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Optimization of Distance Protection Performance Used in Wind Farms' Collection Networks

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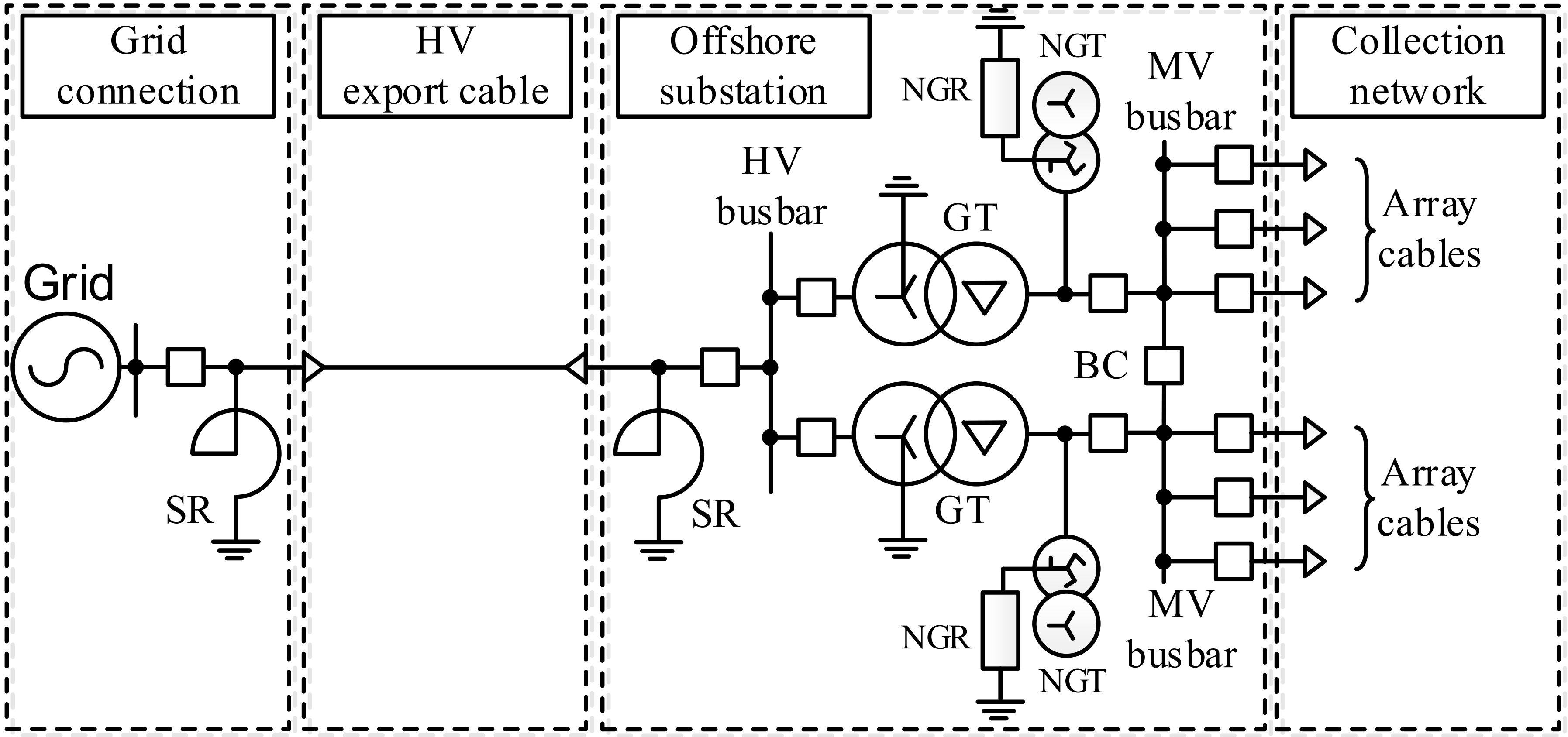
Overview

- Short introduction to wind farms
- Problem description
- Problem solution
- Solution verification
- Site testing (commissioning)
- Conclusions

Short introduction to wind farms

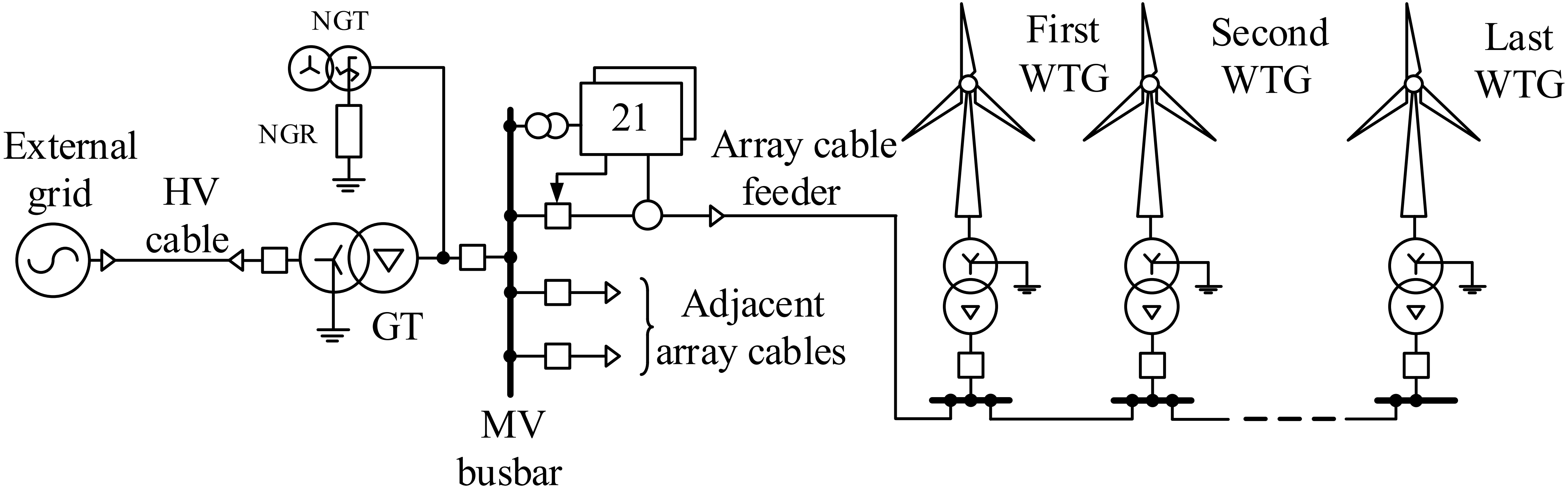
- Wind farm power system overview



Typical SLD of an offshore wind farm

Short introduction to wind farms

- Wind farm power system overview



Typical SLD of a wind farm collector network

Short introduction to wind farms

- For WF having 33kV MV system:
  - grid transformer ~ 200MVA
  - NGR ~ 300A - 2000A
  - WTG up to 8MW; up to 8 per feeder
  - array cable feeder length up to 20km
  - 3I0_cap* ~ 100A
- For WF having 66kV MV system:
  - grid transformer ~ 300MVA
  - NGR ~ 1000A - 4000A
  - WTG up to 10MW; up to 10 per feeder
  - array cable feeder length up to 40km
  - 3I0_cap* ~ 400A

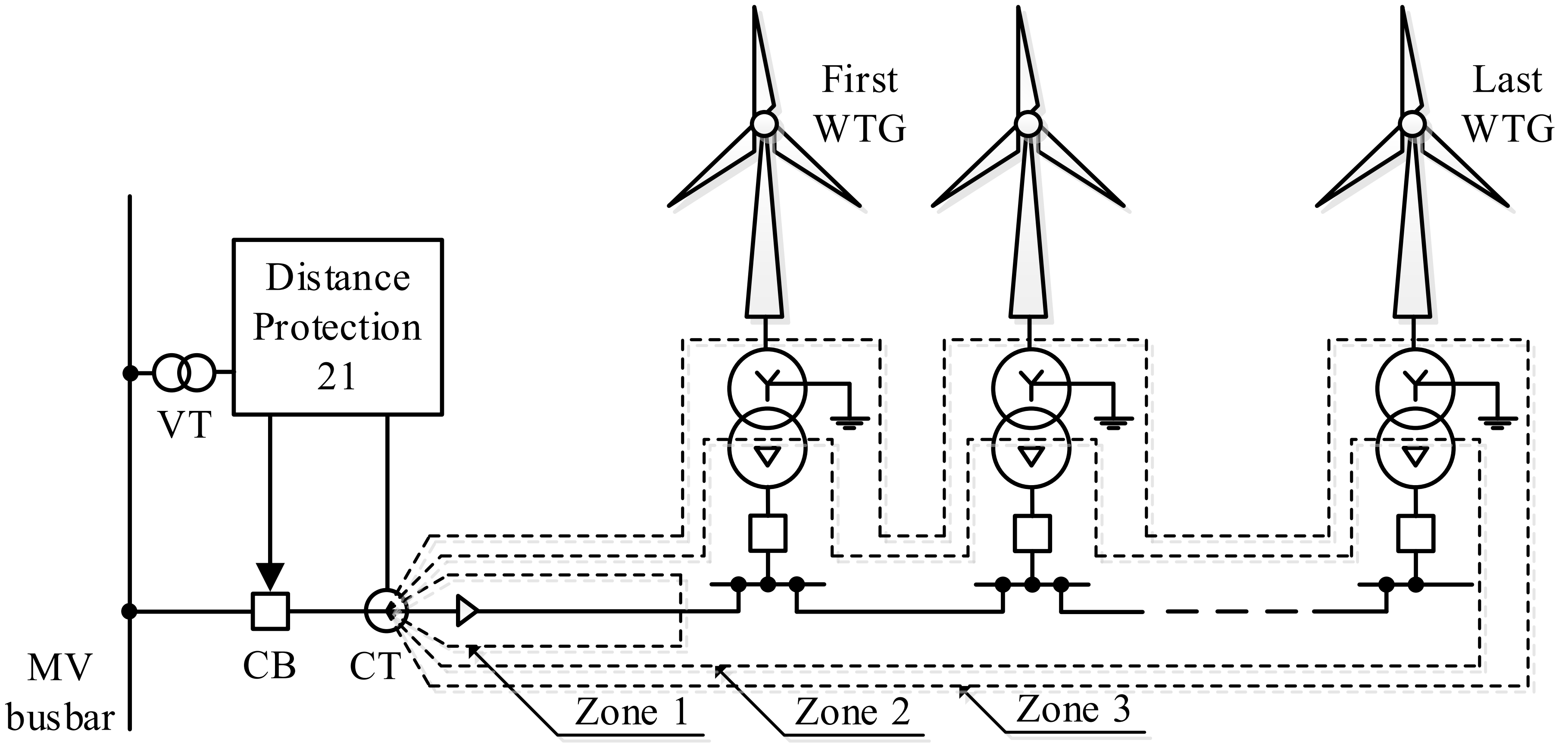
*capacitive ground fault contribution from healthy feeders for SLG fault elsewhere in the MV system

Problem description

- Distance protection recap
  - provides fast fault clearance time with good sensitivity and selectivity
  - is traditionally used for transmission high voltage (HV) systems
  - widespread use of numerical Intelligent Electronic Devices (IEDs) has made it possible to achieve all the benefits of distance protection applications on lower voltage systems such as distribution and sub-transmission medium voltage (MV) systems
  - stepped distance protection is nowadays used as a main protection for the array cable systems of wind farm collection networks
  - these applications normally have resistive grounding via a neutral grounding resistor (NGR)
  - distance protection is not optimized for such applications as it is primarily designed for protection of HV overhead lines <u>in a solidly grounded power system where current will lag voltage in the faulty phase or loop</u>

Problem description

- Ørsted distance protection philosophy for an array cable feeder

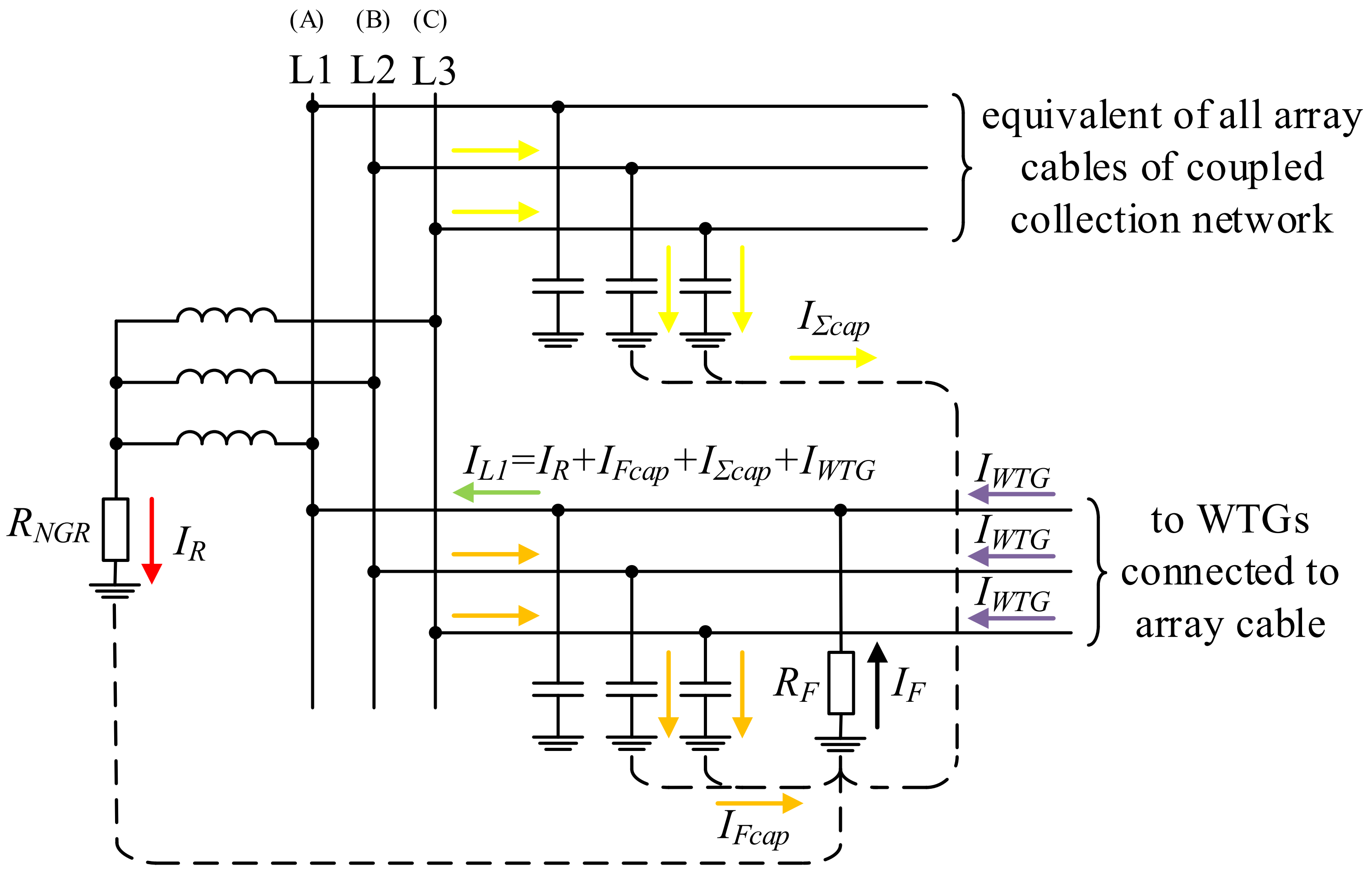


Problem description

- When a single line-to-ground fault occurs on a cable feeder
  - the ground fault current on the MV side is limited to a certain value (typically 600A to 2500A primary)
  - the NGT/NGR component of the ground current is dominantly resistive in nature
  - however, at the same time there is quite a large capacitive ground fault current contribution from each parallel connected healthy cable feeder – this capacitive component of ground fault current from each healthy feeder varies, but in extreme cases it can be up to 100A primary per 33kV feeder and even up to 400A primary per 66kV feeder

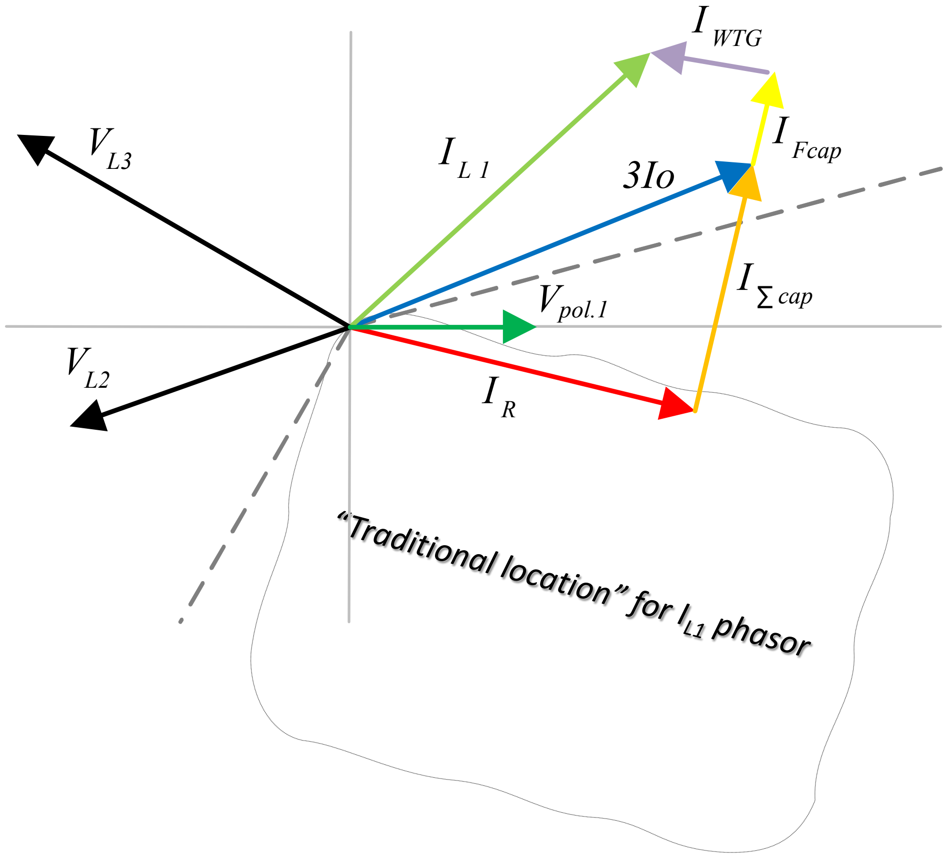
Problem description

- Single line-to-ground fault in Phase A (L1) on a cable feeder in the collection network
- The resultant Phase A (L1) fault current comprises
  - fault current through the NGT+NGR (I_R)
  - capacitive ground fault currents of all adjacent healthy feeders ($I_{\Sigma cap}$)
  - capacitive ground fault current of the faulted feeder (I_{Fcap})
  - load current (P/Q power export) before the fault (I_{WTG})



Problem description

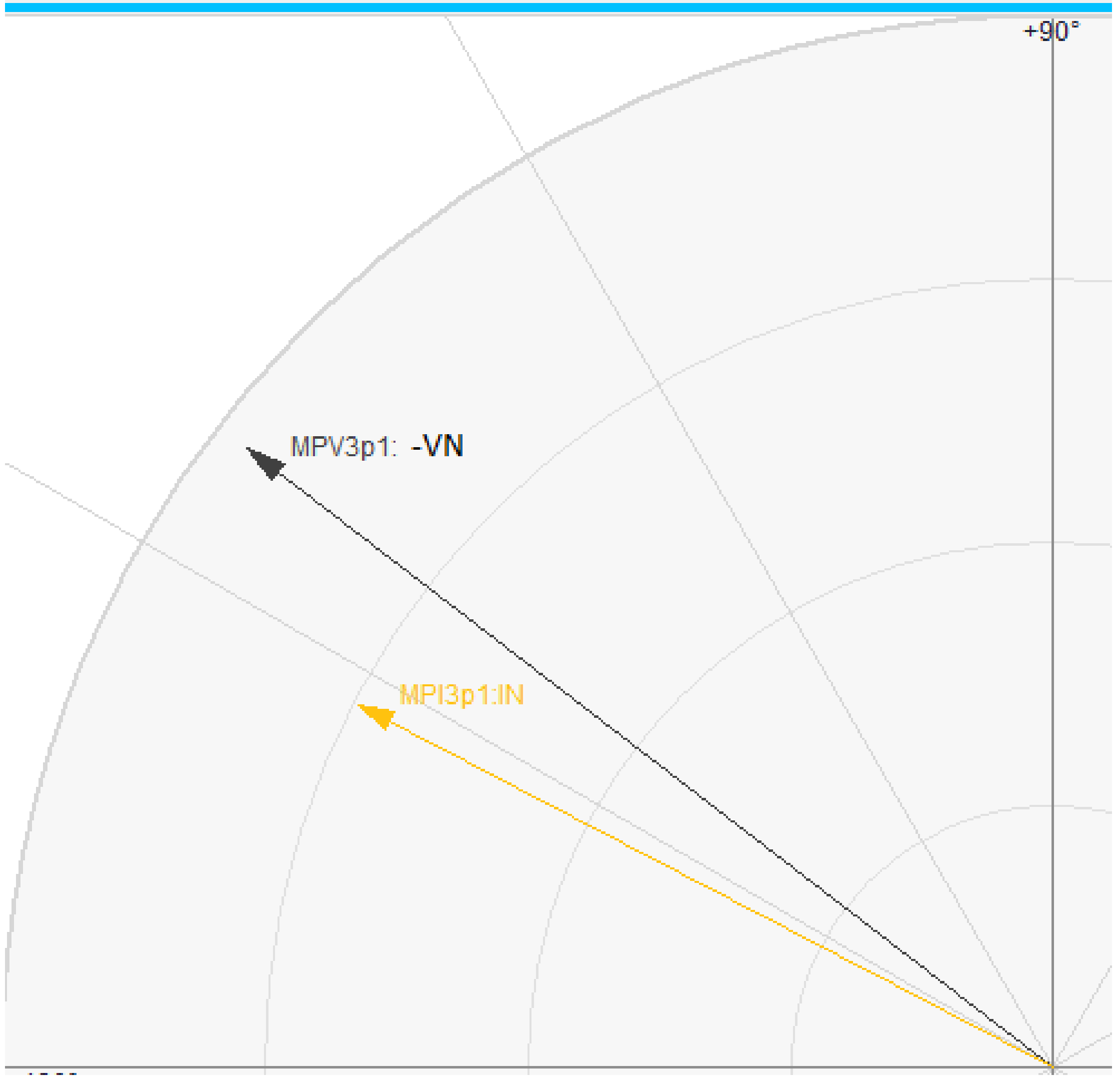
- Phasor diagram for a forward Phase A (L1) to ground fault (at the distance protection location)



- forward fault, BUT
  - I_{L1} (I_A) – the faulty phase current – under certain conditions may lead V_{pol1} – faulty phase positive sequence voltage
    - not lag, as would typically be expected, for a forward fault
  - NGR+NGT will limit the available ground fault current – the lower this current is the more problematic it will be for Ph-Gnd loops to operate

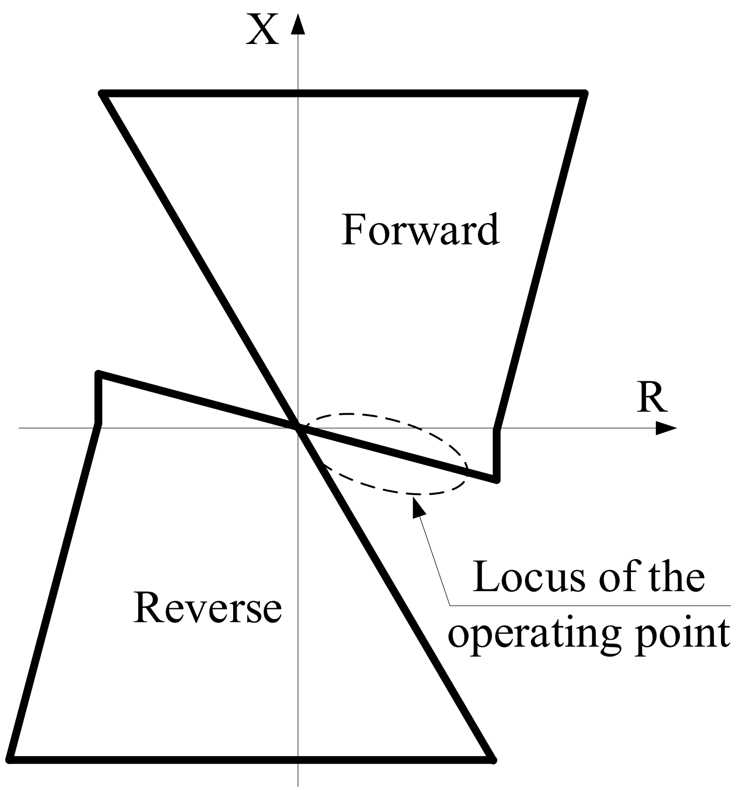
Problem description

- IN and -VN phasors from a recorded field case
  - very good match with the presented “theory” in the previous slides for the field DR for the faulty feeder
  - Note:
    - IN=3I0
    - VN=3V0



Problem description

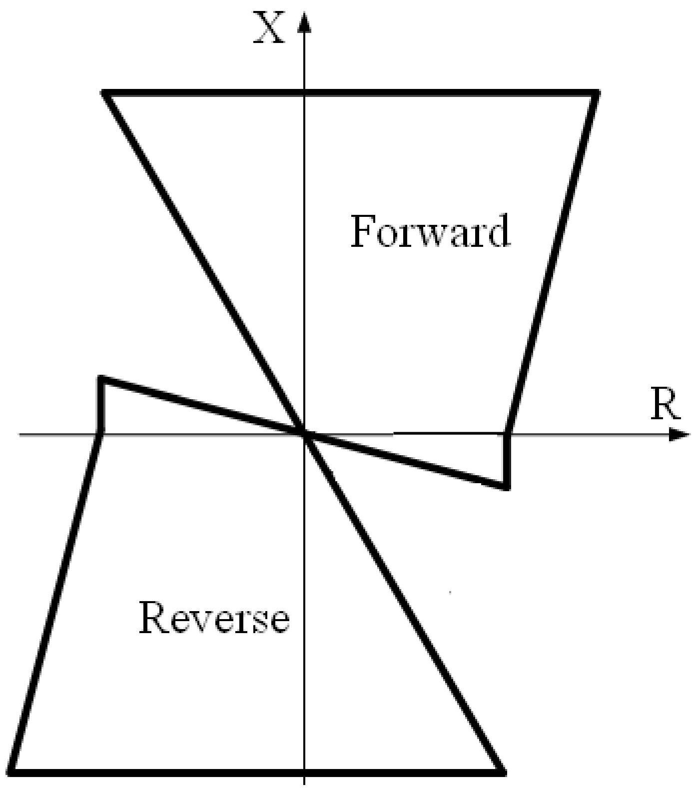
- For I_{L1} (I_A) leading V_{pol1}
  - the impedance measured by the distance protection in the faulty phase (A) will be in the 4th quadrant, and could fall outside the forward directional zone



- therefore, due to the combination of
  - large capacitive currents
  - current-limiting resistance in the system neutral point
  - high WTG infeed, etc.

  during a single line-to-ground fault, the distance protection used on the array cable feeders in the collection networks of wind farms is prone to maloperation due to incorrect determination of fault direction – not declared as forward fault
- consequences
  - undetected faults / longer fault clearance times
  - excessive damage to primary equipment / revenue loss

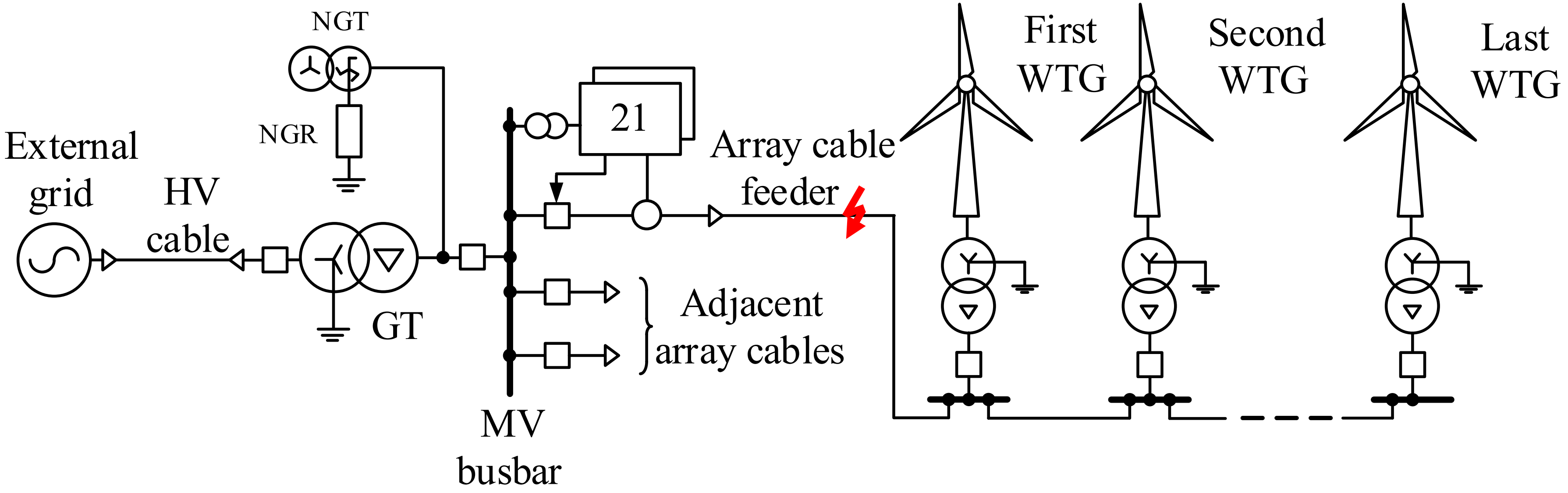
Problem description



- As the MV bus voltage level in WFs is increasing (e.g. from 33kV to 66kV) the capacitive ground fault current contribution from healthy array cable feeders is also becoming much larger (e.g. up to 400A primary per feeder at 66kV depending on the length of the cable feeder sections)
- Such high ground fault current level in a healthy feeder during a ground fault somewhere else in the MV system might cause problems for distance protection which is installed on the healthy feeder
  - e.g. if during a single line-to-ground fault on another cable feeder, $I_{cap} \geq I_{WTG}$ the distance protection may declare such a reverse fault to be in the forward direction and consequently it can maloperate

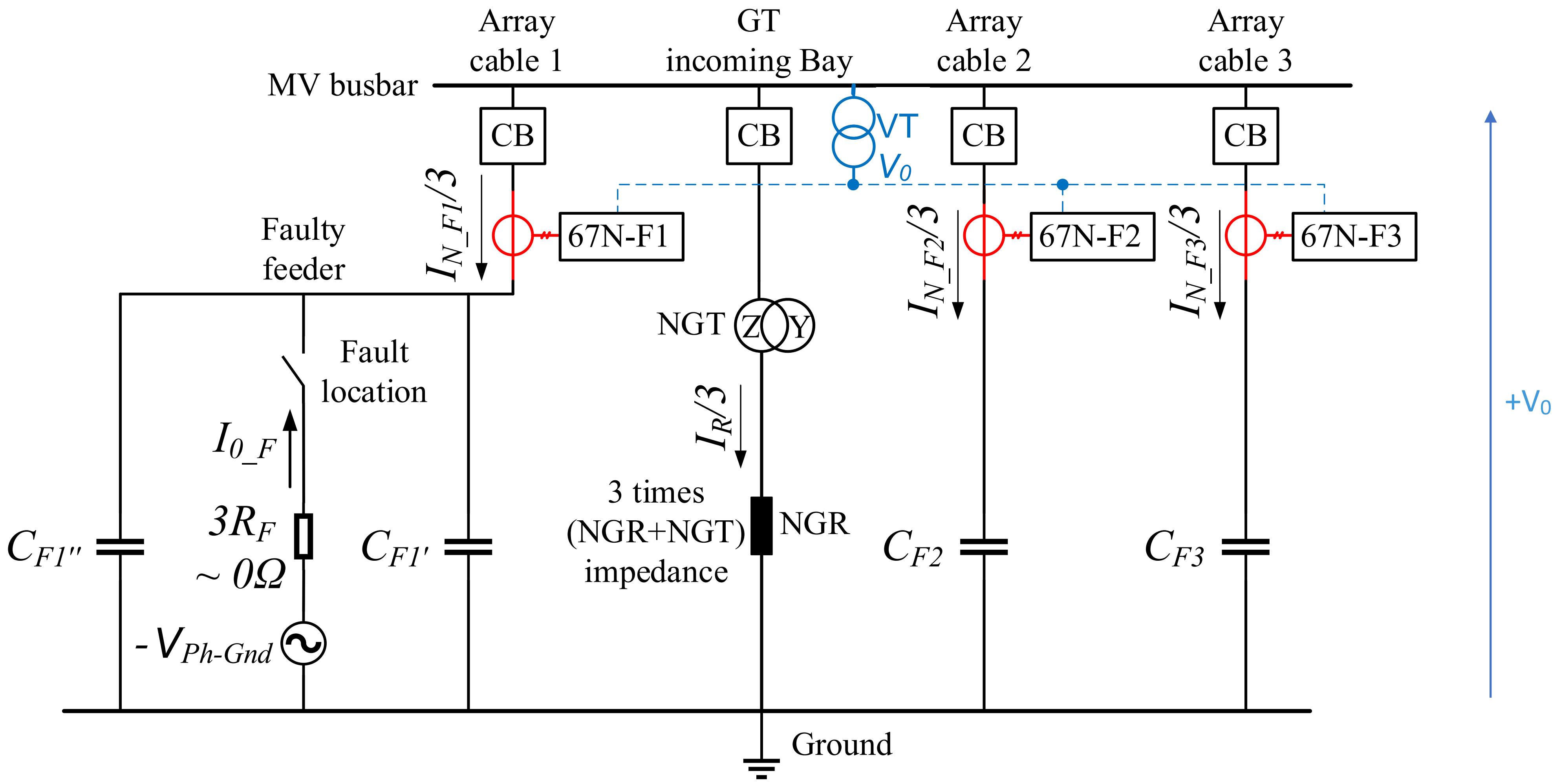
Problem solution

- Directional ground fault protection (67N) can be used in MV collection networks of WFs as it can provide correct determination of direction for forward faults
- Analysis of the 67N function operation during ground faults can be done using the zero sequence equivalent circuit
- Phase A (L1) to ground fault on a cable feeder



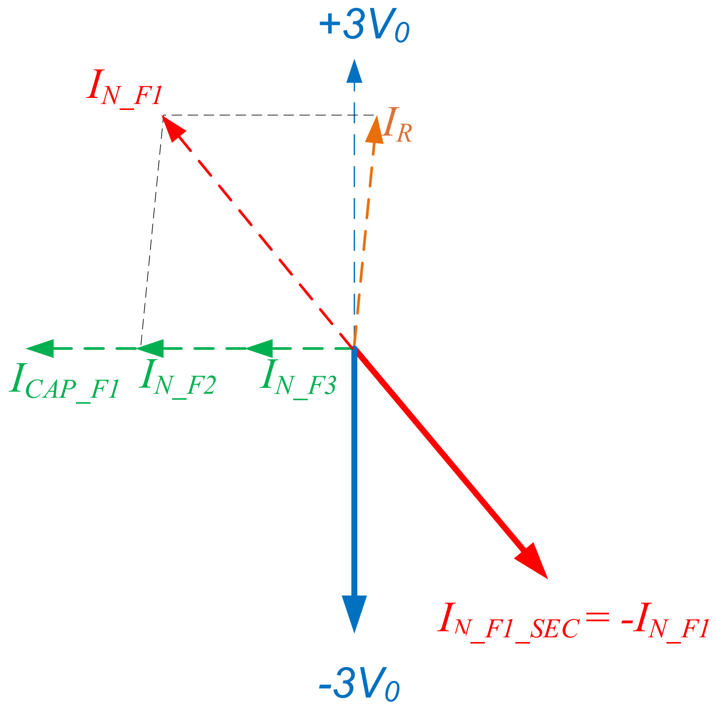
Problem solution

- Simplified zero sequence circuit of a collection network for a single line-to-ground fault

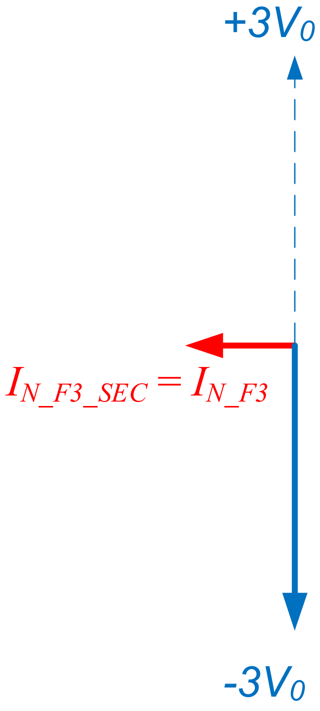


Problem solution

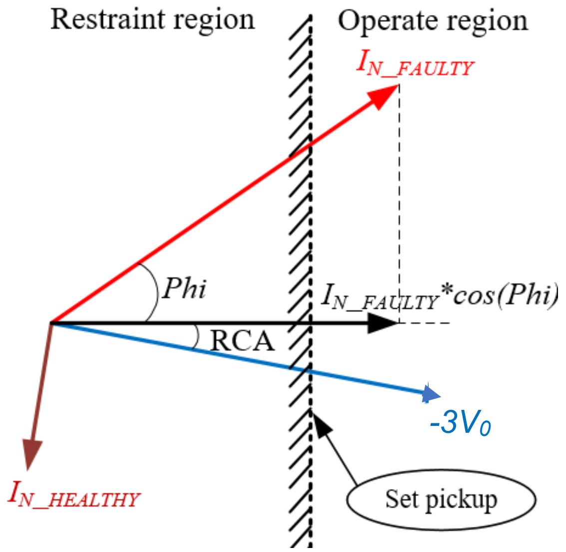
- Directional ground fault protection
- Phasor diagram for the faulted array cable (1)



- Phasor diagram for a healthy array cable (3)



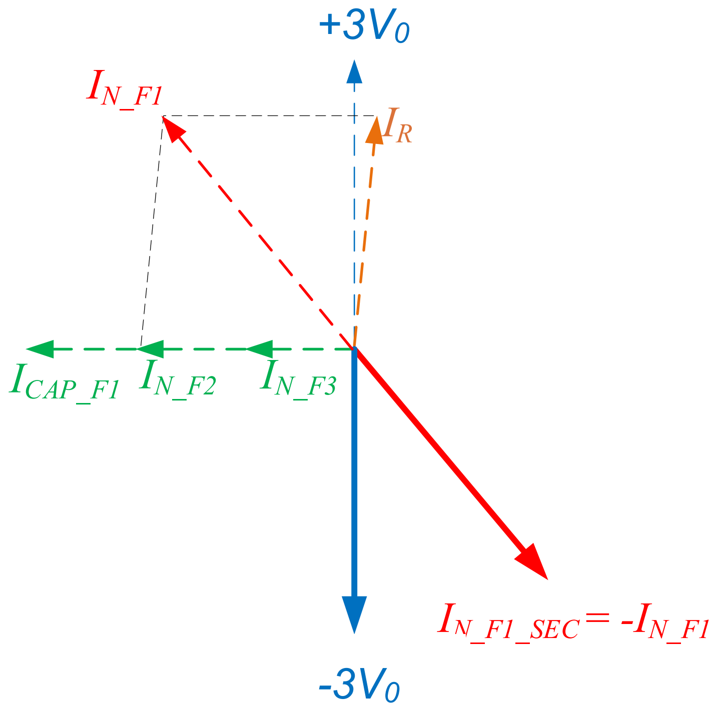
- Directional characteristic of 67N protection

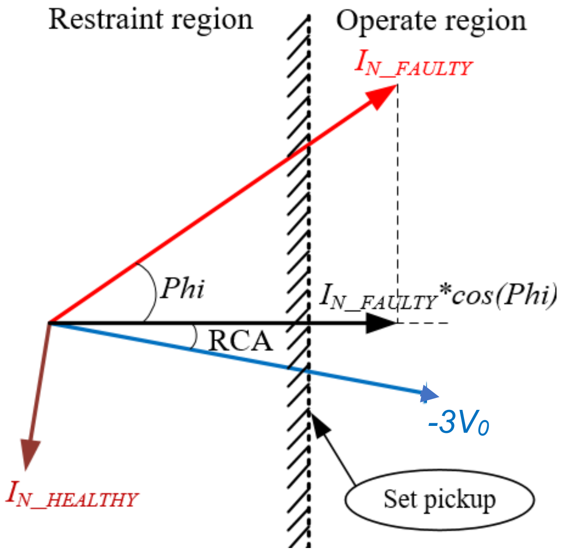


- Only the 67N ground fault protection installed in the faulty feeder will measure the NGR resistive current component

Problem solution

- Directional ground fault protection – requirements

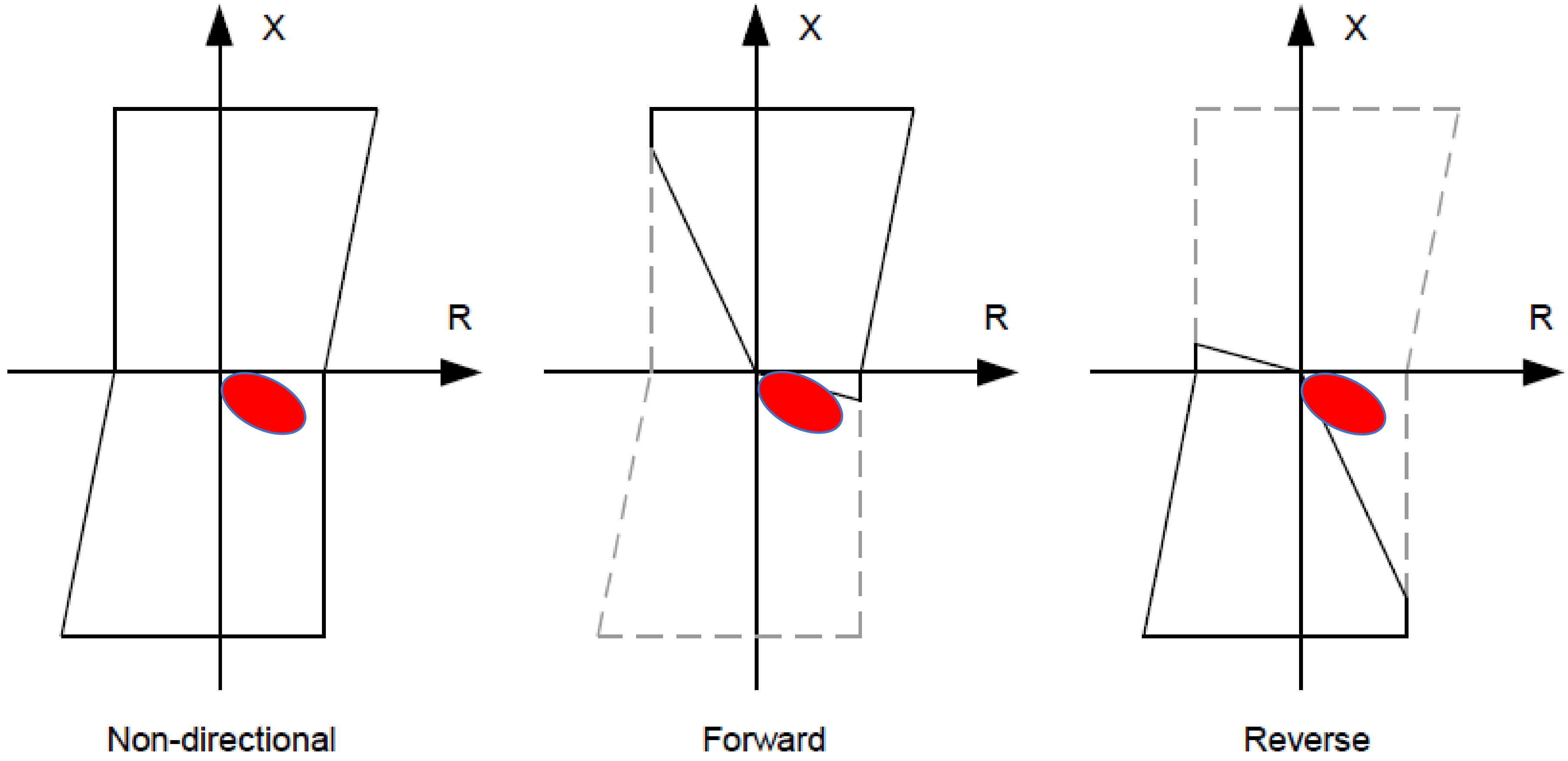




- exporting power from all WTG can be quite large (dependent on wind conditions) and it subtracts from the resistor current
- the chosen NGR rating must allow high enough resistive fault current when compared to the load current of the WTGs

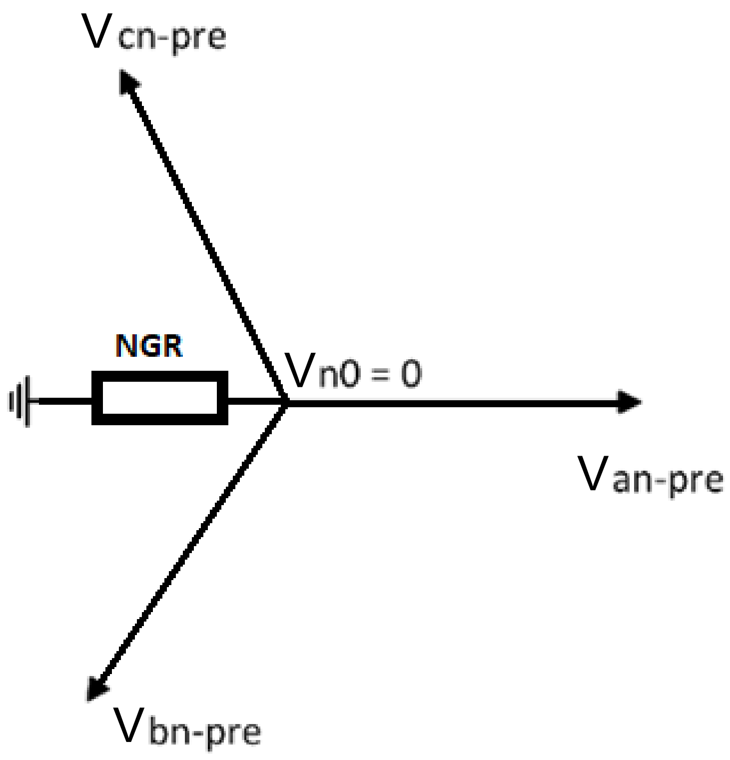
Problem solution

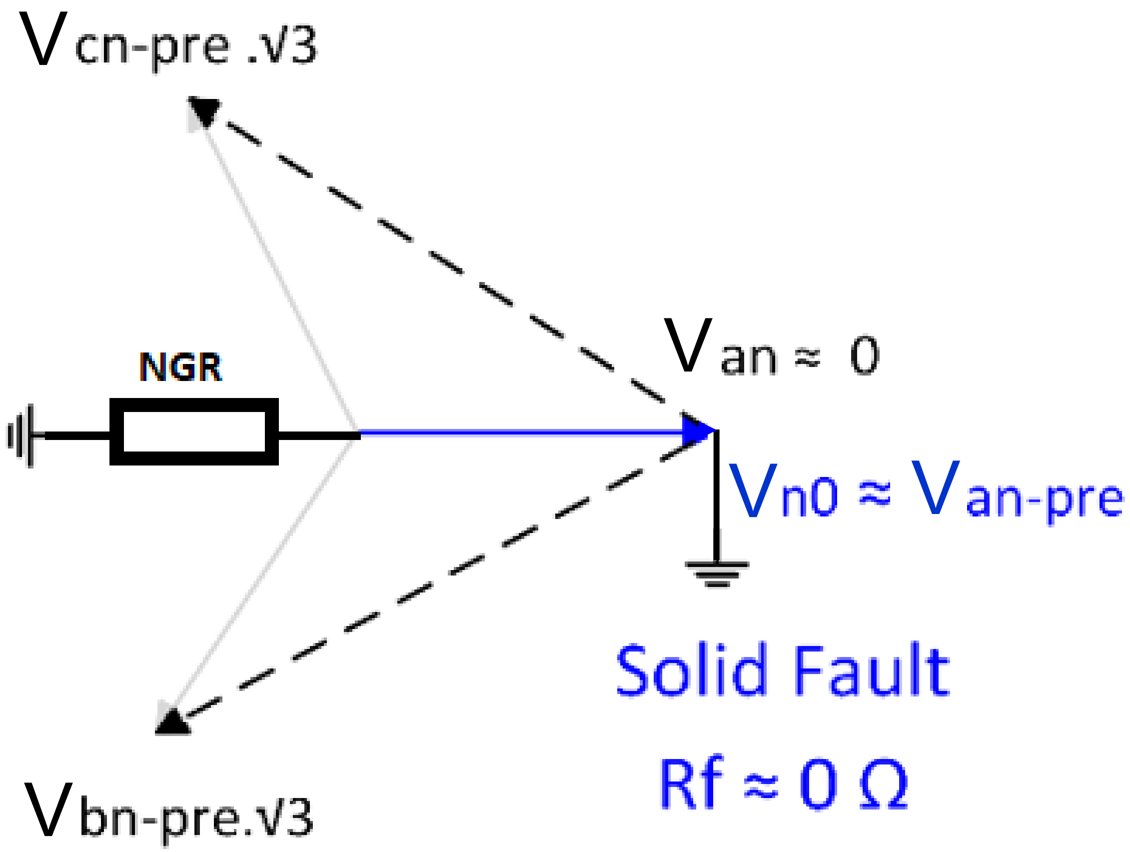
- Non-directional vs directional characteristic for distance protection function



Problem solution

- Voltage phasor diagram for a ground fault

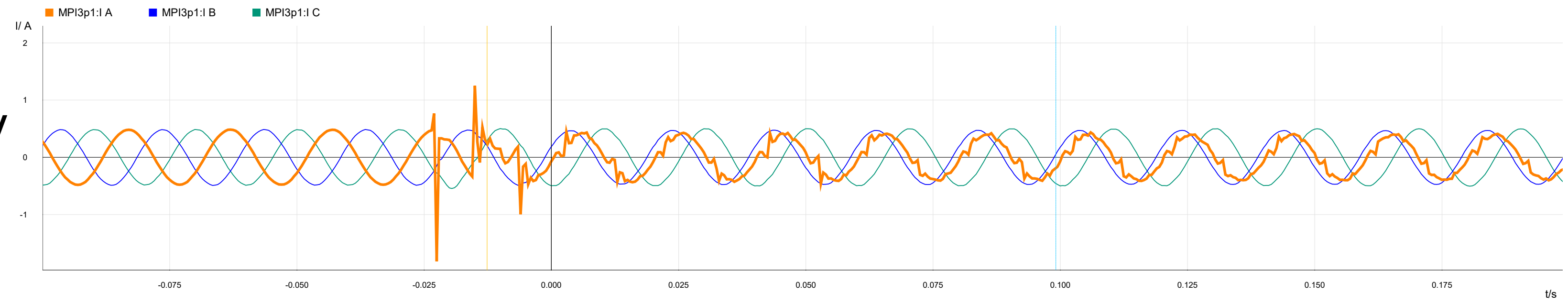




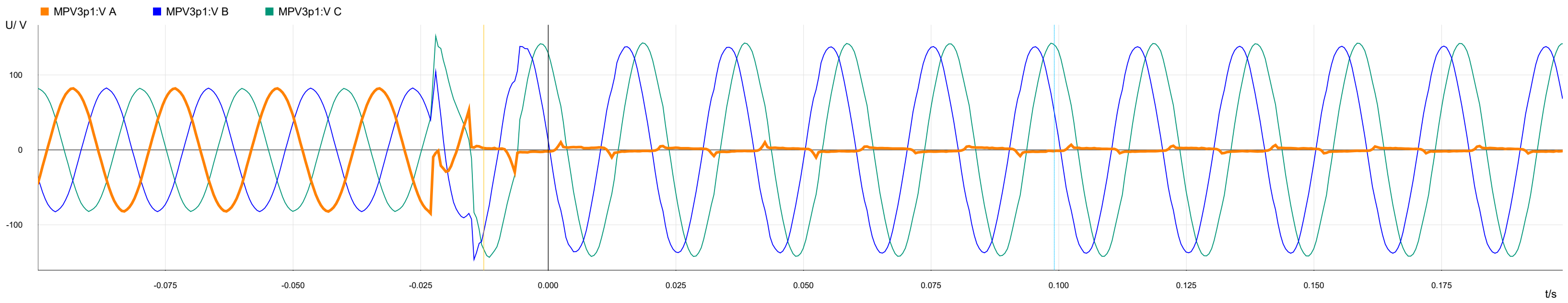
Problem solution

- Disturbance record from Ørsted WF having 33kV MV system and 600A NGR

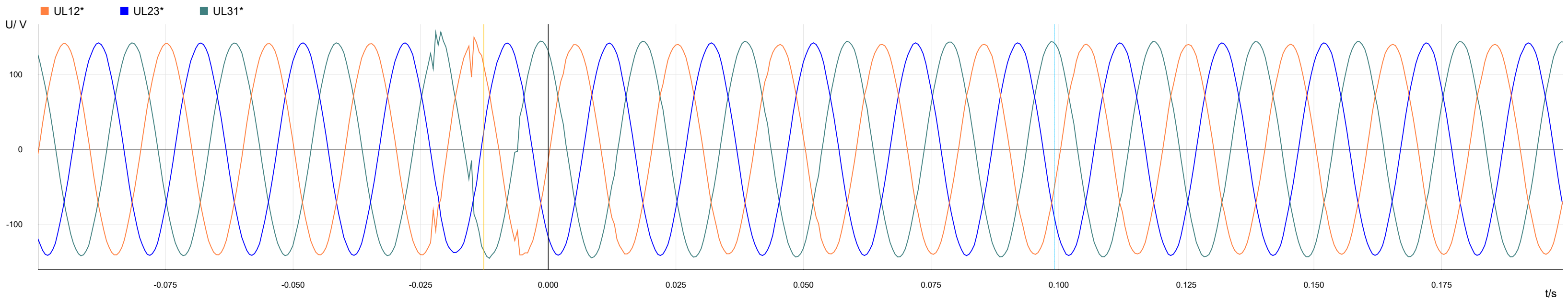
Faulty feeder 1A CT secondary current waveforms



VT Ph-Gnd secondary voltage waveforms



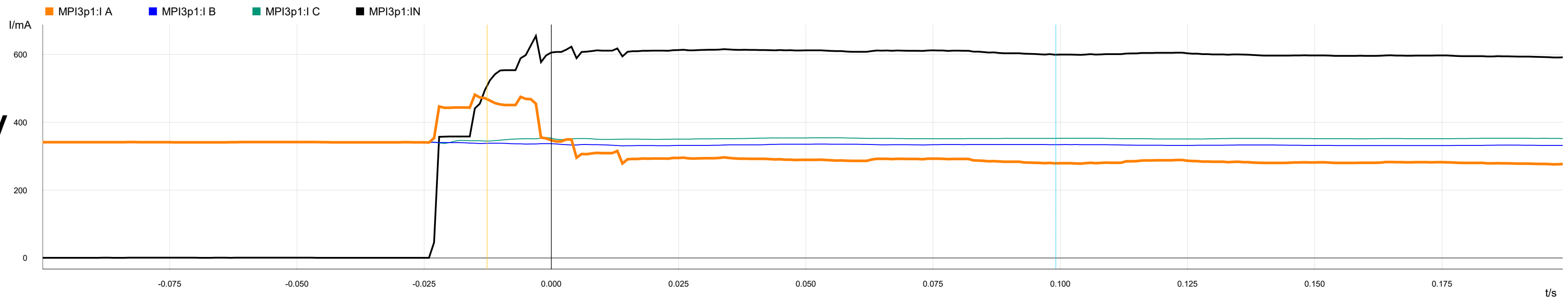
VT Ph-Ph secondary voltage waveforms



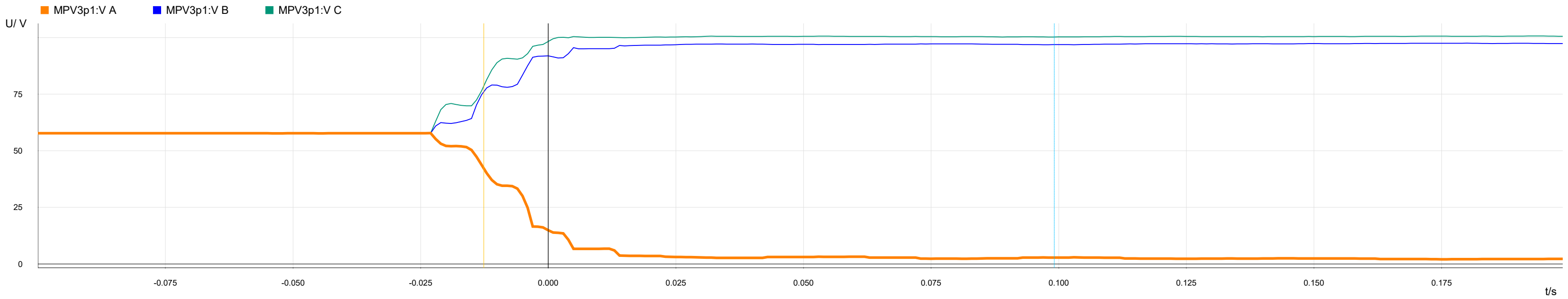
Problem solution

- Disturbance record from Ørsted WF having 33kV MV system and 600A NGR

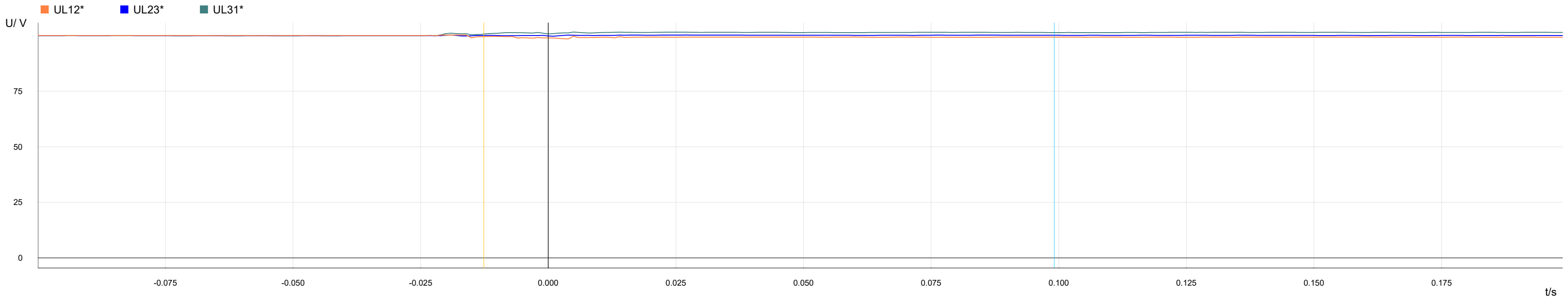
Faulty feeder 1A CT secondary current magnitudes



VT Ph-Gnd secondary voltage magnitudes

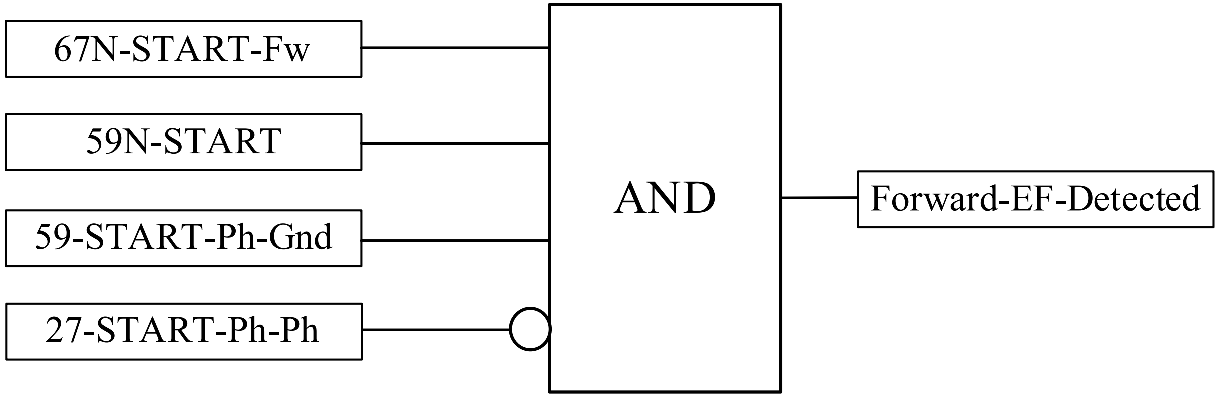


VT Ph-Ph secondary voltage magnitudes



Problem solution

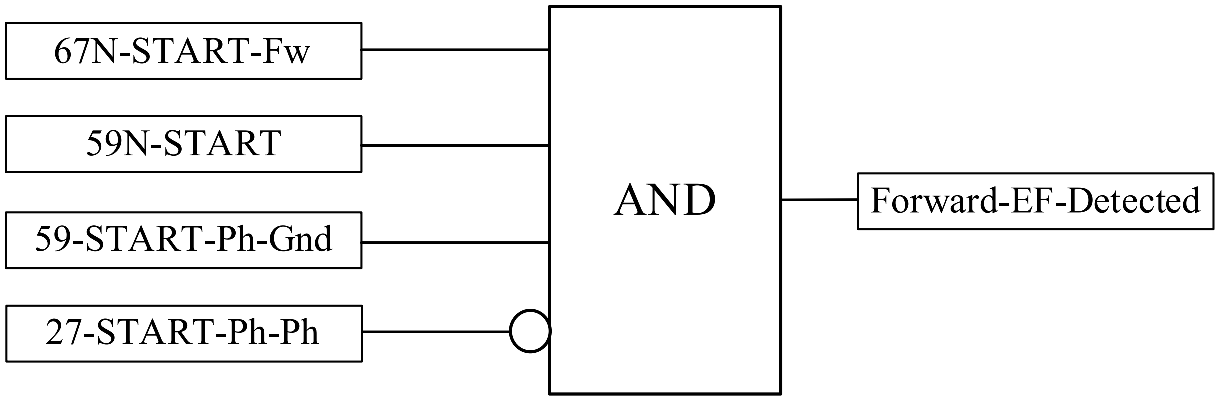
- Optimized ground distance protection logic – faulty feeder
  - logic to detect a forward ground fault



- 67N-START-Fw
  - from the 67N directional ground fault protection function
  - pickup 20% of the ground fault current component determined by the NGT and NGR sizing
  - RCA 0° (or even to -5° to increase the margin towards the capacitive ground fault current in the healthy feeders)

Problem solution

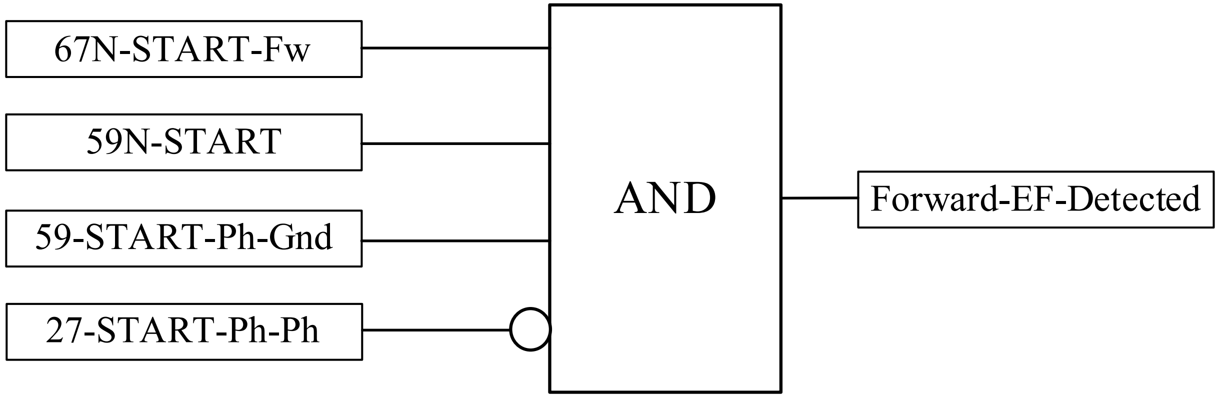
- Optimized ground distance protection logic – faulty feeder
  - logic to detect a forward ground fault



- 59N-START
  - from the 59N residual overvoltage function
  - pickup 30% of the rated phase-to-ground voltage
  - verifies that a residual voltage has been detected, which typically means that a fault involving ground has occurred

Problem solution

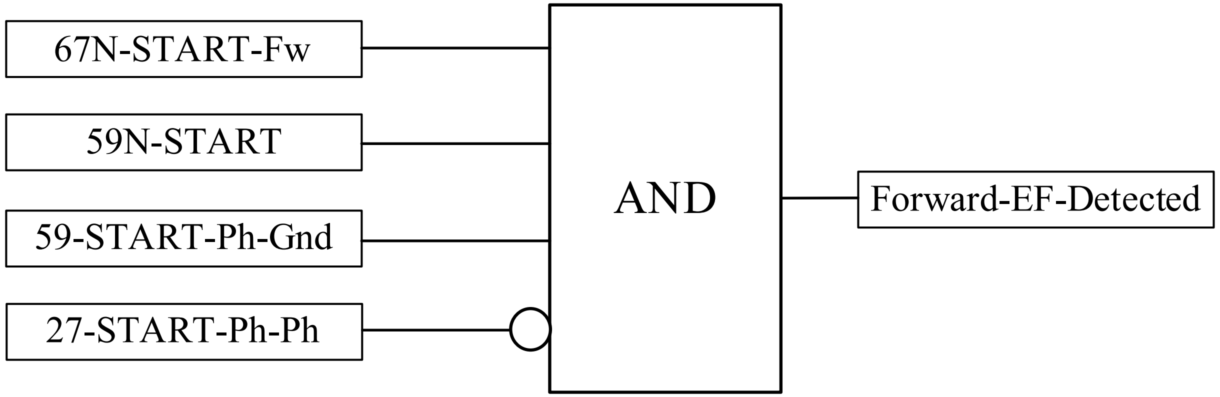
- Optimized ground distance protection logic – faulty feeder
  - logic to detect a forward ground fault



- 59-START-Ph-Gnd
  - from the 59 overvoltage function, which measures the three phase-to-ground voltages
  - pickup 125% of the rated phase-to-ground voltage
  - verifies that a high voltage is detected in at least one of the three phases – during a ground fault in a wind farm MV system, two phase-to-ground voltages will typically exceed this set level

Problem solution

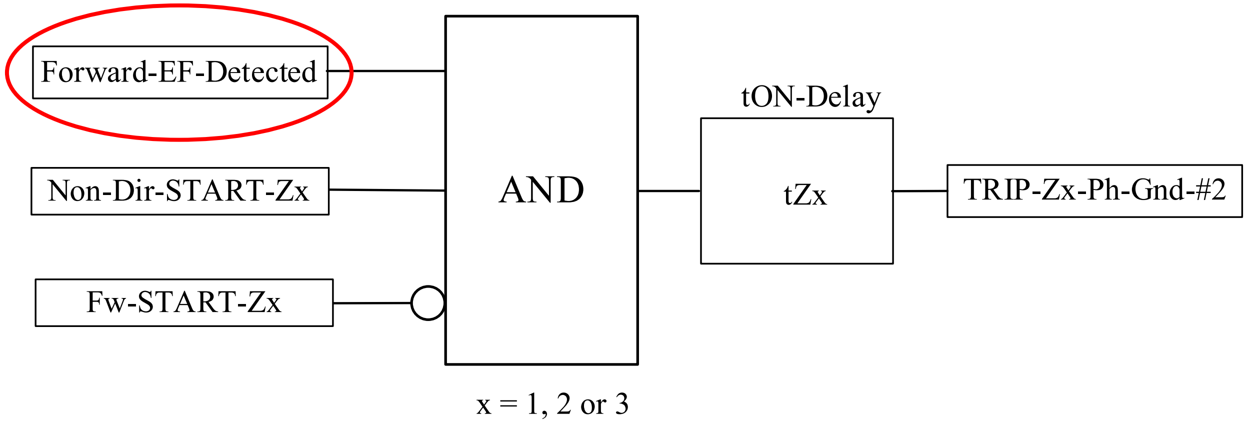
- Optimized ground distance protection logic – faulty feeder
  - logic to detect a forward ground fault



- 27-START-Ph-Ph
  - from the 27 undervoltage function, which measures the three phase-to-phase voltages
  - pickup 75% of the rated phase-to-phase voltage
  - blocking signal
    - verifies that a low phase-to-phase voltage is not detected among any two phases
    - its pickup prevents operation of this logic in case of a multi-phase fault in the MV system

Problem solution

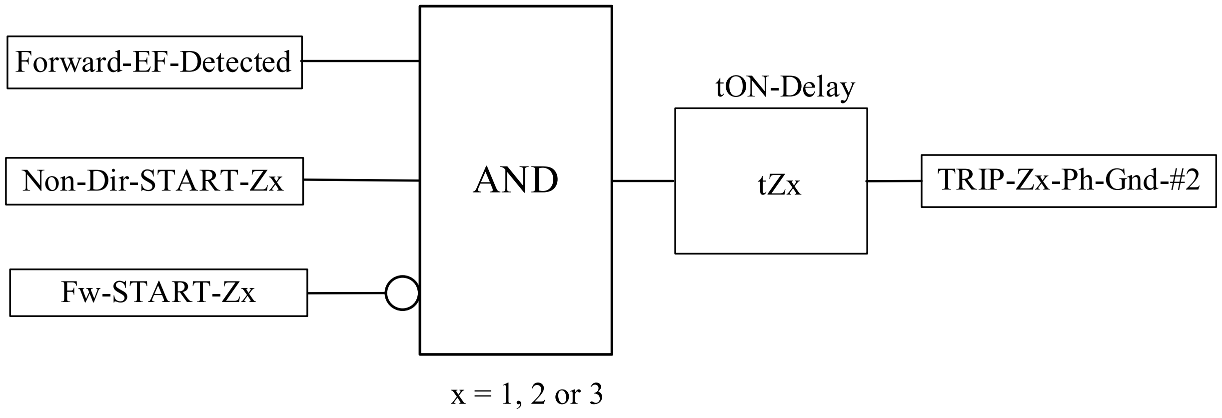
- Optimized ground distance protection logic – faulty feeder
  - additional directional supervision logic for each forward distance protection zone



- Non-Dir-START-Zx
  - from distance protection function “zone x”
  - indicates that a non-directional start has been given from “zone x”
- Fw-START-Zx
  - from distance protection function “zone x”
  - indicates that a forward direction start has been given from “zone x”
  - blocking signal
    - verifies that a forward direction start has <u>not</u> been given – a forward direction start prevents operation of this logic

Problem solution

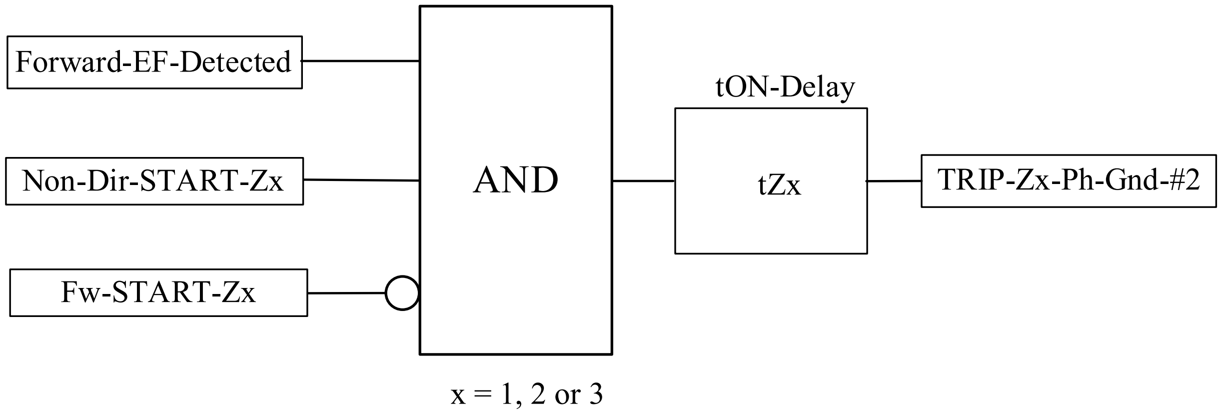
- Optimized ground distance protection logic – faulty feeder
  - additional directional supervision logic for each forward distance protection zone



- Note that the described logic works in parallel with the standard ground distance protection zones, which perhaps will still operate for the majority of the fault cases

Problem solution

- Optimized ground distance protection logic – faulty feeder
  - additional directional supervision logic for each forward distance protection zone

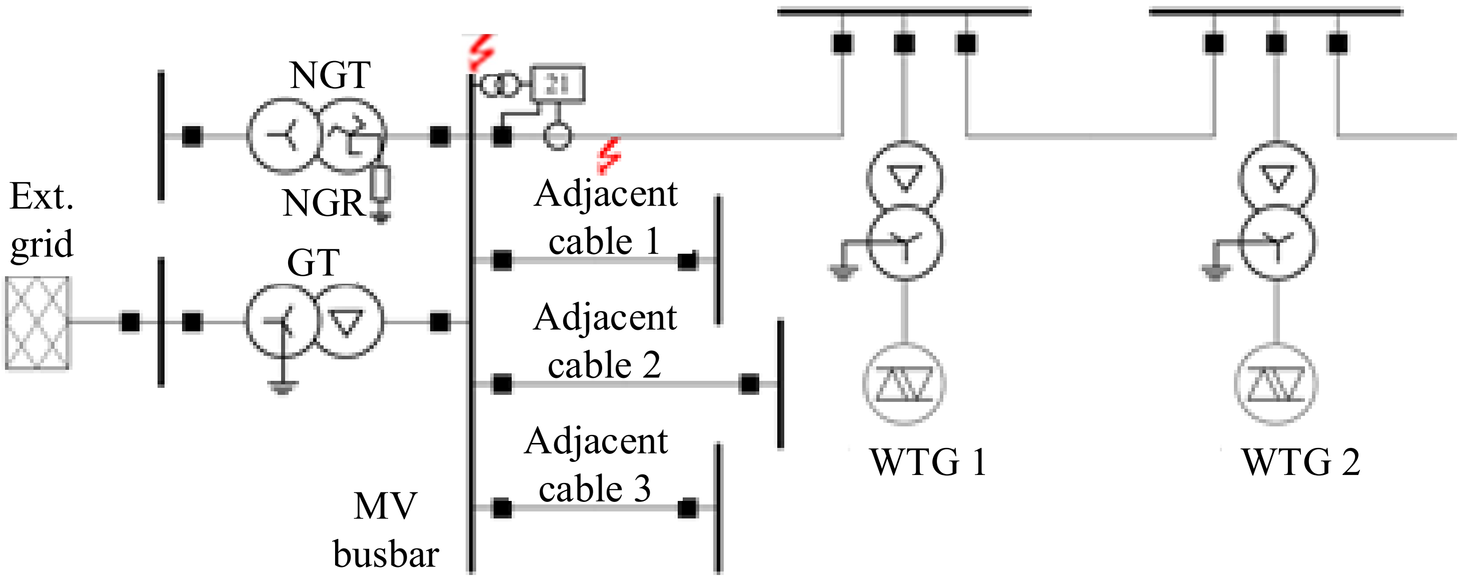


- tON
  - same time as “zone x”
  - exception zone 1 – add a small time delay (e.g. 30ms) to ensure no security problems occur during ground fault clearance in a neighboring array feeder connected to the same MV bus

Problem description

- Ground distance protection – healthy feeder
  - use the following solution
    - the magnitude of the ground fault current supplied by the NGT/NGR combination is, in practice, typically larger than the capacitive ground fault current contribution from the longest healthy feeder
    - if true
      - set a neutral current level which must be exceeded for the phase-to-ground measuring loops within the distance protection to be released for operation
        - set release threshold > the capacitive current of the array feeder (+ a safety margin)
      - if properly set, the phase-to-ground loops will effectively be disabled for all healthy feeders during reverse ground faults, and only be enabled in the faulty feeder
        - a time delay for the release is normally not required- however, for more challenging applications (e.g. if the capacitive ground fault current of the feeder is close to the set level), a small time delay (e.g. 25 ms) can be used in order to avoid transient pickup during ground fault inception

Solution verification



SLD of PowerFactory® model

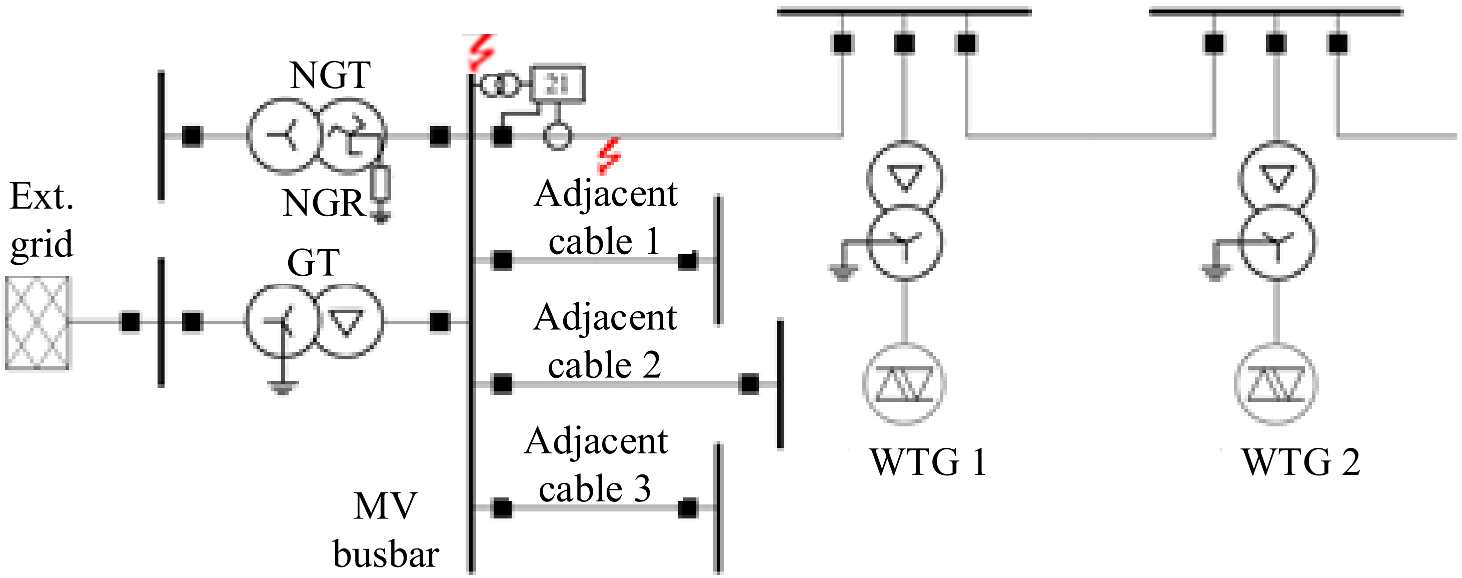
- Software simulations
  - phasor-based (steady-state)

Summary of results

Function	Case 1	Case 2	Case 3	Case 4
67N FW	YES	YES	YES	NO
59N	YES 119.63 kV	YES 148.23 kV	YES 156.33 kV	YES 156.34 kV
59PhG	YES 80.7 kV	YES 99.62 kV	YES 105.06 kV	YES 105.06 kV
27PhPh	NO 55.41 kV	NO 61.91 kV	NO 65.29 kV	NO 65.29 kV
FW EF	FW	FW	FW	REV
21N	FW	UDT	UDT	REV

UDT = undetermined

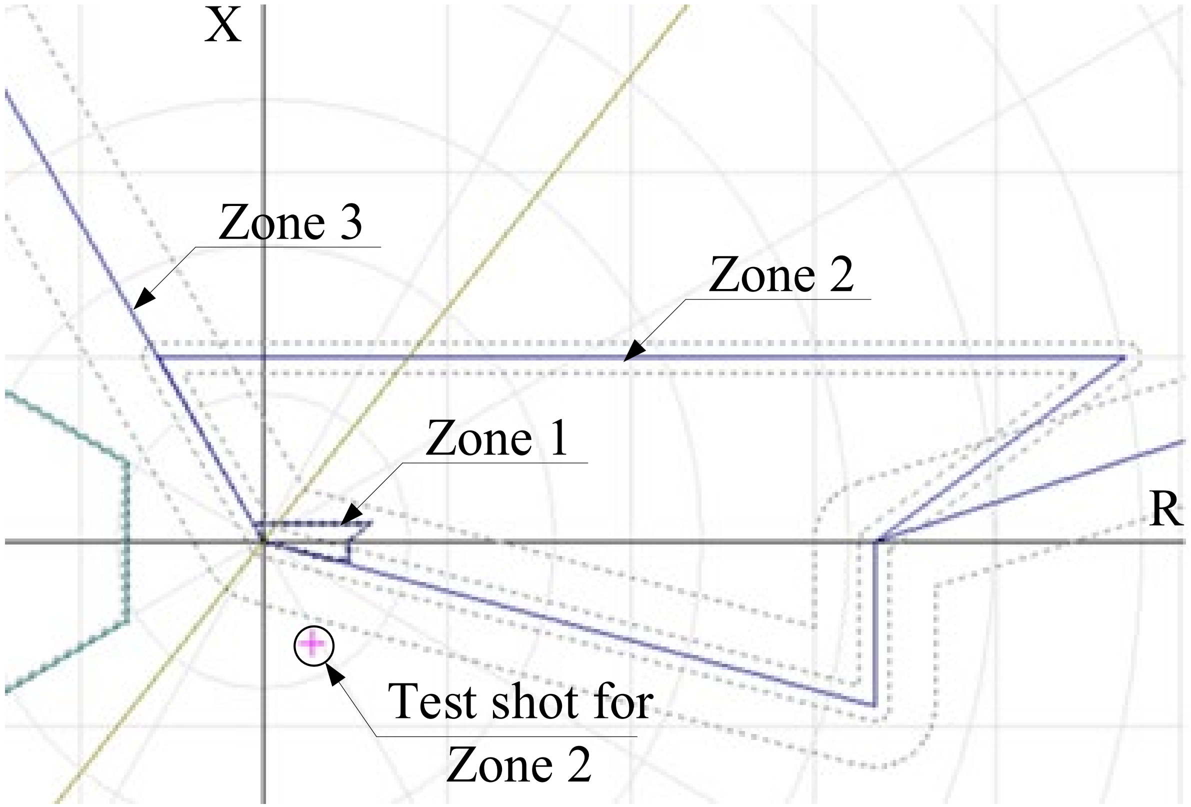
Solution verification



SLD of PowerFactory® model

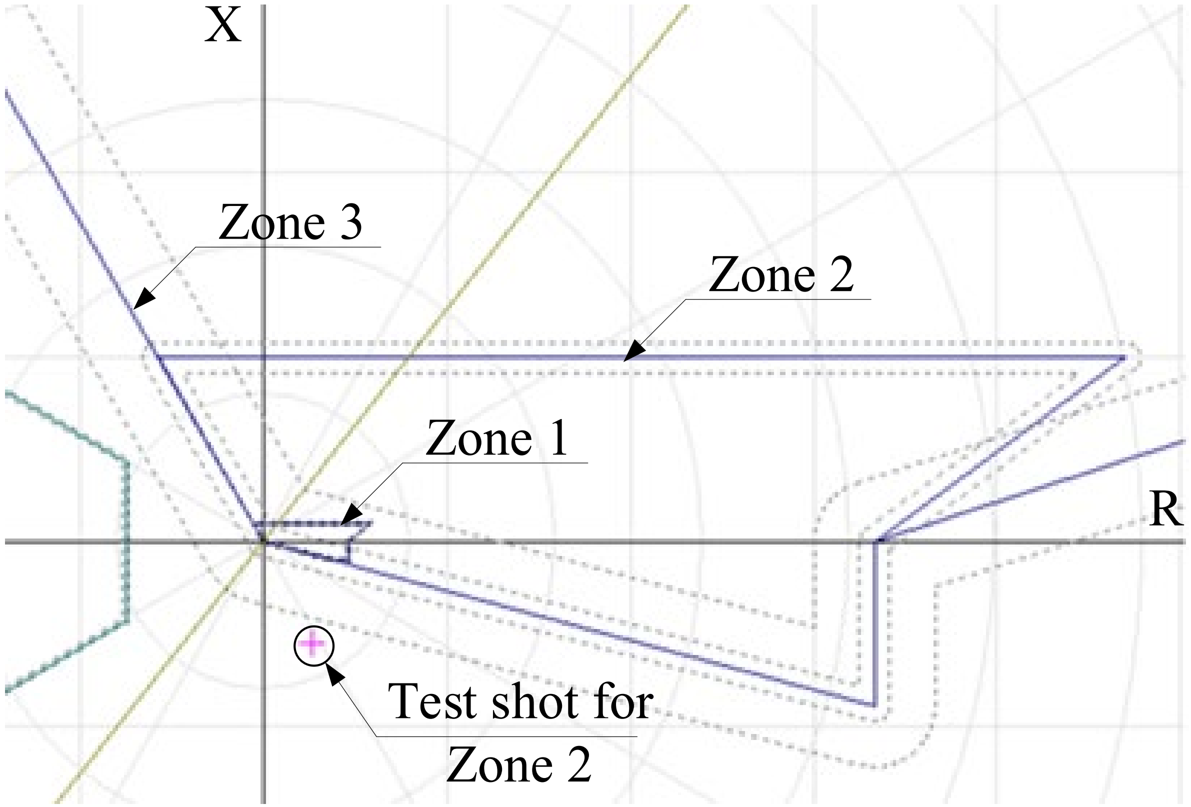
- Dynamic EMT simulations
- EMT simulation results => COMTRADE
- COMTRADE => secondary injection
- Analysis of relay response

Site testing (commissioning)



- Testing of individual directional ground distance zone settings via conventional search tests or shot tests
- Testing of individual settings for additional functional elements used (pickup current and RCA for 67N directional ground fault element; pickup settings for 59N, 59 phase-to-ground, and 27 phase-to-phase elements; and overall test of the new forward ground fault detected logic
- Testing of individual non-directional ground distance zone settings via conventional search tests or shot tests (for each forward-looking distance protection zone)

Site testing (commissioning)



- Testing of the tripping logic for the optimized directional supervision function for each forward-looking distance protection zone
  - this is to be done via shot tests for faults simulated outside of the zone of standard directional ground distance protection with fulfilled conditions for the operation of the new forward ground fault detected logic and non-directional start of ground distance zone

Conclusions

- Special measures shall be taken to optimize ground distance protection performance during single line to ground faults in wind farm collection networks
- New optimized logic for ground distance protection has been proposed, verified, tested, installed and commissioned. Scheme is already in operation
- Application of the optimized logic will improve ground distance protection selectivity and stability during ground faults, improve reliability and availability of wind power generation

Conclusions

- Be aware of what you are taking "for granted" in modern power system especially if they are grounded via an impedance and a lot of power cables are used
- For example, the following assumptions <u>might be wrong</u>:
  - for forward faults measured impedance by distance protection will be always in the first quadrant
  - capacitive ground fault currents are small, and consequently they can be neglected
  - power system is always inductive
  - source impedance angles are always close to 90 degrees