An Expanded Fault Detection and Clearing Strategy Application to a Hybrid Wind Farm integrated to an AC grid

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AGENDA

- Abstract
- My contribution to the dissertation
- Problem Statement
- Research Methodology(**Remaining Task**)
- Test Topology or Outline
- Why DC Fault Interruption in VSC_based technology is a challenge?
- Identification of Different Zones of Protection
- DC Fault Clearing Strategies
- Fault Ride Through Schemes for DFIG and PMSG
- MMC Converters Used in Research
- Modeling of Cable and Transmission Line
- Control schemes Implemented for the Topology
- DC Fault Detection, Localization and Classification
- Main Reference and Contributory Literature

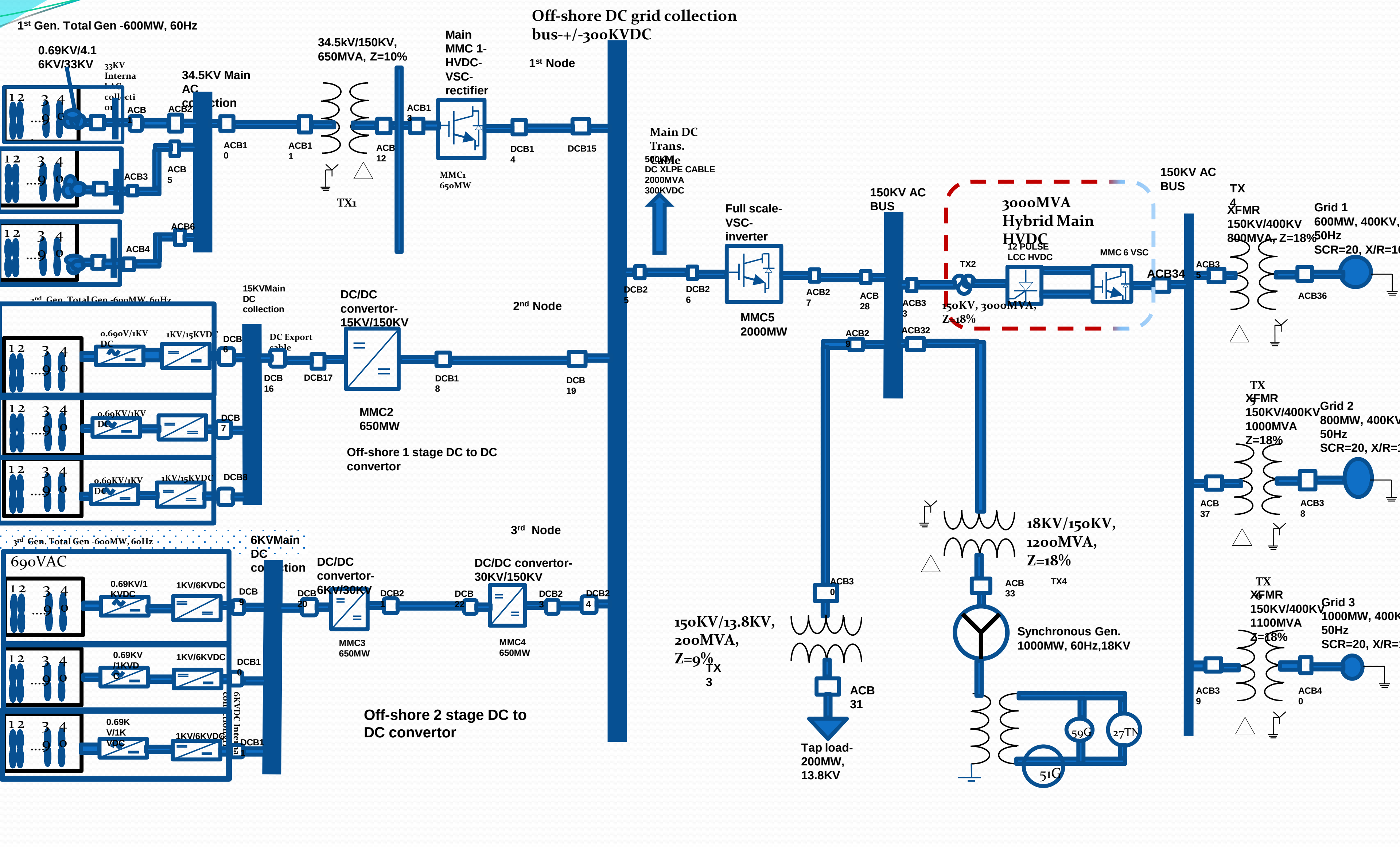
Abstract and Introduction

- **Abstract**
  - LCC_HVDC
  - VSC_HVDC
  - Hybrid HVDC
  - Doubly Fed Induction Generator(DFIG)
  - Permanent Magnet Synchronous Generator(PMSG)
  - MMC_VSC Topology
  - DC Grids

My Contribution to Research

- My contribution to this dissertation research
- **Hybrid Wind Farm (DFIG plus PMSG Wind Turbines) integrated to Main DC Grid and Main Transmission Level HVDC Hybrid Converter and AC grid**
- Topology consists of 3 nodes or groups of aggregate models of total wind turbine generation source totaling 1800MW, 60Hz.
- The first node or group generation source consists of a 600MW of DFIG, each DFIG with an output of 5MW which have been grouped in 3 subgroups of Qty (40) DFIG.
- Rating of DFIG is 5MW, 60Hz with stator rating of 0.69KV and Rotor rating of 4.16KV
- The output of the stringed DFIG AC windfarm is integrated to an internal 33kv AC collector bus which is stringed together to form the main offshore AC collector bus with an output of 34.5kVac.
- The main 34.5KVAC collector bus is then integrated with a step-up power transformer which steps the output voltage from 34.5KVac to 150KV ac.
- The 150KV side of the step-up transformer is integrated with a one terminal full scale Main HVDC MMC-VSC_1 which act as a rectifier which converts the AC voltage to DC voltage before it is integrated to an HVDC main +/-150KV DC collection grid bus all located offshore.

Test Topology Outline



My Contribution to Research

- **My contribution to this dissertation research**

- The second aggregate of generation consists of 600MW of 3 sets of Qty (40) of Permanent Magnet Synchronous Generator
- The rating of each PMSG is 5MW, 60Hz, 0.69KV
- PMSG AC output of 0.69kv is converted to 1kV dc through 3-level NPC VSC
- PMSG internal Booster DC-DC Converter steps the voltage from 1kv to 15kvDC
- The overall PMSG output is integrated with only one stage of step-up voltage 15KV/150KV DC to DC converter located offshore,
- The entire outline is integrated to a +/-150KV DC grid collector bus.

My Contribution to Research

- **My contribution to this dissertation research**
  - The third aggregate of generation consists of a 600MW of 3 sets of Qty (40)PMSG each
  - The rating of each PMSG is 5MW,0.69kv
  - The PMSG is integrated to an internal 3-level NPC VSC acting as a rectifier to convert 0.69KV to 1KV dc
  - PMSG internal Booster DC-DC Converter steps the voltage from 1kv to 6kvDC
  - The overall PMSG output is integrated with two stage DAB_MMC_VSC of step-up voltage 6KV/30KV DC and 30KV/150KV all located offshore
  - The entire outline is integrated to a +/-150KV DC grid collector bus.

My Contribution to Research

- **My Contribution to Research**

- **Expanded AC and DC Fault with Fault Resistance Application**
- A focus on an expanded and improved AC and DC fault application
- For AC side Faults,SLG,DLG,DLL,3-Phase, 3-Phase to ground at 10%, 20%, 40%,60%,80% of the cable and line length with different fault resistances ranging from (0 to 40ohms)
- DC Faults Pole to ground and Pole to Pole with fault resistance will be considered. The expanded faults on the windfarm side will be faults that will be internal to the wind farm, internal and external AC and DC collection grid.
- Expanded faults will also be extended to the Main AC and DC collection grid, internal and external components of DC to DC converter, Main MMC-VSC HVDC converters, Main Hybrid HVDC Converters, internal and terminal faults of the infeed synchronous generator

My Contribution to Research

- **My Contribution to Research**
- **Fault Clearing Strategies**
- Fault clearing strategy which consist of Fully Selective Fault Clearing strategy with back-up protection plan will be implemented in various zones of protection utilizing various or combination of Fault Blocking and fault current control capability of Full Bridge Sub Module MMC-VSC topology Fault Blocking Schemes or
- Hybrid MMC-VSC which is a combination of Full Bridge and Half Bridge Sub Module MMC-VSC and High-Speed DC disconnect Switches
- DC-DC Converters with Full Bridge Sub Module MMC-VSC(DAB-FBSM) Fault blocking and isolation or galvanization capability
- Solid State DC breakers(DCCB) and High Speed Mechanical DC Disconnect Switches and DC-DC Converters with Full Bridge Sub Module and using AC circuit breaker on the AC side.

My Contribution to Research

- **My Contribution to Research**

- **Fault Detection and Location using Travelling Wave Algorithm in compliment with Discrete Wavelet Transform(DWT)**

- A novel fault detection and location technique utilizing Travelling Wave theory and Discrete Wavelet Transform after extraction, analysis and classification of the type of fault from the data of transient voltages and currents will be implemented

My Contribution to Research

- **My Contribution**

- **Protection of Hybrid Wind Farm (Doubly Fed Induction Generator and Permanent Synchronous Generator) and Fault Ride Through and Low Voltage Ride through Techniques**

- Fault Clearing Strategy will be complimented with the traditional DFIG Protection scheme of utilizing Active Crowbar Protection to protect overvoltage condition on the rotor and the generator side converter and a DC Chopper to limit overvoltage conditions on the DC link due to active power in-balance.
- For the PMSG, the traditional protection scheme will consist of an AC side Power Electronics Controlled Dynamic Resistor and AC Load Damper to limit overcurrent, prevent rotor acceleration during faults, maintain balance of active power and stability. On the DC side DC breaker will be used to interrupt the DC overcurrent during Capacitor discharge and a DC Link Chopper Resistor will be used to limit any overvoltage that might occur.
- In addition, there will be a DC series Dynamic resistor that will be implemented to limit overcurrent in the DC cable and DC Link.

My Contribution to Research

- **My Contribution**

- **Validation of the proposed protection scheme detection and location algorithm will be validated in PSCAD-EMTDC software platform and Matlab Simulink Tool Box**

- The testing and validation of the developed hybrid algorithm will be performed in PSCAD software and the Discrete Wavelet Transform fault extraction and analysis will be performed in Matlab/Simulink Power System Tool box in a closed loop environment of a microprocessor protective relay or Intelligent Electronic Device(IED) identified for each zone of protection.

Problem Statement

- Current protection methods that are employed and implemented in LCC_HVDC cannot be implemented in VSC_HVDC
- MMC is one of the main topologies of the VSC and has been an excellent choice for long-bulk power transmission and HVDC network grid. However, due to the use of long distance transmission lines and cables, the HVDC is prone to faults.
- VSC-HVDC integrated to Wind Energy Conversion system are vulnerable to DC faults
- Wind Energy Conversion system are vulnerable to DC faults because DC Faults have significant difference in fault characteristic in terms of absence of zero crossing and having very low impedance of DC fault which makes it to achieve very fast rise with steep slope when compared to the traditional AC fault current.
- Several fault detection, classification and localization techniques have been proposed such as overcurrent, under-voltage and rate of change of voltage and current but lacks the required sensitivity for detecting high resistance fault.
- Other fault detection schemes like impedance-based fault detection and location have also been proposed and implemented but the drawback associated with this type of fault detection includes influence from transmission line parameters, fault resistance, mutual zero sequence just to mention a few.

Problem Statement

- The capacity of offshore wind power increases in addition to continuously increasing rating of the individual wind turbine power rating which will require a large geographical area and footprint and large offshore substation for interconnection and because of the larger power rating of the wind turbines it will require larger separation distance.
- The wind power when generated need to be integrated to the grid through the most less costly technology.

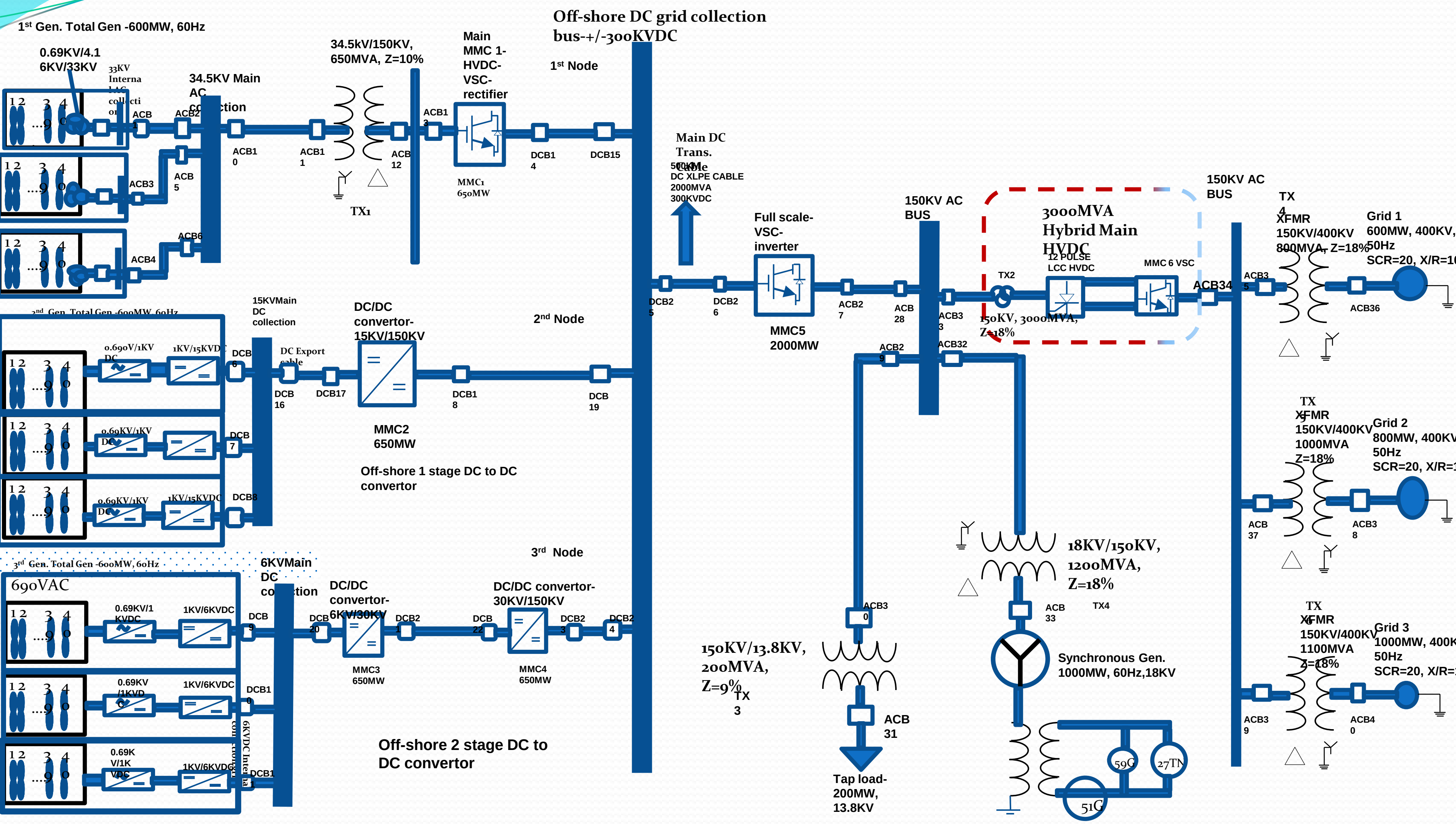
Research Methodology

- **Main Remaining Items Methodology**
- ➢ Identify the type of fault detection technique that will be used for this test model, most likely it will be a hybrid algorithm which consist of a combination of Travelling Wave and Discrete Wavelet transformation technique
- ➢ Identify the zones of protection for the proposed test topology and the IED or protective relays that will be used in compliment with the fault detection algorithms
- ➢ Identify the best mother wavelet technique which will characterize the fault classification for the Discrete Wavelet Transformation decomposition.
- ➢ Design and validate the proposed hybrid fault detection algorithm, discrete wavelet transformation using wavelet energy spectrum entropy in Matlab/Simulink power system tools and travelling wave in PSCAD

Remaining Work to be done

- **Methodology**
  - Design Parameters and Control Schemes
  - PSCAD Modeling of the Components of the Topology
  - Matlab/Simulink Code programming of Travelling wave Interface with PSCAD
- Simulation-COMTRADE

Test Topology Outline



Why DC faults associated with MMC HVDC are Difficult to Interrupt?

- **Difficult interruption of DC fault**
- DC Faults have a significant fault characteristics when compared with the traditional AC
- DC faults Rise Up quickly with a steep slope when compared with the traditional AC fault
- The impedance of the DC fault is very small when compared with AC faults
- DC Faults do not have a zero crossing when compared with the traditional AC faults
- VSC does not have the capability to control the DC fault

Selection of Protection scheme and Fault Coordination Strategy

- **DFIG and PMSG**
- **AC Bus**
- **DC Bus**
- **Power Transformer and Converter Transformer**
- **MMC**
- **DC-DC Converter**
- **150KV DC Main Transmission Line**
- **400KV Main AC Transmission Line**
- **1000MW Synchronous Generator**

Fault Control and Clearing Strategies

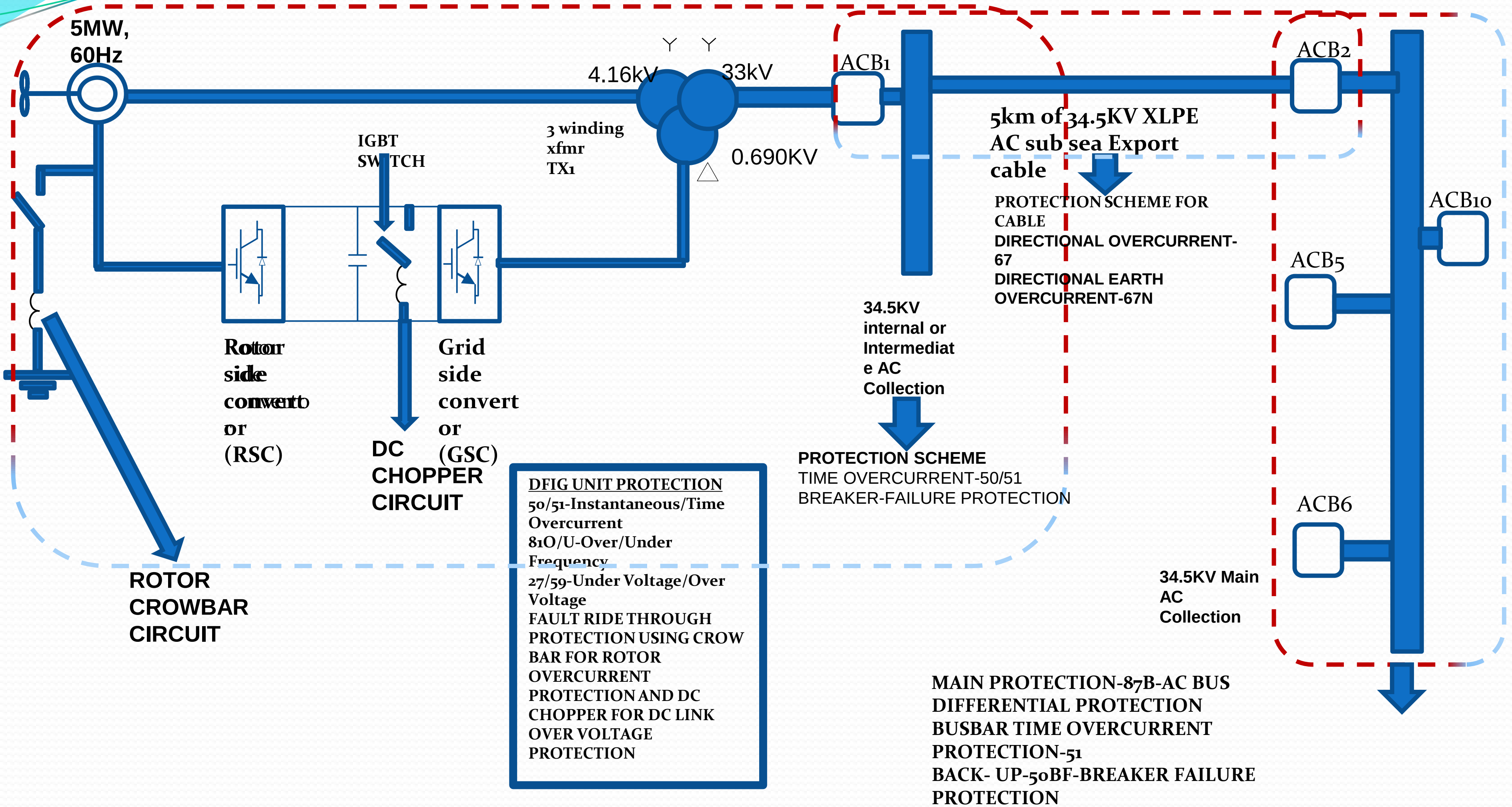
- **Fault Clearing strategy of MMC and DC-DC Converter**

-Full Selective Fault Clearing Strategy-Using DC solid state breakers and High Speed Mechanical Switches

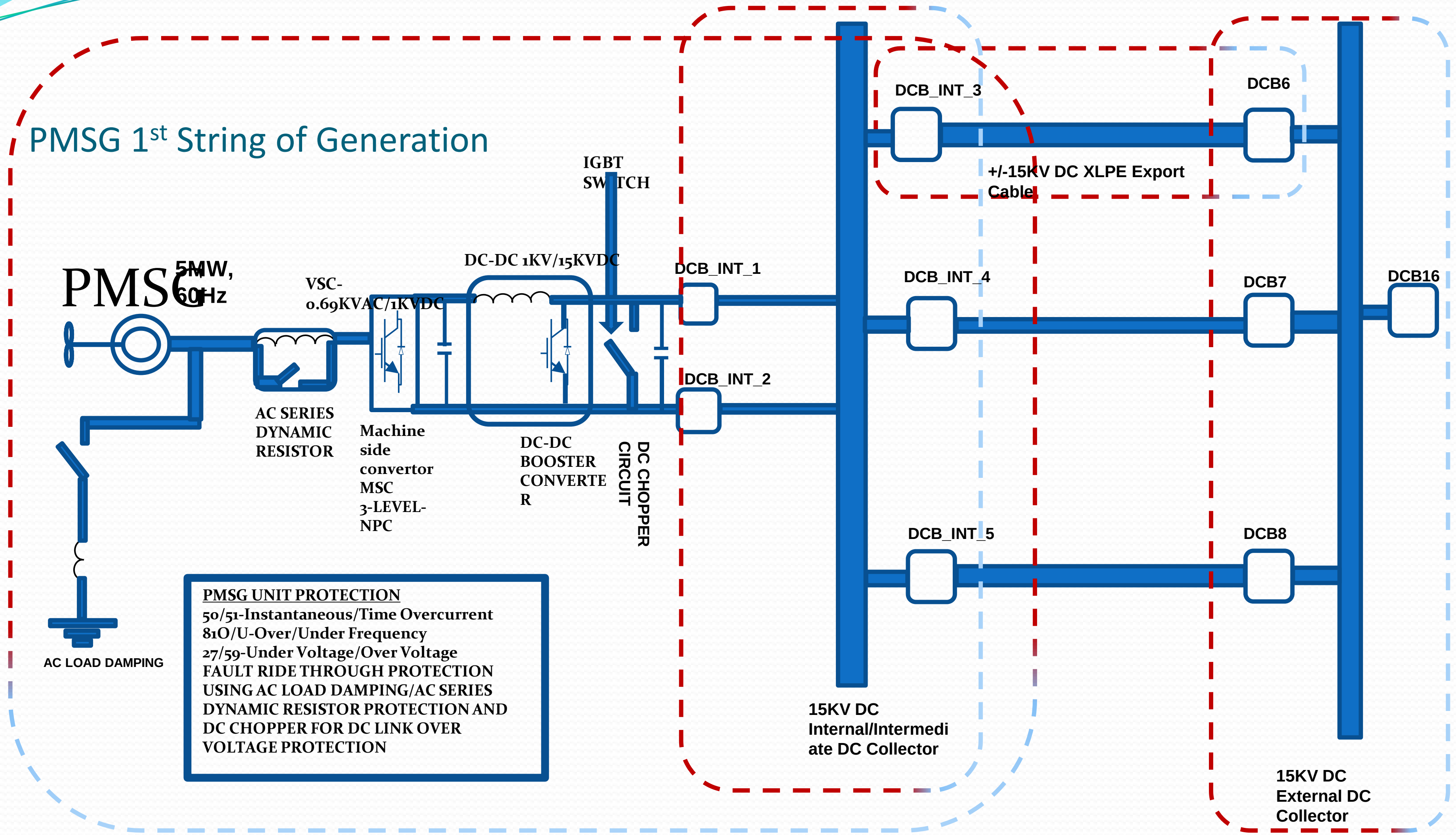
-Non-Selective Fault Clearing Strategy-Using Fault Blocking capability of MMC-Full Bridge Sub Module and DC-DC Converter-DAB

-Back-Up Protection using AC Breakers

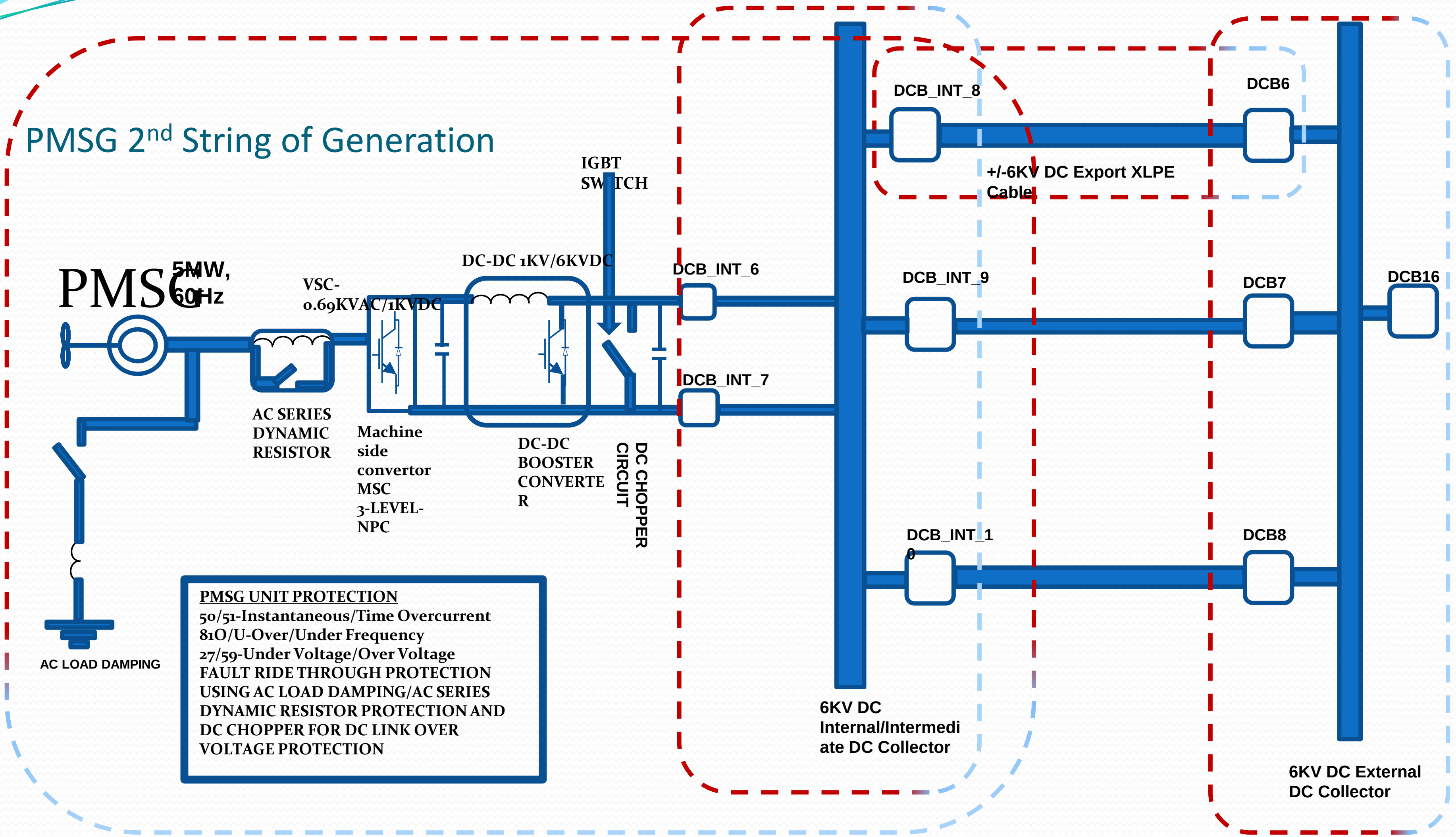
Identified Zone of Protection



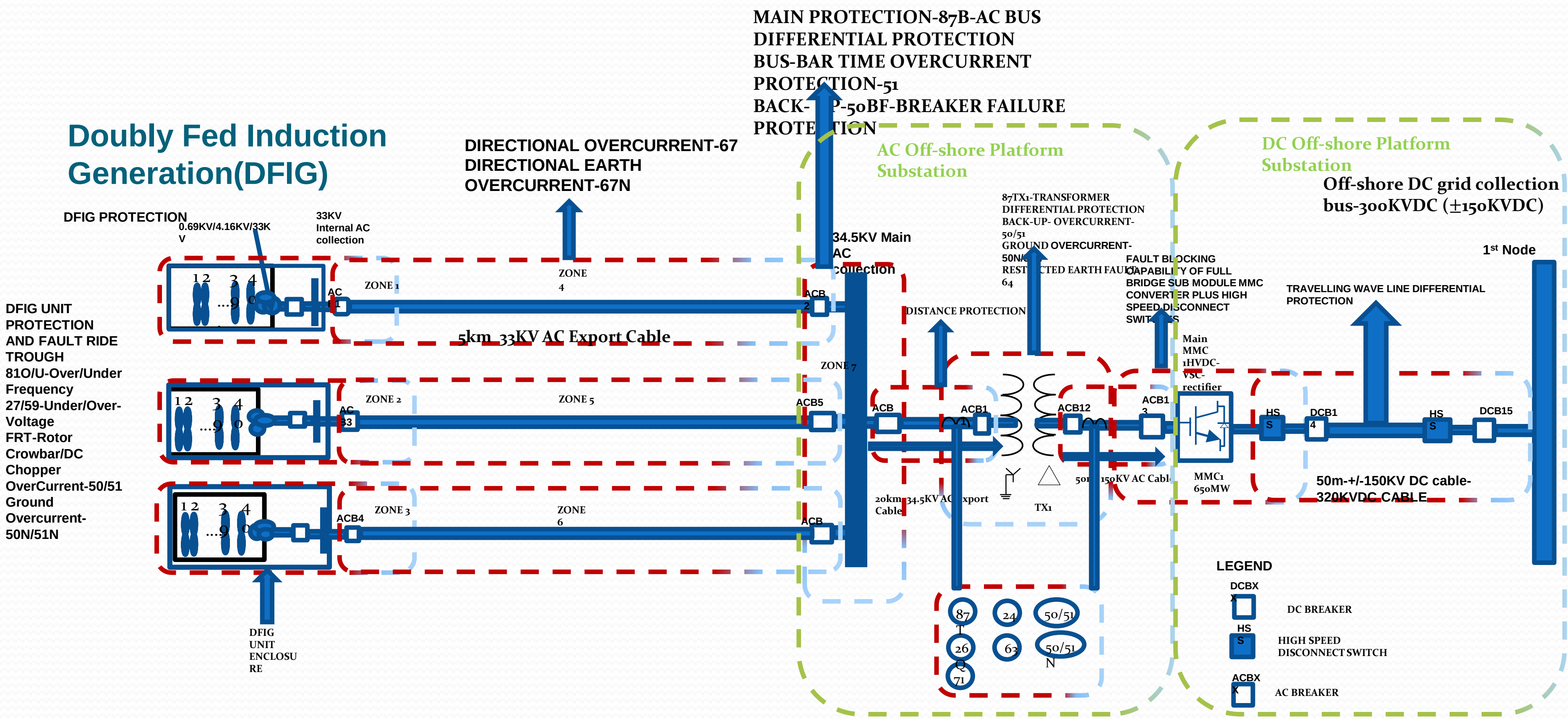
Identified Zone of Protection



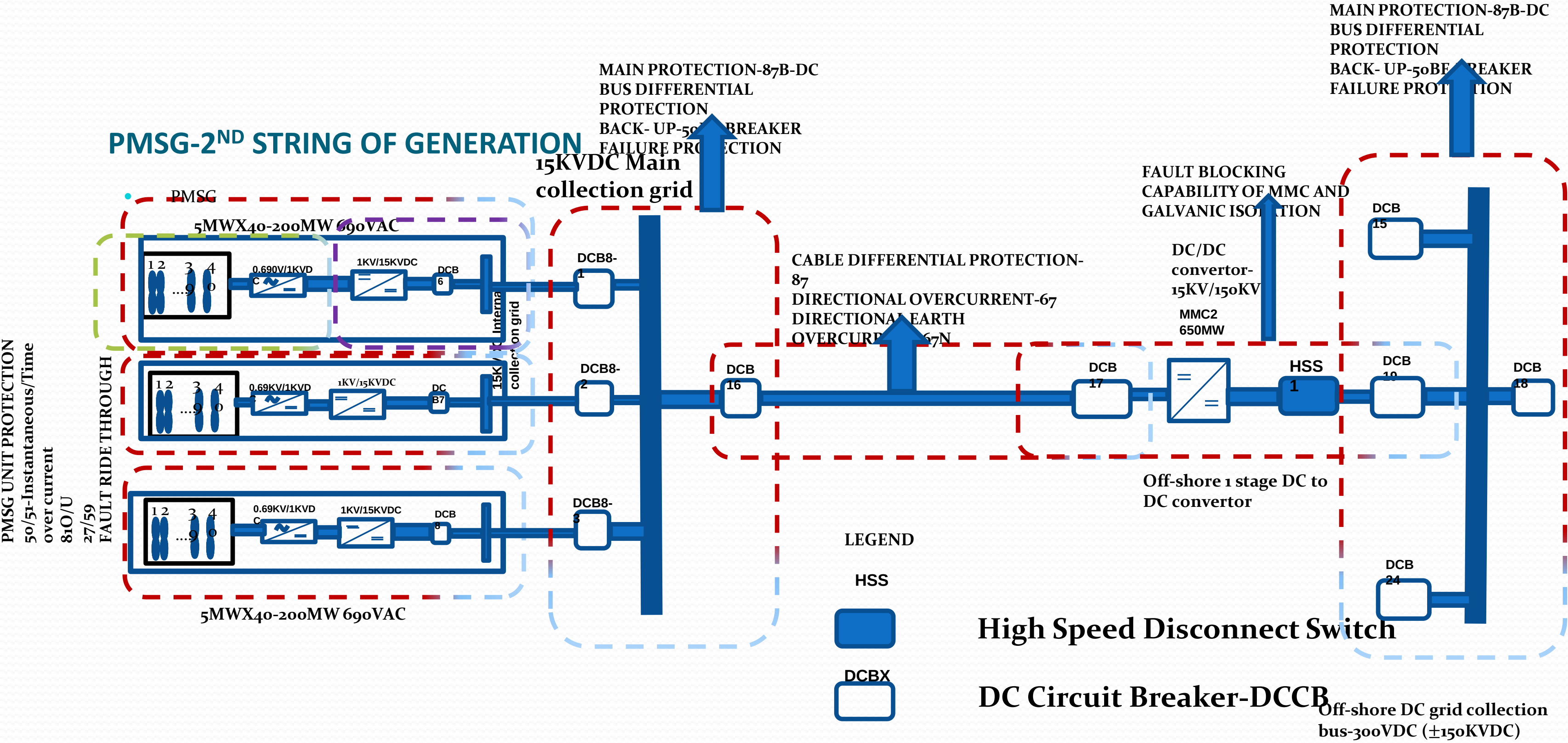
Identified Zone of Protection



Identified Zone of Protection

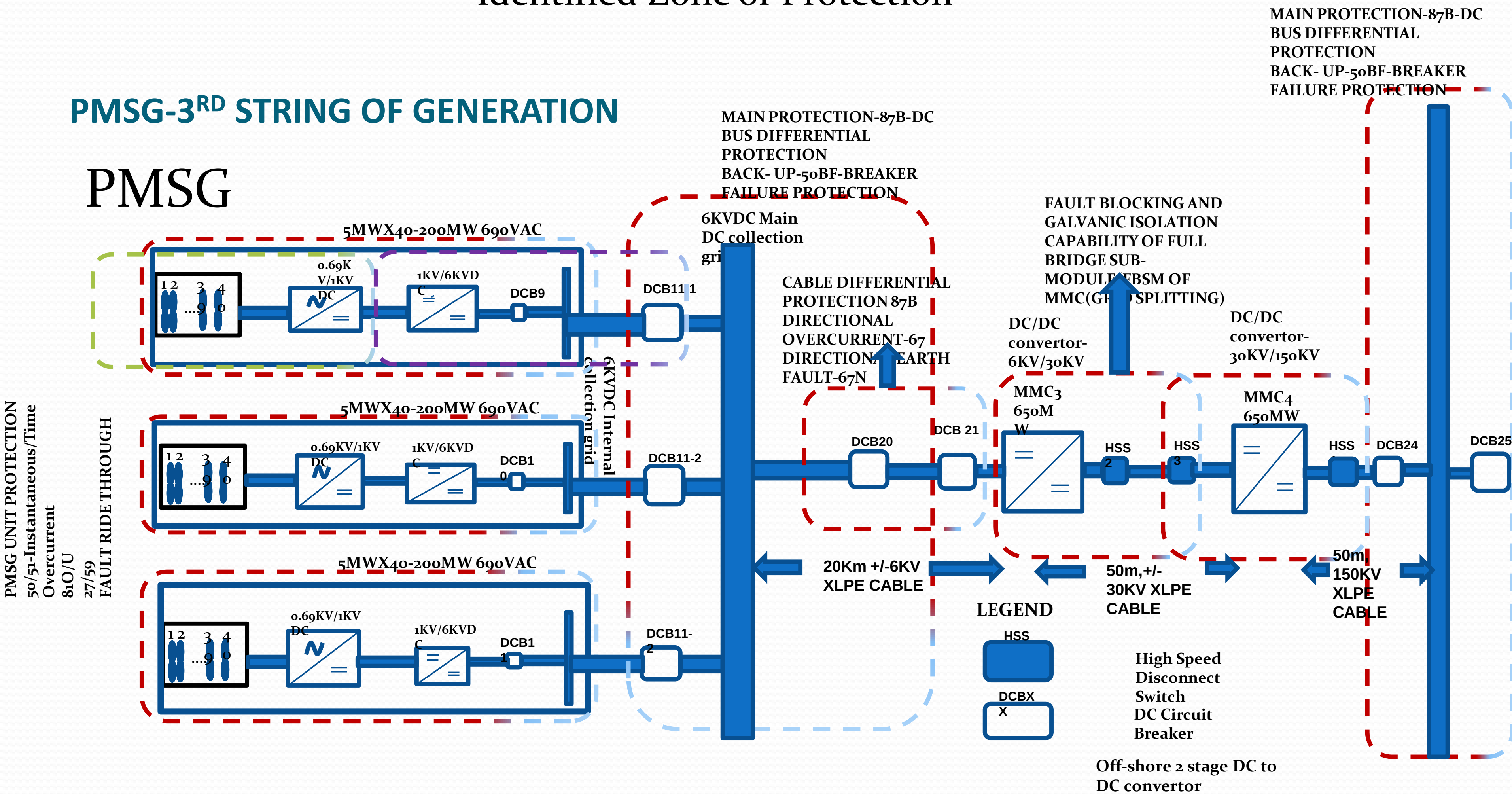


Identified Zone of Protection

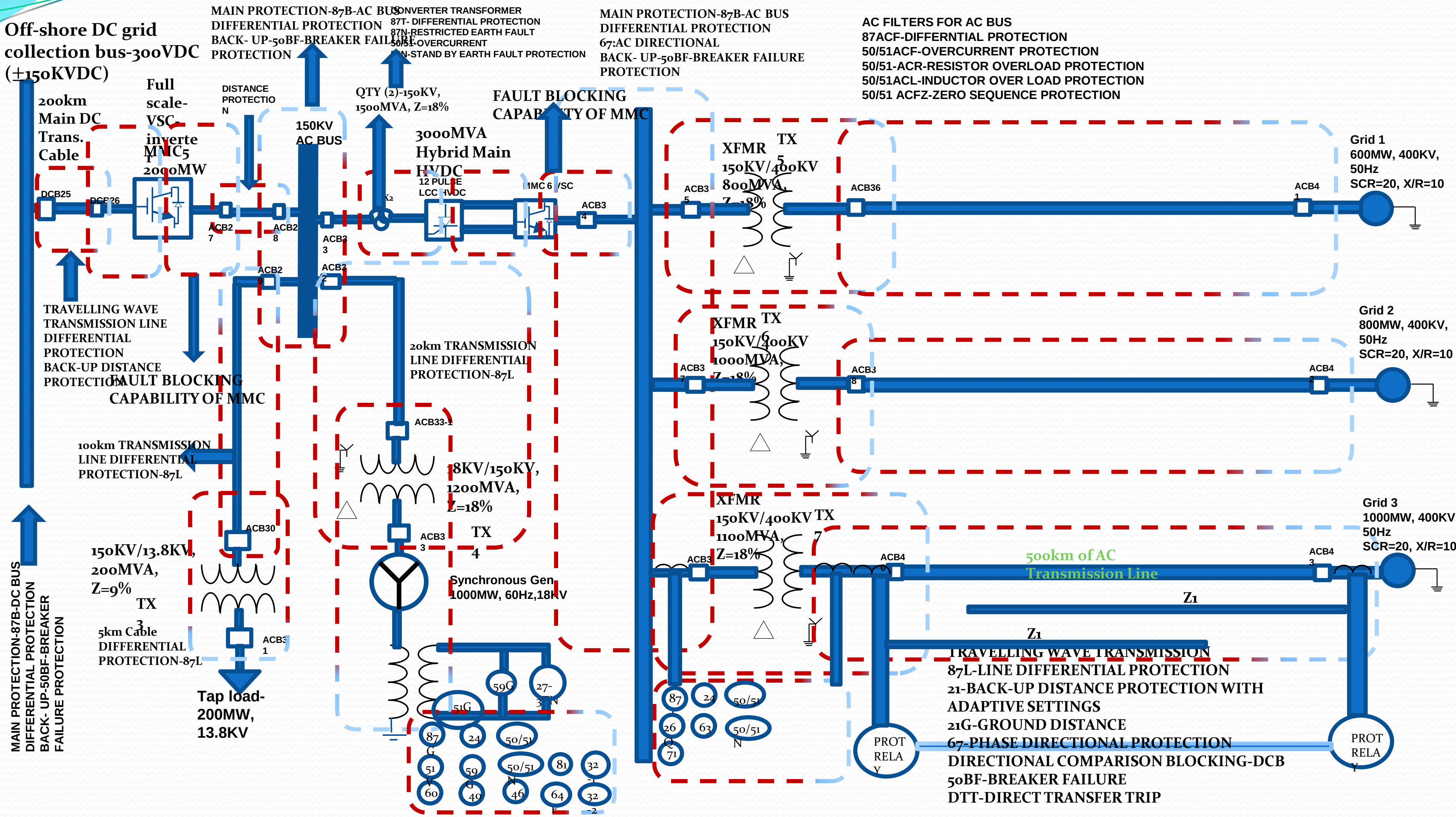


Identified Zone of Protection

PMSG-3RD STRING OF GENERATION

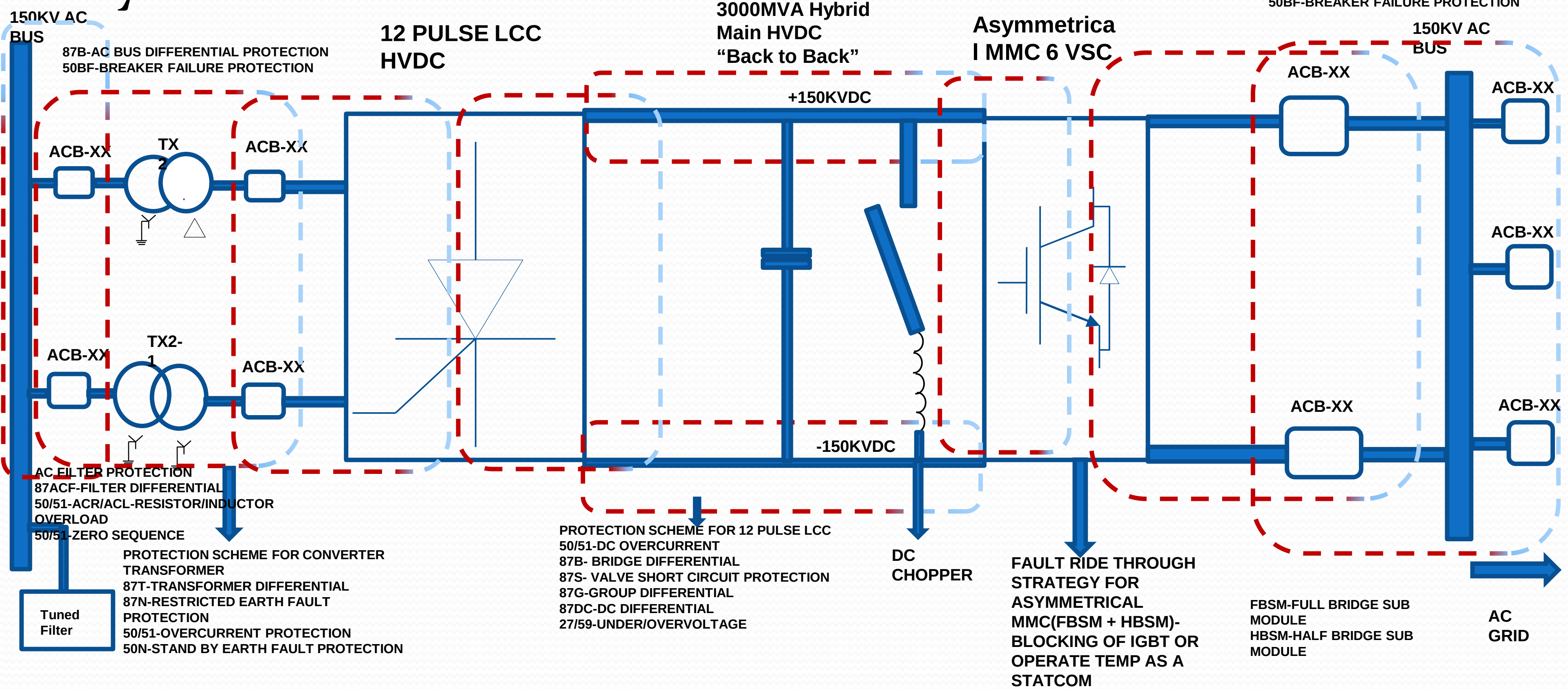


Identified Zone of Protection



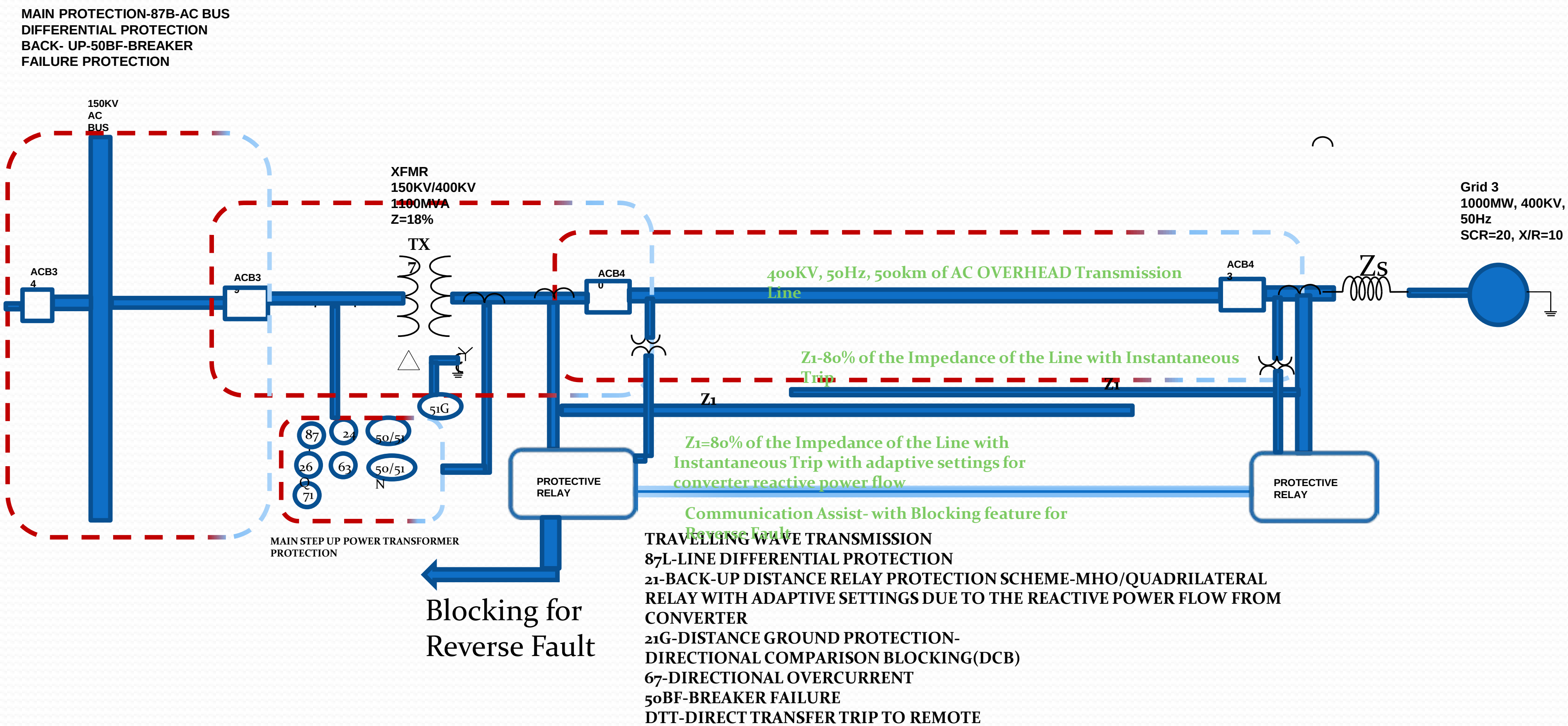
Hybrid Transmission Level HVDC Protection

- Hybrid HVDC Protection



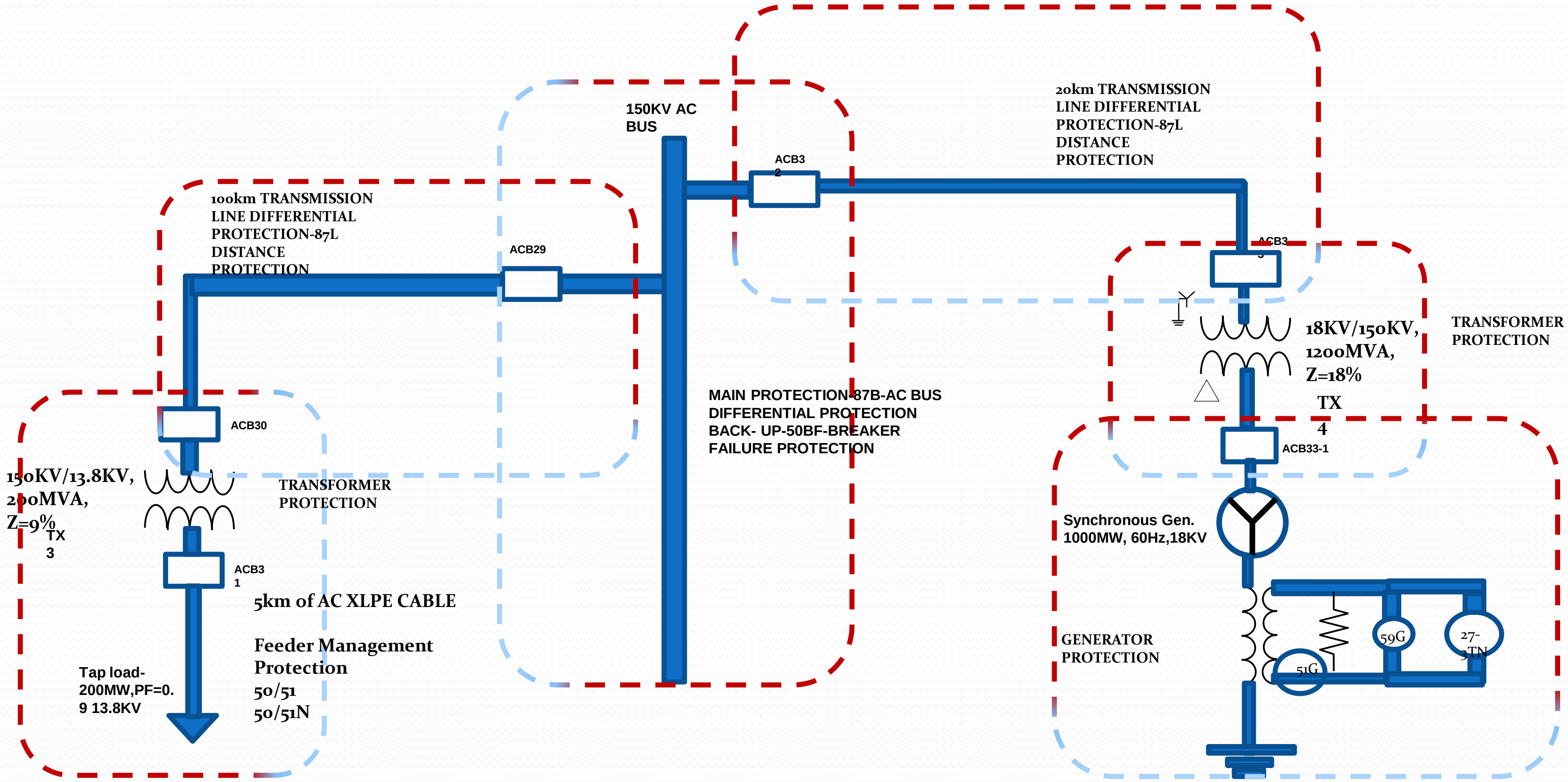
400KV OVERHEAD AC Transmission Line

- 400KV OVERHEAD AC Transmission Line



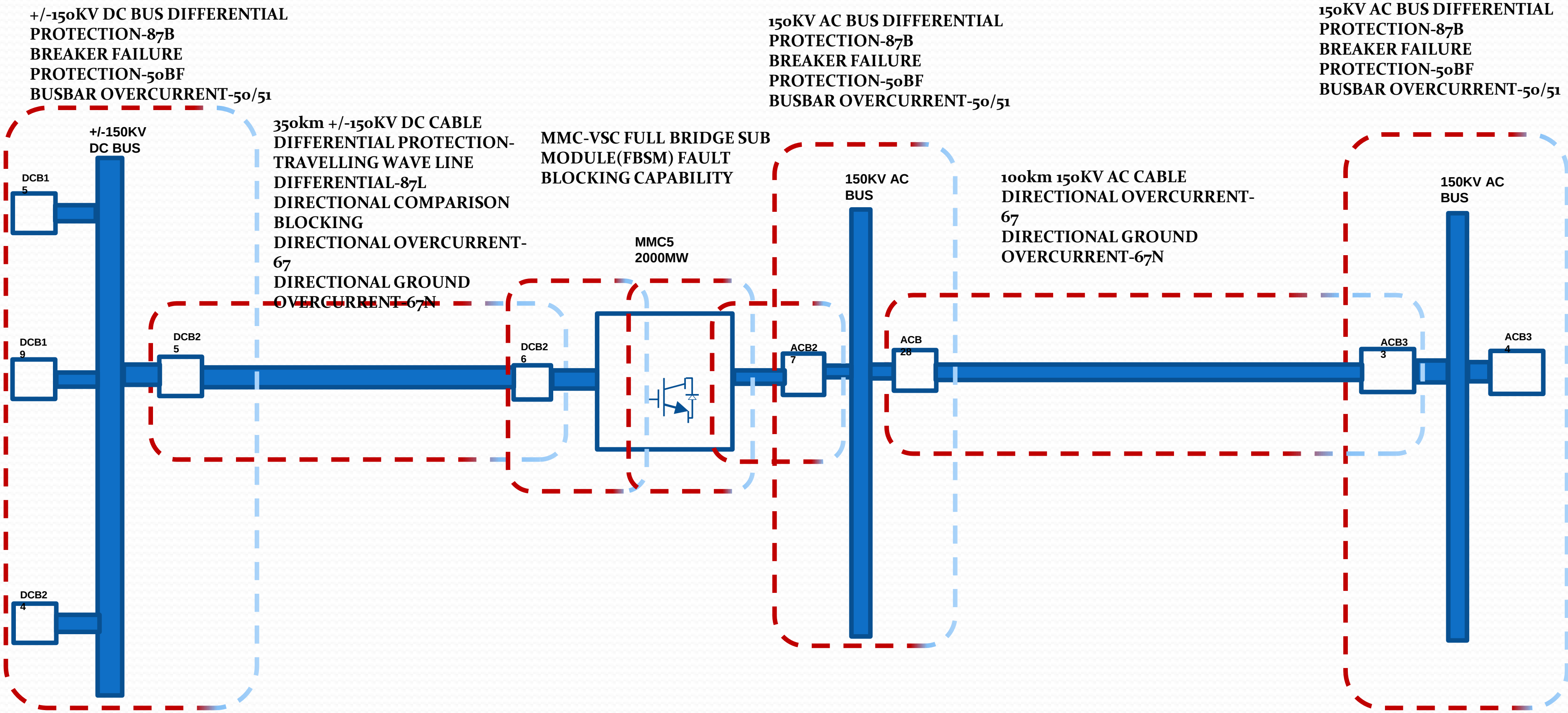
Generator and Feeder Load Protection

- Generator and Feeder Load Protection



Identified Zone of Protection

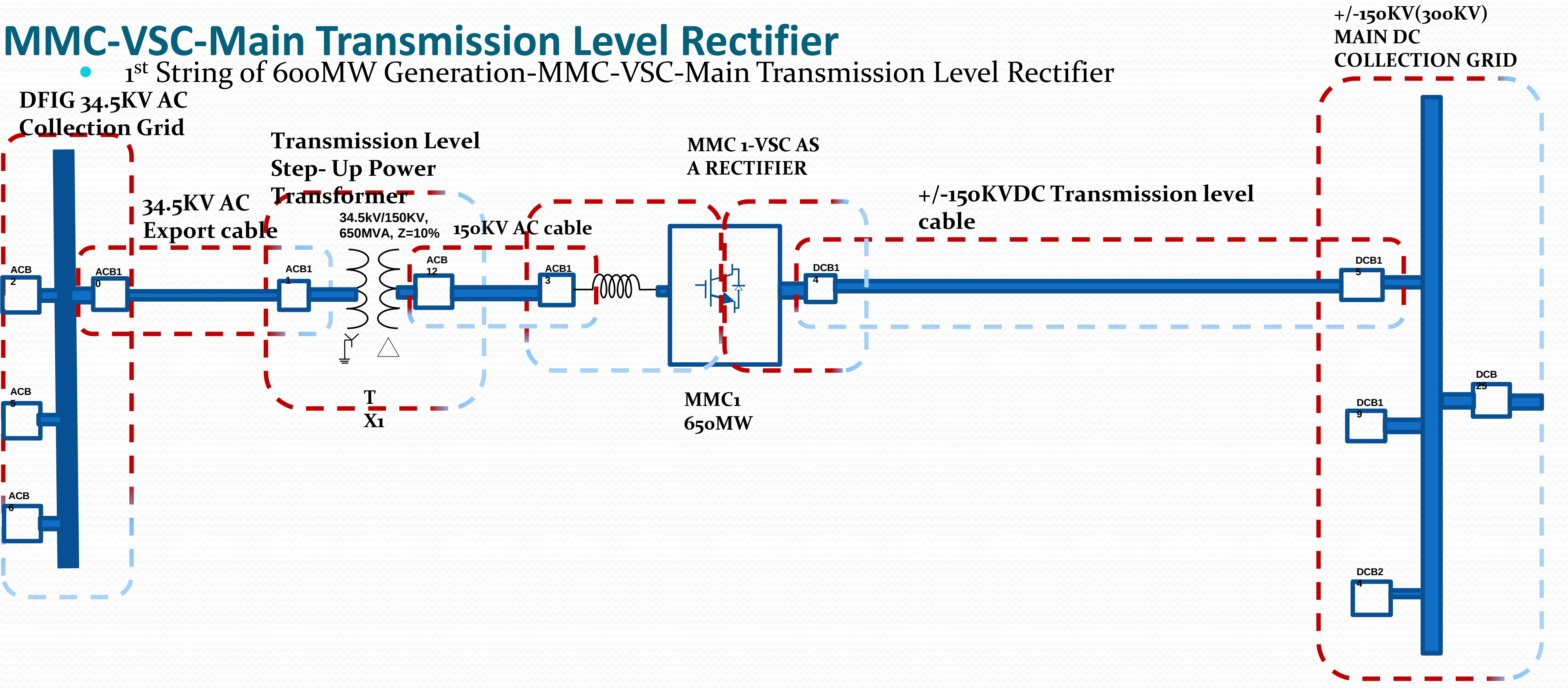
MMC-VSC MAIN TRANSMISSION LEVEL CONVERTER



Identified Zone of Protection

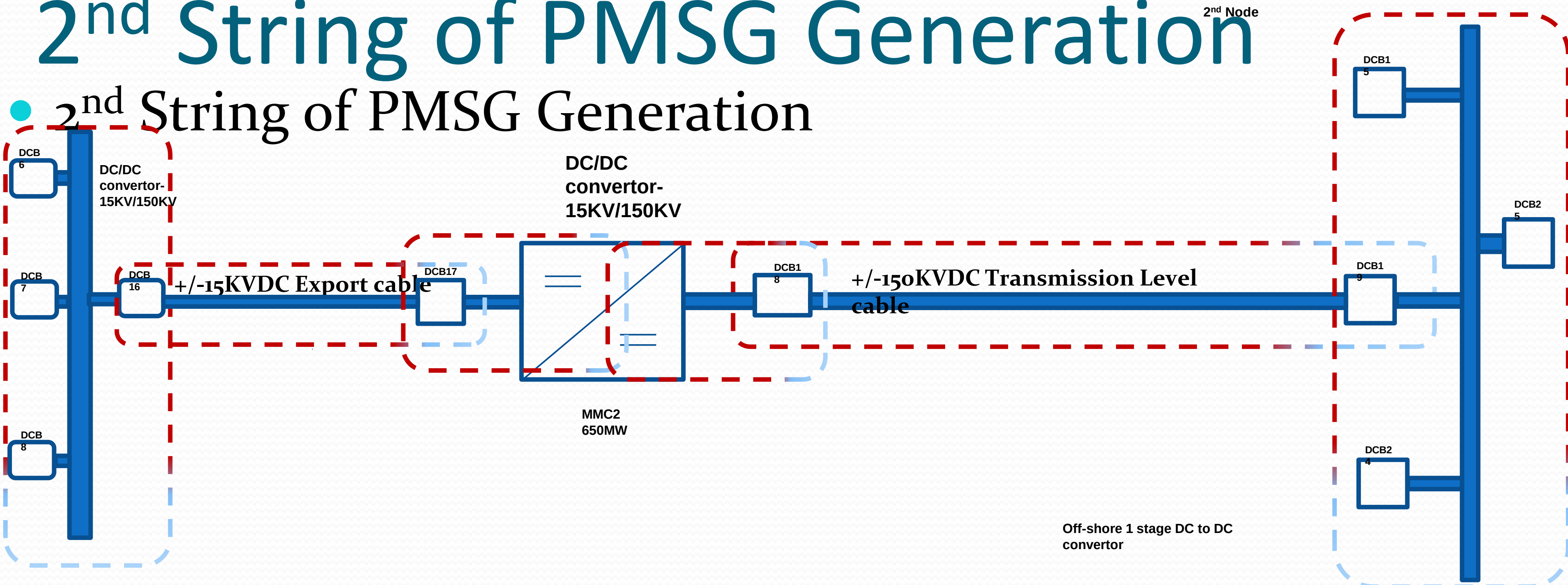
MMC-VSC-Main Transmission Level Rectifier

- 1st String of 600MW Generation-MMC-VSC-Main Transmission Level Rectifier



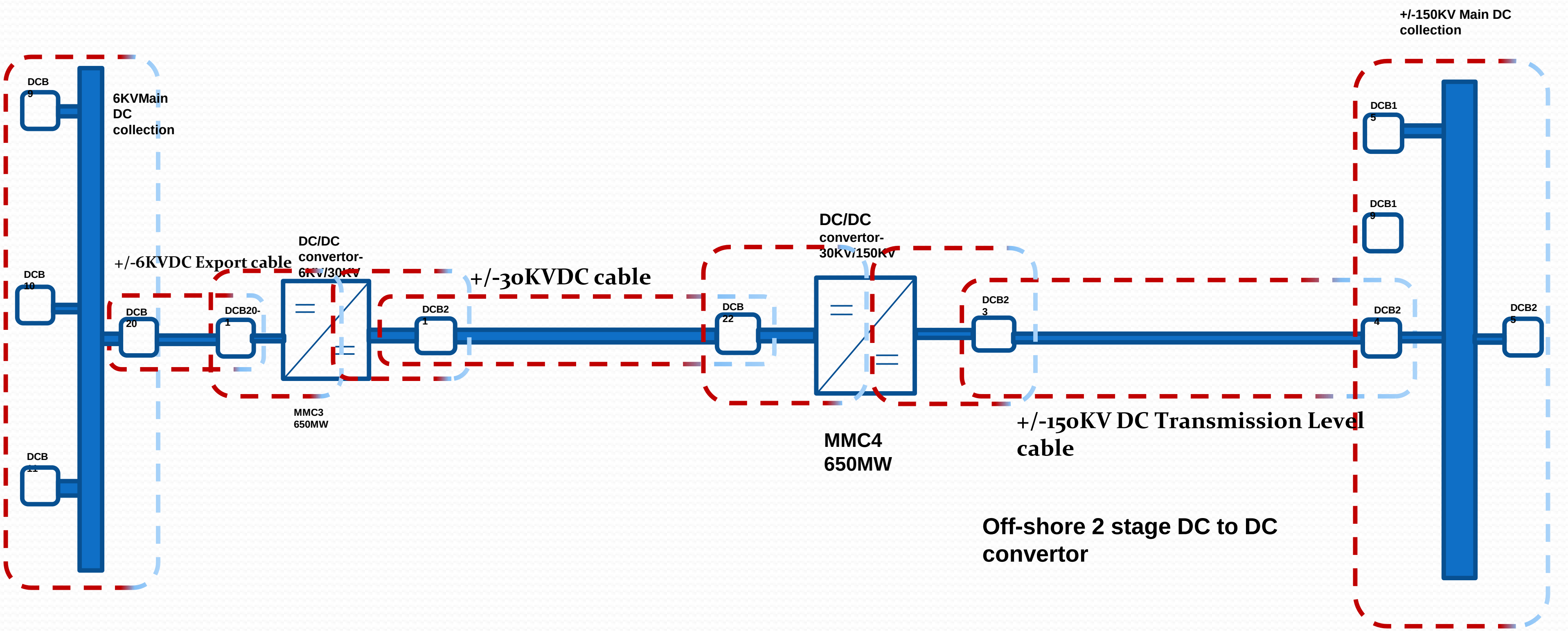
2^{nd} String of PMSG Generation

- 2^{nd} String of PMSG Generation



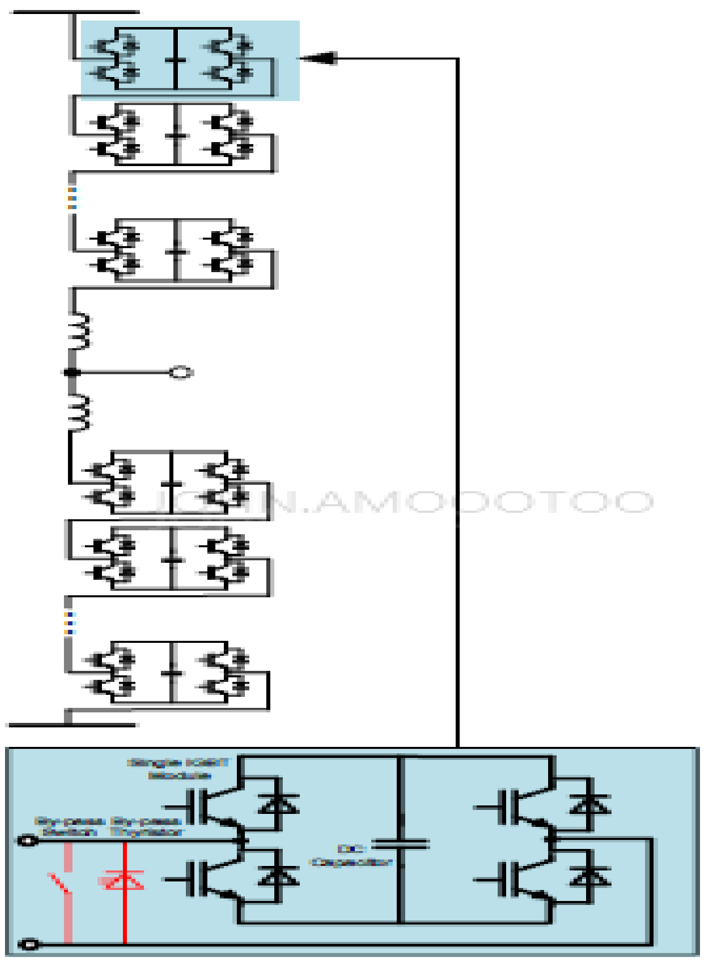
3rd String of Generation-PMSG

- 3RD String of Generation



Full Bridge Sub Module MMC

- FB MMC-Reference-Sztykiel, Michal,etc “Modular Multi-Level converter Modeling, Control, Analysis under grid frequency Deviations, Technical University of Denmark,2012



Full-bridge MMC Modular Cell
(~1.6 kV)

DC-DC DAB Converters

- **DC-DC DAB**-MMC-Reference-Sztykiel, Michal,etc "Modular Multi-Level converter Modeling, Control, Analysis under grid frequency Deviations, Technical University of Denmark, 2012

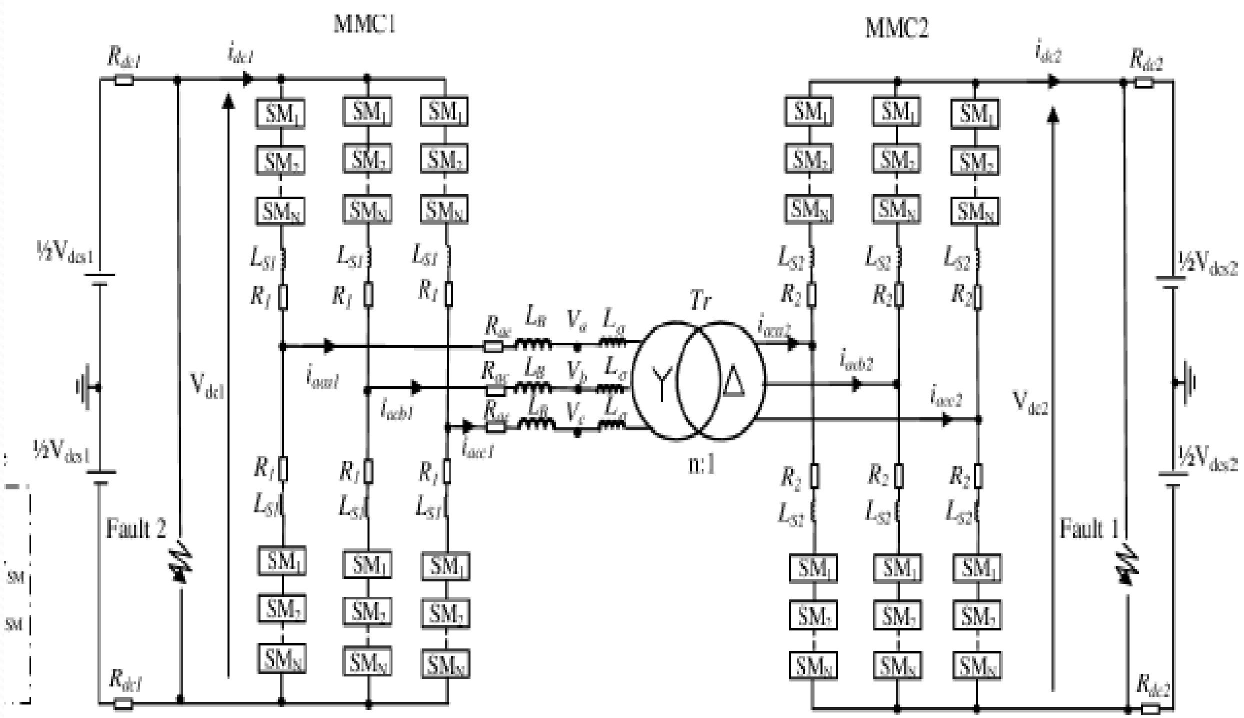
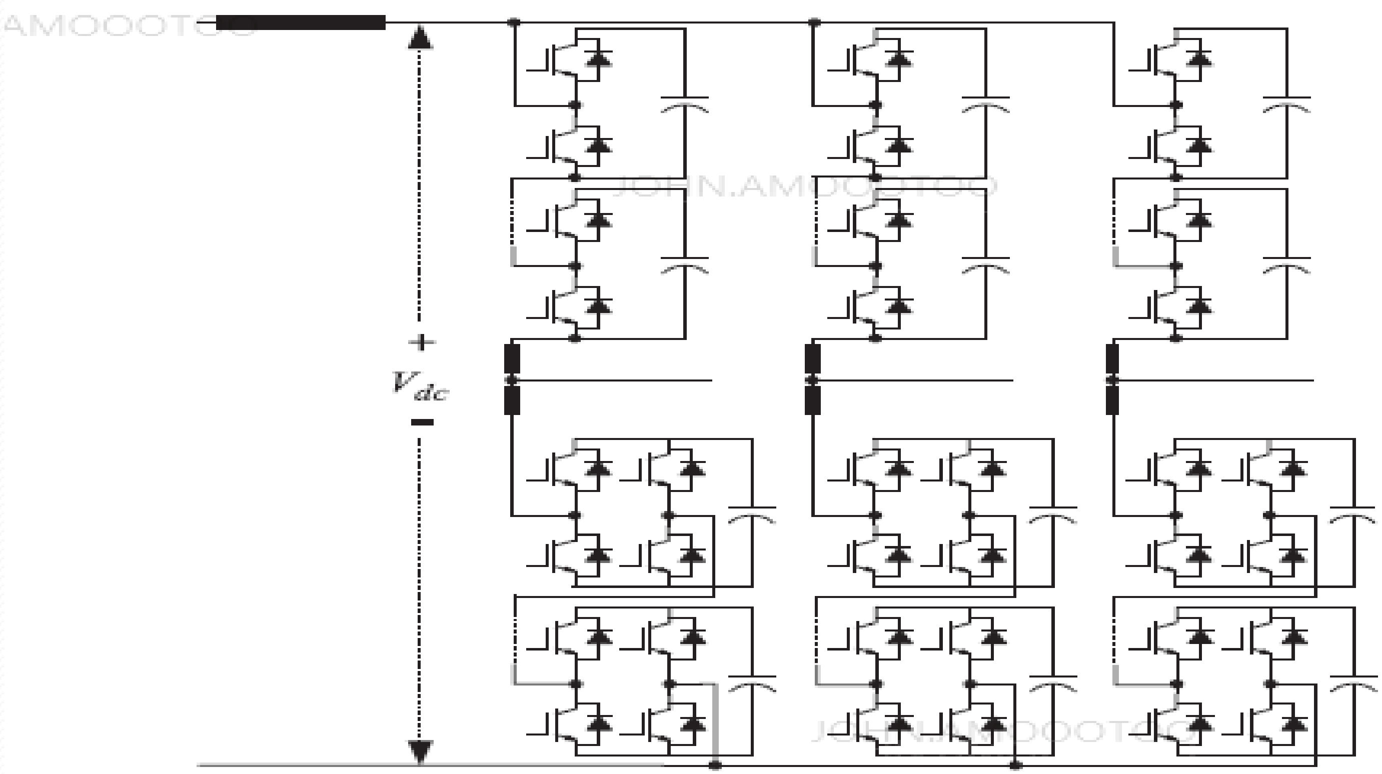


Figure. 1 The DAB MMC DCDC converter

Asymmetric Model-Hybrid MMC

- Asymmetric Model-Reference- **DAB**-MMC-Reference-Sztykiel, Michal,etc “Modular Multi-Level converter Modeling, Control, Analysis under grid frequency Deviations, Technical University of Denmark,2012



(b)

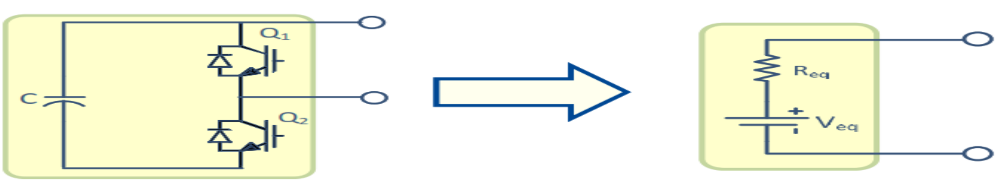
Modelling of MMC

- **Modelling of MMC-Detailed Equivalent Model**
- Performs a circuit reduction of the simplified circuit
- Thevenin's equivalent for each converter arm which used the nest fasted simulation to improve upon the time for simulation
- The topology can be reduced to subnetworks with admittance matrix of each network reducing computation time
- Easy calculation of multivalve voltage based on the measurement of resistance and current values of the valve
- In conducting state the resistance is low and in blocked state the resistance is high

- Using Thevenin equivalent: (detailed equivalent model)

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

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



Modeling of Transmission Line

- **Modelling of AC Transmission Line and DC Cable**

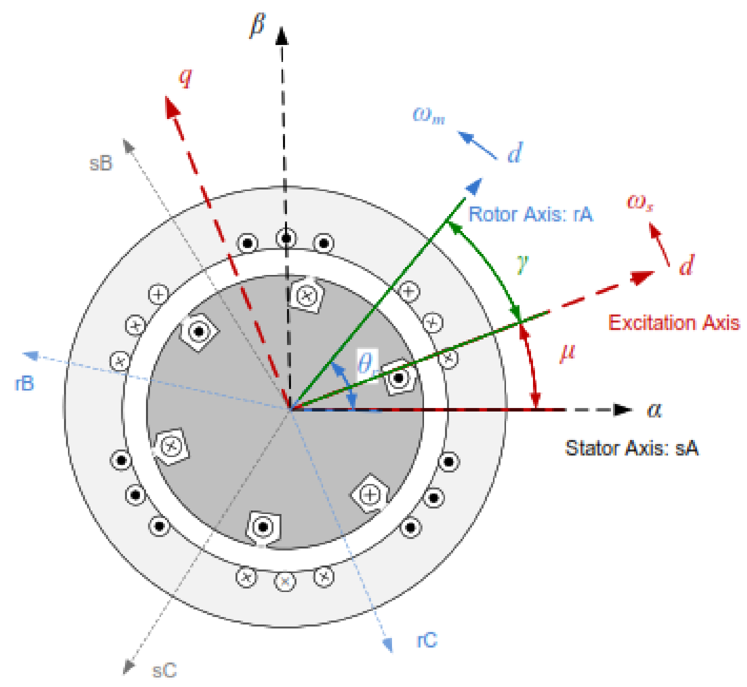
- Resistance in ohms/km
- Inductance in henries/Km
- Capacitance in Microfarad/Km
- Conductance in S/km
- Length of the AC Transmission Line

- Frequency Dependent Phase(**Cable Model**) and Mode(**Transmission Line**) Model

- Based on the travelling wave theory
- Frequency dependent of the parameters and termed to be the best
- Accurate representation of the current and voltages both in steady state and transient
- PSCAD-simulation in time domain and converted to frequency domain using wavelet transformation or Fourier transform

DFIG ANG PMSG DYNAMIC EQUATION

- DFIG Dynamic Modeled Equations



$$v_{abcs} = i_{abcs} R_{abcs} + \frac{d}{dt} \lambda_{abcs}$$

DFIG AND PMSG DYNAMIC MODEL EQUATION

- DFIG Model Equations

$$\lambda_{ds} = \lambda_D = L_s i_D + L_m i_d$$

$$\lambda_{qs} = \lambda_Q = L_s i_Q + L_m i_q$$

$$\lambda_{dr} = \lambda_d = L_r i_d + L_m i_D$$

$$\lambda_{qr} = \lambda_q = L_r i_q + L_m i_Q$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$$

$$T_{dev} = \frac{3}{2}\frac{P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right)$$

$$P_s = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right)$$

$$Q_s = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right)$$

Vector Control Schemes

- **Field Oriented Vector Control Schemes**

DFIG Vector Control

- Stator Flux Oriented Vector Control
- Grid Voltage Oriented Vector Control
- Pitch Angle Control
- Maximum Power Point Tracking(MPPT)

PMSG Vector Control

-Stator Voltage Oriented Control

-Grid Vector Oriented Vector Control

Control Schemes

- **Control of PMSG and DFIG**
- **Inner Control Loop with PI**
  - Current Control Loop
- **Outer Control Loop with PI**
  - DC Link Voltage Control Loop
  - Stator Voltage Control Loop
  - Active Power/MPPT Control Loop

Travelling Wave

- **Travelling Wave**
- When faults occur it develops into transients(voltages and currents) that move back and forth
- The transients move close to the speed of light
- Concept is based on the time it takes to travel from the point of discontinuity to the measuring point
- The velocity of the travelling wave is much based on the inductance and capacitance of the line
- Knowing the speed of the travelling wave and the time, the distance of the fault location can be calculated
- Success of the travelling wave is much based on the accurate detection or capturing the wavefront

Travelling Wave

- **Travelling Wave**

- Because the speed of a travelling wave is little quite less than the speed of light, it requires a high sampling rate
- Wave-front close to the end of the line are difficult to detect because of the high speed of the wave
- Components of travelling wave are high frequency and vulnerable to interference
- Faults that occur for zero voltage inception are difficult to detect

Travelling Wave

- Travelling Wave-Reference-B. K. Johnson, Stephen Marx, e'tal" Travelling Wave Fault Location in Protective Relays, Design Testing and Results, 16th Annual Georgia Tech Relay Conference, May 6-7, 2013

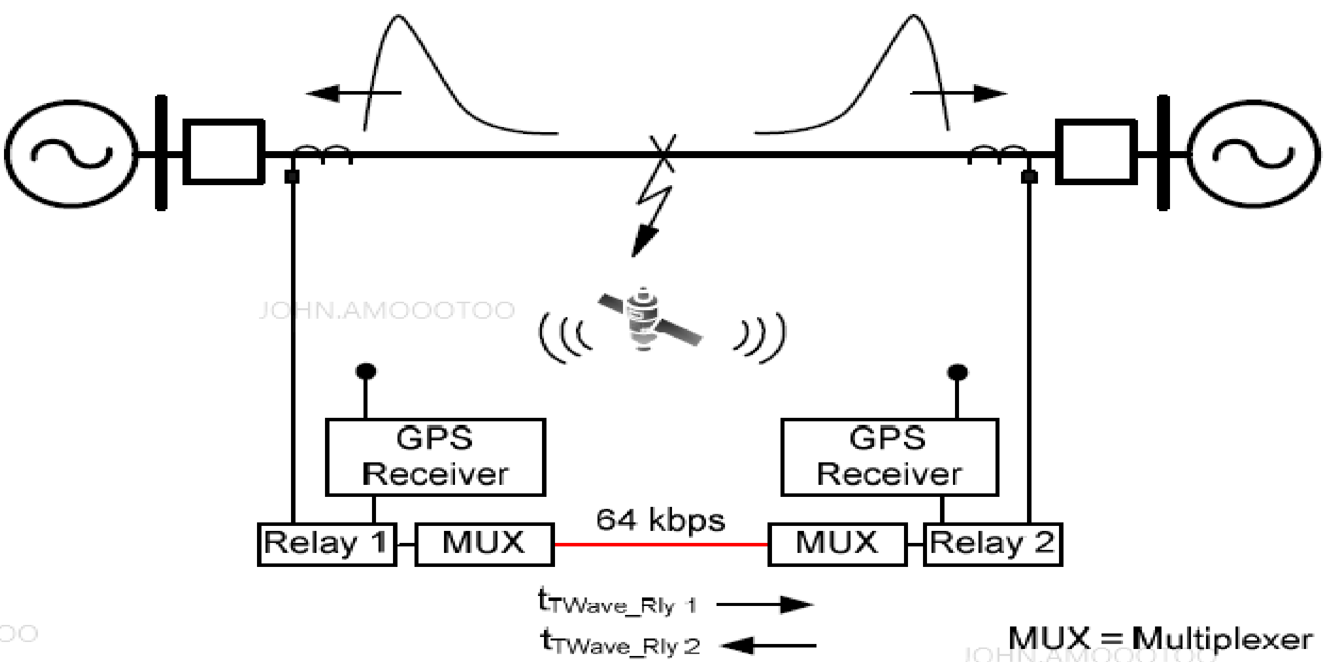
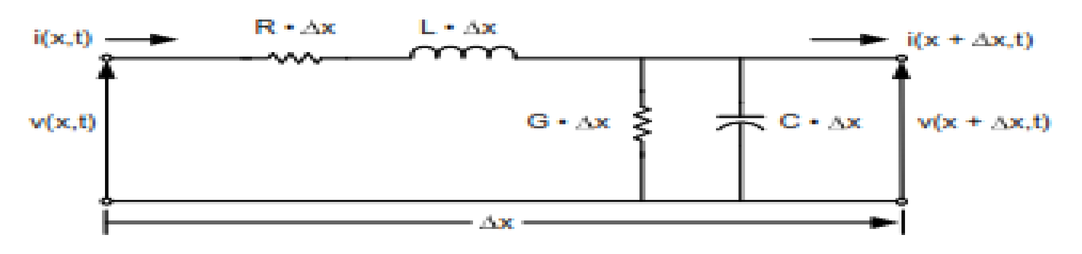


Fig. 4. Relays exchange the time of arrival of the TW to estimate the fault location in real time.

Travelling Wave Equations

- Travelling Wave



- Developing Kirchoff's voltage and current equation based on the current and voltage at **x** and **x+Delta x**

$$v(x,t) = R.\Delta x.\mathrm{i}(x,t) + \mathrm{L}\,\Delta x\frac{\partial i(x,t)}{\partial t} + v(\mathrm{x}+\Delta x,t) + \mathrm{i(x,t)} = \mathrm{G}\,\Delta x + v(x+\Delta x,t) + C\Delta x\frac{\partial v(x+\Delta x,t)}{\partial t} + i(\mathrm{x}+\Delta x,t)$$

Equations of voltage and current as a function of time

$$\frac{\partial v(x,t)}{\partial t} = -R.\mathrm{i}(x,t) - \mathrm{L}\frac{\partial i(x,t)}{\partial t}$$

$$\frac{\partial i(x,t)}{\partial t} = -G.\mathrm{i}(x,t) - C\frac{\partial v(x,t)}{\partial t}$$

Differentiating with respect to t

$$\frac{\partial^2 v(x,t)}{\partial x^2} = -R.\frac{\partial i(x,t)}{\partial x} - \mathrm{L}\frac{\partial^2 i(x,t)}{\partial x \partial t}$$

$$\frac{\partial^2 i(x,t)}{\partial x \partial t} = -G.\frac{\partial v(x,t)}{\partial x} - C\frac{\partial^2 v(x,t)}{\partial t^2}$$

Travelling Wave Equations

- Travelling Wave Equations
- Substituting the values of into equations

$$\frac{\partial i(x,t)}{\partial t} \qquad \frac{\partial^2 i(x,t)}{\partial x \partial t}$$

$$\frac{\partial^2 v(x,t)}{\partial x^2} = LC\frac{\partial^2 v(x,t)}{\partial t^2} + (\mathrm{RC}+\mathrm{GL})\frac{\partial v(x,t)}{\partial t} + GRv(x.t)$$

$$\frac{\partial^2 v(x,t)}{\partial x \partial t} = -R.\frac{\partial i(x,t)}{\partial x} - \mathrm{L}\frac{\partial^2 i(x,t)}{\partial^2 t}$$

$$\frac{\partial^2\, \mathrm{i}(x,t)}{\partial^2 x} = -G.\frac{\partial v(x,t)}{\partial t} - \mathrm{L}\frac{\partial^2\, \mathrm{v}(x,t)}{\partial x \partial t}$$

- Substituting to derive the current equation

$$\frac{\partial v(x,t)}{\partial t} \qquad \frac{\partial^2\, \mathrm{v}(x,t)}{\partial x \partial t}$$

$$\frac{\partial^2\, \mathrm{i}(x,t)}{\partial^2 x} = -G.\left(-R.\mathrm{i}(x,t) - \mathrm{L}\frac{\partial i(x,t)}{\partial t}\right) - \mathrm{L}\left(-R.\frac{\partial i(x,t)}{\partial x} - \mathrm{L}\frac{\partial^2 i(x,t)}{\partial^2 t}\right)$$

$$\frac{\partial^2\, \mathrm{i}(x,t)}{\partial x^2} = \mathrm{LC}\frac{\partial^2 i(x,t)}{\partial x^2} + (RC+GL)\frac{\partial i(x,t)}{\partial x} + GR.i(x,t)$$

Main Travelling Wave Equations

$$\frac{\partial^2 v(x,t)}{\partial x \partial t} = -R.\frac{\partial i(x,t)}{\partial x} - \mathrm{L}\frac{\partial^2 i(x,t)}{\partial^2 t}$$

$$\frac{\partial^2\ \mathrm{i}(x,t)}{\partial x^2} = \mathrm{LC}\frac{\partial^2 i(x,t)}{\partial x^2} + \left(RC + GL\right)\frac{\partial i(x,t)}{\partial x} + GR.i(x,t)$$

$$TWFL = \frac{LL + \left(TWA - TWB\right).\mathrm{c}.\mathrm{Prop\_Vel}}{2}$$

Fault Detection Types

- **Other Forms of Fault Detection Techniques**
  - Fourier Transformer
  - Short Time Fourier Transform
  - Artificial Neural Network
  - Fuzzy Logic
  - Hybrid Fault Detection
  - Impedance Fault Detection
  - Change in voltage-dv/dt and Change in Current-di/dt
  - Wavelet Transform
- **Examples of Wavelet Families**
  - Daubechies
  - Coiflet
  - Haar
  - Symlet
  - Mexican Hat
  - Morlet

DC Fault Detection, Location, classification

- **My focus will be on Discrete Wavelet Transform**

- It analyzes small wavelets in terms of dilation and translation
- Capability to analyze in time and frequency
- At high frequencies used narrow window and at low frequencies uses wider window
- Very good in the capturing and analysis of Power System Transients that have sharp discontinuities and abrupt signals
- Analysis starts with a mother wavelet
- They are computationally fast and have the capability to provide effective analysis during fault analysis
- The general form of the Discrete wavelet Transform is where j,k are integers id the d_0 dilation factor and is the translation factor τ_0

$$DWT = W_{j,k}(t) = \frac{1}{\sqrt{d_0{}^{j}}} W\left(\frac{t - k\tau_0 d_0{}^{j}}{d_0{}^{j}}\right)$$

$$w(t) = \sum_{K=-1}^{N-2} -1^{k} C_{k+1} W(2t+k)$$

Discrete Wavelet Transform

- **Discrete Wavelet Transform**

w is the scaling function of the mother wavelet and are the wavelet C_k coefficient

- ➢ The coefficient will consist of dominant patterns of high and low filter

Process of DWT

- ➢ Clark Modal Transformation to the voltage and current samples
- ➢ DWT is applied to the modal voltage and the squares of the wavelet transform coefficient to determine the peak of the energy
- ➢ Faulty Classification-Grounded, Phase
- ➢ Fault Location is based on the use of the lattice diagram of the aerial mode voltages using two ended synchronized measurements and GPS

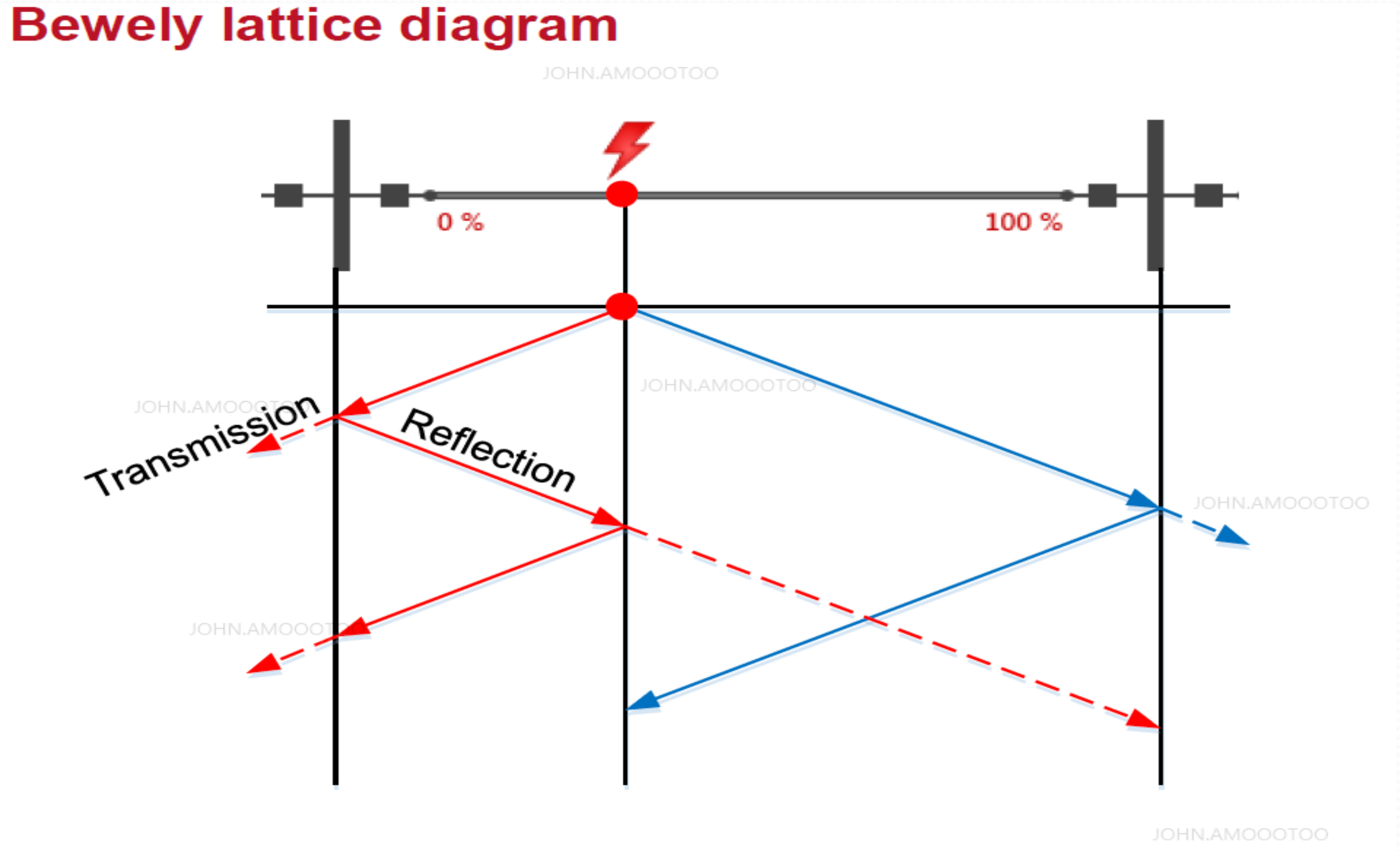
Clark's Transformation

- **Phase to Modal Transformation**

- This is much based on the electromagnetic coupling of the transmission line and cable
- Modal Transformation Matrix allows the decomposition of the matrix into several independent modes
- Three phase model can be decomposed into three single phase having its own characteristic impedance Z_c and time delay τ
- Each mode will have a distinct time delay and velocity

Travelling Wave Lattice Diagram

- TW-Reference-Meggar ”New Possibilities of Testing Travelling Wave Fault location functions in the field”



Questions

- Questions