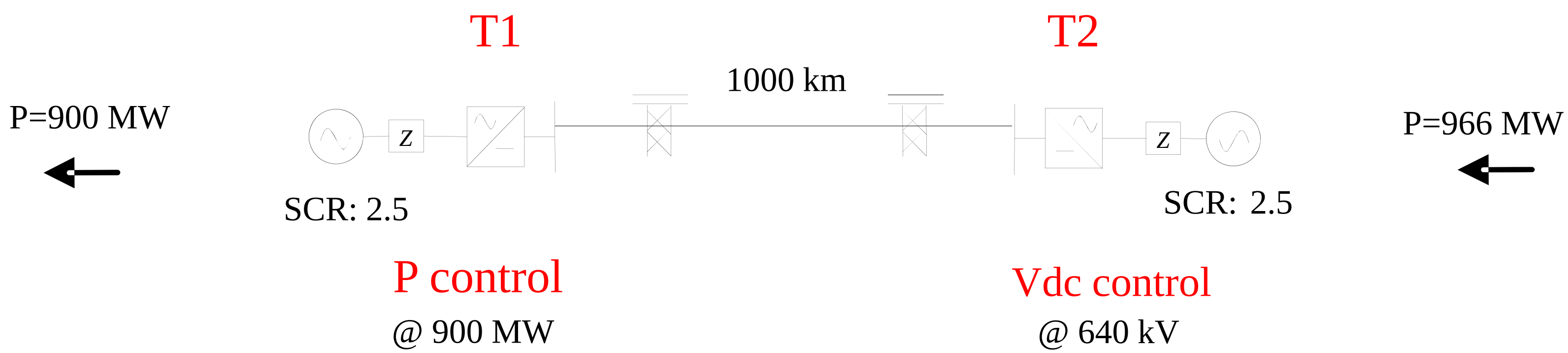
Use start-up resistor to limit current.

Short resistor with by pass switch

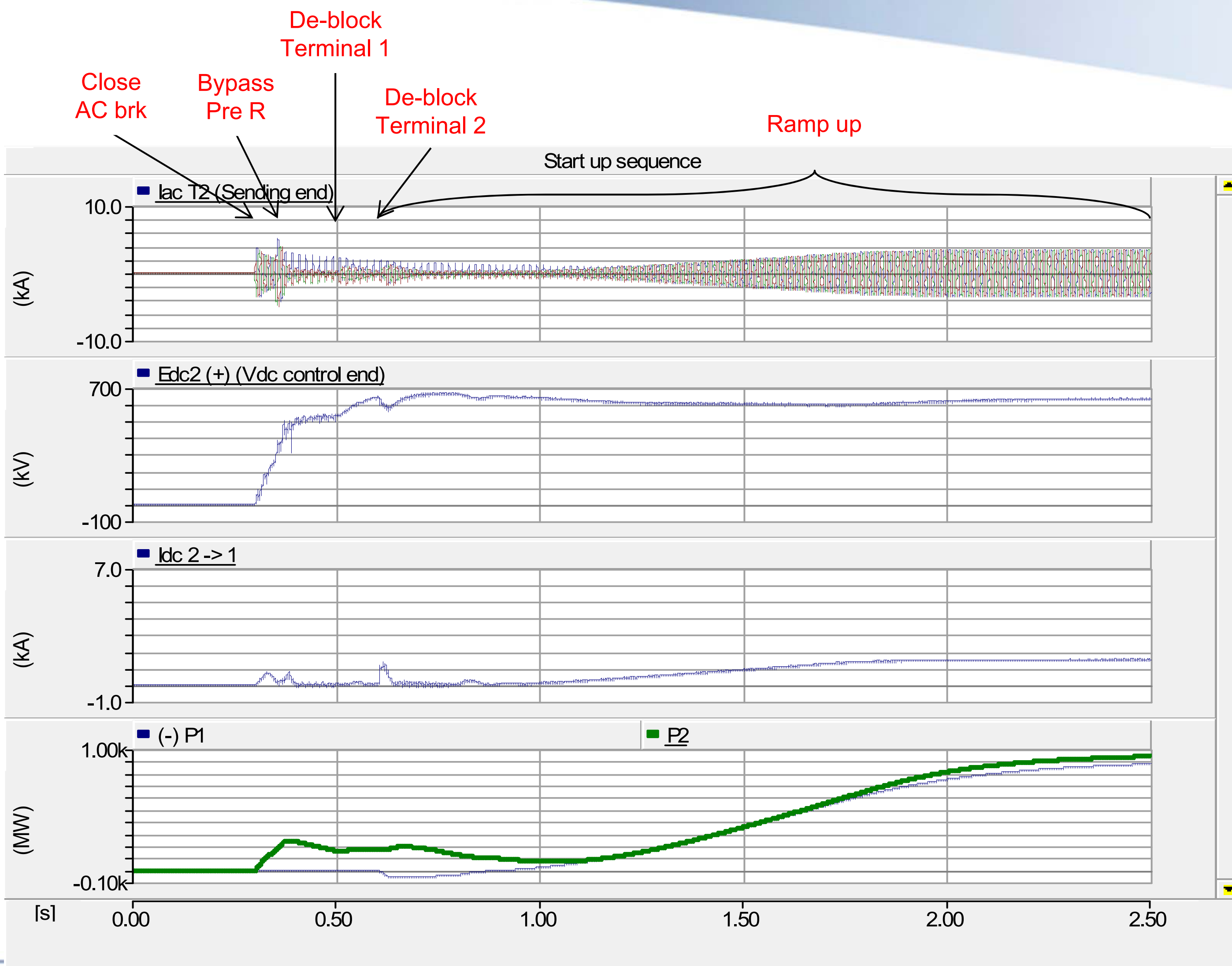
Deblock pulses Conv 1 and then Conv 2

Ramp power to desired setpoints

# Session 3: VSC system start up



# Session 3: VSC system start up



# Summary Issues VSC Start-up

During start-up energization of both transformers and all capacitors therefore Larger Inrush

Inrush resistor commonly added with bypass switch

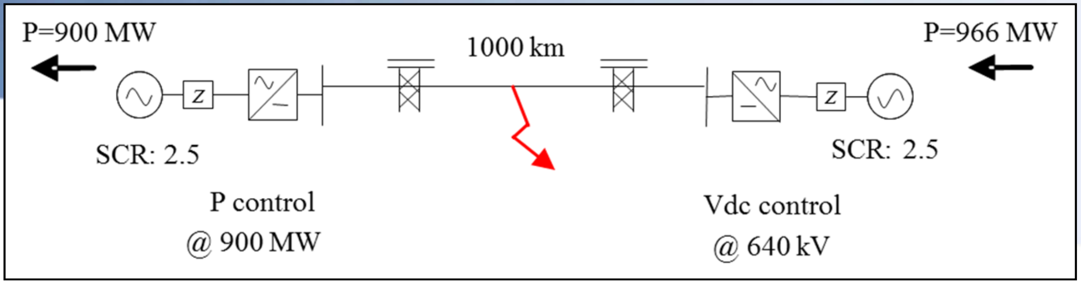
Diodes: with no firing pulse and diodes will conduct resulting in a Dc voltage

VDC=1.41 peak of Vac L-L

(charge capacitors and line (or Cable)

rww1

# DC Line Fault




VSC scheme with overhead line (based on Caprivi)

no Dc Fast (4 msec) breaker installed

Resonant DC Breaker (50-75 msec installed)

On DC fault.. Block firing pulse.. MMC capacitors cannot discharge into line but diodes will continue to commutate and feed DC fault (as 6P LCC rectifier)

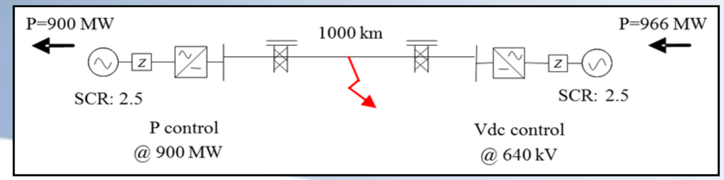
Open AC breaker .. Remove 6p rectifier diode current

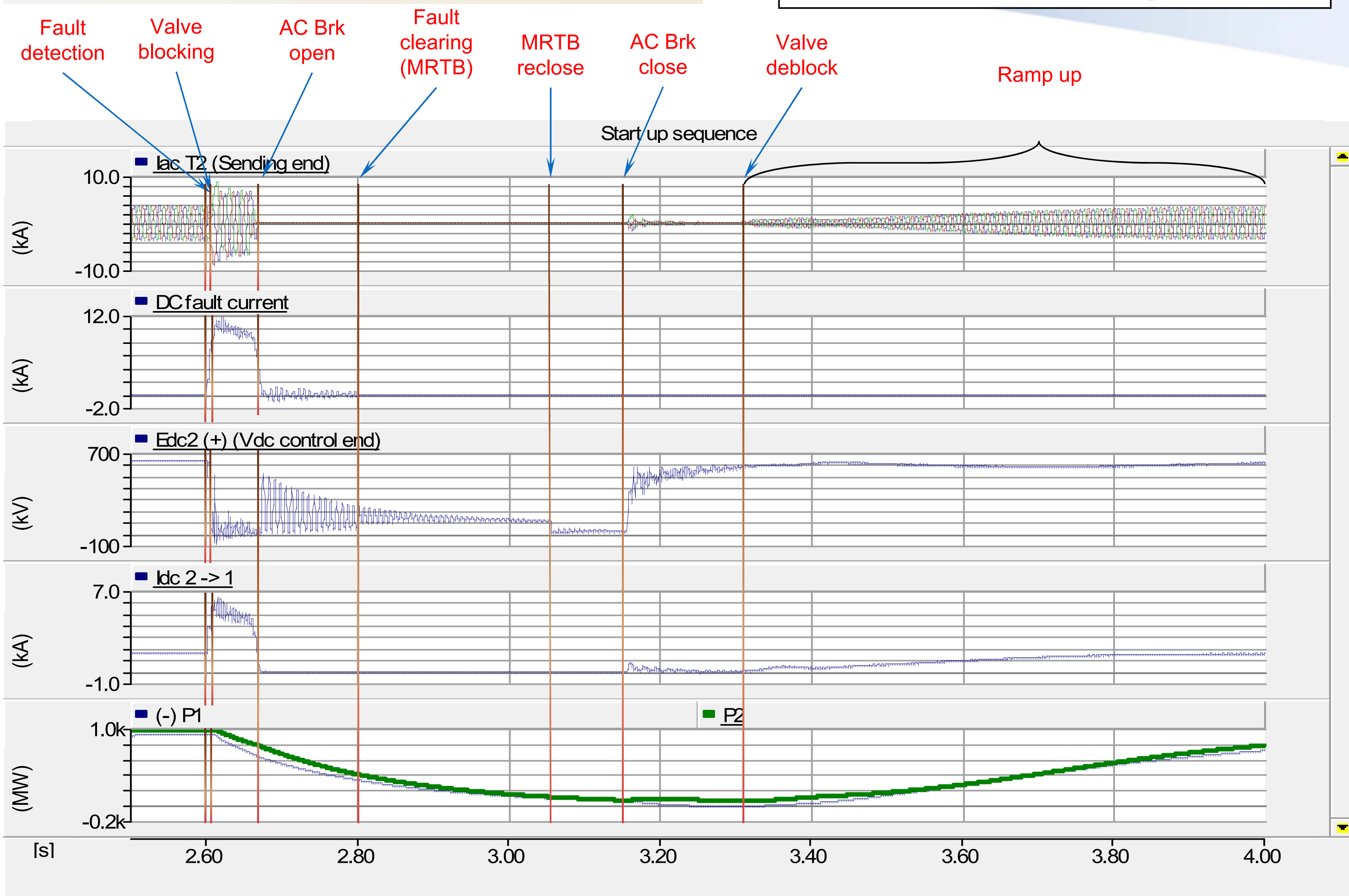
DC line will discharge slowly.. Based on the R/L circuit of the Dc line will keep the post fault DC current present for seconds up to a couple of minutes .

A dc switching action is required to allow Dc fault recovery

JCGA1

# DC Line Fault - restart



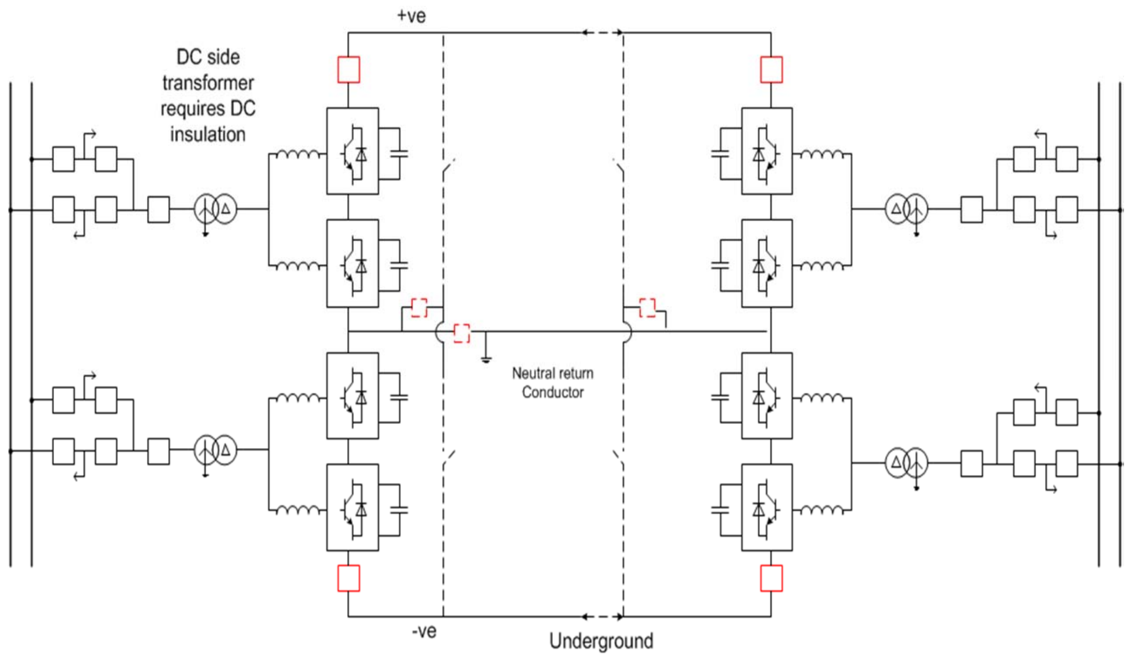



# Summary for VSC Dc Line Faults

- Pulse Blocking removes discharge of capacitors quickly
- AC breaker is required to open to remove 6P diode current.
- For a weak ac system .. DC fault draws fault current from AC bus. dc fault = ac fault
- Post fault residual dc current requires resonant Dc breaker
- For recovery inrush.. MMC capacitors are already charged
- Power ramp rate is determined by ac system strength not dc controls .

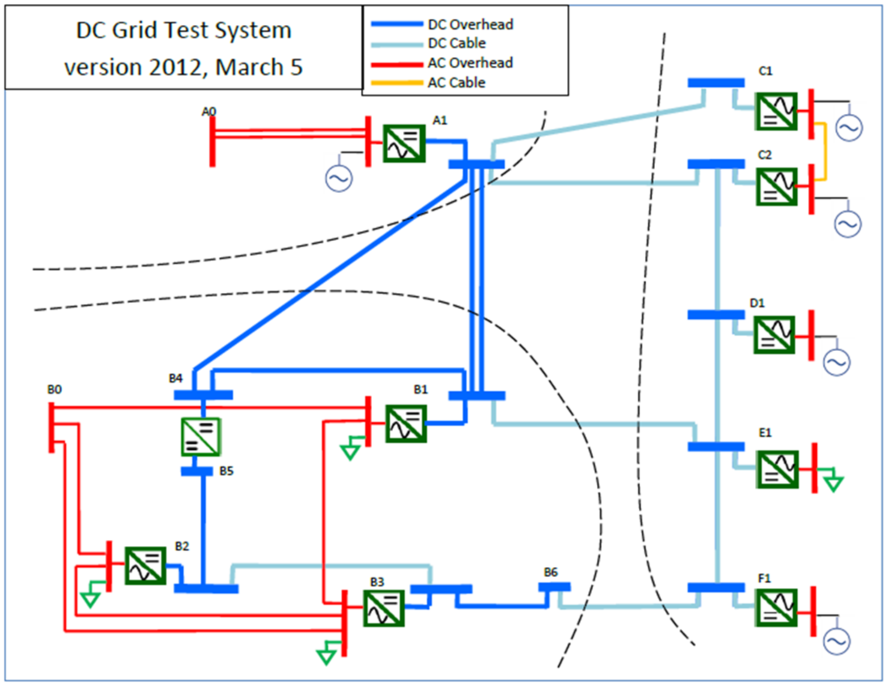
# Neutral Return

- Eliminate ground currents
- Increased line losses
- DC voltage offset at remote station.. Requires more dc insulation
- Neutral current can be controlled to zero by bipole controller
- During pole outage, the pole conductor can be used to reduce losses.




VSC Bipole

# DC Grid Modelling Test System (B4-58)




B4-57 has developed T-line and cable parameters for test case

A base PSCAD and EMPT-RV test cases are available.

Models are changing ..

Test Case alternatives

- Monopole
- Bipole with neutral return
- Bipole with ground/ sea electrodes.

Thank you…

Questions?