Export Cable Protection for Offshore Wind Farms Using Type-IV Wind Turbine Generators

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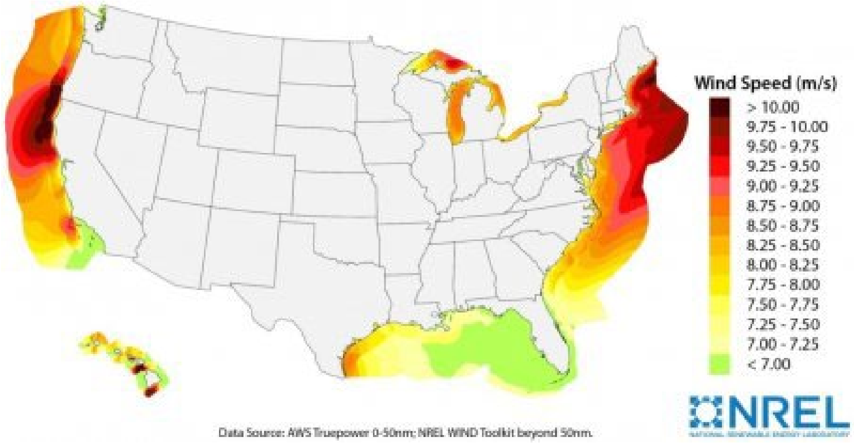
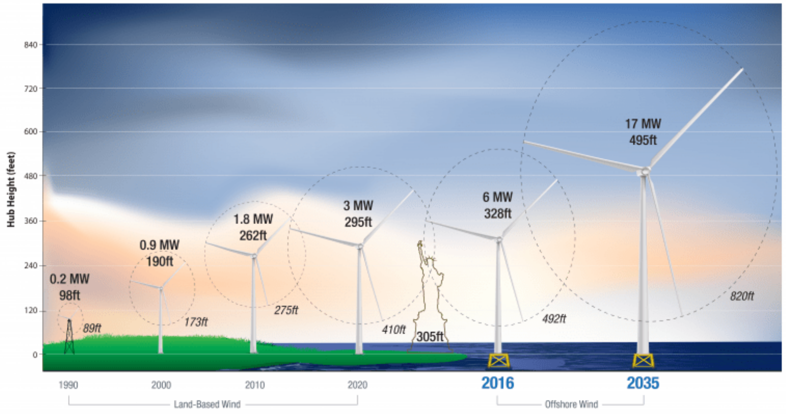
Why Offshore Wind?

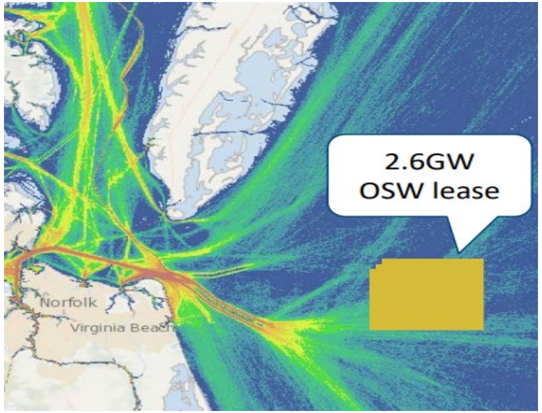
- Offshore wind resources are abundant in the USA.
- Offshore wind turbines are more efficient.
- Offshore wind has lower environmental impact.



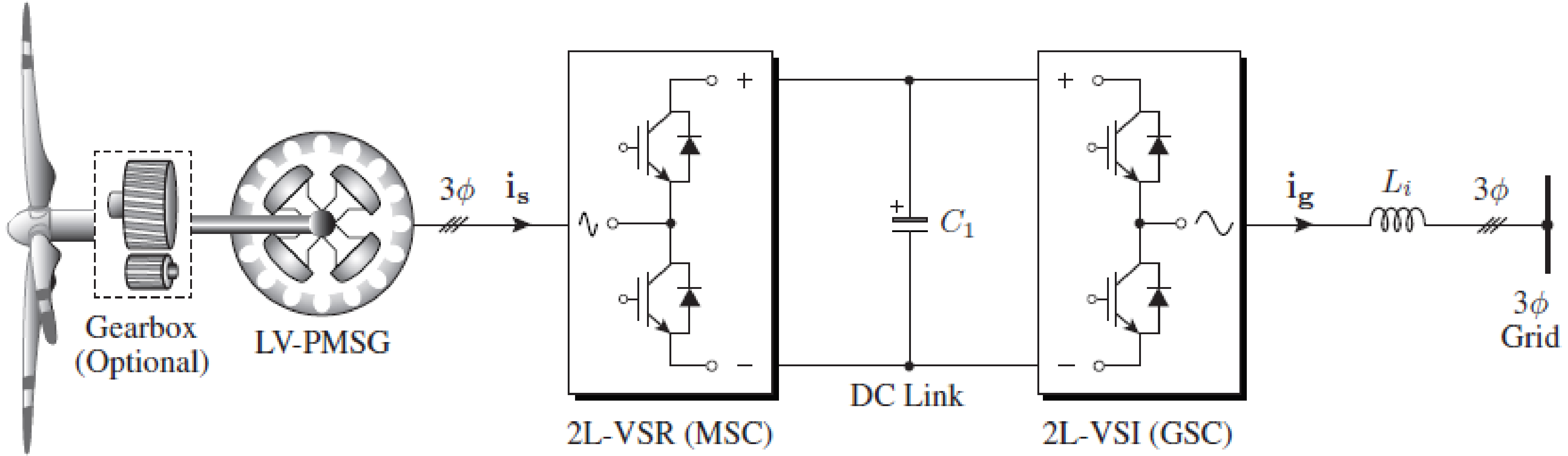


Coastal Virginia Offshore Wind (CVOW) Project

- First of two 6 MW pilot turbines installed on June 20, 2020
- First wind power in Atlantic federal waters
- 2,640 MW project completion in 2026

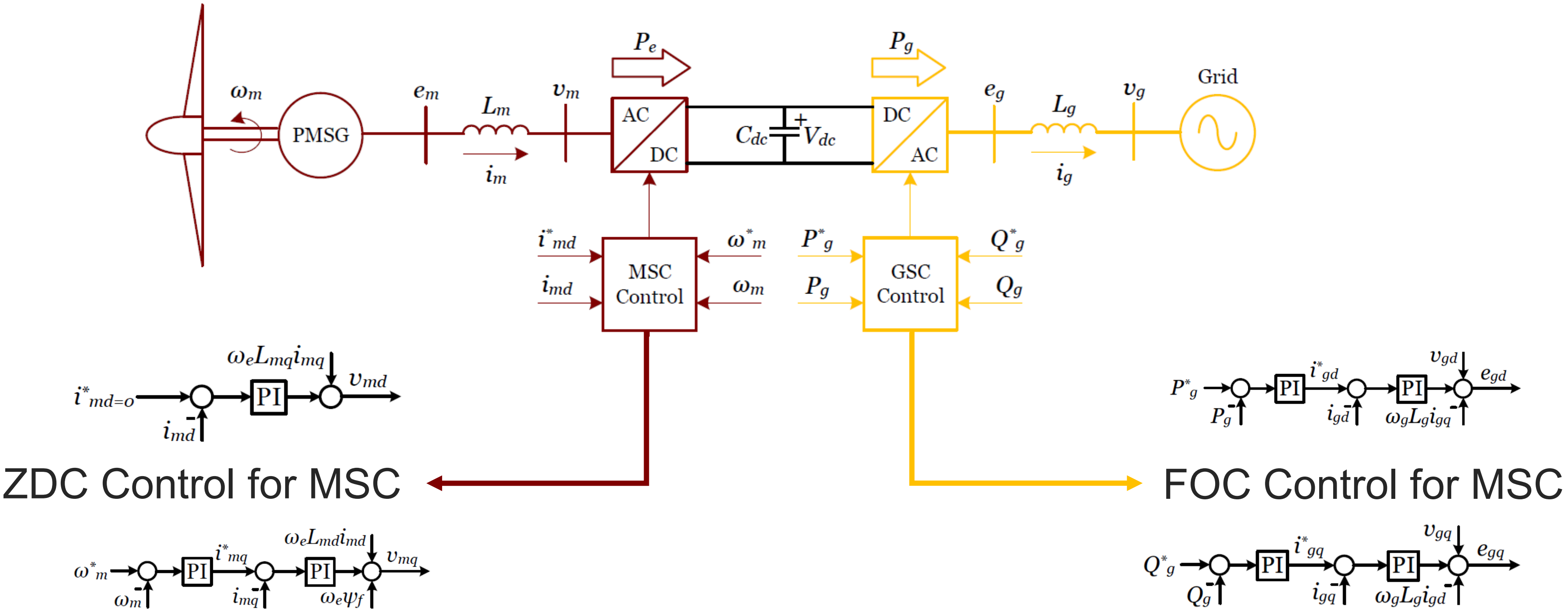


Overview of Type-IV Wind Turbine Technology

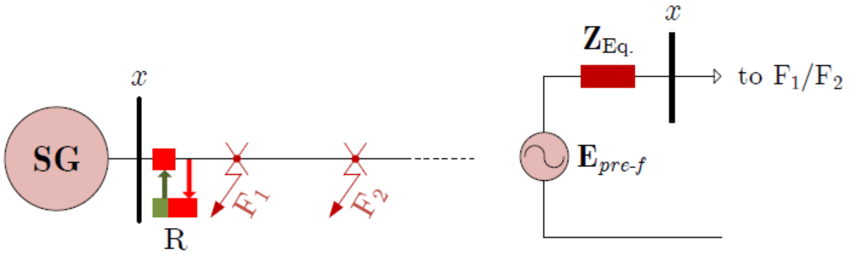


- PMSG: Permanent Magnet Synchronous Generator
- MSC: Machine-Side Converter
- GSC: Grid-Side Converter

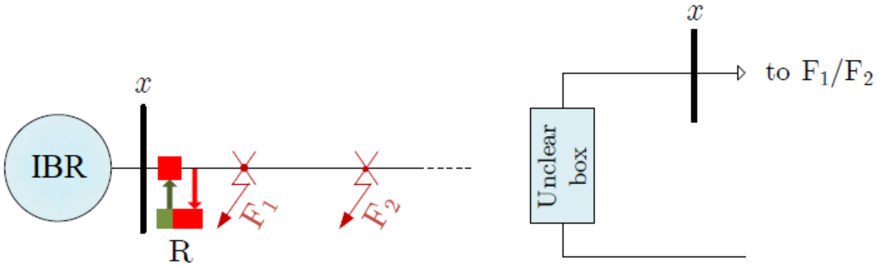
Employed Type-IV Wind Turbine Control System



GSC Operation Under Faults

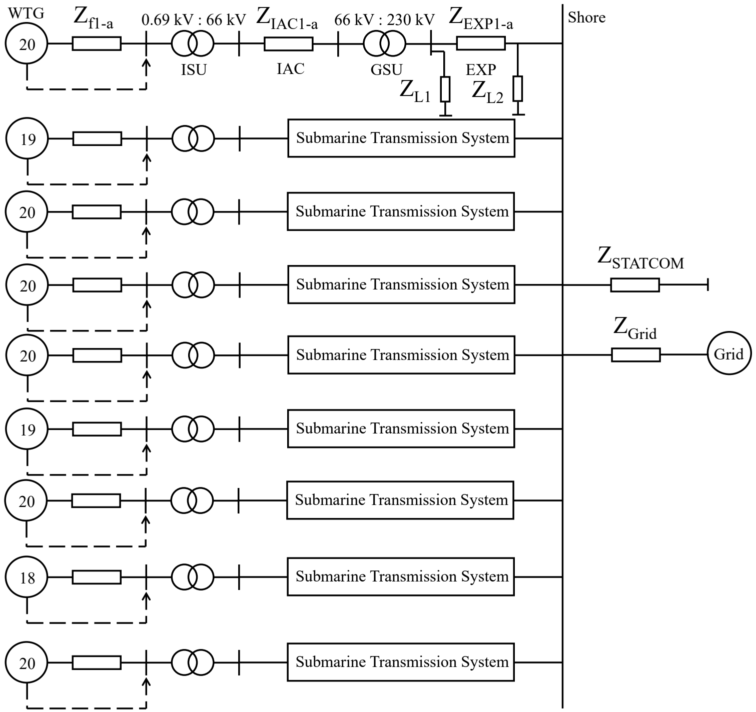


- Conventional synchronous generators (SG) have a well-documented response to grid faults.
- Current protection systems are designed to operate with conventional generation.



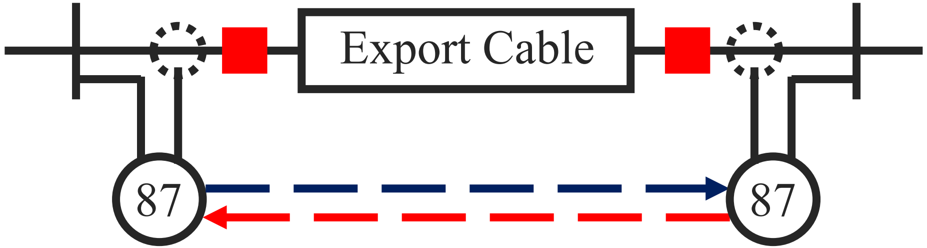
- Inverter-based resources (IBR) are interfaced with the grid via static power electronic circuits.
- IBRs demonstrate a very unconventional response to faults in the system.

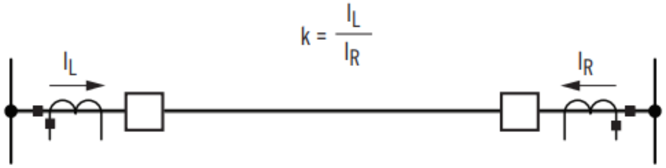
Employed Offshore Wind Farm Model

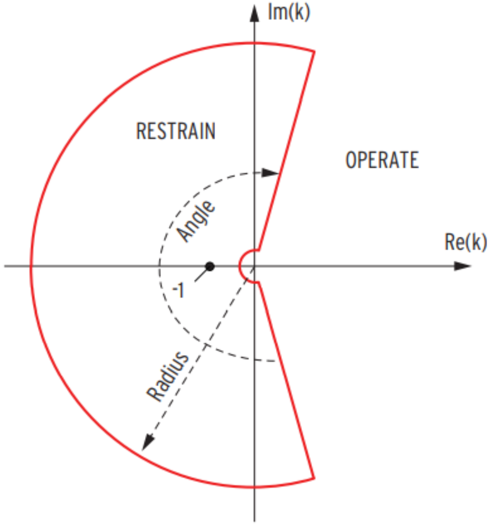


- The employed RTDS model includes three offshore substations, each interconnected with three aggregated wind turbine strings.
- Each aggregated string connects to the onshore substation via an aggregated inverter step-up transformer, submarine inter-array cable, generator step-up transformer, and an export cable.
- Shunt reactors are added offshore and onshore with three onshore STATCOMs.

Export Cable Primary Protection Design

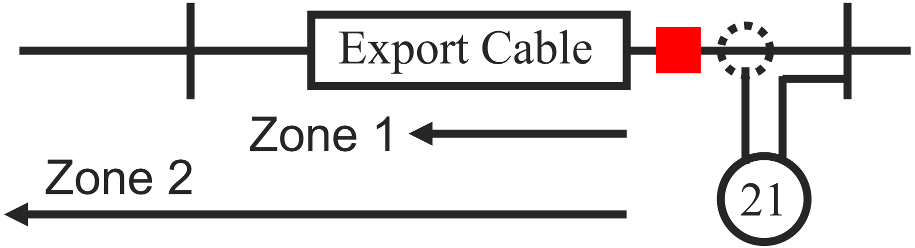


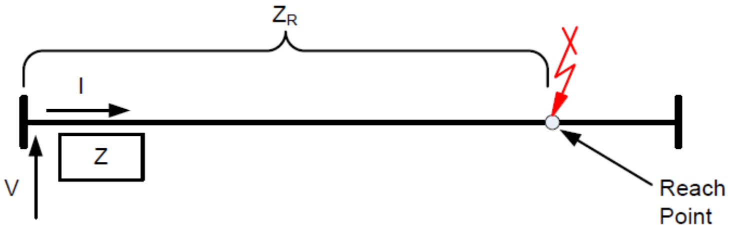




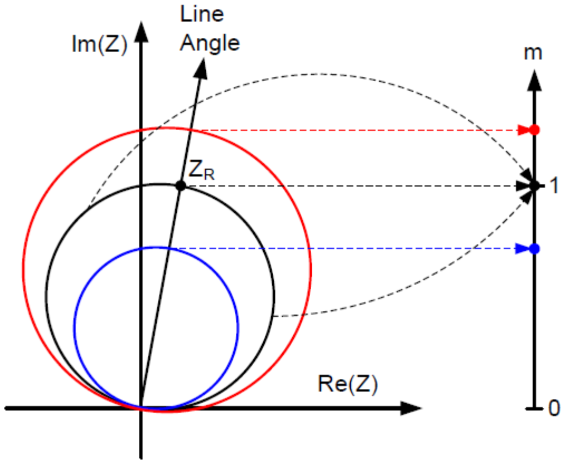
- Primary export cable protection scheme is set to current differential (87).
- Differential relays communicate with current phasors.
- Current phasor ratio is calculated by each relay.
- The relay trips if the ratio falls in the operate region.

Export Cable Backup Protection Design



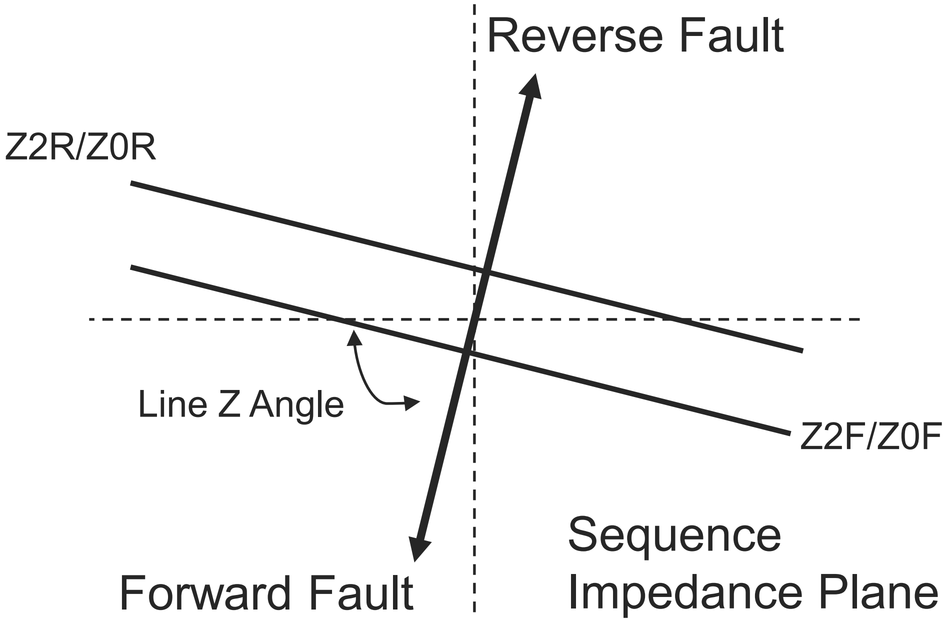


- Distance protection (21) is used as backup onshore.
- Zone 1 reaches for 80% of the line.
- Zone 2 reaches for 150% of the line.
- Instantaneous trip is issued for Zone 1 faults.
- Relay operation is delayed by 42 cycles for Zone 2 faults.

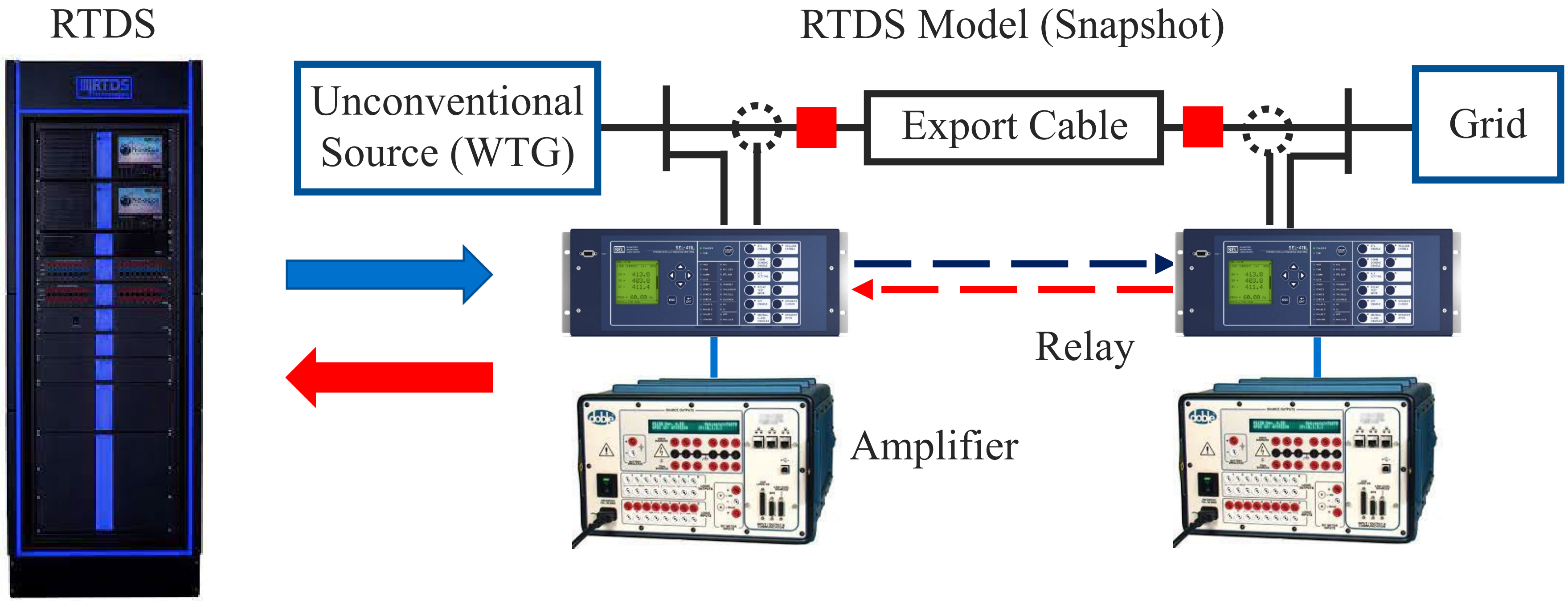


Export Cable Protection Directionality Elements

- Zero-sequence voltage has priority for ground fault directionality.
- Negative-sequence voltage has priority for phase fault directionality, followed by positive-sequence voltage.
- Sequence impedance thresholds recommended by the relay manufacturer were used.
- Z2F = Z0F = -0.3.
- Z2R = Z0R = 0.3.



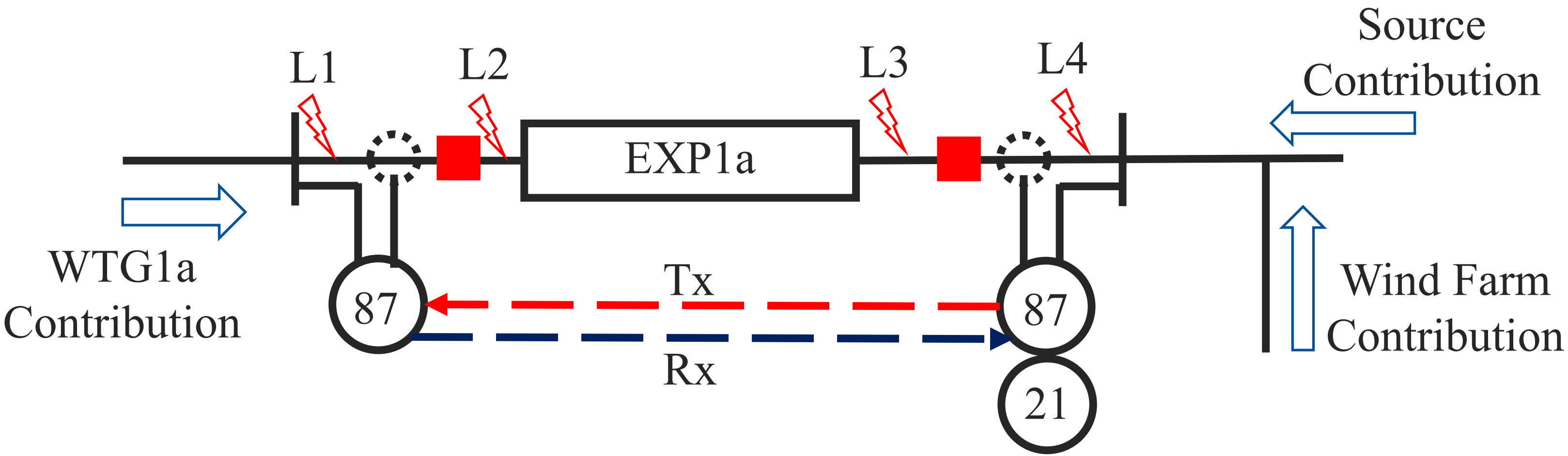
Export Cable Protection Testing Design Using HIL



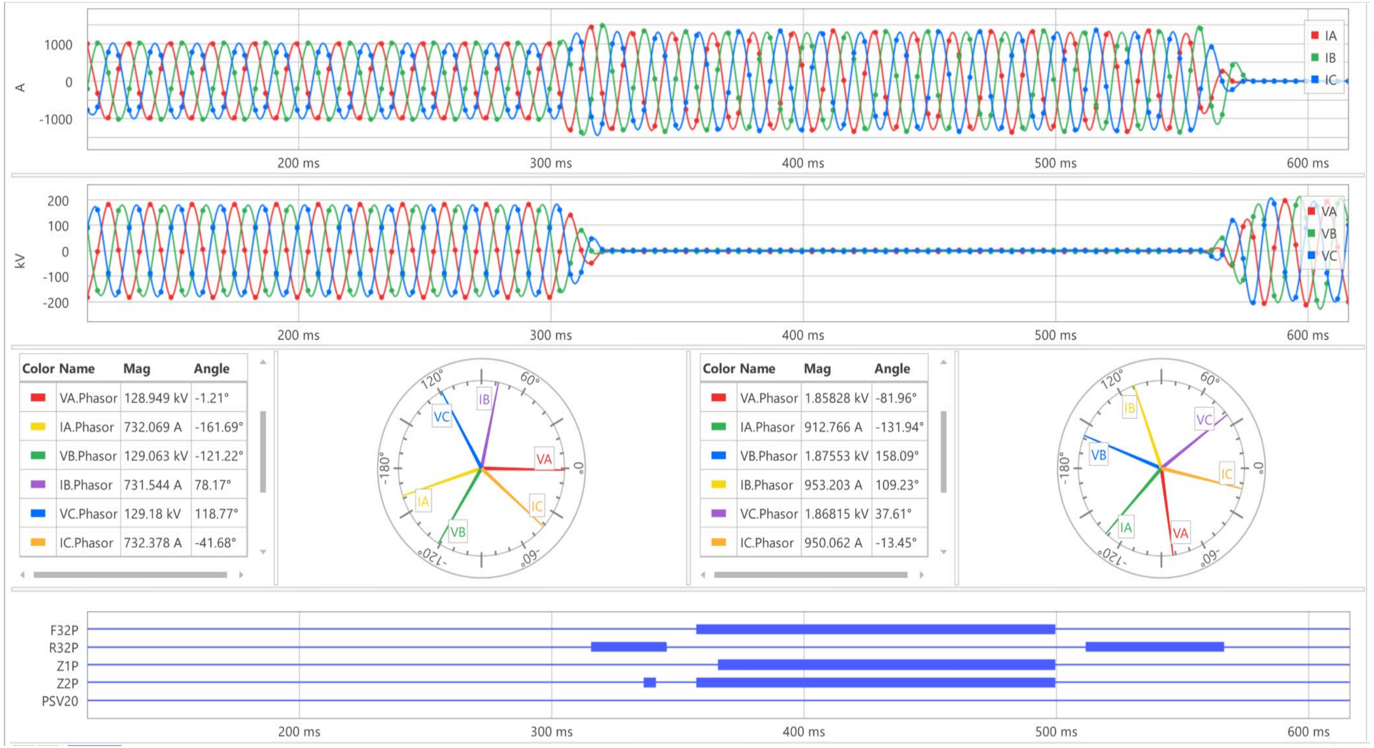
Export Cable Protection Design Using HIL

- RTDS is used for real-time simulation.
- Two relays are used for protection testing.
- Fiber optic links are established for communication.
- Signal amplification is provided by two amplifiers.
- Relay event reports are extracted and analyzed.

Case Studies



Performance Evaluation for ABCG Fault at L4



Color	Name	Mag	Angle
	VA.Phasor	128.949 kV	-1.21°
	IA.Phasor	732.069 A	-161.69°
	VB.Phasor	129.063 kV	-121.22°
	IB.Phasor	731.544 A	78.17°
	VC.Phasor	129.18 kV	118.77°
	IC.Phasor	732.378 A	-41.68°

Color	Name	Mag	Angle
	VA.Phasor	1.85828 kV	-81.96°
	IA.Phasor	912.766 A	-131.94°
	VB.Phasor	1.87553 kV	158.09°
	IB.Phasor	953.203 A	109.23°
	VC.Phasor	1.86815 kV	37.61°
	IC.Phasor	950.062 A	-13.45°

Onshore Relay Performance under ABCG Fault at L4:

- F32P asserted.
- Z1P asserted.
- Trip issued.

Performance Evaluation Summary

Performance Summary for the Relay Onshore

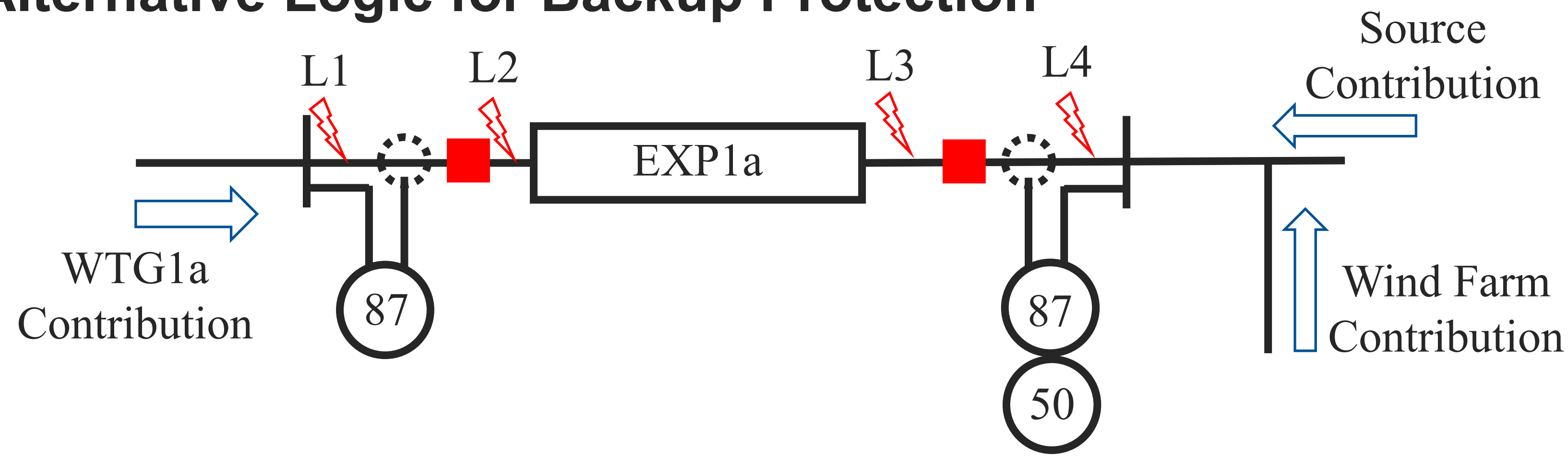
Misoperation

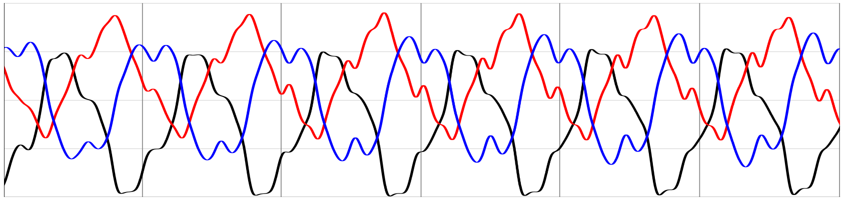
Fault Location	Operating Element			Directionality Results			Operation Time		
	ABCG	AB	AG	ABCG	AB	AG	ABCG	AB	AG
L1 (Out-of-Zone)	Z2P Distance	Z2P Distance	51G	F32P	F32P	F32V	708.47 ms	704.16 ms	855 ms
L2 (In-Zone)	87OP	87OP	87OP	F32P	F32P	F32V	4 ms	16.667 ms	8 ms
L3 (In-Zone)	87OP	87OP	87OP	F32P	F32P	F32V	8 ms	12.5 ms	8 ms
L4 (Reverse)	**Z1P Distance**	**Z1P Distance**	--	**F32P**	**F32P**	R32V	--	--	--

Performance Summary for the Relay Offshore

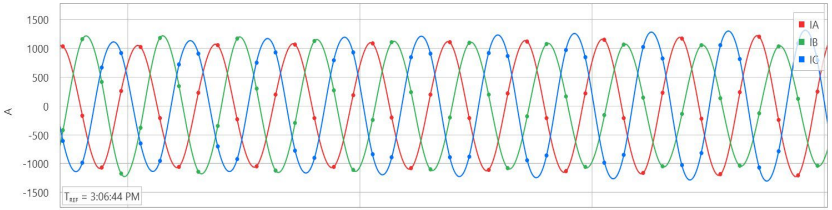
Fault Location	Operating Element			Directionality Results			Operation Time		
	ABCG	AB	AG	ABCG	AB	AG	ABCG	AB	AG
L1 (Out-of-Zone)	--	--	--	--	--	--	--	--	--
L2 (In-Zone)	87OP	87OP	87OP	F32P	F32P	F32V	4 ms	16.667 ms	8 ms
L3 (In-Zone)	87OP	87OP	87OP	F32P	F32P	F32V	8 ms	12.5 ms	8 ms
L4 (Reverse)	--	--	--	--	--	--	--	--	--

Alternative Logic for Backup Protection





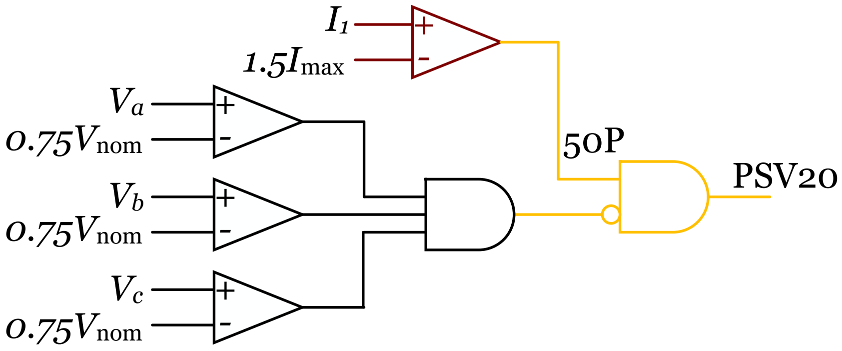
Actual WTG Response



Filtered WTG Response

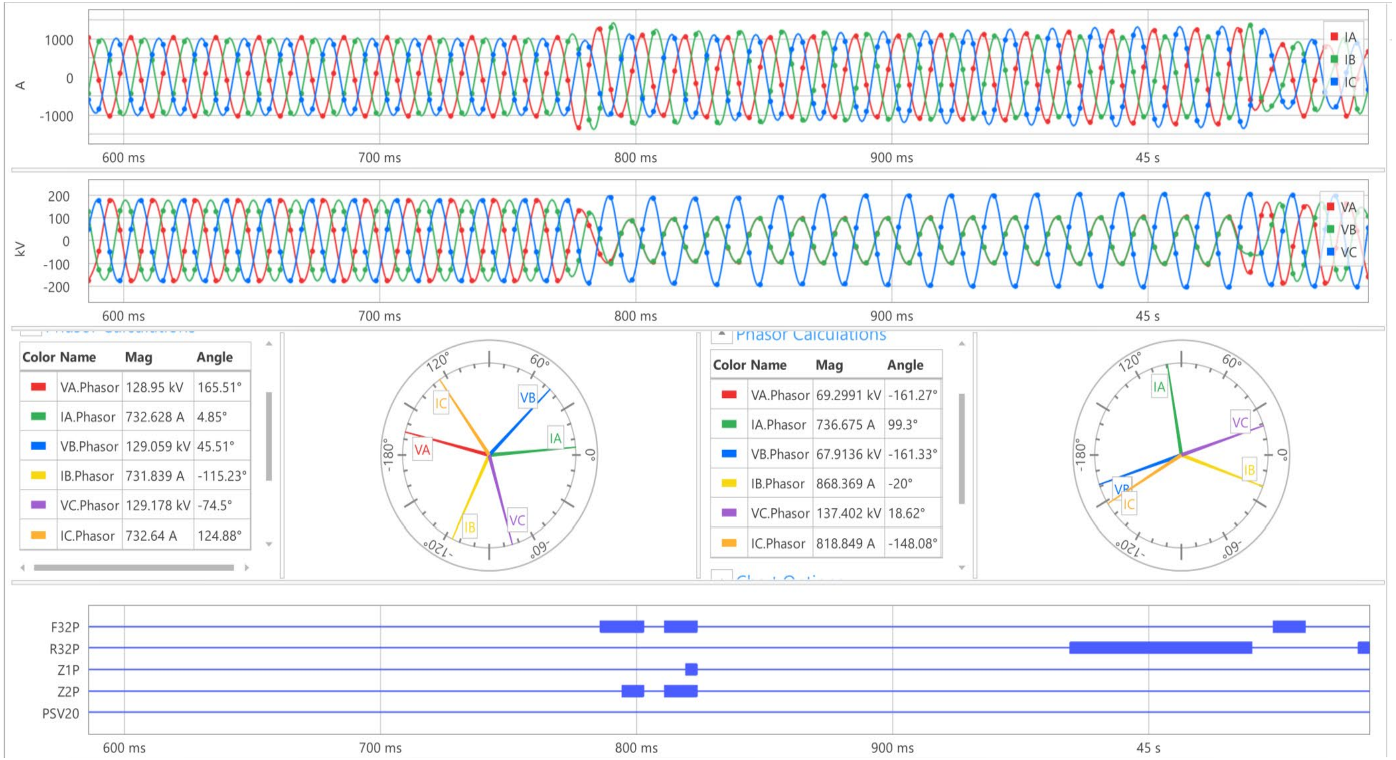
Alternative Logic for Backup Protection

- Voltage-restrained overcurrent logic provides adequate coverage while increasing scheme security.
- Overcurrent elements are less likely to misoperate due to distorted waveforms.
- Element will not operate if voltage is > 75% of nominal on all three phases.
- Overcurrent pickup set at 150% of export cable load allowance.



Proposed Logic

Performance Evaluation for AB Fault at L4 (Proposed Logic)



Onshore Relay Performance under AB Fault at L4:

- F32P asserted.
- Z1P asserted.
- PSV20 remains de-asserted.

Conclusions

- Current differential protection operated correctly for all scenarios.
- Distance protection misoperated under reverse ABCG and AB faults.
- An overcurrent logic is proposed to replace distance protection.

Future Work

- Dynamic modeling of STATCOMs onshore for further protection studies.
- Protection studies with fault ride-through (FRT) enabled for wind turbines.
- Analyze impact of WTG generation on the proposed logic's performance.