DC FAULT PROTECTION AND CLEARING STRATEGY FOR AN MMC BASED HVDC TRANSMISSION SYSTEM WITH HYBRID DC BREAKER

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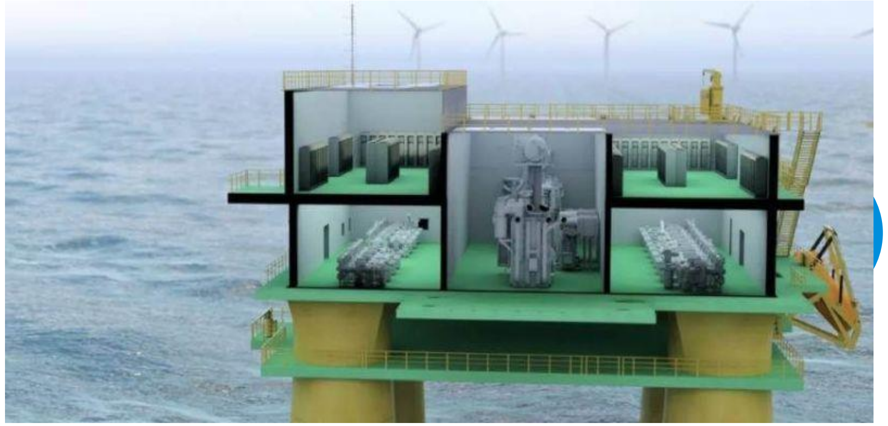

Agenda

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- Introduction
- Test Topology or Model
- Structured Control of MMC
- Proposed Fault Clearing Strategy
- Proposed Protection Strategy and Criterion
- Proposed Fault Processing Scheme
- Fault Simulation Data and Analysis
- Question Time

Introduction/Background:

Introduction

- Existing challenges from current energy sources
- HVDC has been the choice to integrate to offshore windfarms
- VSC_MMC HVDC has been technology and topology of choice
  - Challenges with DC faults
    - Challenges with DC current fault detection and processing schemes
- Basis and focus for research topic
  - Offshore wind farm and hydrogen production and capability to be extended to DC grid

Source [www.offshorewinbiz.com]

Introduction/Background:

Current HVDC Fault Detection Techniques:

- Overcurrent (OC), Non-Unit Based
- Under Voltage (UV), Non-Unit Based or change in DC line Voltage
- Differential Protection, Unit Based, Main protection
- Rate of Change of Voltage (ROCOV) & Rate of change of Current (ROCOC), Non-Unit Based,
- Directional Travelling Wave (TW), Non-Unit and Unit Based, Used as Main Protection
- Travelling Wave (TW) Current Differential, Non-Unit & Unit Based, Used as Main Protection

Introduction/Background:

Advantages of Current HVDC Fault Detection Techniques:

- Simple to implement
- Derivatives very fast, high speed and very mature technology
- Very effective
- ROCOC & ROCOV has selectivity

Drawbacks with Current HVDC Fault Detection Techniques for DC Grids:

- Inability to detect high impedance faults
- Influence of transmission line parameters
- Challenge in detecting high frequency components of faults current

Introduction/Background:

Current HVDC Fault Processing Schemes/ Techniques (from literature & research):

- Techniques based on Fourier Transform(FT)
- Techniques based on Short Time Fourier Transform(STFT)
- Hilbert-Huang Transformation
- S Transform
- Discrete Wavelet Transform (DWT)
- Continuous Wavelet Transform (CWT)
- Artificial Neural Network (ANN) & Fuzzy Logic based

Drawbacks with Current HVDC Fault Processing Techniques:

- Fourier Transform(FT) can only process fault transformation only in the frequency domain
- Short time Fourier Transform(STFT) can process the fault signal in smaller window in time and frequency domain

Introduction/Background:

Current HVDC installations and Fault Clearing Strategy literature versus commercial

- Current installations consist of 2-level VSC, three-level, and HB_SM MMC HVDC—converter topology
    - Planned Hybrid (FB & HB) configuration – Siemens FB scheme in Germany – AC to DC line conversion
        - 2nd VSC system in world with overhead lines
            - Faster reclosing for temporary faults (only in overhead line)
- In a “point to point” symmetric monopole, asymmetric monopole and bipole configuration (papers only)
- MTDC configuration – mesh/grid topology for VSC –selective fault clearing matters
- A traditional AC circuit breaker is employed in Non-Selective fault clearing strategy
    - Standard practice with VSCs, even the MTDC

    -It takes a longer for the current ac breakers used in current VSC_HVDC protection to interrupt the fault
- 2-level VSC, 3-level & HB_SM MMC lack fault blocking and control capability

Introduction/Background: Challenges with DC Faults

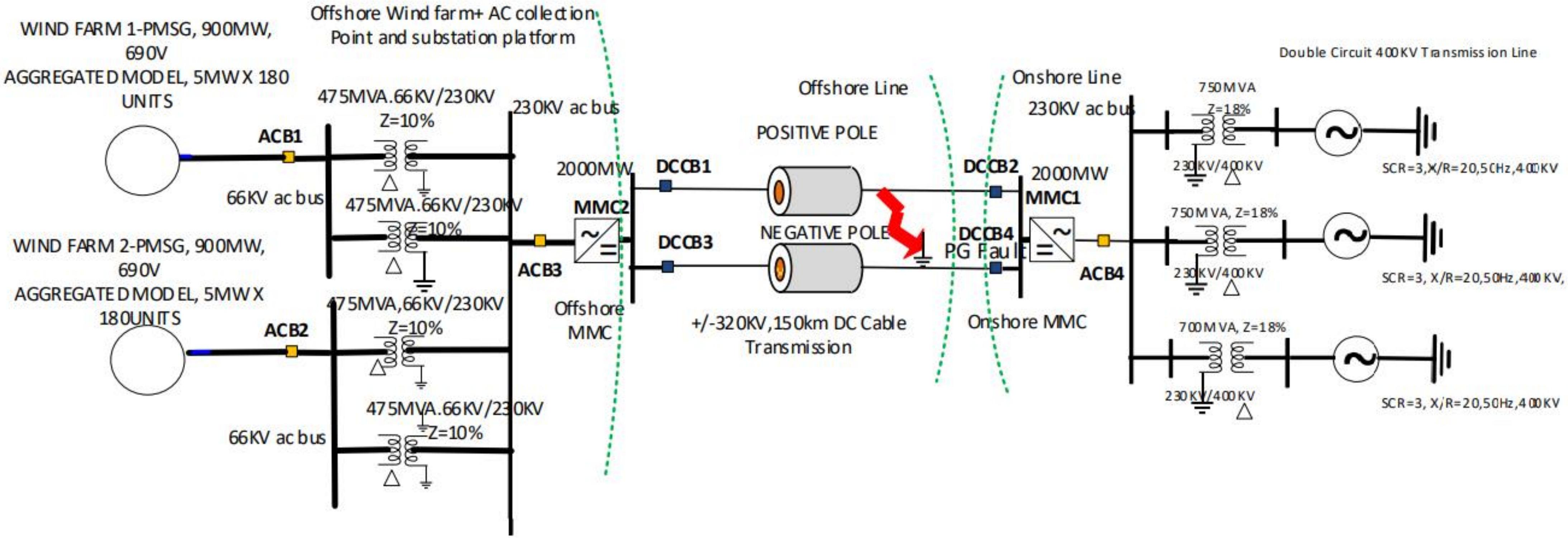
Challenges with interrupting and clearing DC Faults:

• DC Faults rise up quickly due to smaller reactance/impedance of the DC cable when compared to ac faults

• DC Faults do not have natural zero crossing when compared to ac faults

Test Topology or Model:

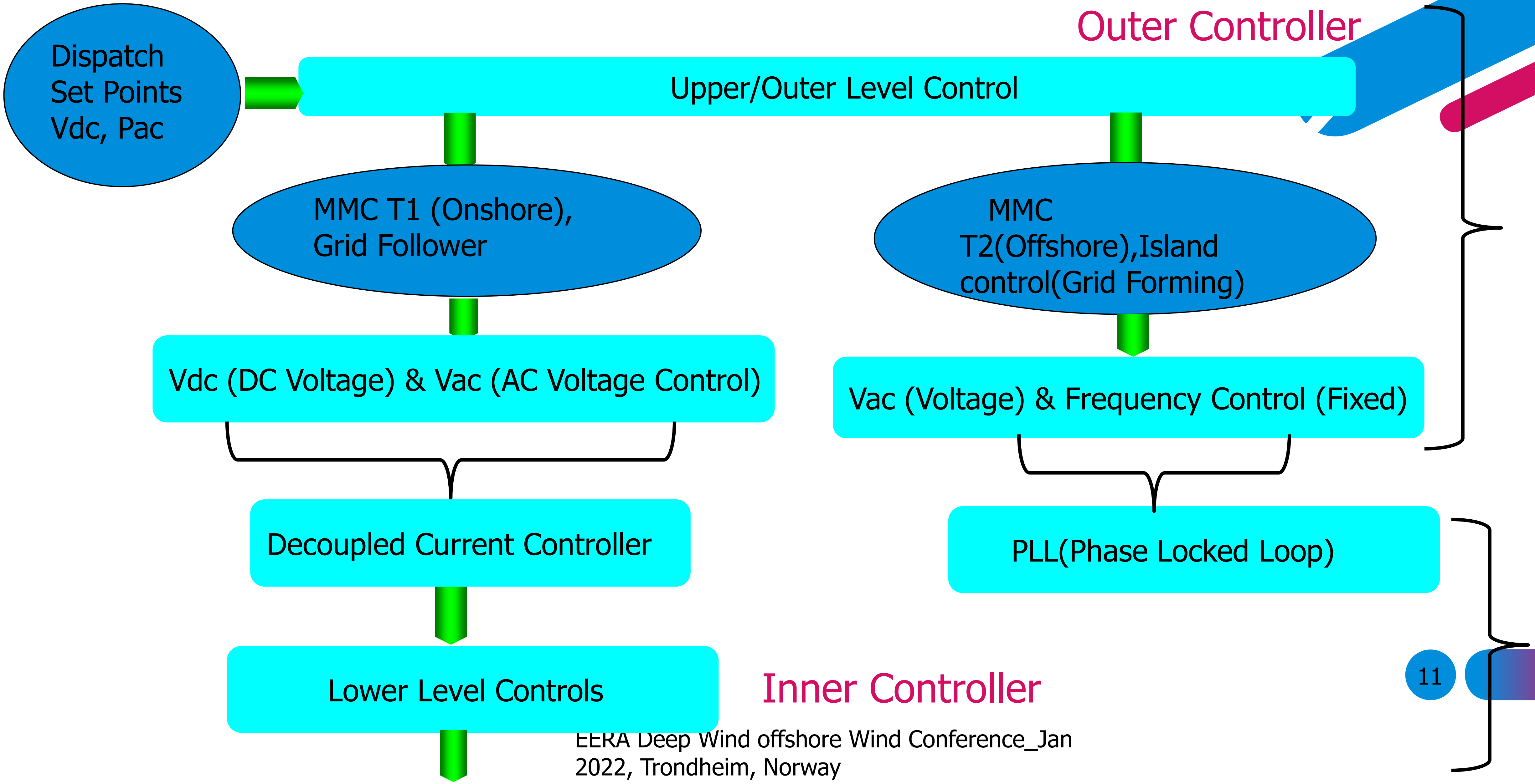
- Test Topology Model



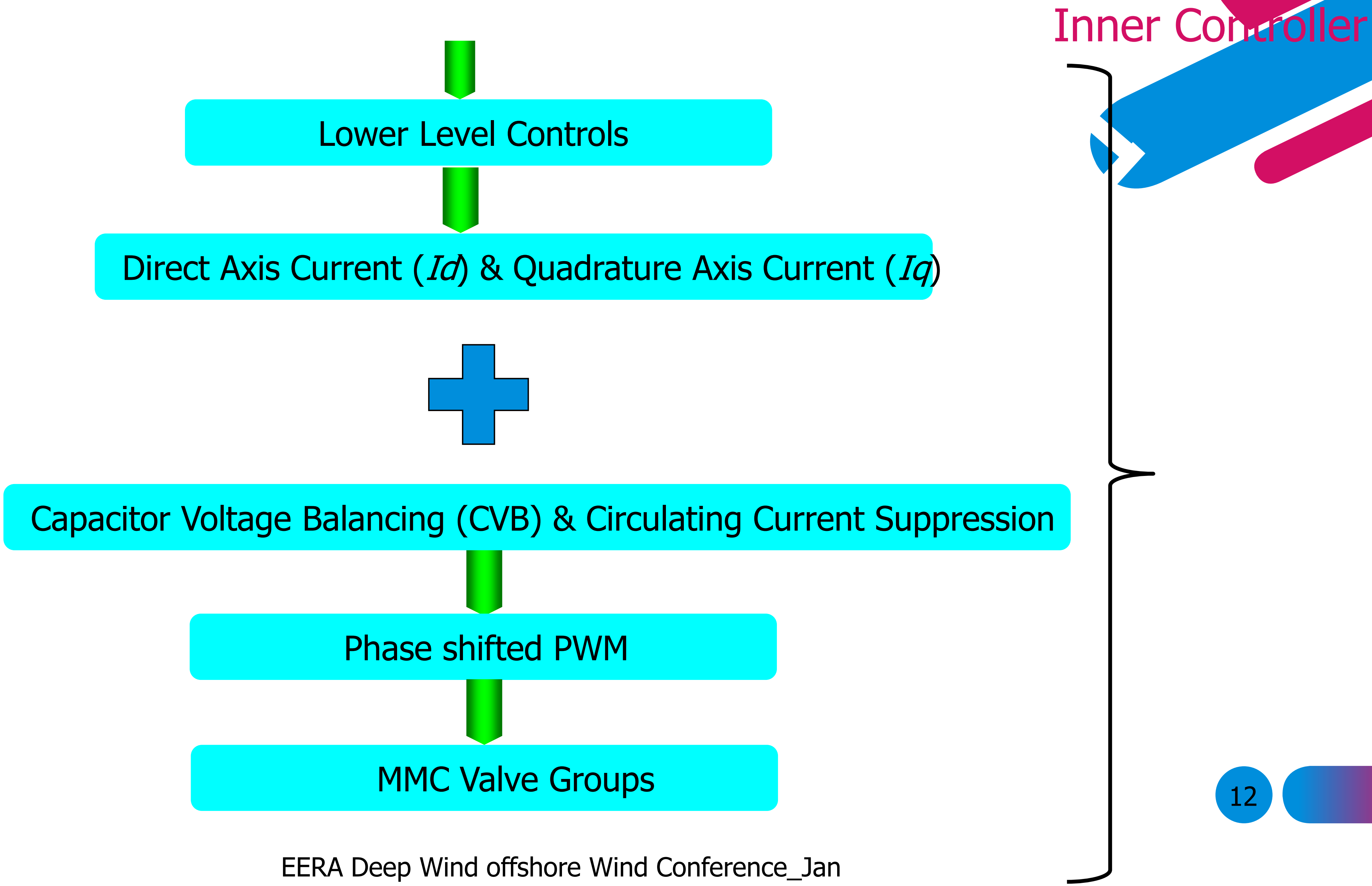
PARAMETERS OF 77 LEVELS of MMC 1 and MMC2

Component Description	Parameter
Rated Power of MMC1 & MMC2	2000MW
Nominal AC system Voltage at MMC1 & MMC2 (Rectifier)	230 kV
Nominal Frequency	50 Hz
Transformer Voltage at MMC1 & MMC2	230KV/370 Kv & 370 kV/230 kV
Nominal DC Current	3.125kA
Nominal DC Voltage	+/-320 kV, 640 kV pole-to-pole
Number of Sub Module	76, Upper Arm: 38, Lower Arm: 38
Number of Levels of MMC	77
Sub Module Capacitance	192000 micro farad
Sub Module Arm Inductance	8.704 mH
IGBT On Resistance	0.01 ohm
IGBT off Resistance	10 Mohm
Switching Frequency	150 Hz
Length of DC Cable Transmission	150 km

Structured Control for MMC



Structured Control for MMC control



Existing Academic and Industry Research based Fault Clearing Strategy

- **Classification of Fault-Clearing strategies**
  - Fully selective
  - Partial selective
  - Non-selective

Proposed Protection Scheme

Hybrid Protection Scheme (Time Based TW & Frequency Based DWT)

A. Time Domain DC Fault Detection: TW (Travelling Wave) based method

- Used to analyze TW propagation behaviors which reveals the difference between Internal and External fault

B. Time-Frequency Domain: DWT (Discrete Wavelet Transform) & MRA (Multi-Resolution Analysis) based method of processing

- The frequency domain analysis is used for analysis
- Detects the wave front of TW (Travelling Wave)

Proposed Discrete Wavelet Based Protection

Proposed Fault Protection Scheme Using DWT Elements:

- DWT Wavelet Coefficients
- DWT Wavelet Entropy

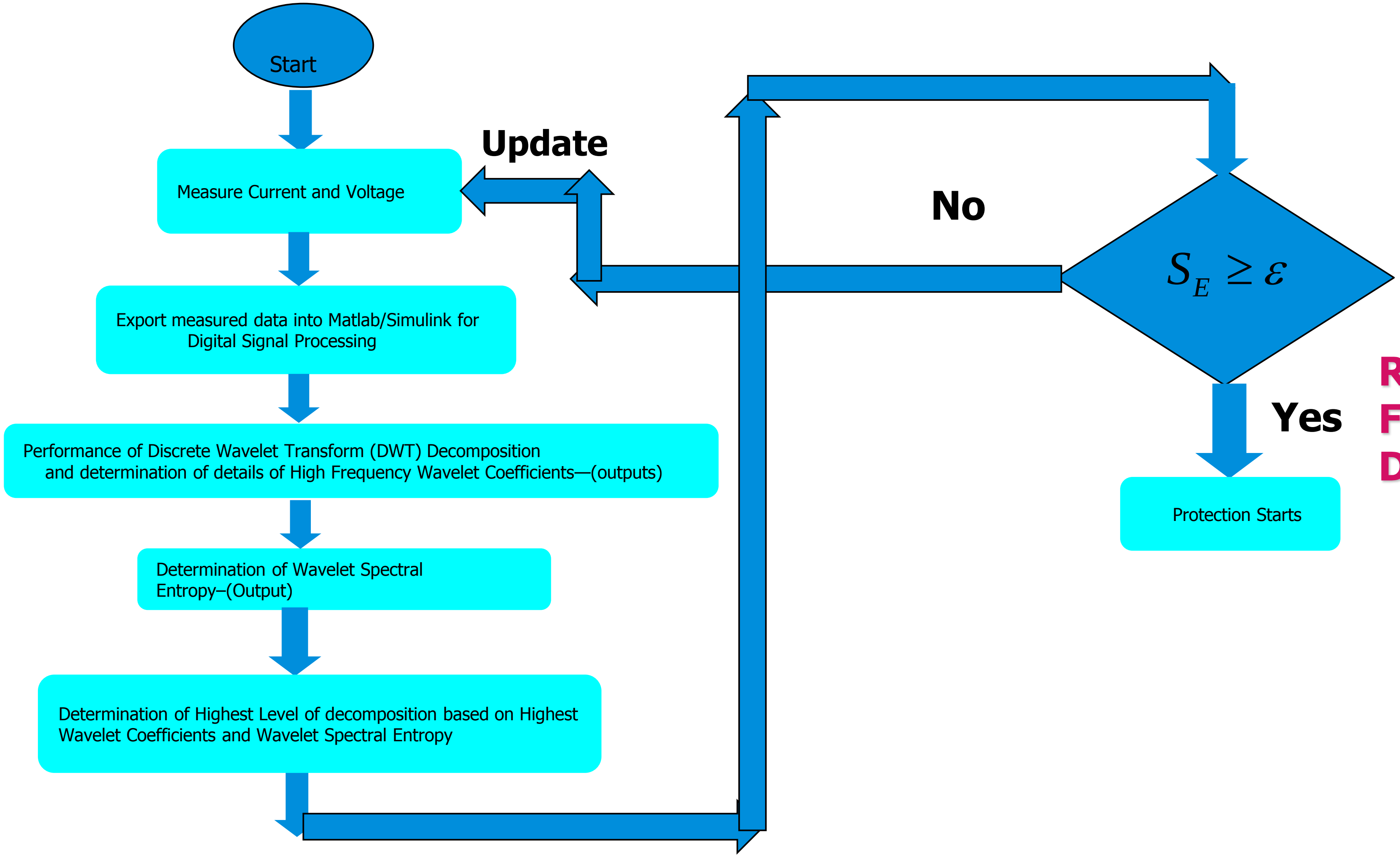
} Initiation of Fault Detection or Protection Criterion & Detect the Wave Front of the Initial TW & Rising Edge

- DWT Relative Entropy } Distinguish between Internal and External Fault

- Wavelet Transform Maximum Modulus (WTMM) } Fault Classification: PG & PP fault

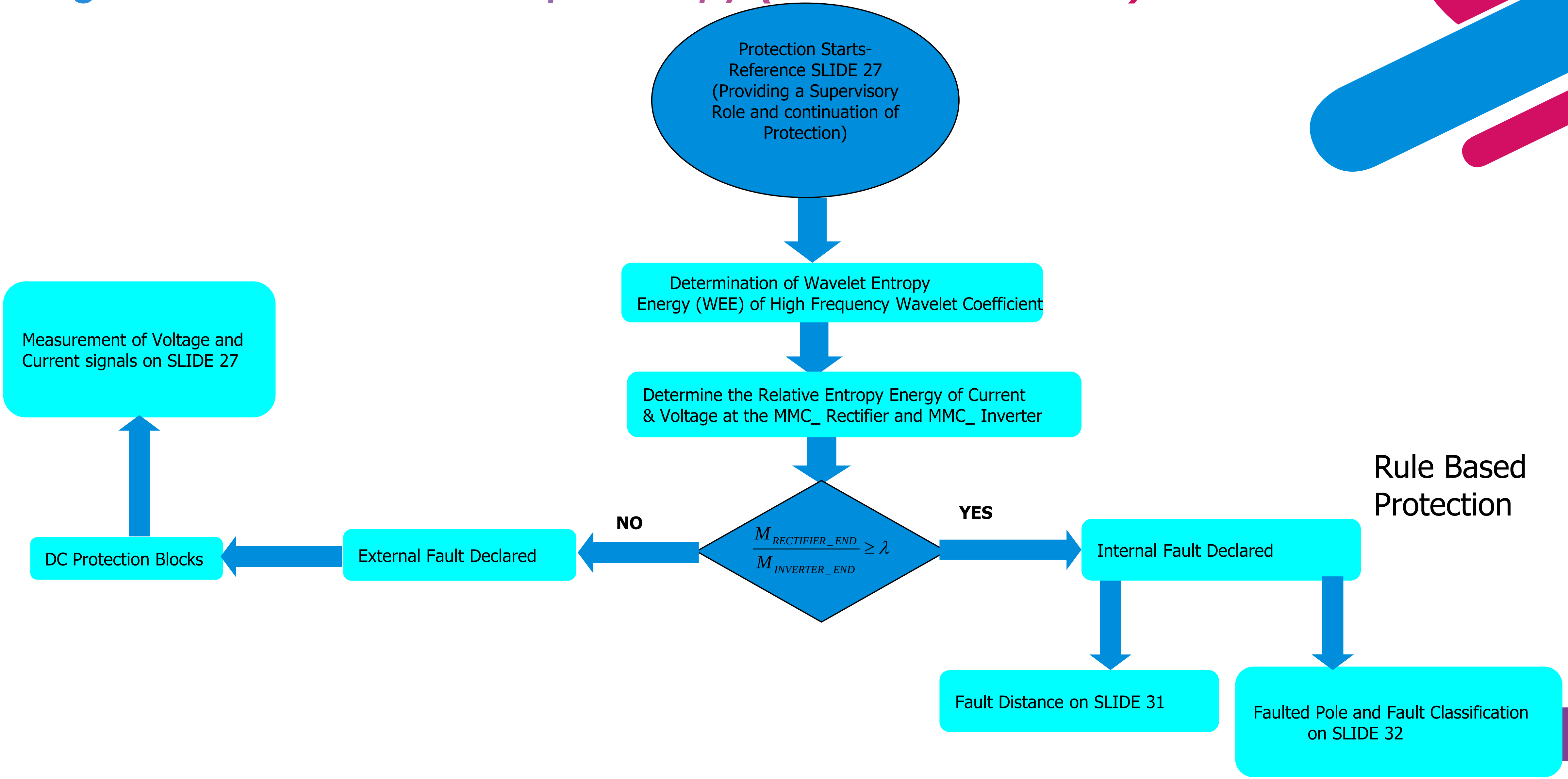
Proposed Protection Criterion Strategy: Protection Start

Fault Detection Algorithm



Rule Based Fault Detection

Criterion Distinguishing between Internal and External Fault (reference, *Sheng Lin, Shan Gao, e'tal, Mdpi, entropy (2015, 17, 5257-5273)*



Rule Based Protection

Proposed Fault Distance Determination

Determined Travelling Wave Propagation Velocity based on formula

$$V = \frac{c}{\sqrt{LC}}$$

From SLIDE 30 (Providing a Supervisory Role and continuation of Protection)

Determination of the arrival times τ_1 and τ_2 of TW

Determination of the Fault Distance $X = \frac{l}{2} - \frac{v(\tau_1 - \tau_2)}{2}$

Flowchart of Fault Classification-Fault Type and Faulted Pole

Internal Fault Declared and continuation of Supervisory Protection Scheme from SLIDE 30

Compute WTMM (Wavelet Transform Modulus Maxima) of the bus terminal Voltage and Current fault data

Rule Based Algorithm

$$\chi_i = \left| \frac{M_{ij}(P)}{M_{ji}(N)} \right|$$

$$\chi_i \geq 1 + K$$

Positive Pole to Ground (PG)

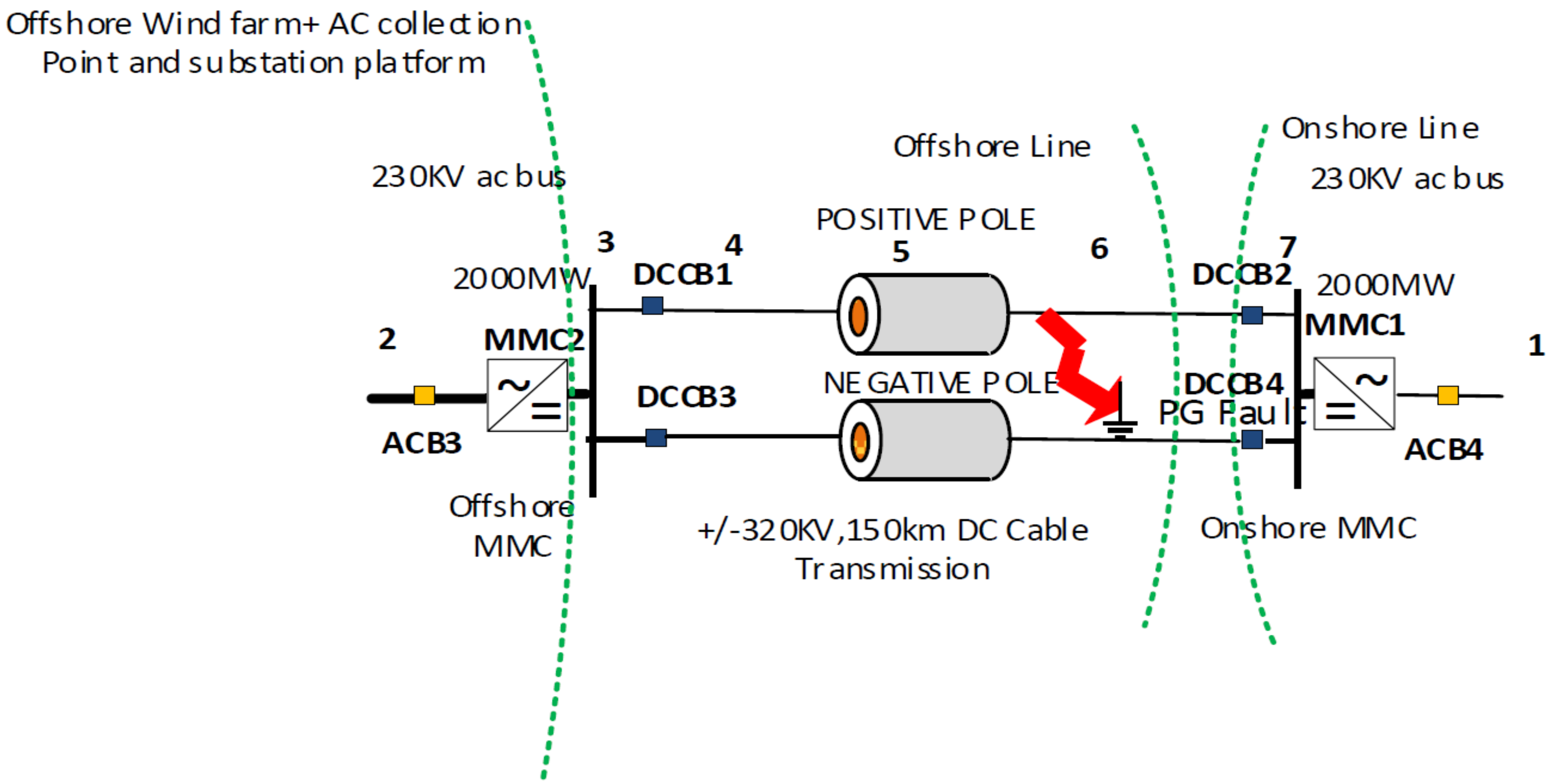
$$\chi_i = \left| \frac{M_{ij}(P)}{M_{ji}(N)} \right|$$

$$\chi_i \leq 1 + K$$

Pole to Pole to Ground (PG)

Location of Measuring Instruments

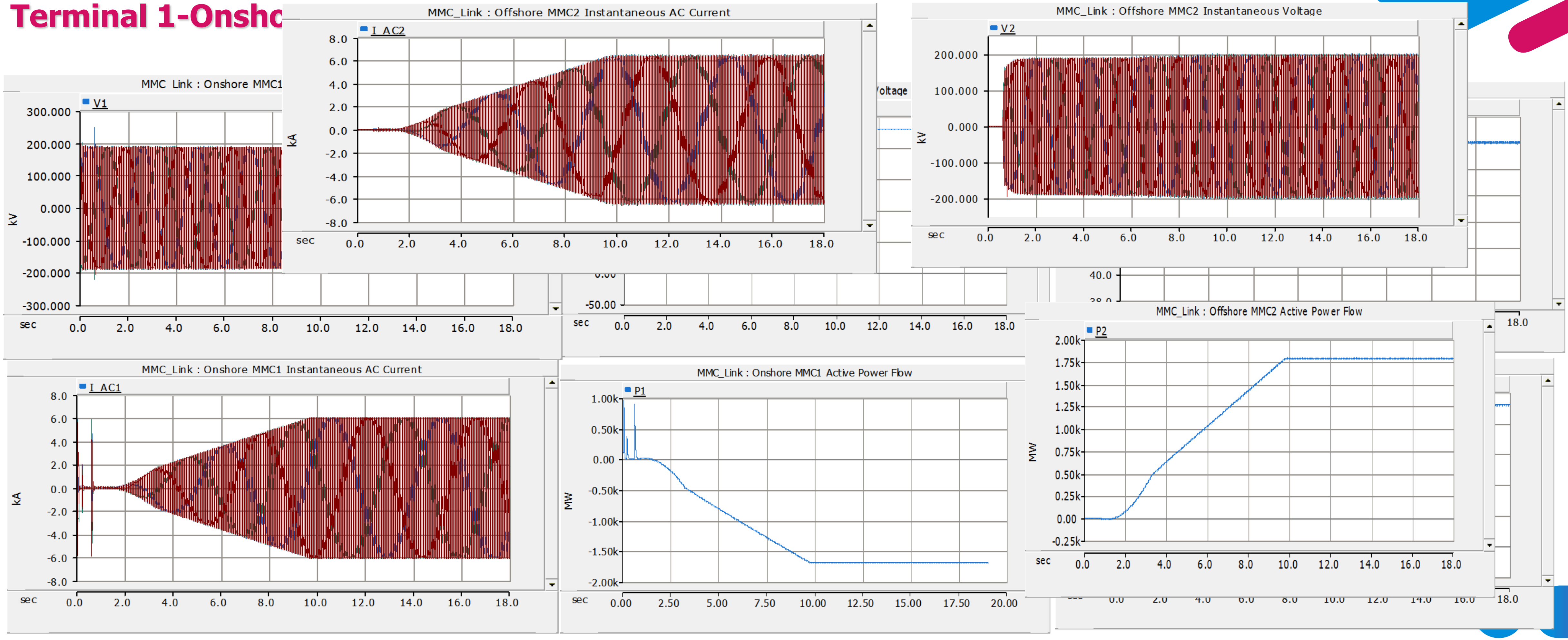
Location of Measuring devices and Multi-Meters (AC & DC side)



Simulation Results & Analysis_Steady State

Simulation Results of Bringing to Steady State of PSCAD/EMTDC Model

Terminal 1-Onsho



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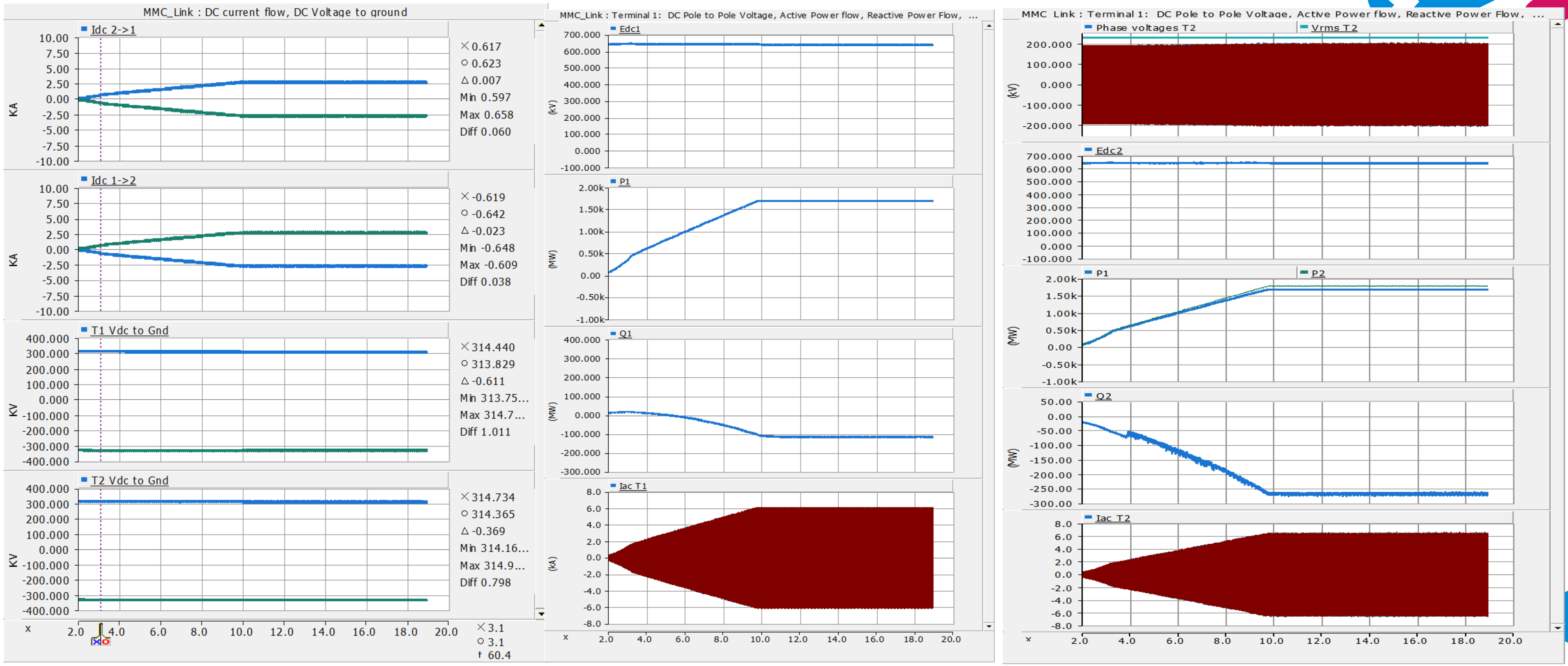
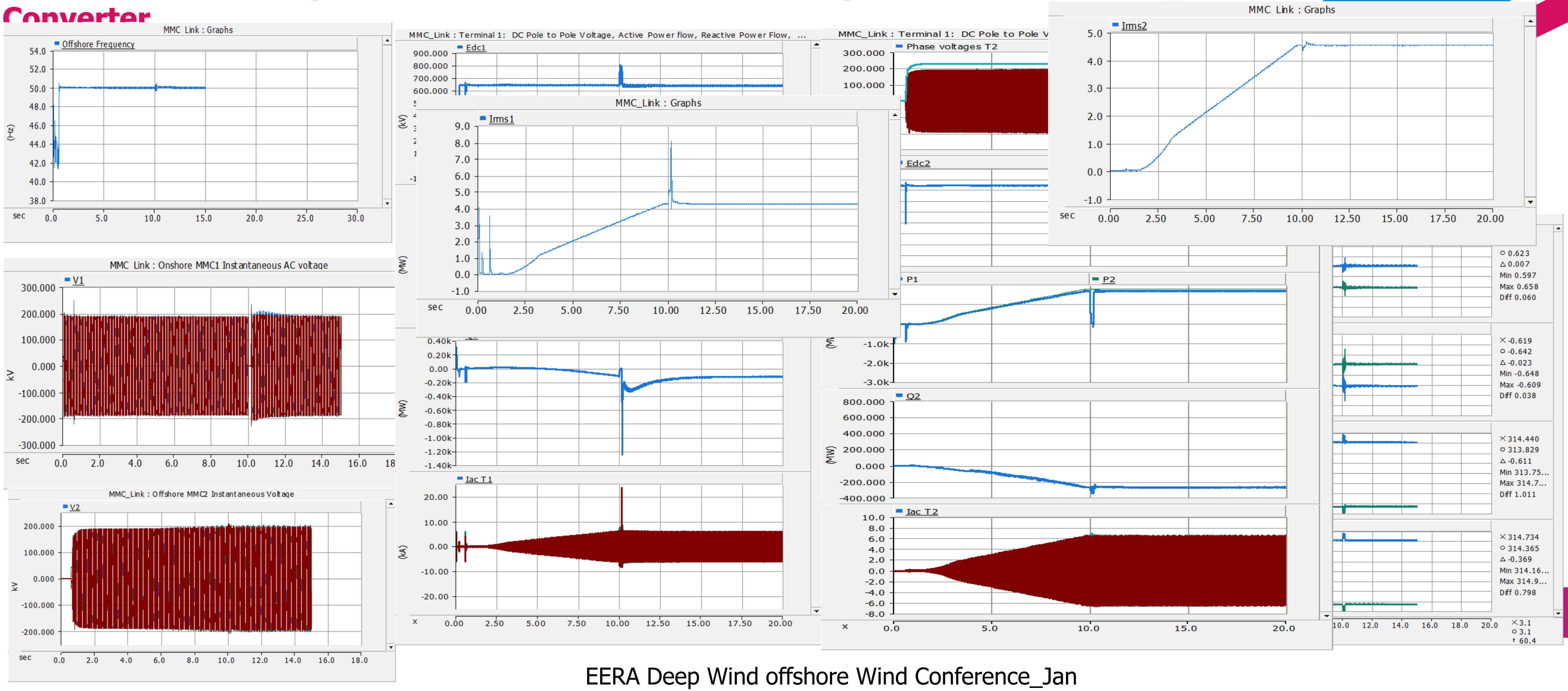
Simulation Results & Analysis_Steady State

MMC Link: DC current Flow & DC Voltage to Ground & offshore Frequency



Simulation Results & Analysis

AC Simulation Fault (3 Phase to Ground Fault with 0hms) on the side of MMC1_Onshore Converter



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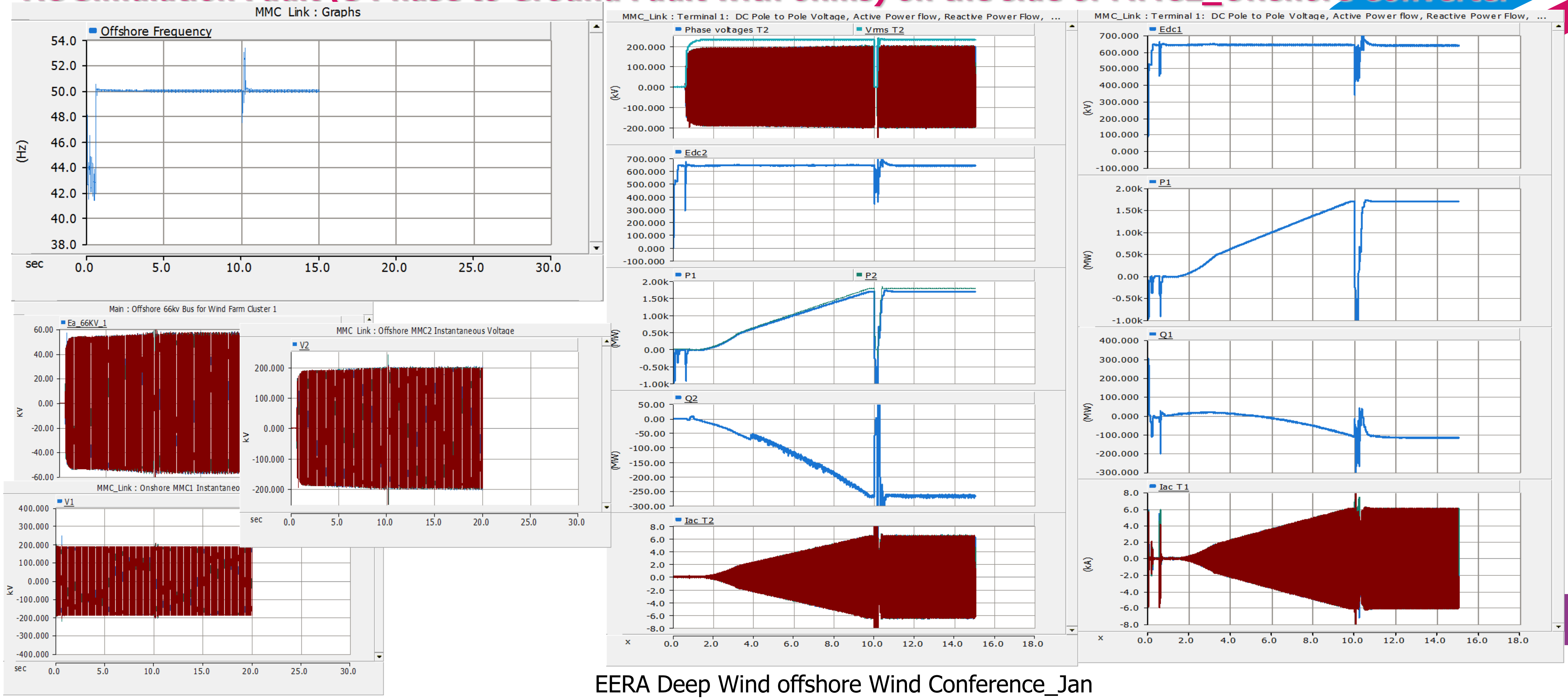
Simulation Results & Analysis

AC Simulation Fault (3 Phase to Ground Fault with 0hms) on the side of MMC2_Offshore Converter



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Simulation Results & Analysis

MMC1_Onshore_230kV_AC side Fault Simulation Data & Results

Type of Fault 230kV Bus	Fault Current(kA)_MMC1_Idc1	Fault Current(kA)_MMC2_Idc2	Voltage(kV)_MMC1	Voltage(kV)_MMC2	DC Voltage: Pole to Pole Voltage_Edc1	DC Voltage: Pole to Pole Voltage_Edc2	T1: DC Voltage: Pole to Ground_Vdc1 &Vdc2	T2: DC Voltage to Ground_Vdc1 &Vdc2
Type of Fault								
Single Line to Ground(SLG)	11.47kA	4.46kA	183kV	233kV				
Single Line to Ground(SLG) with 5 0hms with Fault Resistance	8.15kA	4.50kA	220.80kV	230.98kV				
Single Line to Ground(SLG) with 20 0hms with Fault Resistance	4.83kA	4.54kA	231.49kV	229.97kV				
Single Line to Ground(SLG) with 50 0hms with Fault Resistance	4.34kA	4.54kA	231.06kV	229.78kV				
3 Phase to Ground 0 ohms fault resistance	8.09kA	4.50kA	86.53kV	233.0kV				
3 Phase to Ground with 5 ohms Fault Resistance	5.06kA	4.47kA	163.81kV	234.55kV				
3 Phase to Ground with 20 ohms Fault Resistance	4.45kA	4.534 kA	232.43kV	232.59kV				
3 Phase to Ground with 50ohms Fault Resistance	4.32kA	4.53kA	233.94kV	229.54kV				

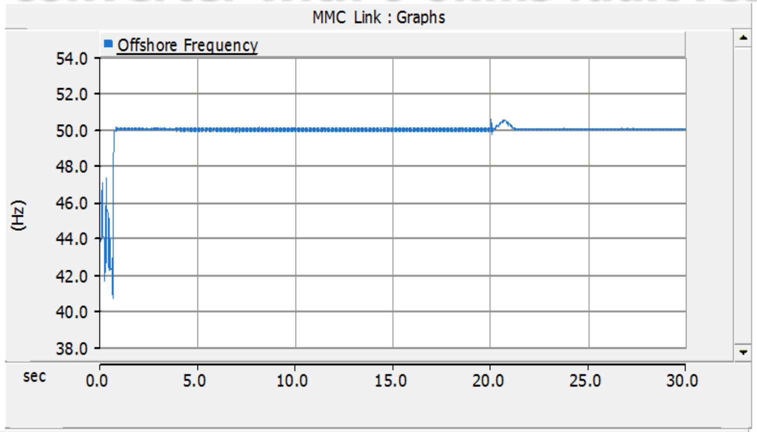
Simulation Results & Analysis

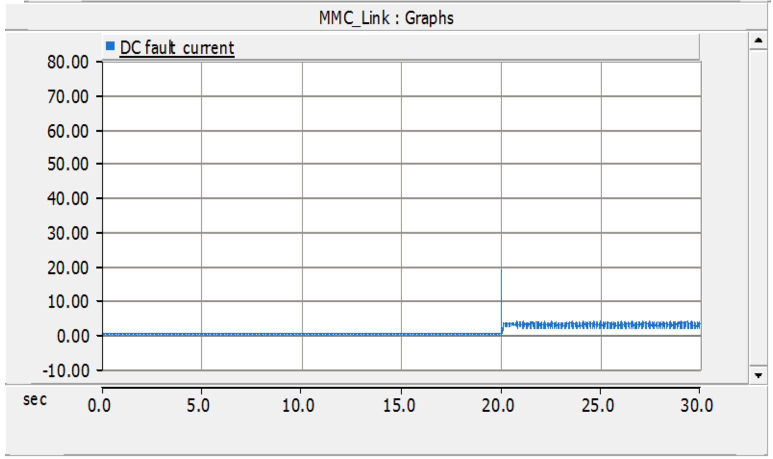
MMC2_Offshore_230kV_AC side Fault Simulation Data & Results

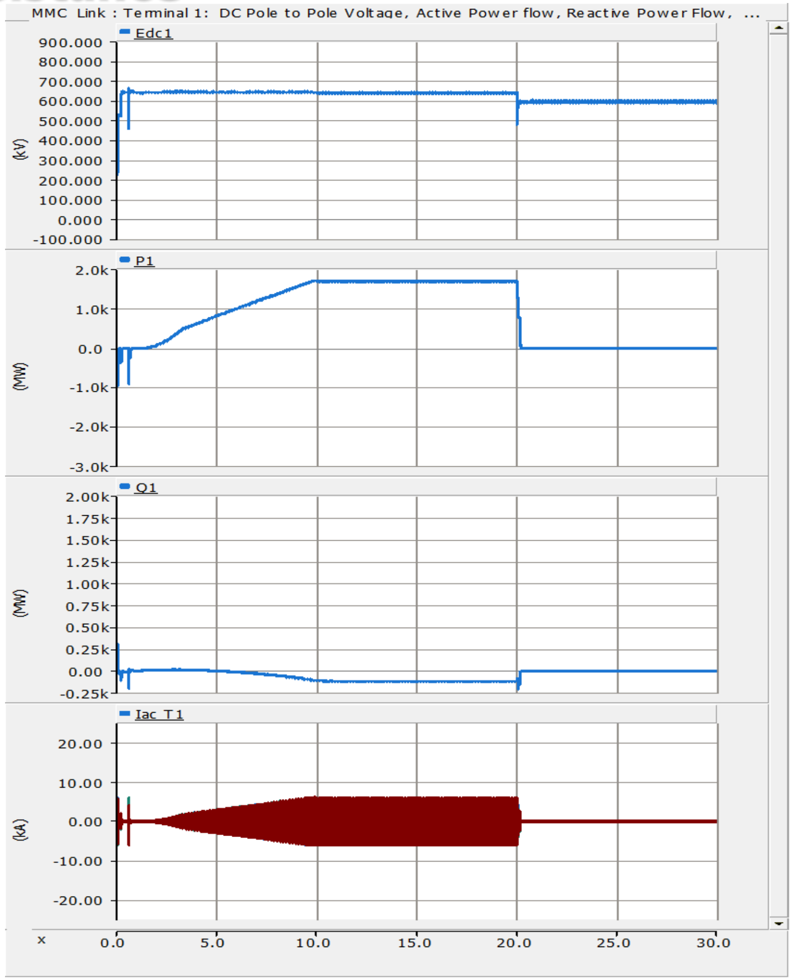
Type of Fault 230kV Bus	Fault Current(kA)_MMC1_Idc1	Fault Current(kA)_MMC2_Idc2	Voltage(kV)_MMC1	Voltage(kV)_MMC2	DC Voltage: Pole to Pole Voltage: Edc1	DC Voltage: Pole to Pole Voltage: Edc2	T1: DC Voltage : Pole to Ground_ Vdc1	T1: DC Voltage : Pole to Ground_ Vdc2
Type of Fault								
Single Line to Ground(SLG)	2.51kA	24.77kA	238.03kV	122.99kV				
Single Line to Ground(SLG) with 5 0hms with Fault Resistance	1.56kA	7.39kA	231.98kV	196.61kV				
Single Line to Ground(SLG) with 20 0hms with Fault Resistance	3.02kA	4.66kA	232.8kV	233.79kV				
Single Line to Ground(SLG) with 50 0hms with Fault Resistance	4.30kA	4.54kA	229.59kV	229.60kV				
3 Phase to Ground 0 ohms fault resistance	4.05kA	29.72kA	241.24kV	0.63kV				
3 Phase to Ground with 5 ohms Fault Resistance	17.29kA	6.41kA	143.41kV	234.38kV				
3 Phase to Ground with 20 ohms Fault Resistance	4.55kA	4.27kA	229.8kV	229.86kV				
3 Phase to Ground with 50ohms Fault Resistance	4.27kA	4.55kA	229.80kV	229.86kV				

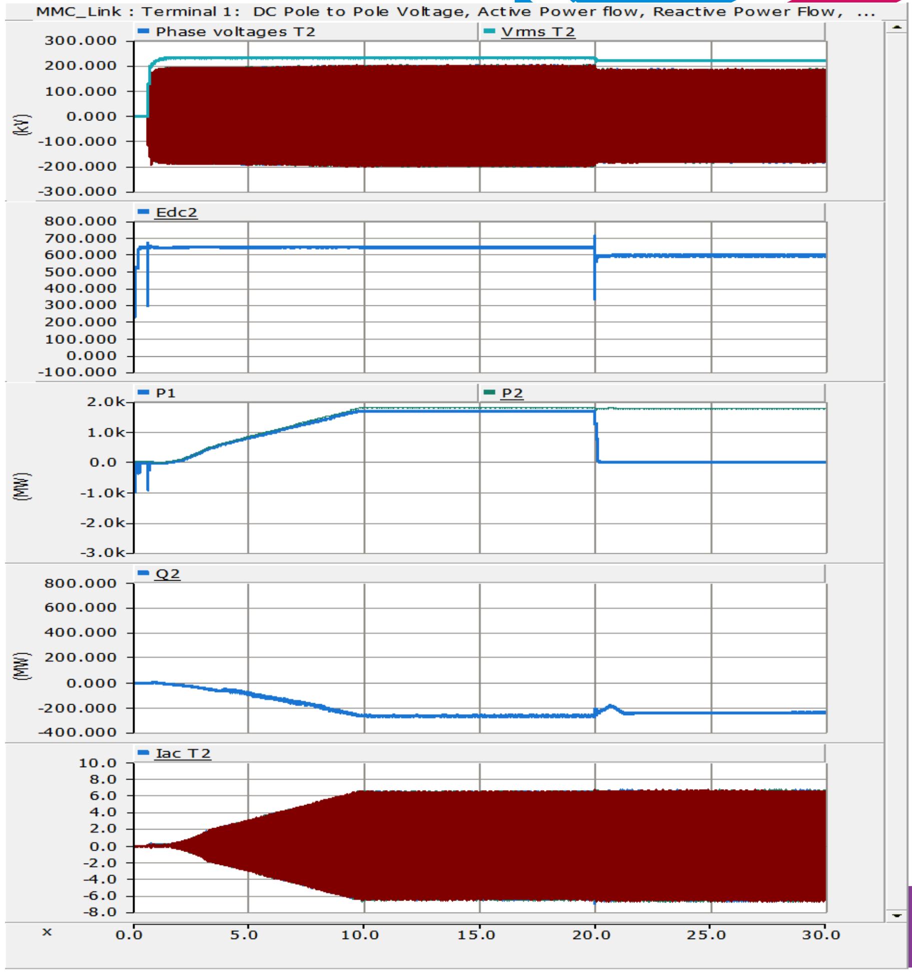
Simulation Results & Analysis

Simulation of DC Faults_ Positive Pole to Ground (PG) Fault at 0km(From Terminal 1_Onshore MMC1 converter with 0 ohms fault resistance



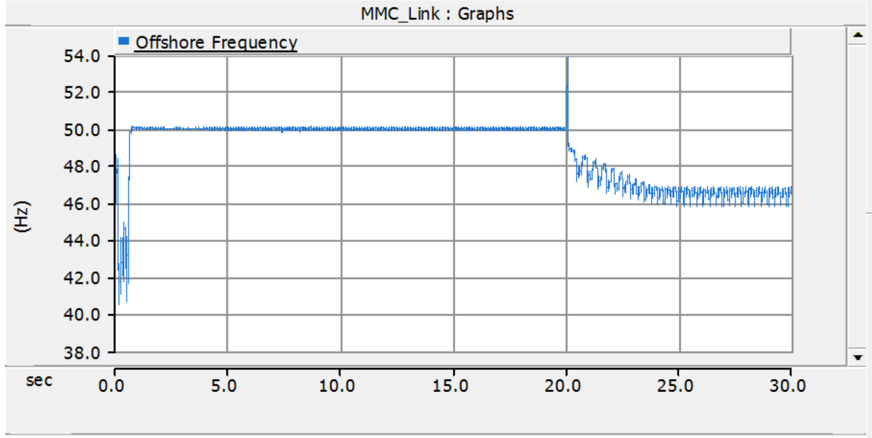


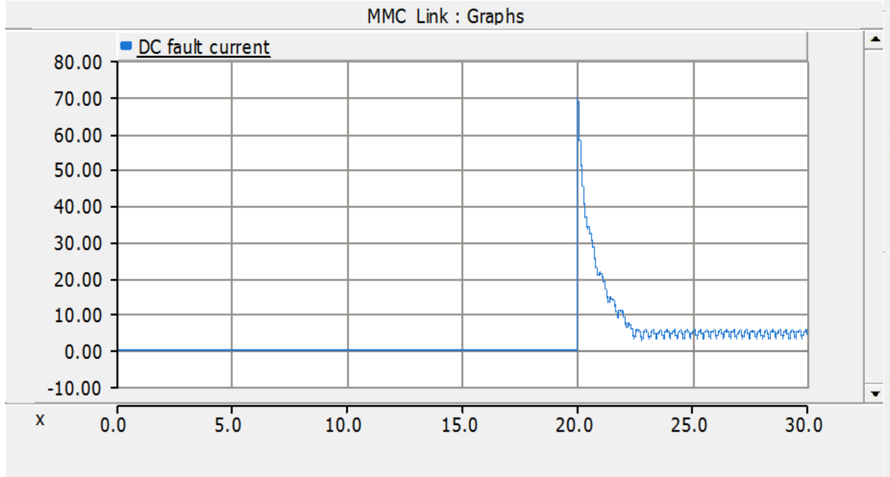


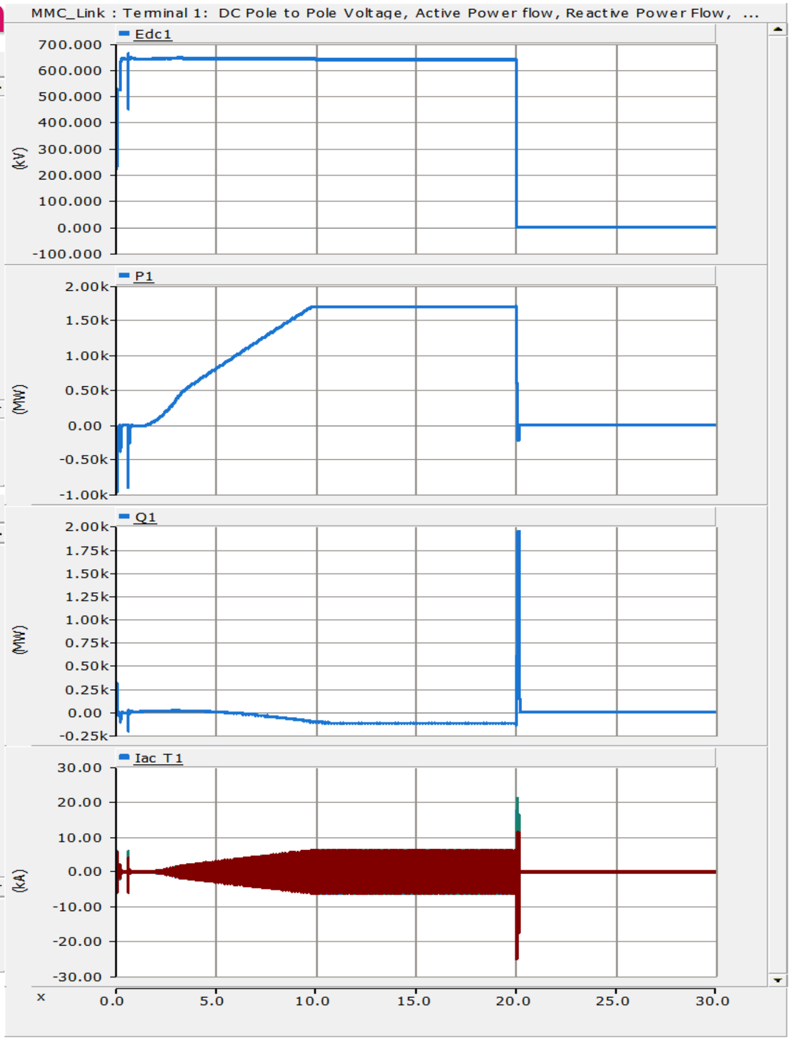


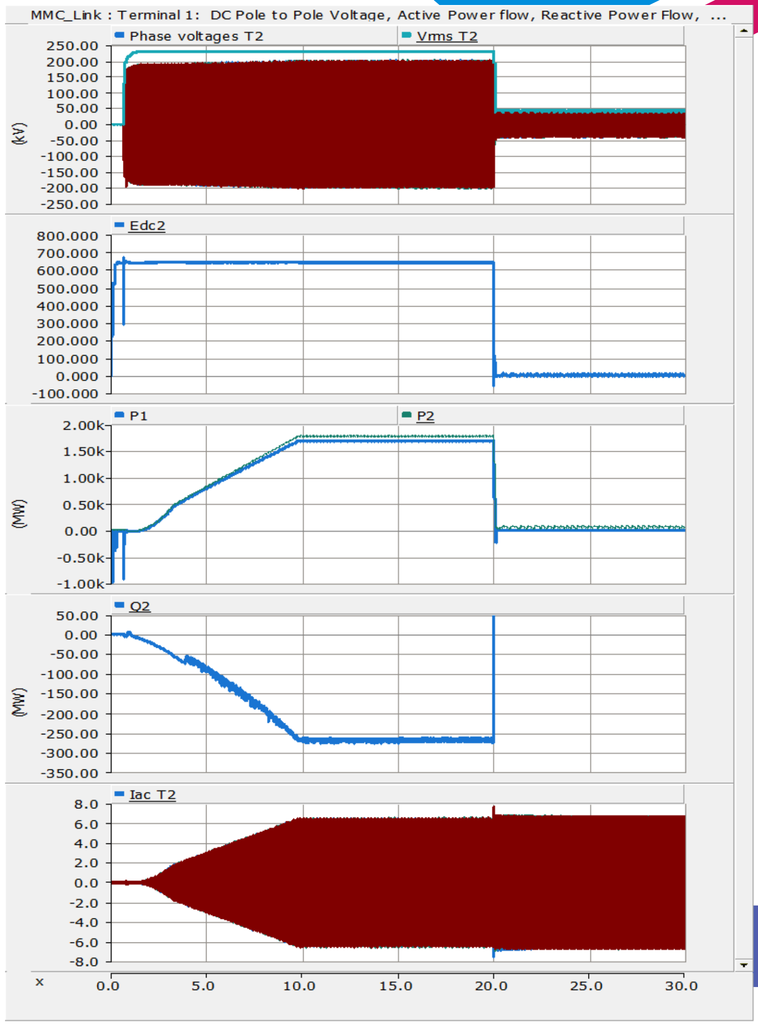
Simulation Results & Analysis

Simulation of DC Faults_ Positive to Negative Pole Fault at 0km(From Terminal 1_Onshore MMC1 converter with 0ohms fault resistan









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Simulation Results & Analysis

- **DC Transmission Cable Fault Current: Simulation Data_Pole to Ground (PG) Fault**

Type of Fault	DC Fault Current_Idc at Fault Point	Fault Current at MMC1 (Onshore)_Idc1	Fault Current at MMC2 (Offshore)_Idc2	Terminal 1: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 1: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 2: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 2: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 1: DC Pole to Pole Voltage (Edc1)	Terminal 2: DC Pole to Pole Voltage (Edc2)	MMC1_Vrms1	MMC2_Vrms2	MMC1_Irms1	MMC_Irms2
Pole to Ground (PG)													
PG @ 0km from Terminal 1 (MMC1)													
0 ohms	19.09kA			0.19kV	479kV	-55.73kV	-395kV	479.3kV	339.9kV	227.18kV	229.9kV		
5 ohms	14.59kA	2.51kA	3.95kA	73.07kV	-445.0kV	25.98kV	-381.08kV	518.15kV	407.6kV	226.76kV	229.89kV	4.22kA	4.53kA
20ohms	8.55kA	0.37kA	3.46kA	171.25kV	-398.24kV	140.55kV	-360.24kV	539.49kV	501.79kV	227.12kV	229.89kV	4.23kA	4.54kA
50 ohms	2.28kA	0.196kA	2.31kA	83.47kV	-565.09kV	105.68kV	-584.27kV	648.57kV	689.95kV	337.15kV	232.81kV	0.002kA	0.002kA
PG @ 30km from Terminal 1 (MMC1)													
0 ohms													
5 ohms													
20 ohms													
50 ohms													

Simulation Results & Analysis

- **DC Transmission Cable Fault Current: Simulation Data_Pole to Pole to Ground (PPG) Fault**

Type of Fault	DC Fault Current_Idc at Fault Point	Fault Current at MMC1 (Onshore)_Idc1	Fault Current at MMC2 (Offshore)_Idc2	Terminal 1: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 1: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 2: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 2: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 1: DC Pole to Pole Voltage (Edc1)	Terminal 2: DC Pole to Pole Voltage (Edc2)	MMC1_Vrms1	MMC2_Vrms2	MMC1_Irms1	MMC_Irms2
Pole to Pole to Ground (PPG)													
PPG @ 0km from Terminal 1 (MMC1)													
0 ohms	69.93kA	46.97kA	18.93kA	-9.793kV	-10.49kV	96.35kV	-116.66kV	0.70kV	213.02kV	218.87kV	217.57kV	4.58kA	4.62kA
5 ohms	48.56kA	31.91kA	14.37kA	111.91kV	-132.28kV	301.10kV	-321.48kV	244.20kV	622.58kV	231.56kV	232.03kV	4.16kA	4.55kA
20ohms	17.85kA	8.72kA	9.38kA	168.53kV	-188.91kV	172.56kV	192.89kV	357kV	365.40kV	207.15kV	212.35kV	4.69kA	4.63kA
50 ohms	12.67kA	6.82kA	6.16kA	306.60kV	-326.99kV	331.10kV	-351.51kV	633.59kV	628.61kV	226.65kV	231.03kV	4.02kA	4.54kA
PPG @ 30km from Terminal 1 (MMC1)													
0 ohms	58.44kA	19.38kA	31.05kA	48.99kV	-68.34kV	125.64kV	-145.99kV	118.33kV	271.64kV	226.58kV	228.68kV	4.00kA	4.55kA
5 ohms	45.84kA	24.23kV	15.88kV	159.69kV	-180.07kV	196.63kV	-217.01kV	339.78kV	413.66kV	228.32kV	231.03kV	4.04kA	4.56kA
20 ohms	24.90kA	12.37kA	10.53kA	267.55kV	-287.94kV	283.76kV	-304.14kV	555.48kV	587.90kV	227.71kV	231.27kV	4.09kA	4.56kA
50 ohms	12.58kA	5.39kA	6.99kA	314.25kV	-334.63kV	320.74kV	-341.16kV	648.89kV	661.91kV	226.87kV	231.04kV	4.04kA	4.55kA

Simulation Results & Analysis

DC Transmission Cable Fault Current: Simulation Data_Pole to Pole to Ground (PPG) Fault

Type of Fault	DC Fault Current_Idc at Fault Point	Fault Current at MMC1 (Onshore)_Idc1	Fault Current at MMC2 (Offshore)_Idc2	Terminal 1: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 1: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 2: DC Voltage to Ground 1(Positive Pole)_Vdc1	Terminal 2: DC Voltage to Ground 2(Negative Pole)_Vdc2	Terminal 1: DC Pole to Pole Voltage (Edc1)	Terminal 2: DC Pole to Pole Voltage (Edc2)	MMC1_Vrms1	MMC2_Vrms2	MMC1_Irms1	MMC_Irms2
Pole to Pole to Ground (PPG)													
PPG @ 75km from Terminal 1 (MMC1)													
0 ohms	55.41kA	23.56kA	25.29kA	51.72kV	-71.96kV	32.49kV	-52.75kV	123.69kV	85.23kV	224.40kV	221.17kV	3.88kA	4.66kA
5 ohms	39.04kA	17.44kA	20.51kA	151.12kV	-171.47kV	138.45kV	-158.8kV	322.59kV	297.25kV	225.13kV	226.23kV	3.93kA	4.59kA
20ohms	11.87kA	10.11kA	1.81kA	113.41kV	-133.32kV	109.37kV	-129.27kV	246.74kV	238.64kV	129.53kV	143.96kV	12.54kA	4.08kA
50 ohms	12.24kA	3.58kA	8.24kA	314.96kV	-335.34kV	307.54kV	-327.93kV	650.31kV	635.47kV	227.02kV	231.26kV	4.064kA	4.54kA
PPG @ 112.5km from Terminal 1 (MMC1)													
0 ohms	57.23kA	20.46kA	31.84kA	96.4kV	-116.25kV	29.72kV	-49.05kV	212.75kV	78.77kV	230.27kV	217.97kV	3.93kA	4.66kA
5 ohms	41.49kA	11.63kA	25.07kA	170.92kV	-191.24kV	145.27kV	-165.64kV	362.16kV	310.91kV	228.44kV	229.72kV	4.14kA	4.56kA
20 ohms	23.92kA	5.89kA	15.83kA	270.68kV	-291.06kV	251.72kV	-272.14kV	561.74kV	523.84kV	228.05kV	231.56kV	4.15kA	4.54kA
50 ohms	12.31kA	2.31kA	9.64kA	320.96kV	-341.35kV	303.84kV	-324.24kV	662.32kV	628.08kV	228.39kV	231.24kV	4.10kA	4.54kA

In progress

In Progress

Proposed Fault Processing: DC Fault Processing Schemes_ DWT

(Results will be ready in Jan 2023 EERA Conference)

In progress

In Progress

Validation of Protection Scheme in PSCAD/EMTDC

(*Results will be ready in Jan 2023 EERA Conference*)

In progress

In Progress

Discussion of Influencing Factors

(*Results will be ready in Jan 2023 EERA Conference)*