Framtida utmaningar inom skydds- och styrsystem

How Extensive use of Power Cables influence Protective Relaying?

© 2023 Hitachi Energy. All rights reserved.
2023-04-18

Hitachi Energy

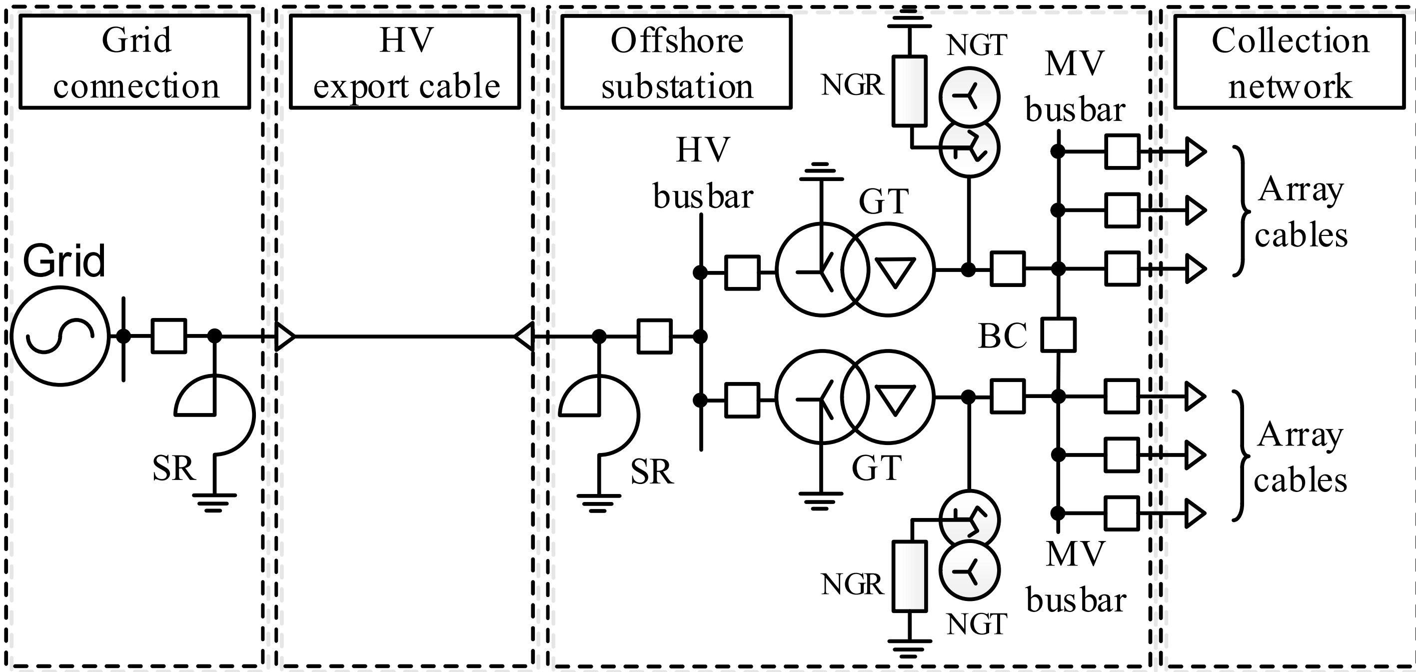
Short Introduction to Wind Farms

HITACHI
Inspire the Next

Offshore Wind Farm

Hitachi Energy

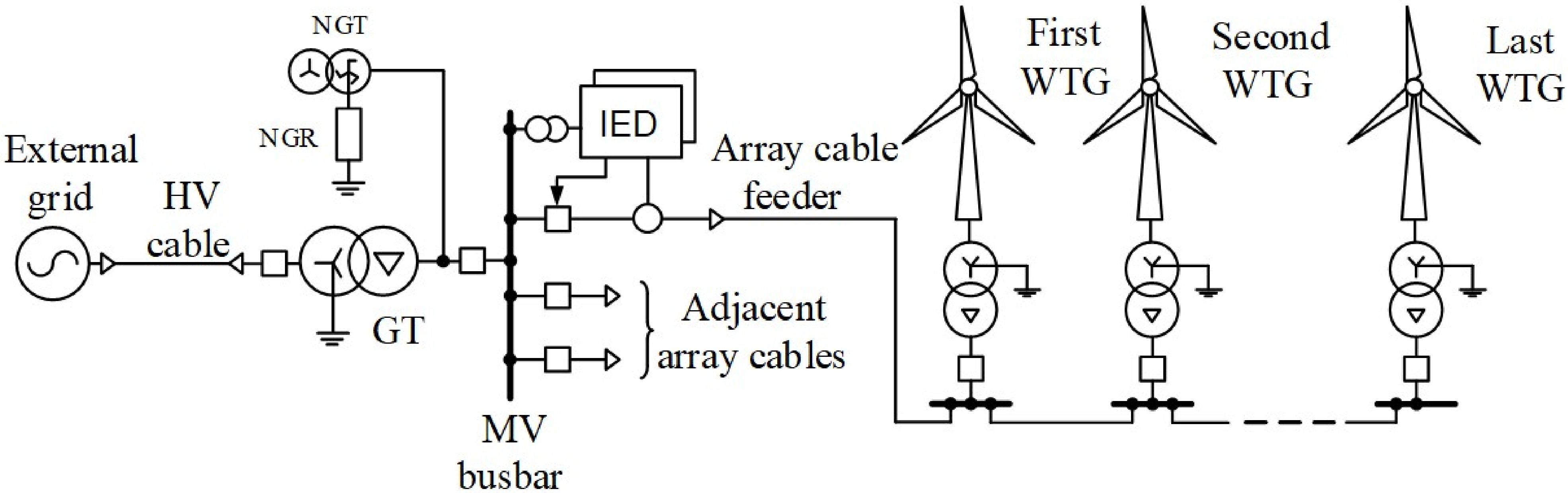
Wind Farm Power System Overview



Typical SLD of an Offshore Wind Farm

Wind Farm Power System Overview

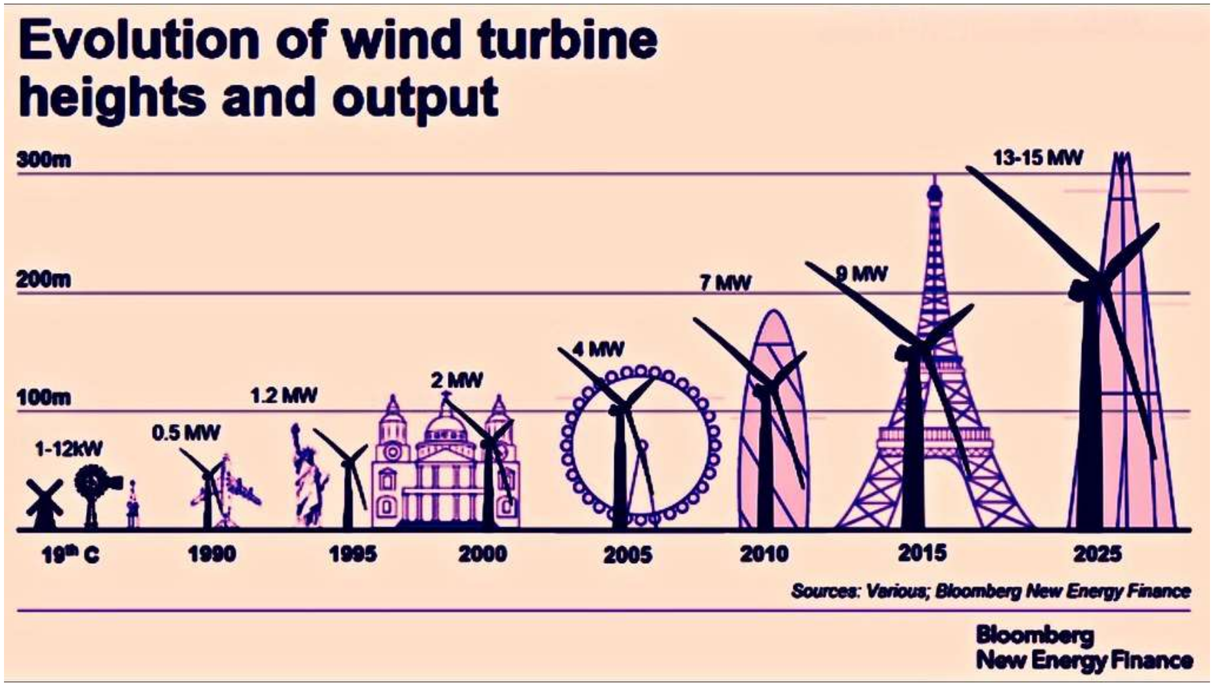
Typical SLD of a wind farm collector network



Public

Wind Turbine Generator (WTG) Development

HITACHI
Inspire the Next



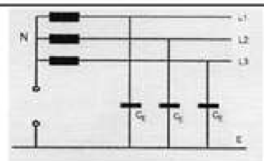
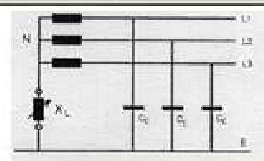
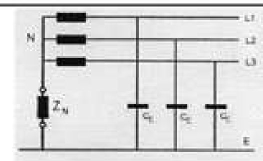
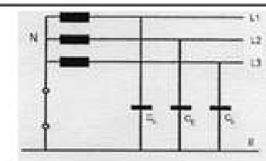
Downloaded from: https://www.flickr.com/photos/80454089@N00/37029096260

Hitachi Energy

Type of grounding used throughout the World

HITACHI
Inspire the Next

Different grounding principle

	isolated	compensated	low impedance	solid
				
EF Current	I_C	**Theoretically 0A**	I_{lim}	I_{SC}
Voltage factor	$k = \sqrt{3}$	$k = \sqrt{3}$	$k \sim 1\text{-}1{,}4$ / $\sqrt{3}$	$k \sim 1\text{-}1{,}4$
EF Property	self extinction possible $I_{fault} < 35A$	self extinction possible $I_{fault} < 65A$	steady arc	steady arc
Relay Action	Uninterrupted power supply	Uninterrupted power supply	immediate interruption	immediate interruption
Application	limited to small networks with $I_C < 35A$	up to an I_C of a few 100 A $I_{fault} < 65A$ / up to **132** kV	Grounding via earthing resistance or earthing reactor	transmission systems solidly grounded

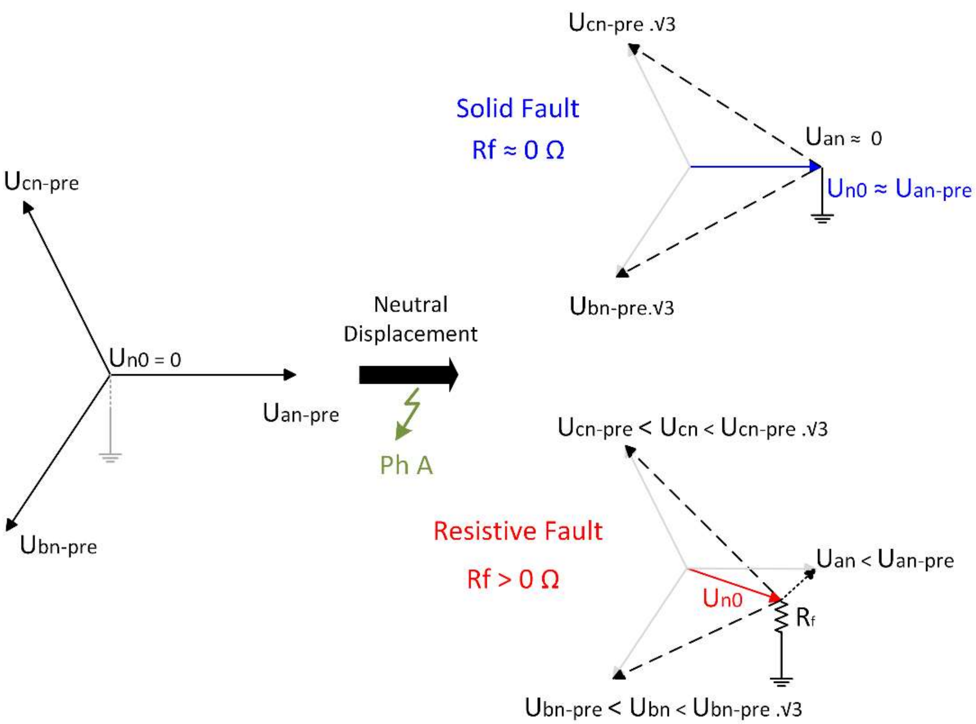
Impedance grounding typically used for WF MV System!

Hitachi Energy

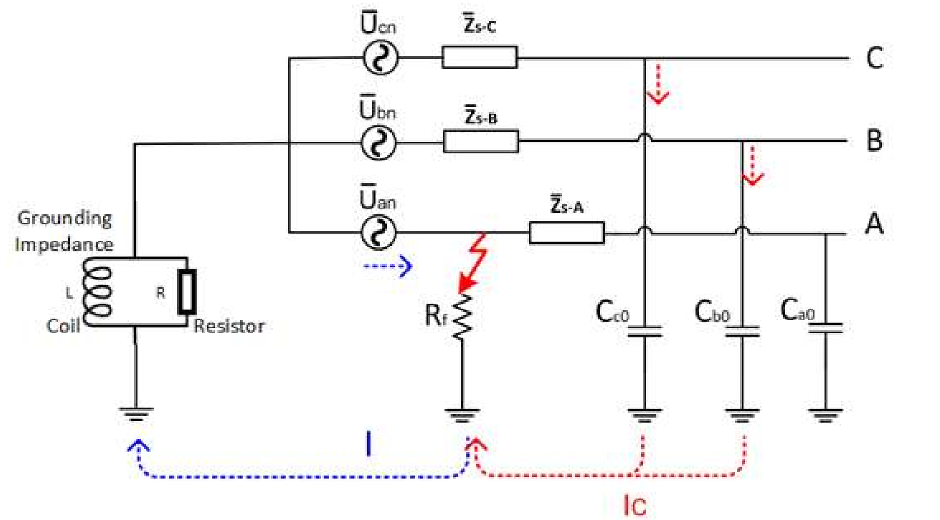
Impedance Grounded Power System, EF Current Distribution

HITACHI
Inspire the Next

What happens for voltages in the two healthy phases:



What happens with currents during an Earth Fault



EF current may become capacitive at the fault point.
Load current is typically ignored.

Hitachi Energy

Some Practical Data about Wind Farm Power System

HITACHI
Inspire the Next

Typical Data

- **For WF having 33kV MV system**:
  - Grid Transformer GT ~ 200MVA
  - NGR ~ 300A - 2000A
  - One WTG up to 8MW; up to 8 per feeder
  - Array Cable Feeder length up to 20km
  - ***3Io_Cap ~ 100A per array feeder***
- **For WF having 66kV MV System:**
  - Grid Transformer GT ~ 300MVA
  - NGR ~ 1000A - 4000A
  - One WTG up to 15MW … ; up to 10 per feeder
  - Array Cable Feeder length up to 40km
  - ***3Io_Cap ~ 400A per array feeder***

- ***In the future 132kV will probably be used on the "MV side"***

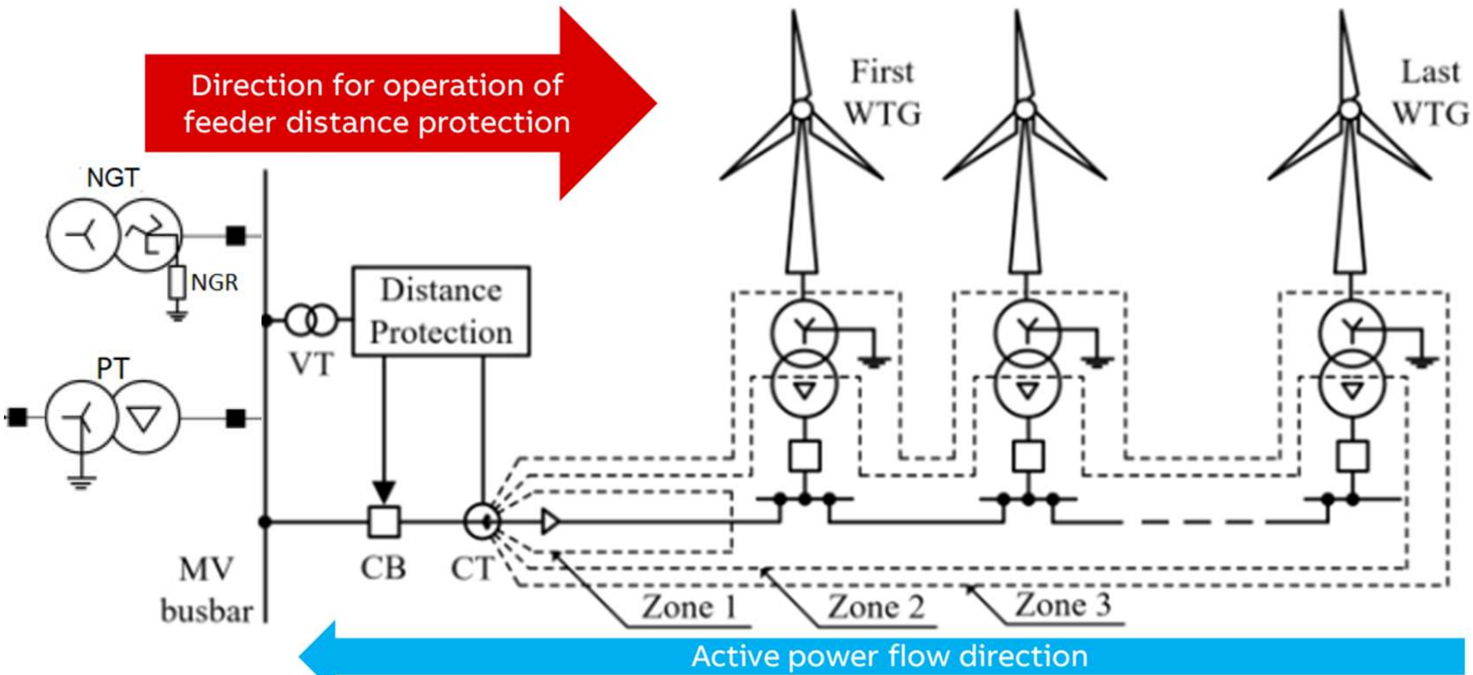
Hitachi Energy

Protection challenges and solution for

MV Array Feeder Distance Protection

Array Cable Feeder in an Offshore Wind Farm

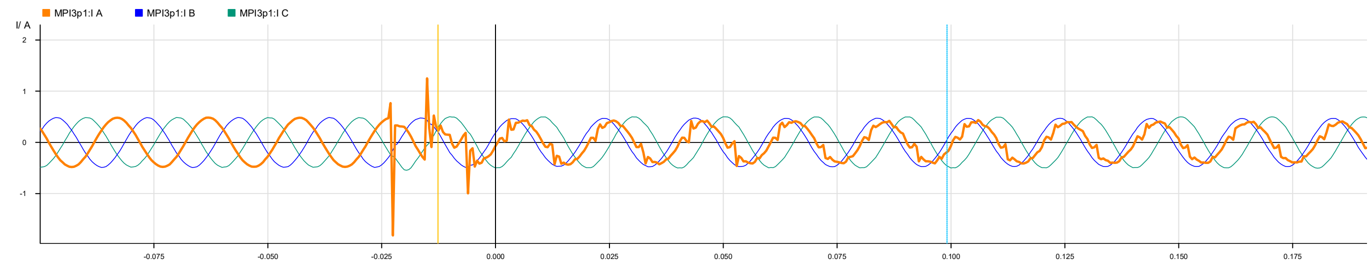
Depending on MV voltage level one Array Cable Feeder can be up to 40km Long !!!



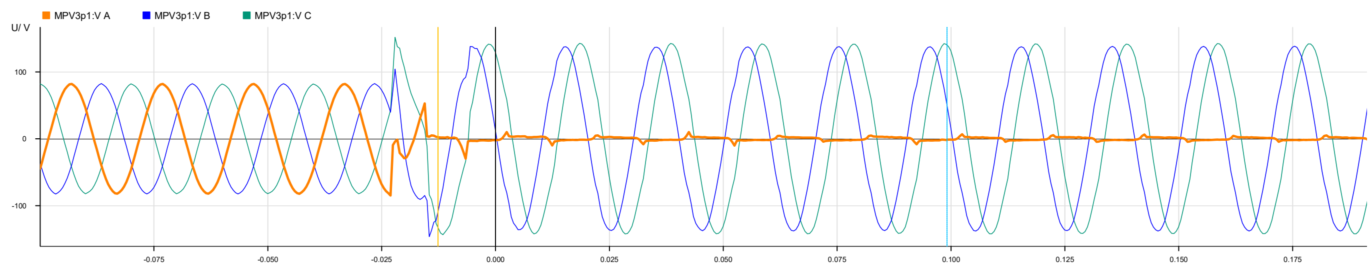
MV Voltage Level: 33kV or even 66kV

DR from WF having 33kV MV Bus and 600A NGR

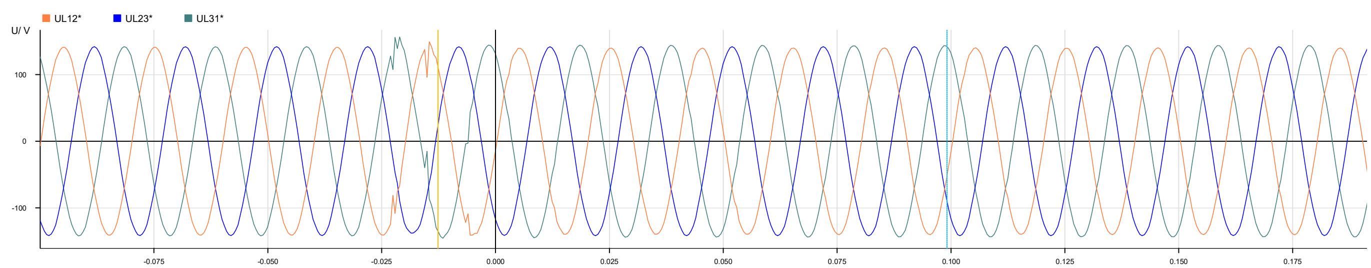
Secondary Current Waveforms
Faulty Feeder 1A CT
for the A-Gnd Fault



Secondary VT
Ph-Gnd Voltage Waveforms
for the A-Gnd Fault



Secondary VT
Ph-Ph Voltage Waveforms
for the A-Gnd Fault



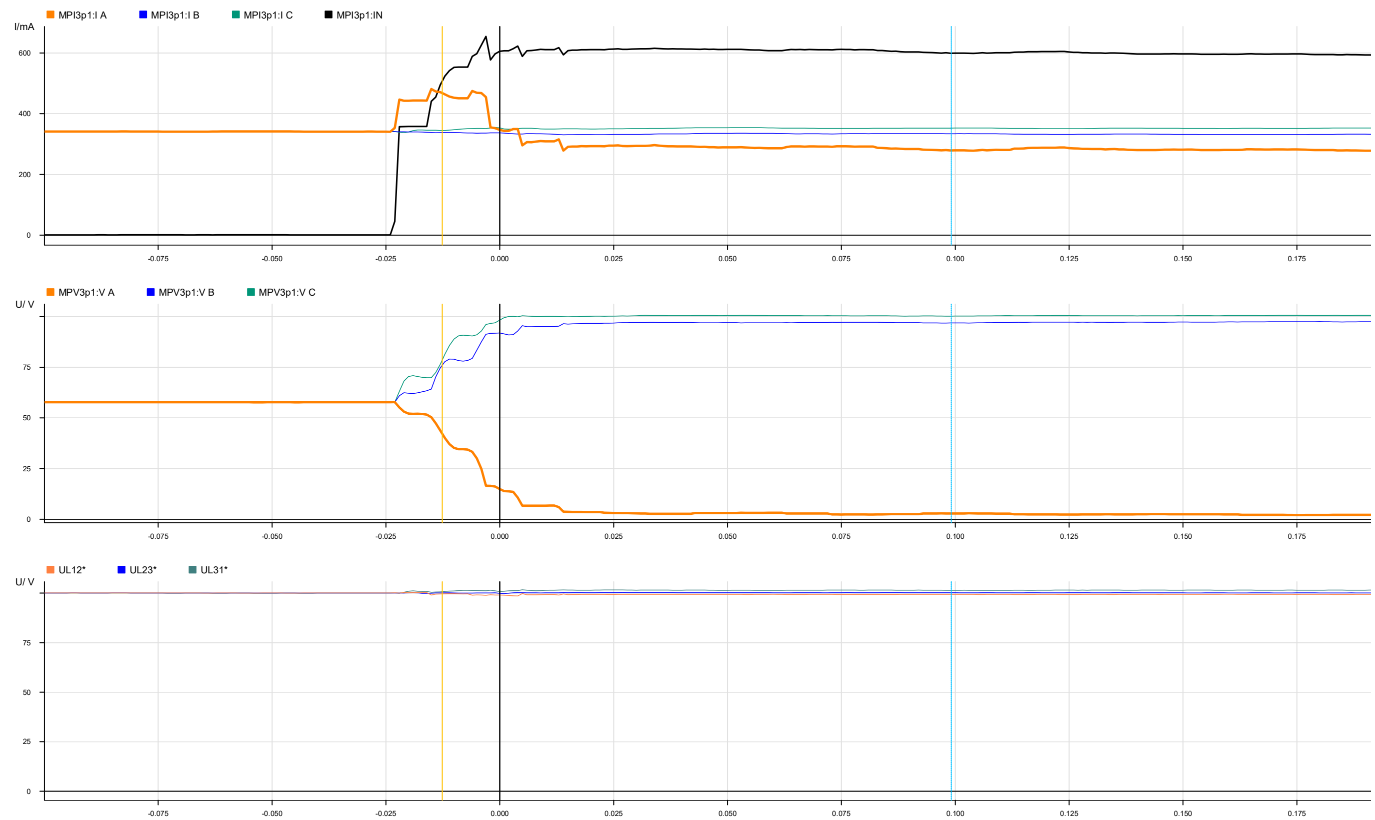
DR from WF having 33kV MV Bus and 600A NGR

Hitachi Inspire the Next

Secondary Current Magnitudes Feeder 1A CT for the A-Gnd Fault

Secondary VT Ph-Gnd Voltage Magnitudes for the A-Gnd Fault

Secondary VT Ph-Ph Voltage Magnitudes for the A-Gnd Fault



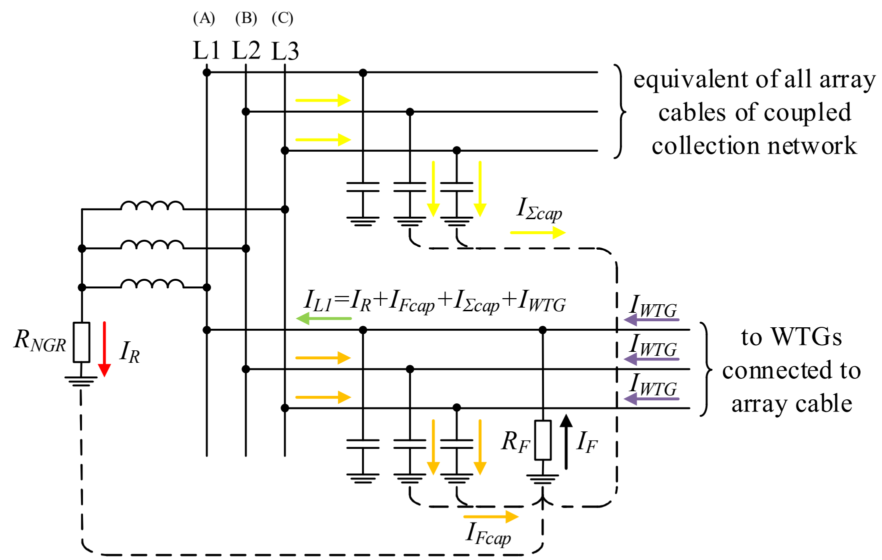
Hitachi Energy

Collection Network Exposed to a SLG Fault in Phase L1

Which fault current components will flow?

What will be the resultant fault current in Phase L1?
The following components will be present:

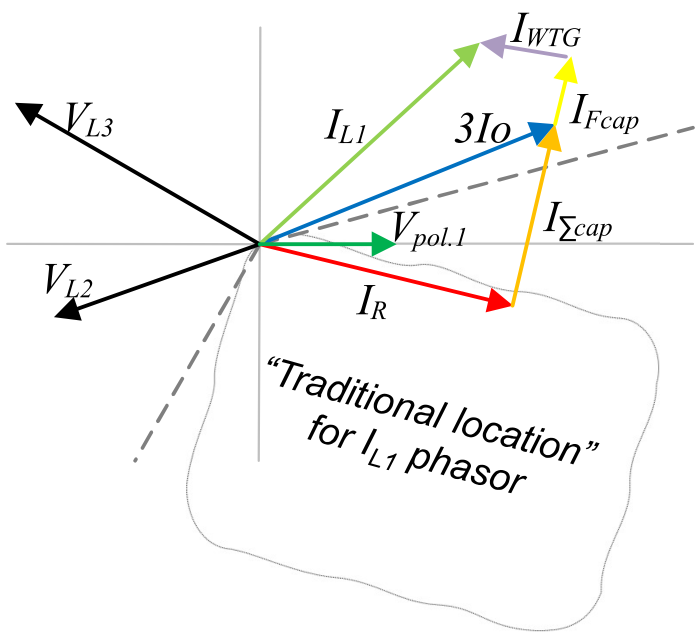
- ➢Load current before the fault (I_{WTG})
- ➢Fault current through the NGT+NGR (I_R)
- ➢Capacitive GF currents of all adjacent Feeders ($I_{\sum cap}$)
- ➢Capacitive GF current of the faulty Feeder (I_{Fcap})



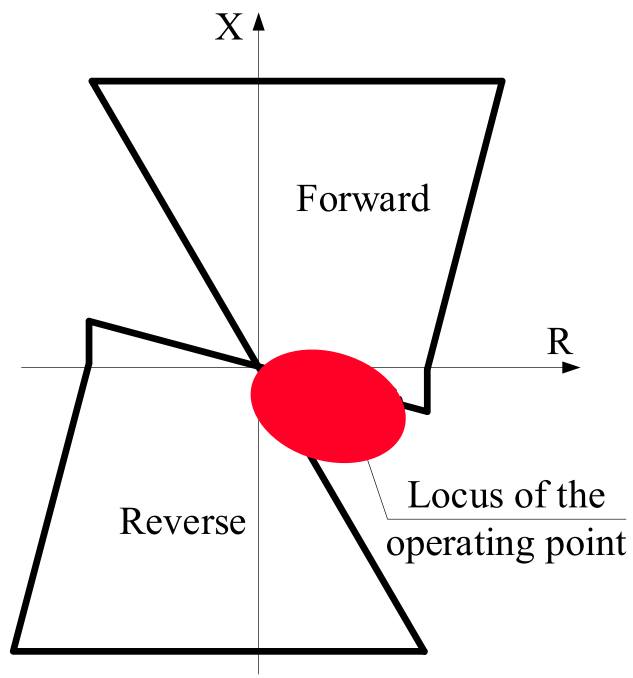
Distance Protection: Problem Description for EFs

HITACHI
Inspire the Next

Phasor diagram seen by the distance protection for a forward Phase A to ground fault



Potential locus of the Z operating point is in the 4th quadrant now! What to do?

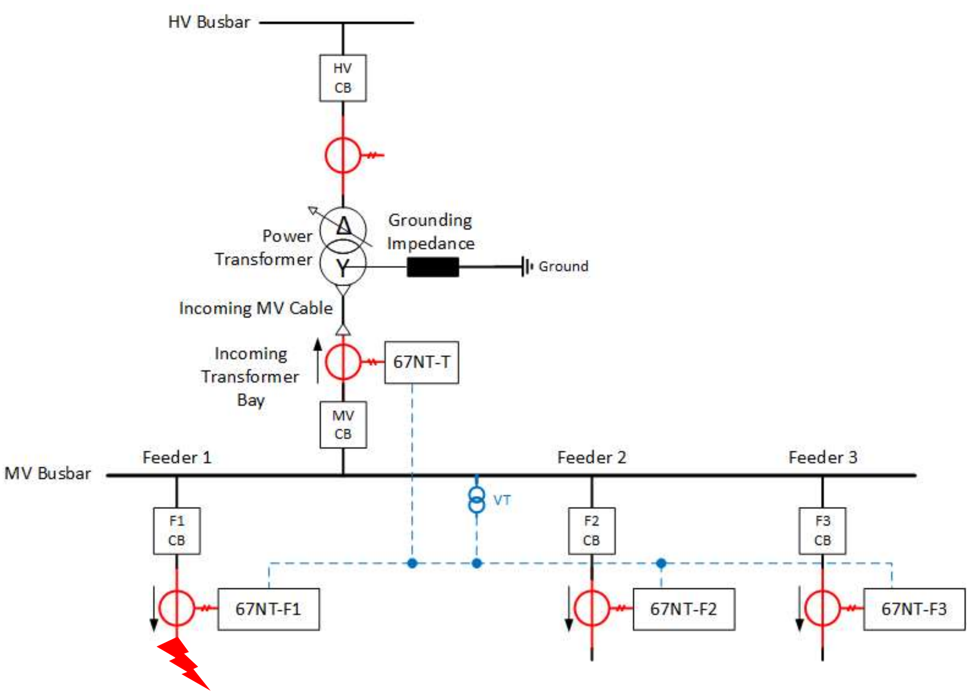


Hitachi Energy

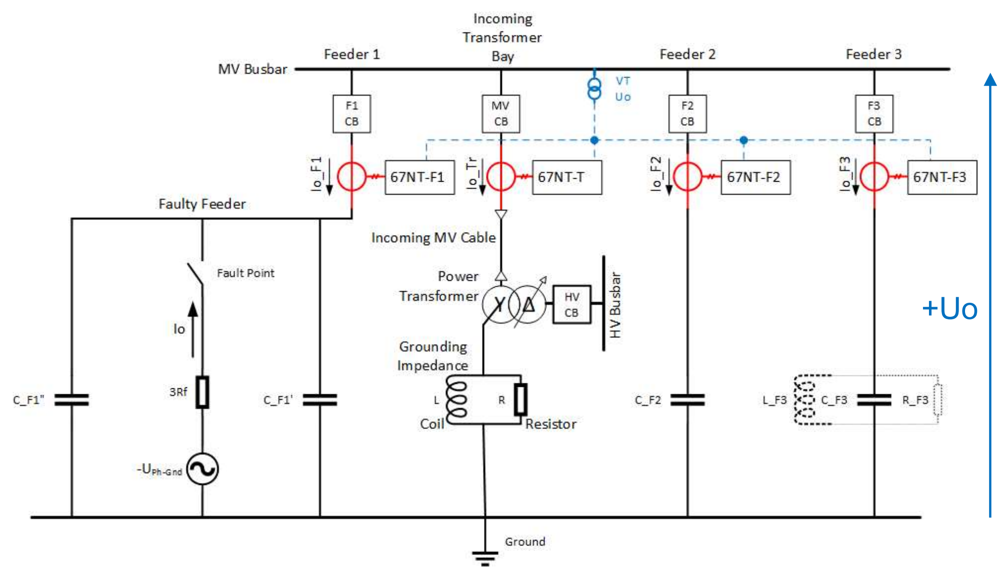
Complete Equivalent Circuits for the Zero-Sequence System

HITACHI
Inspire the Next

Example Substation



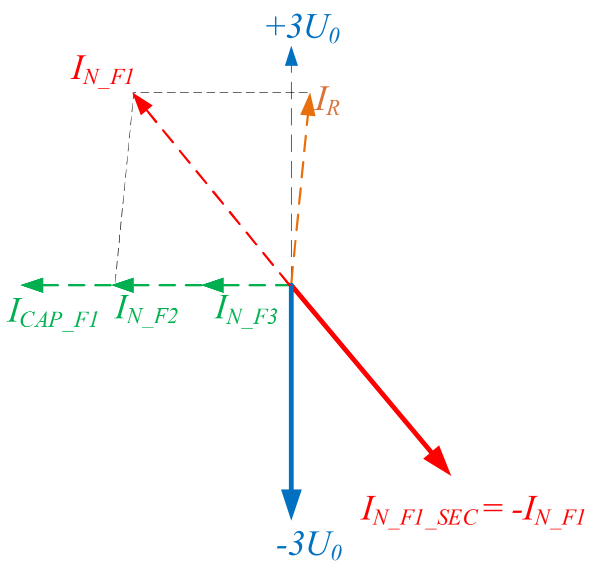
Equivalent Circuit for an GF in Feeder 1



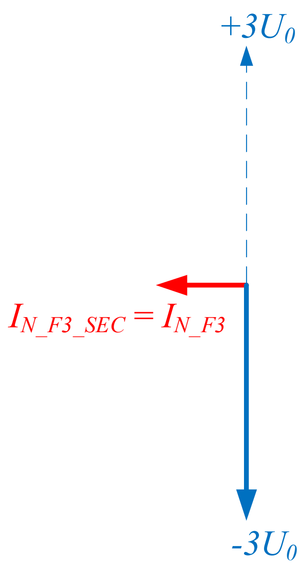
Hitachi Energy

Directional EF Protection in Offshore Wind Farms having NGR

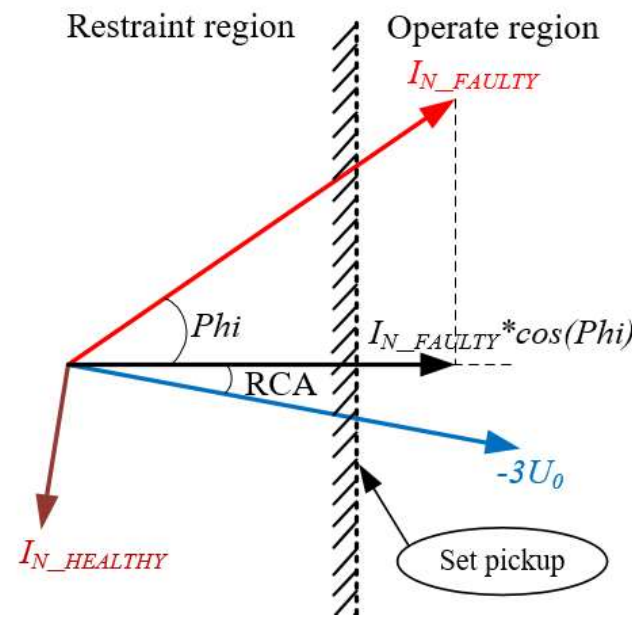
Phasor diagram
for the faulty array cable 1



Phasor diagram
for the healthy array cable 3



Directional characteristic of 67N protection

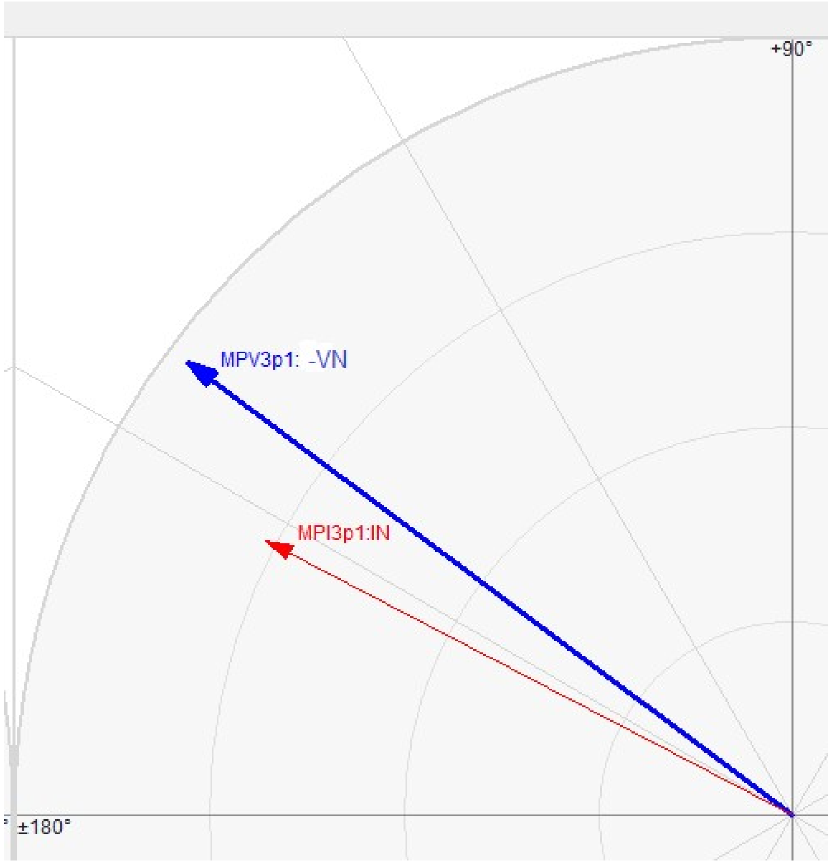


How IN and –VN phasors Looked Like in a Recorded Field Case?

Phasor Diagram

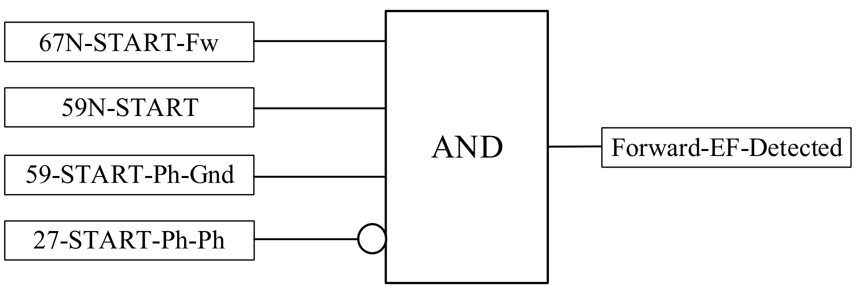
Very good match with the presented "theory" in the previous slides for the field DR for the Faulty Feeder

- Note:
- IN = 3Io
- -VN = -3Uo

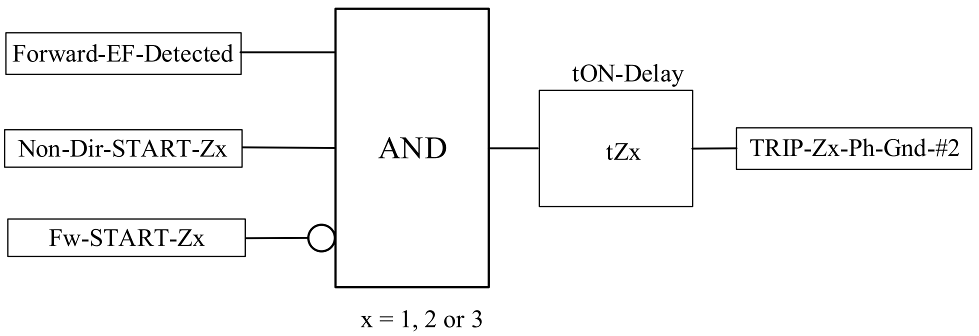


Optimized Ground Distance Protection Logic

Logic to detect a forward ground fault

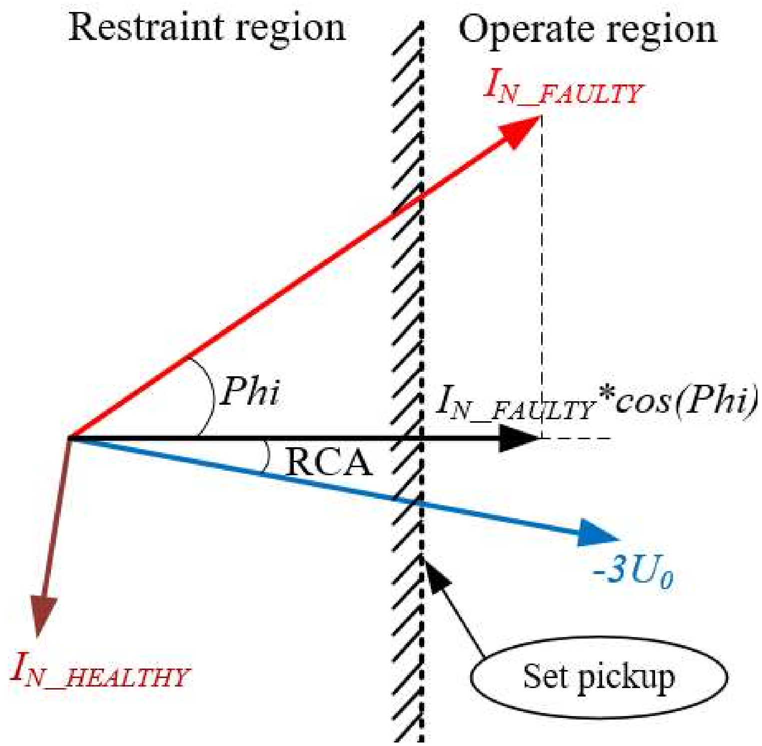


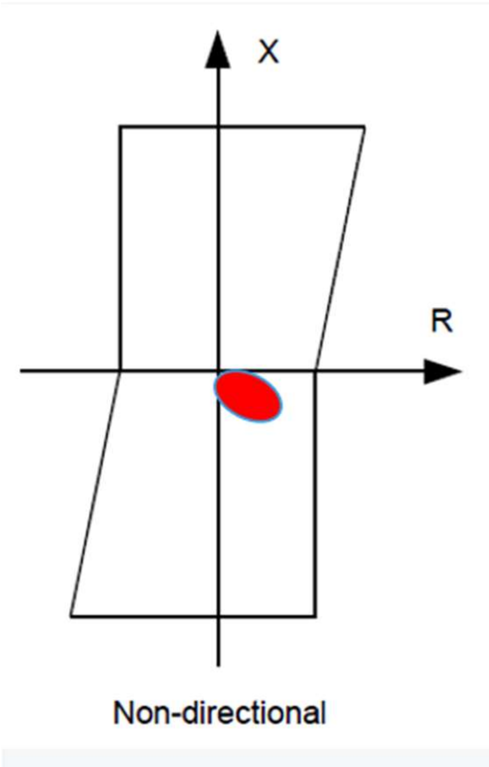
Additional directional supervision logic for each forward distance protection zone



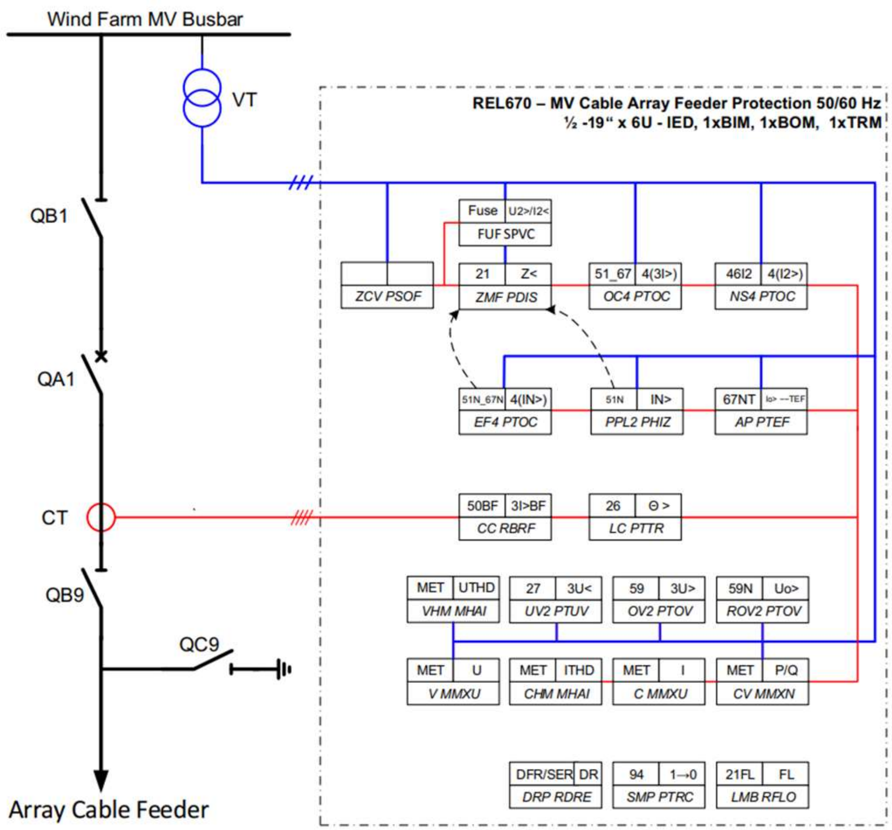
Use non-directional Zone and EF Directionality to trip

This combination works for WF MV systems having NGR





Possible Solution



REL670 block diagram for Wind Farm Array Cable Feeder Protection

Protection challenges and solution for

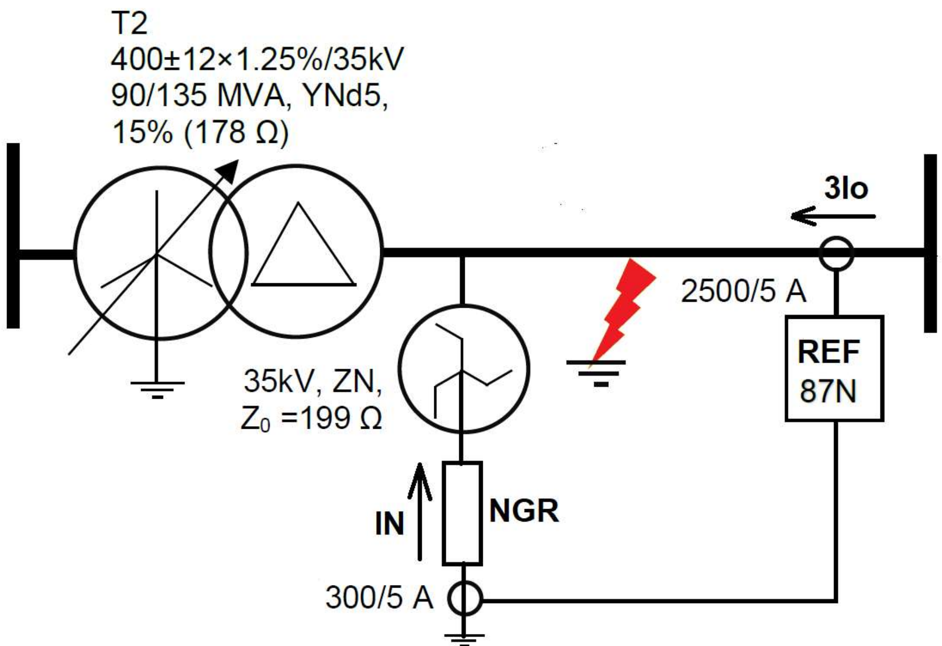
REF protection on GT MV winding

What is the Possible Problem?

Single Resistor used for Grounding

1) Many MV networks around the world have limited earth-fault current by a resistor located in the infeed transformer MV winding neutral point.
2) Simplified single-line diagram of such network for the MV side low-impedance restricted earth-fault protection function (i.e. REF) are shown in the Figure
3) IN is the neutral current
4) 3Io is residual current at the W2 busbar side
5) What can happen in case when power cables are extensively used in network connected to W2 (e.g. in a WF application)?

Example of power system circuit for WF GT MV winding



Low Impedance REF Directional Operating Characteristics used for W2

Low Impedance REF

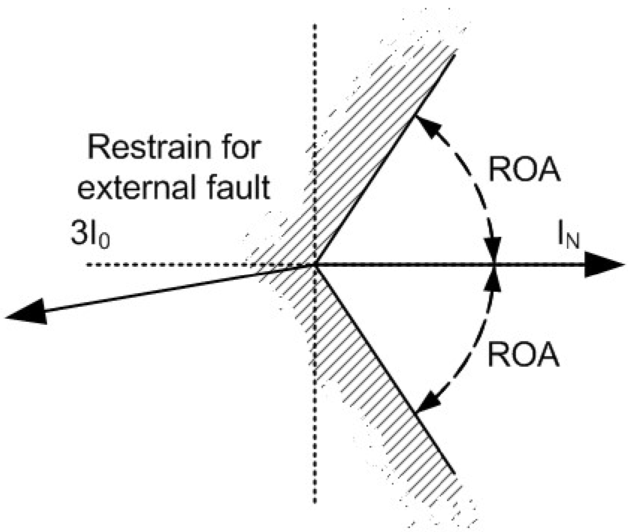
1) The directional check is executed if:
   a) $3I_0$ (terminal side) is bigger than 3%

2) The trip condition is fulfilled if:
   a) both $3I_0$ an I_N are within the operating region

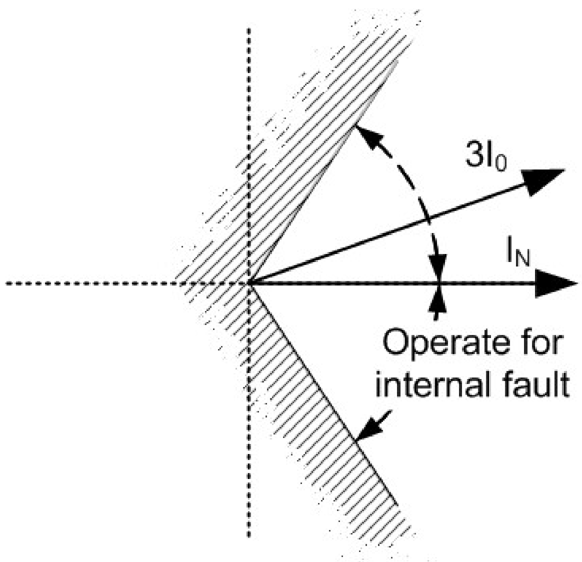
3) If the check is not executed (small 3Io currents) then:
   a) this check is not a condition for trip

4) Default ROA value is set to 60°

Expected for External Fault

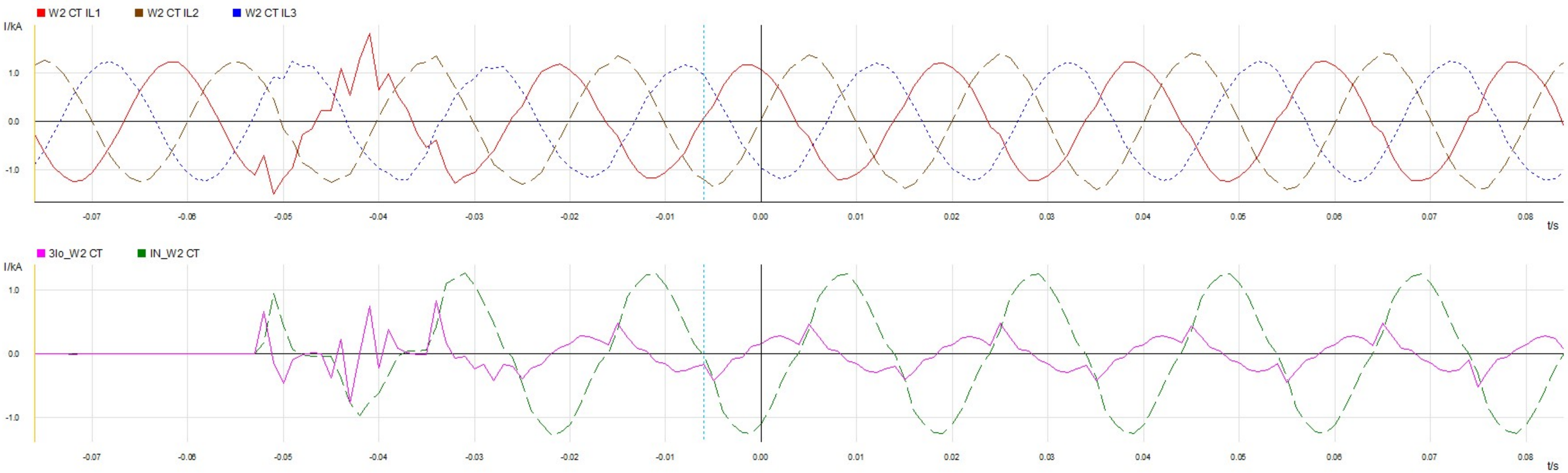


Expected for Internal Fault



Field Example No 1: Current waveforms during Internal Ground Fault

W2 side is a 33kV winding grounded via a 1000A resistor. W2 CTR=2500/1; NP CTR=1600/1



Public

Hitachi Energy

Field Example No 1: Phasor Diagram

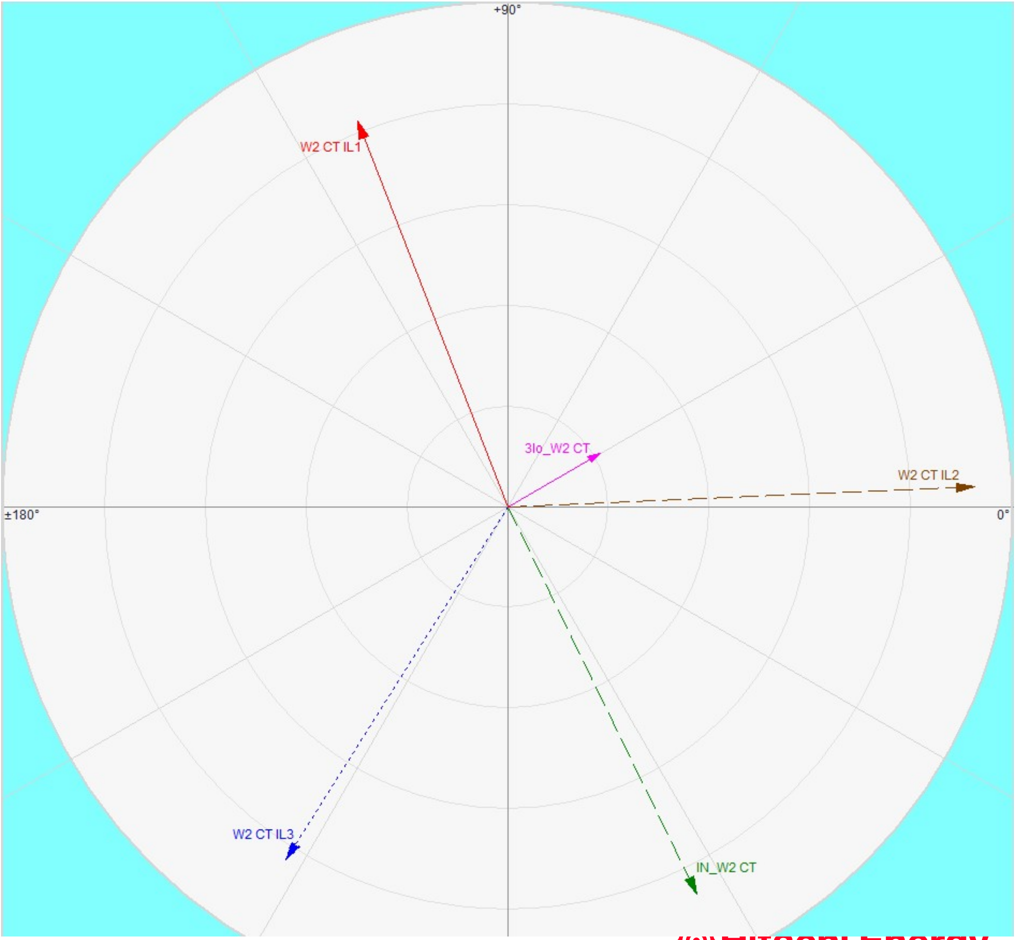
Why angle between 3Io_W2 and IN_W2 is approximately 90˚?

REF protection did not operate for this internal ground fault.

Fault was cleared by the 87T function when it developed into Ph-Ph fault.

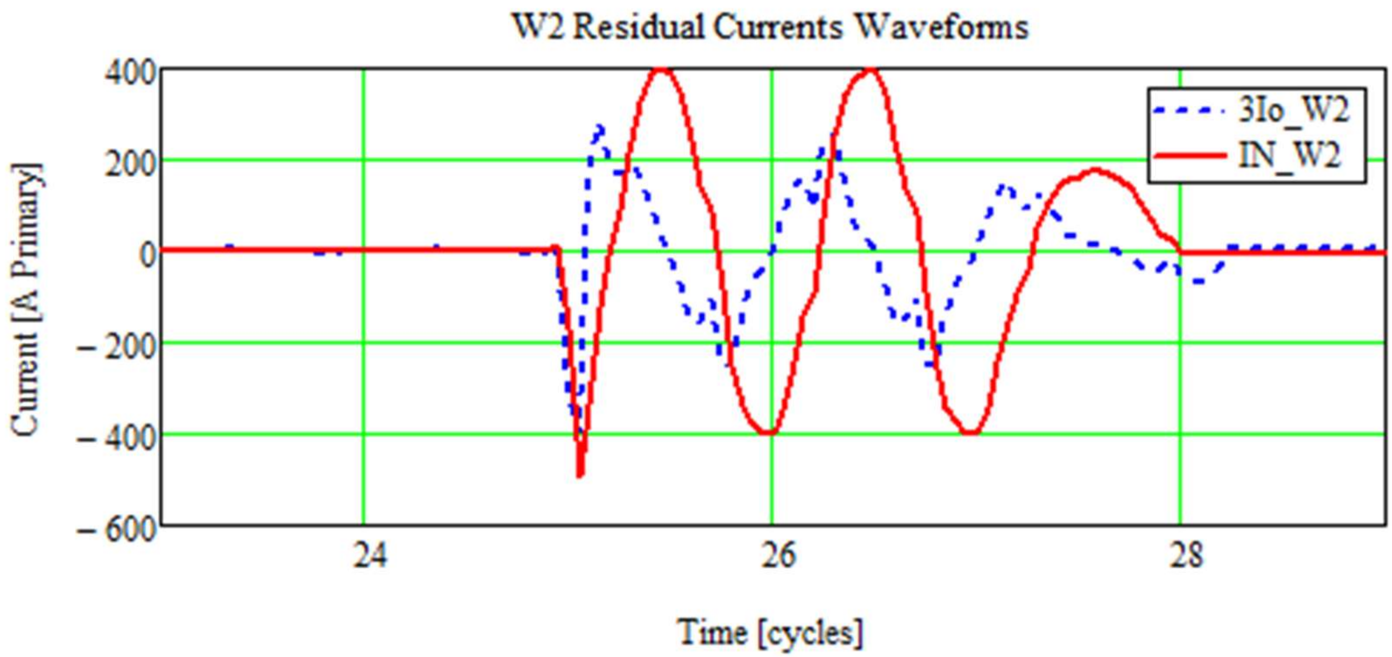
Total fault clearance time was around 300ms.

3Io current was leading the IN current for approximately 90°.



Field Example No 2: Residual current waveforms during internal GF

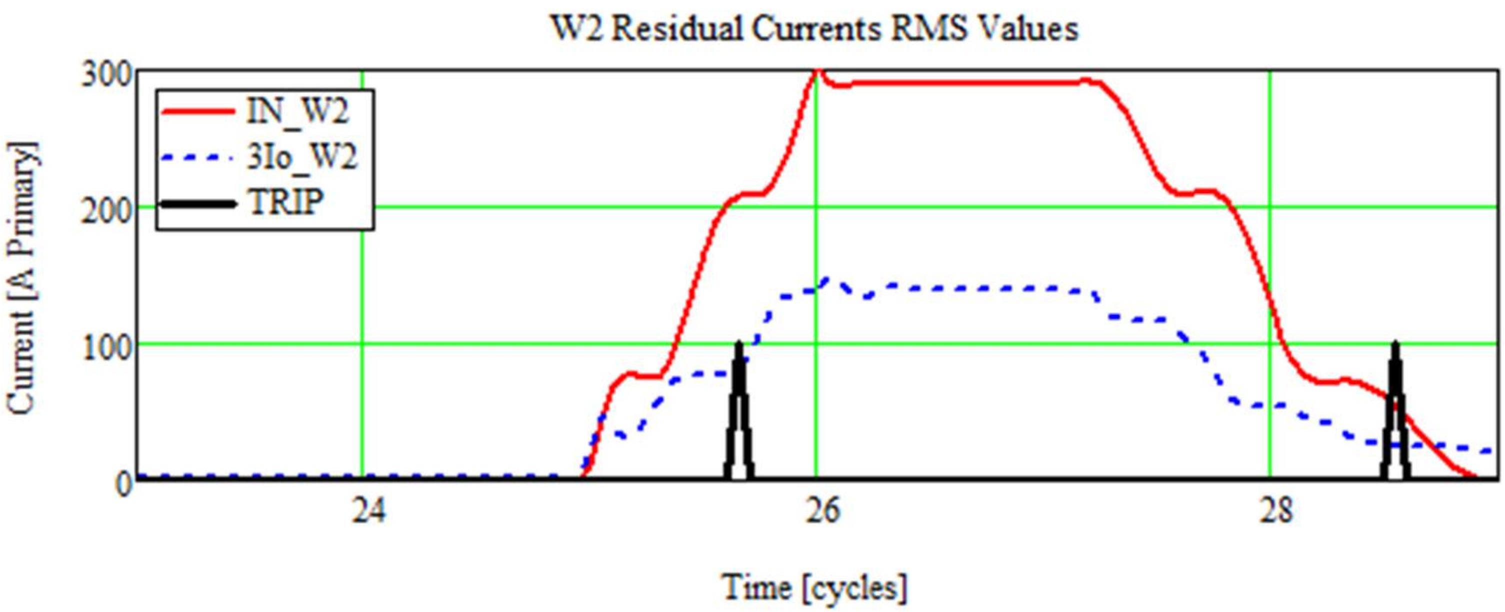
W2 side is a 35kV winding grounded via a 300A resistor. W2 CTR=800/1; NP CTR=800/1



90 degrees phase shift is visible again! Why?

Field Example No 2: Residual Current Magnitudes during internal GF

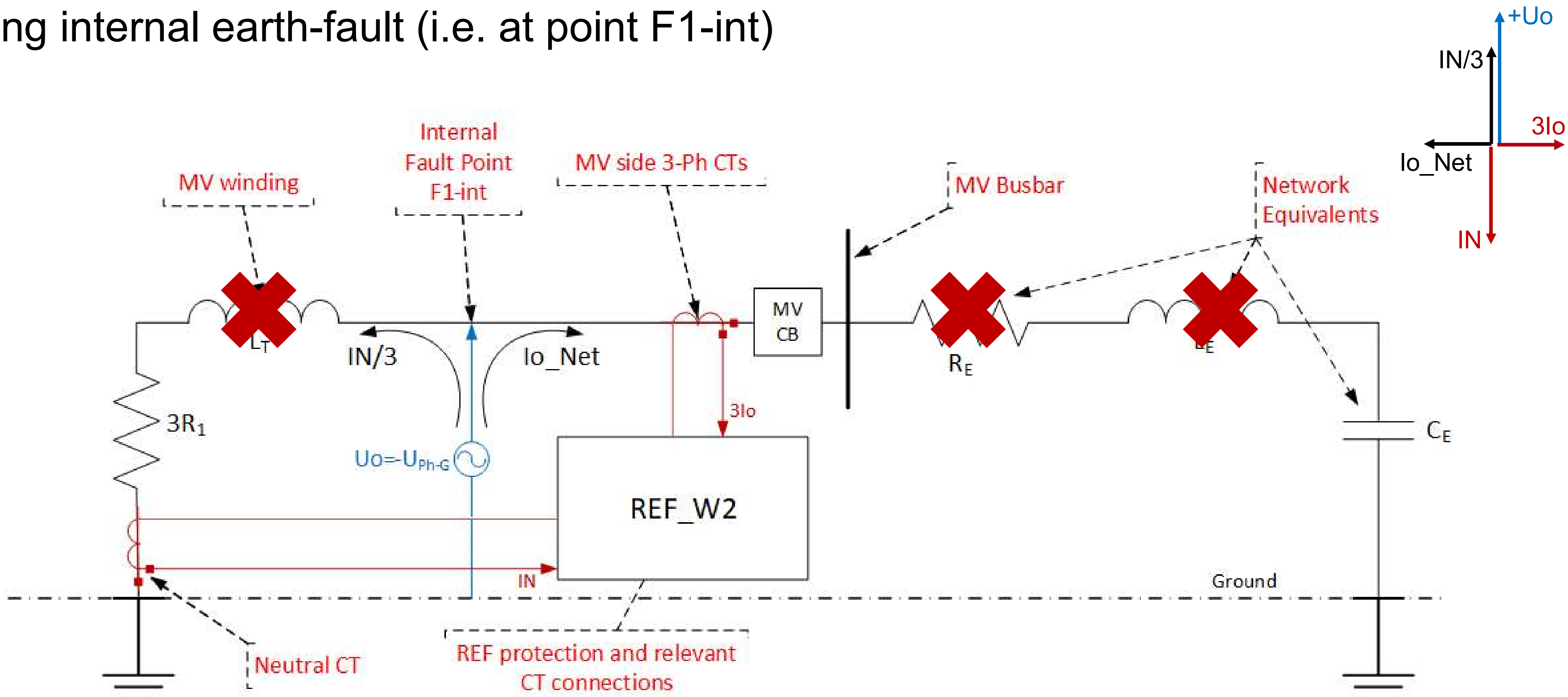
W2 side is a 35kV winding grounded via a 300A resistor. W2 CTR=800/1; NP CTR=800/1



REF protection did operate for this internal ground fault, but the TRIP pulses were extremely short. Why?

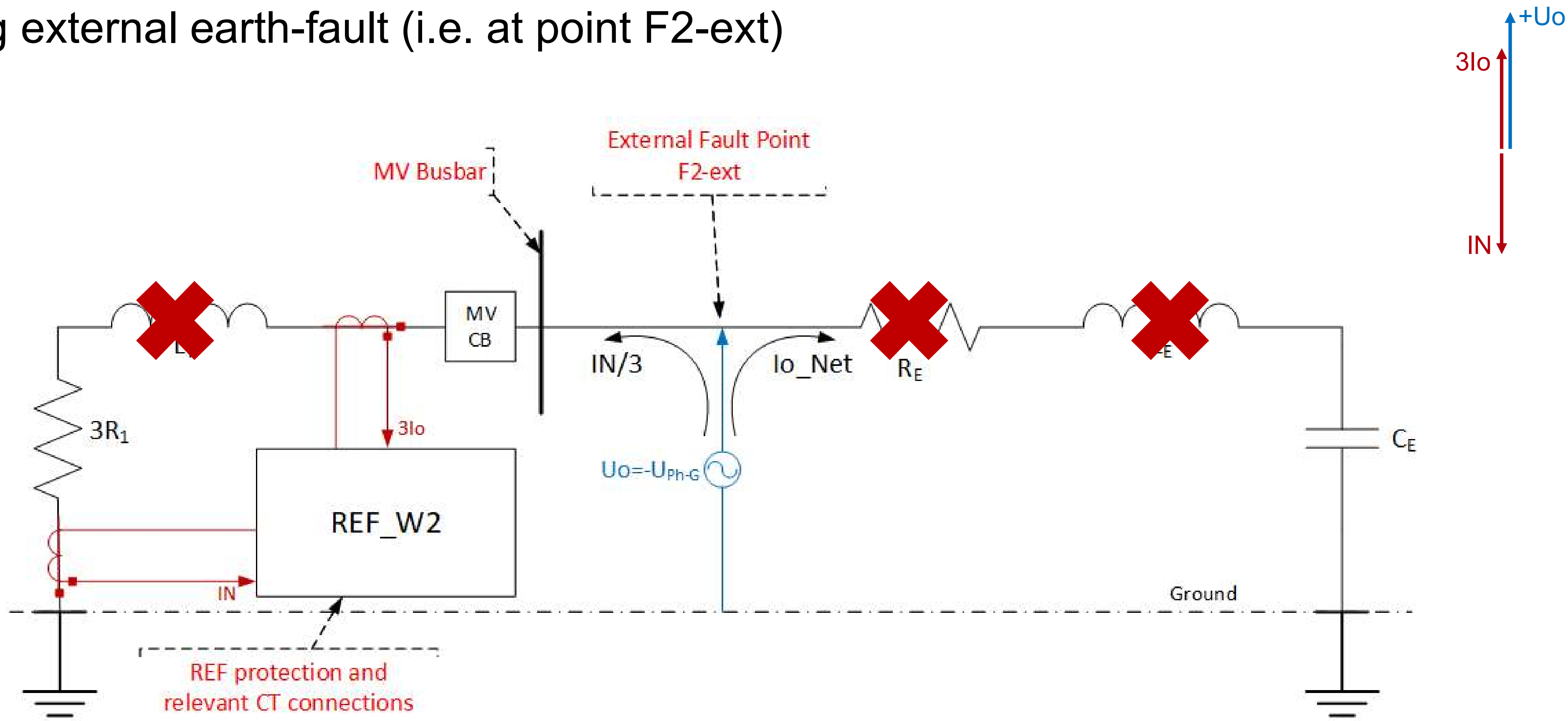
Simplified equivalent circuit for the zero-sequence system

During internal earth-fault (i.e. at point F1-int)



Simplified equivalent circuit for the zero-sequence system

During external earth-fault (i.e. at point F2-ext)



Low Impedance REF Revised Directional Operating Characteristic

Low Impedance REF

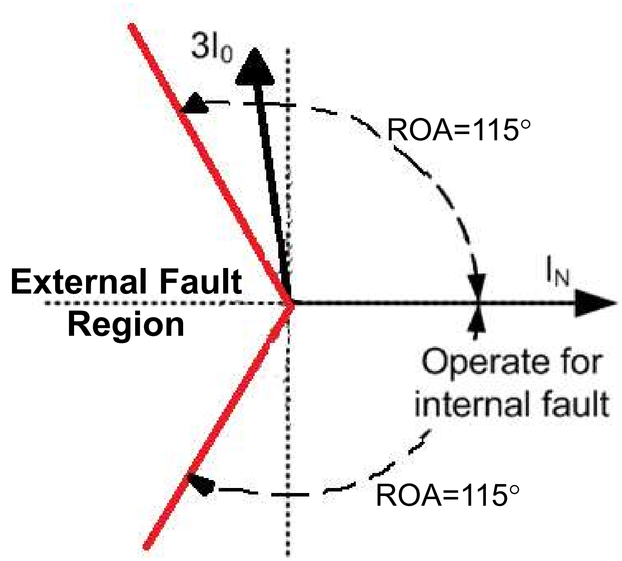
1) The directional check is executed if:
   a) $3I_0$ (terminal side) is bigger than 3%

2) The trip condition is fulfilled if:
   a) both $3I_0$ an I_N are within the operating region

3) If the check is not executed (small 3Io currents) then:
   a) this check is not a condition for trip

4) Change ROA value to 115°

Revised Directional REF Characteristic

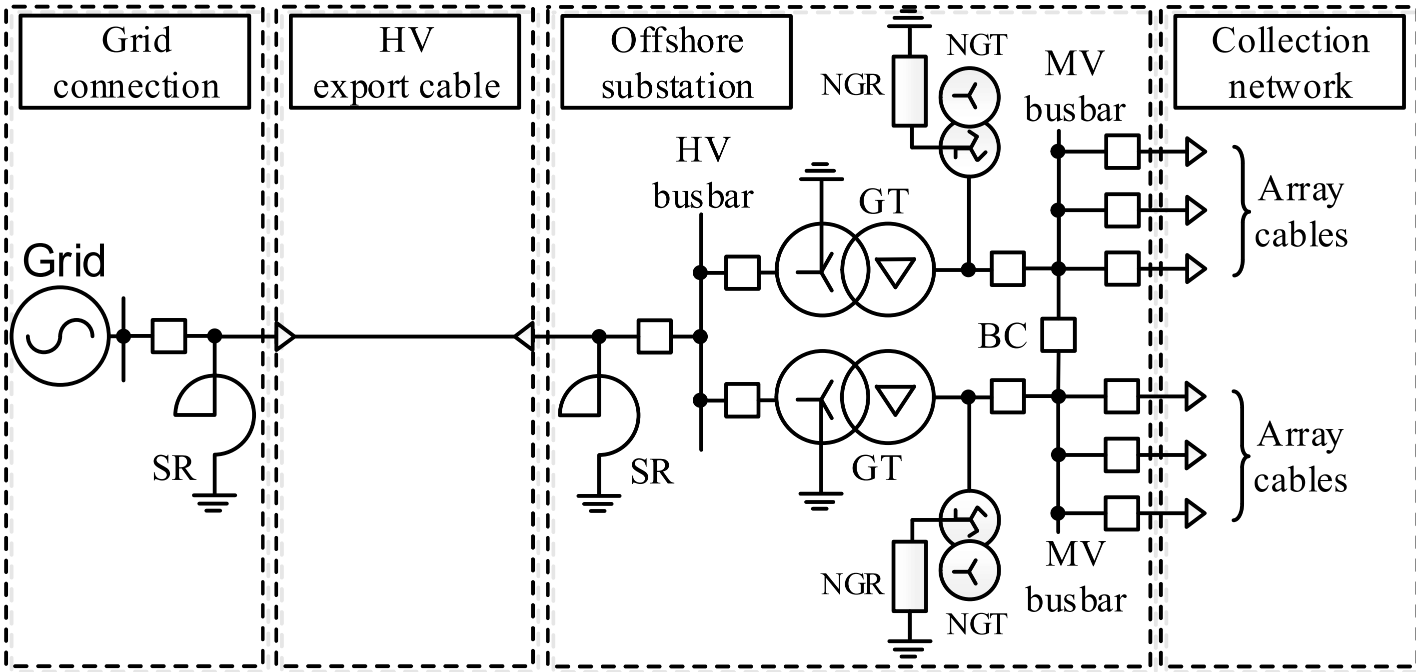


Protection & Control Challenges for

HV Export Cable Application

Wind Farm Power System Overview

HITACHI
Inspire the Next

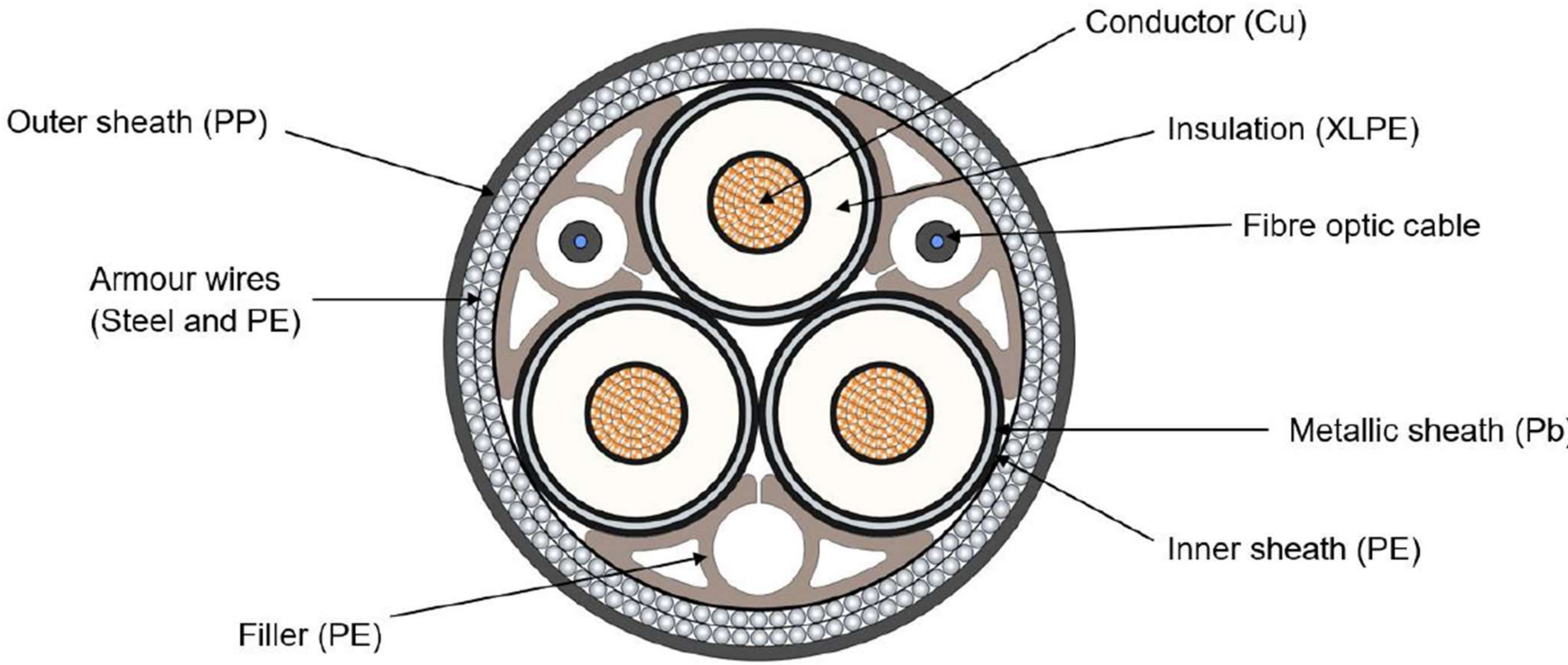


Typical SLD of an Offshore Wind Farm

Hitachi Energy

How Export Cable Looks Like?

Cross section example of an HV three-core submarine cable (up to 275kV)



Offshore Wind Farm Installation, Export Cable Example

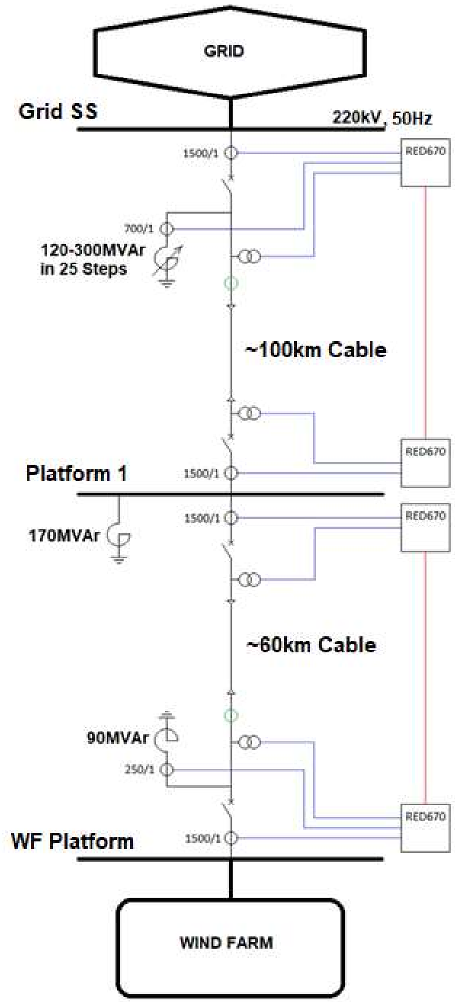
Modern power system becoms more and more complex.

Solidly Grounded 220kV System but charging current of the 100km cable is almost 900A.

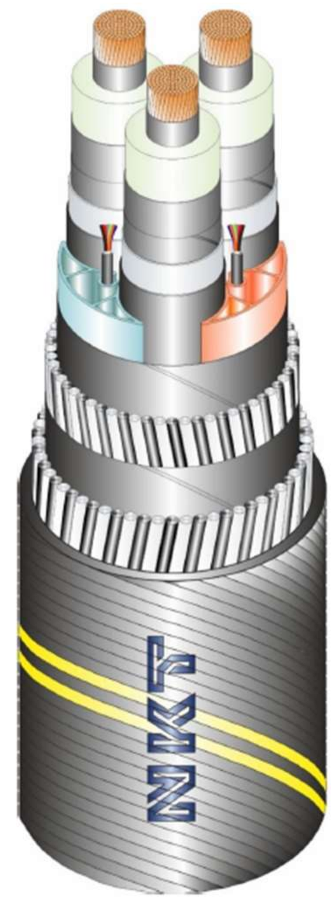
Large & Variable Shunt Reactor permanently connected to the cable.

Presence of large L-C parallel circuit may cause problems for traditional protection principles.

How to set PoW switching equipment?



Active Power Flow Direction



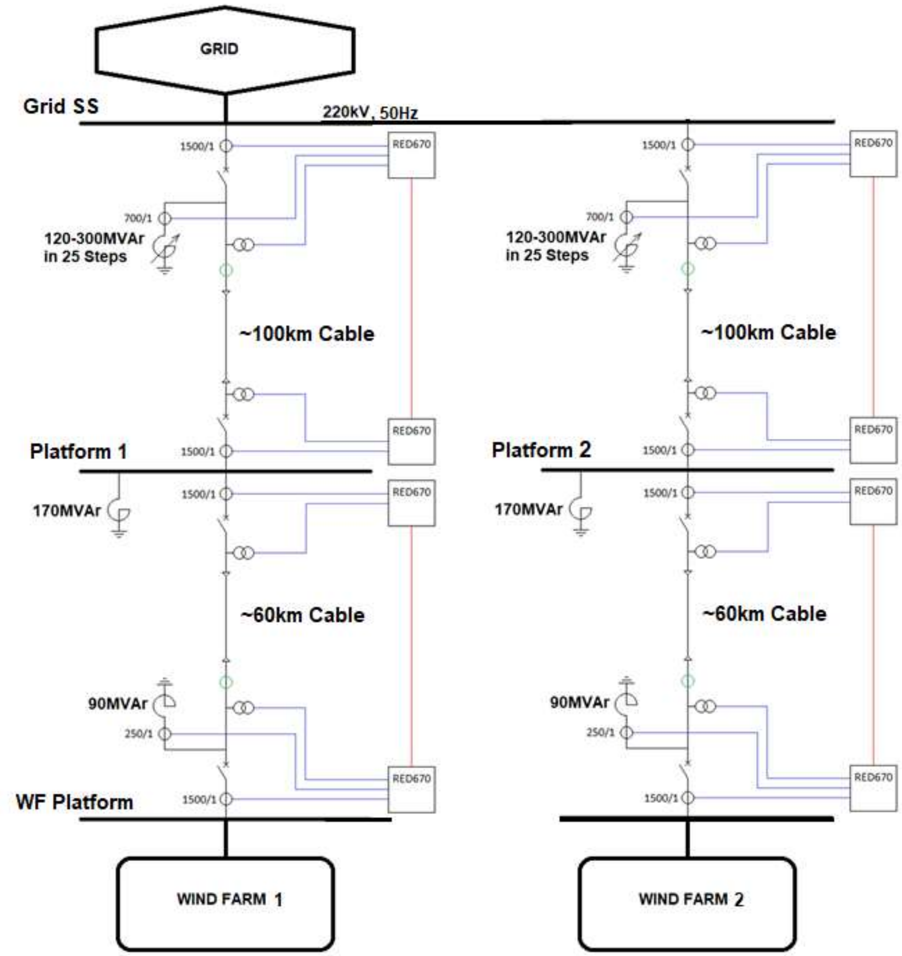
Public

Offshore Wind Farm Installation, Export Cable Example

HITACHI
Inspire the Next

Modern power system becoms more and more complex.

What when several such cables exist in relative proximity?
(i.e. on the same bus)



Hitachi Energy

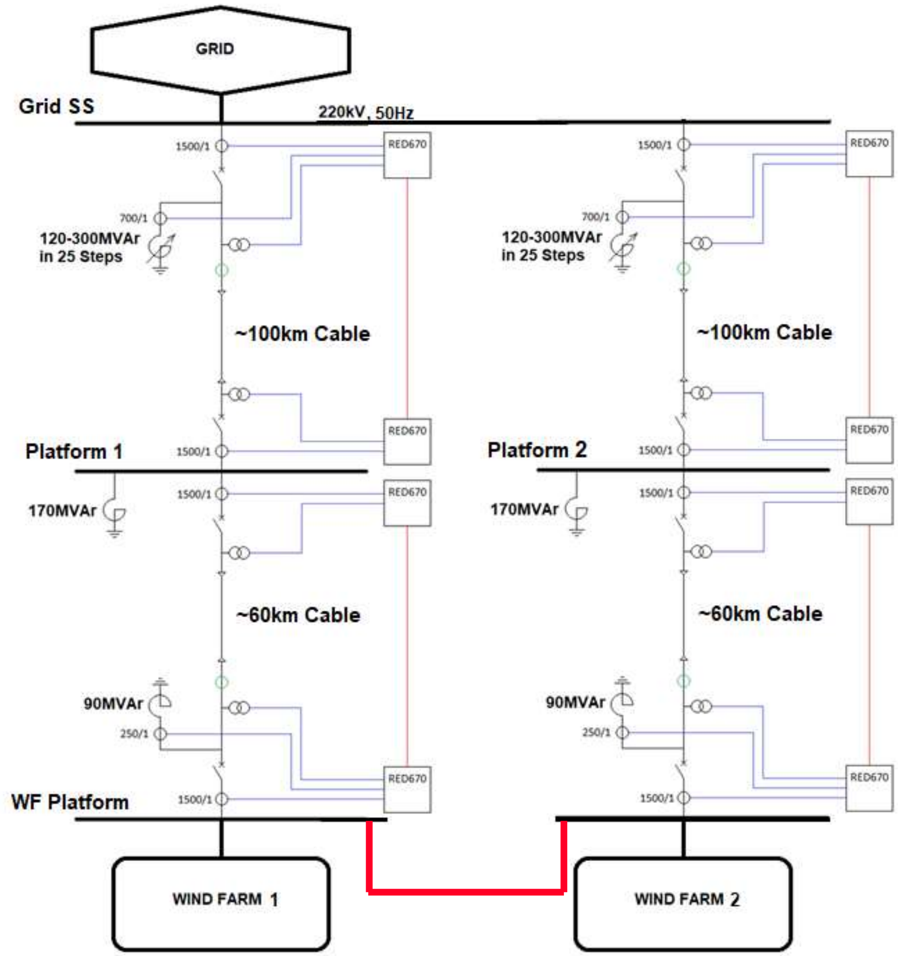
Offshore Wind Farm Installation, Export Cable Example

What happen when Operational People want to run them in parallel due to availability reasons?

Under no circumstances both-cable circuit shall be triped at the same time!

Special settings needed.

Looking into better ways to protect such special installations.

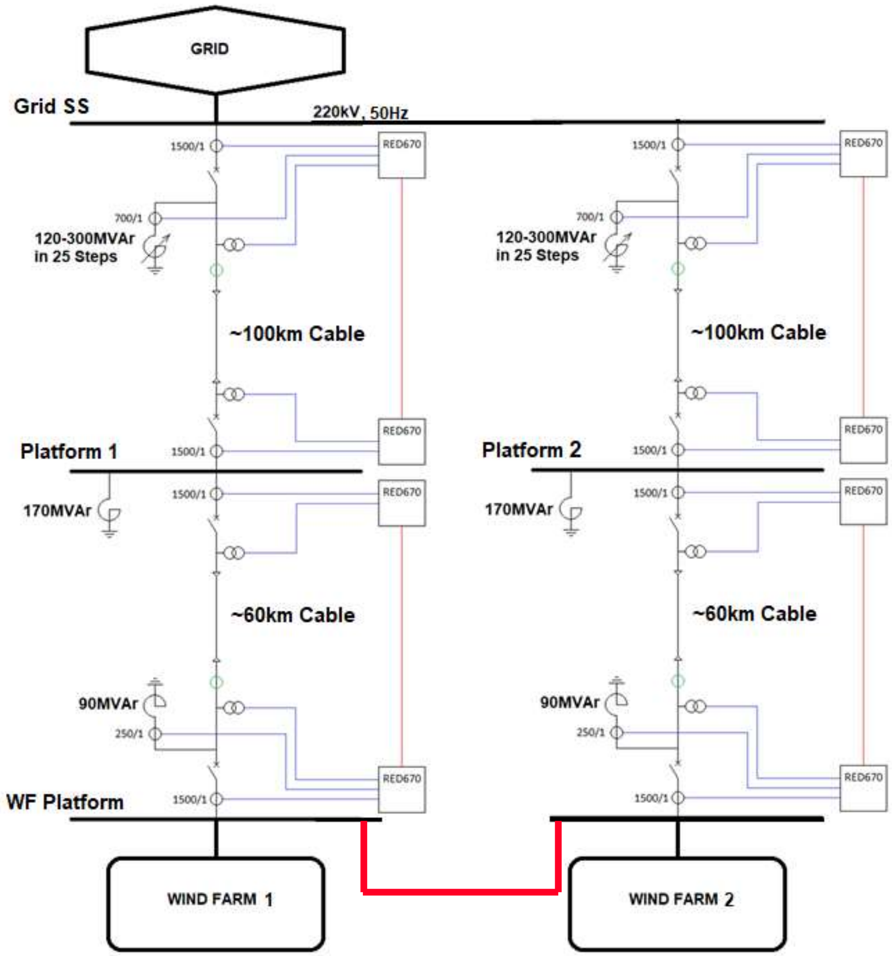


Public

Offshore Wind Farm Installation, Export Cable Example

Present Protection Solution:

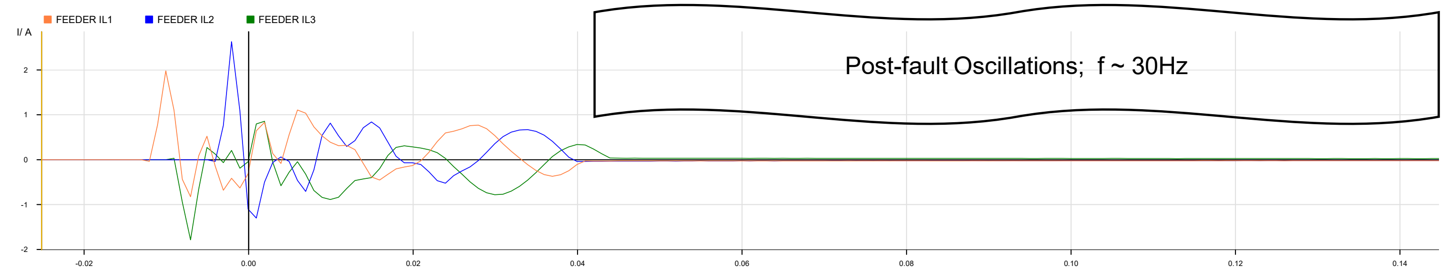
1. Charging current compensation is disabled for Line differential protection
2. Line differential protection is desensitized (i.e. minimum pickup IdMin~150%)
3. Line distance protection Zone 1 is time delayed for 40ms (i.e. potential directionality issue)



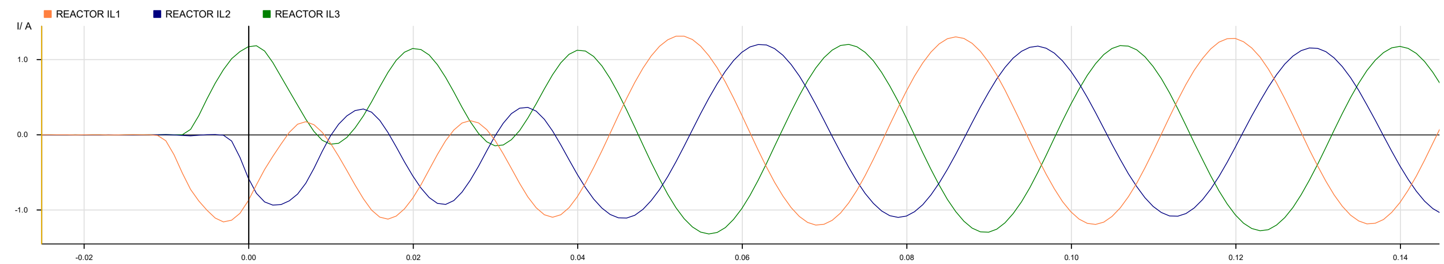
First Energizing of 100km Long Export Cable and Variable Reactor

HITACHI
Inspire the Next

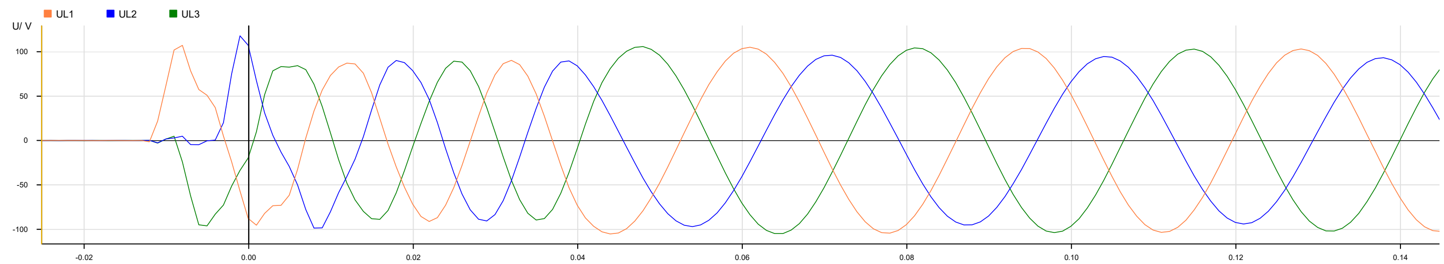
Secondary Current Waveforms
Export Feeder CB



Secondary Current Waveforms
Variable Shunt Reactor



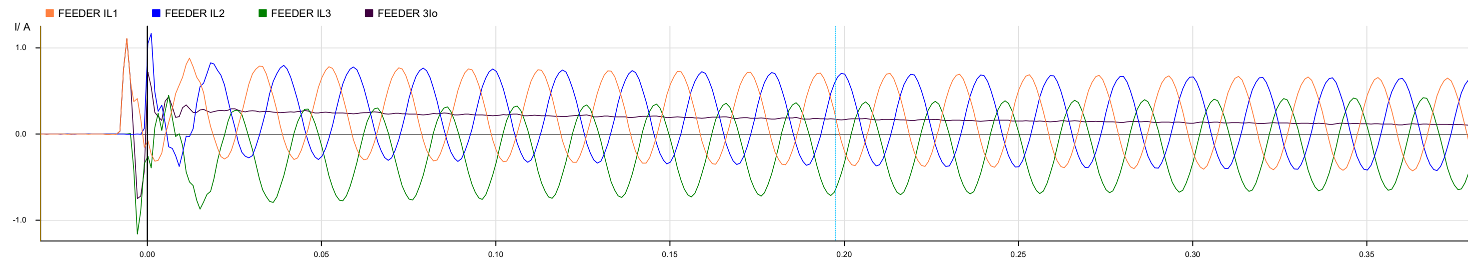
Secondary VT Waveforms
Ph-Gnd Voltages



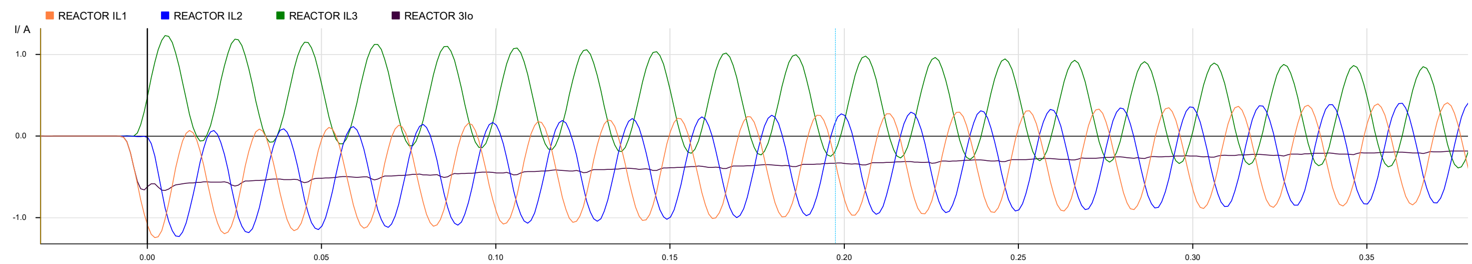
Hitachi Energy

Energizing of 100km Long Export Cable and Variable Reactor

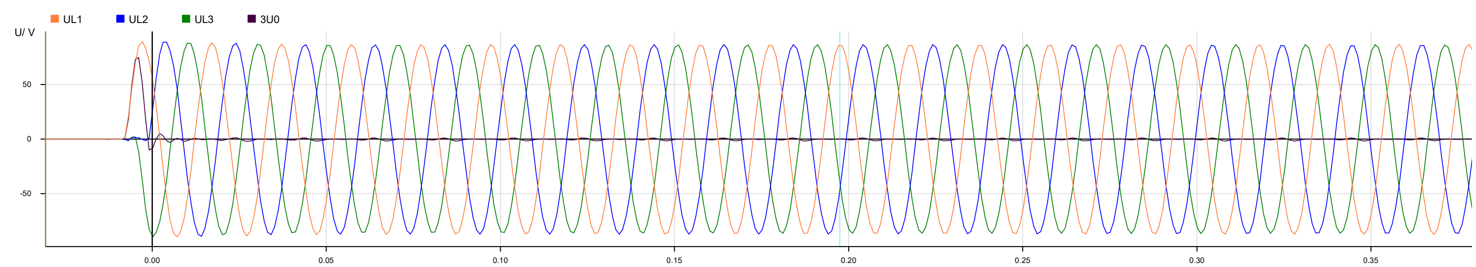
Secondary Current Waveforms Export Feeder CB



Secondary Current Waveforms Variable Shunt Reactor



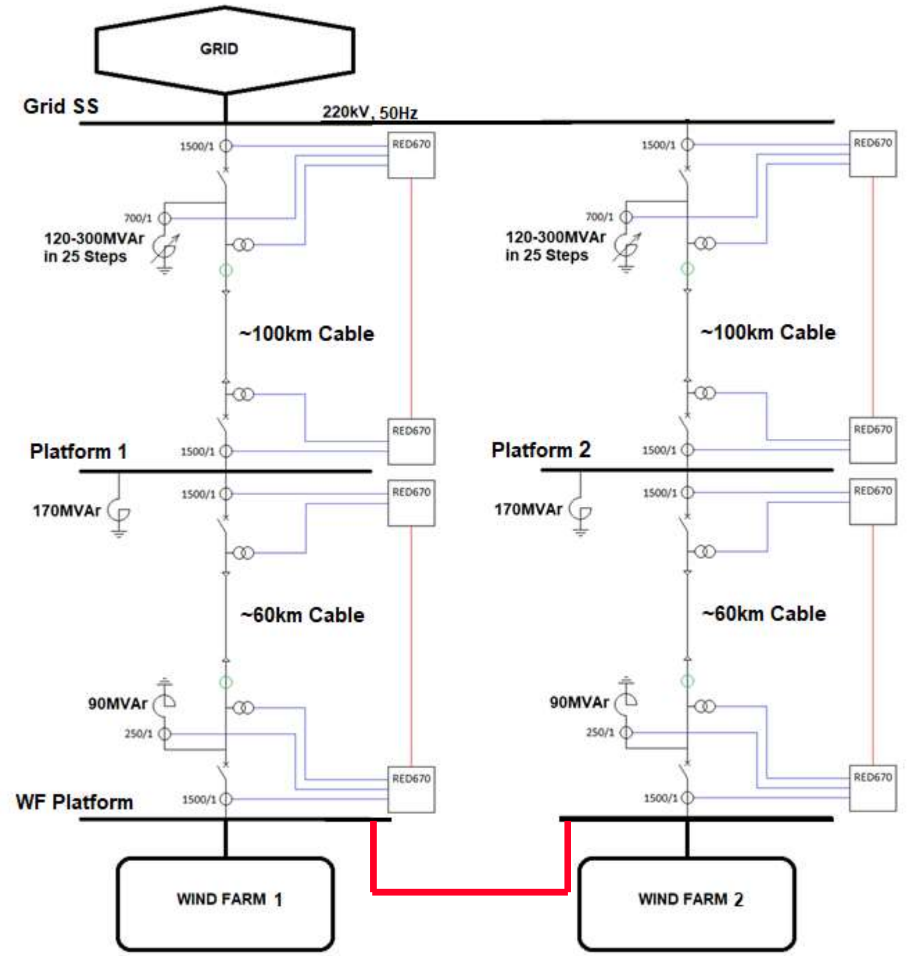
Secondary VT Waveforms Ph-Gnd Voltages



Offshore Wind Farm Installation, Export Cable Example

What about Tap Position regulation of the Variable shunt reactors?

How to coordinate its control with other “reactive power devices” in the surrounding of such installations?



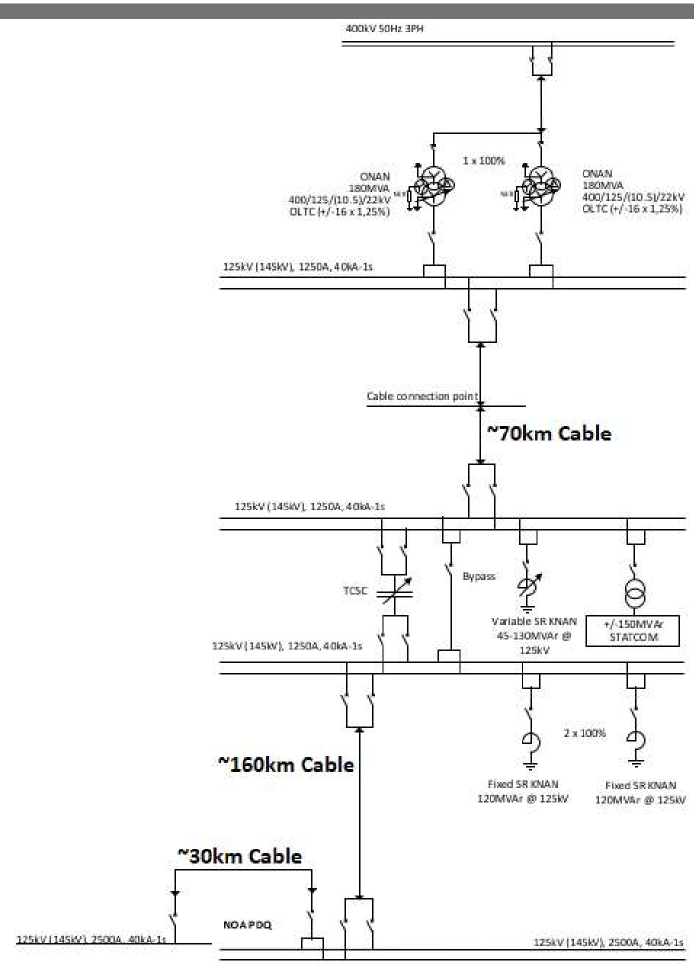
Public

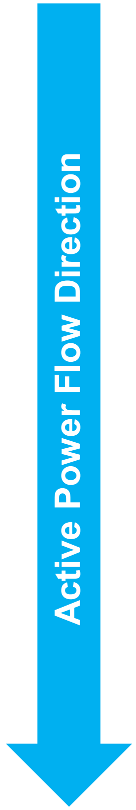
Power from Shore Installation: “Import Cable” Example

For large oil/gas platform similar, but different power system setup is also used.
Used Components:

1. Long cables
2. Fixed Shunt reactors
3. Variable Shunt Reactors
4. FACTS Devices
   a) TCSC
   b) STATCOM
5. Mostly Motor Loads

What about protection and control for such installation?
Shall be in operation in 2025.





Conclusions

Be aware of what you are taking “for granted” in modern power system when power cables are extensively used. For example, the following assumptions will be wrong:

- Current at the beginning and at the end of a long cable are the same
- Capacitive (EF) currents are small, and consequently they can be neglected
- For forward faults the measured impedance by distance protection will be always in the first quadrant
- What will be seen as Forward and what as Reverse fault
- P-flow is always bigger than Q-flow (i.e. p.f. value is close to one)
- Power system is always inductive
- Source impedance angles are always close to 90 degrees
- Etc.

HITACHI
Inspire the Next

HITACHI
Inspire the Next

Hitachi Energy