Protection of Future Power Systems with high Penetration of Distribution Generation

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INTRODUCTION

- OBJECTIVE
  - Proliferation of Power Electronics (PE) devices in the pan-European transmission system.
- TIME HORIZONS
  - Short to medium term
    - Incremental technology-based solutions: Operating the existing electric HVAC system with a growing penetration of PE devices.
  - Long term
    - Breakthrough technology-based solutions: Transition towards an HVAC electric system where all generation and consumption is connected via 100% PE.

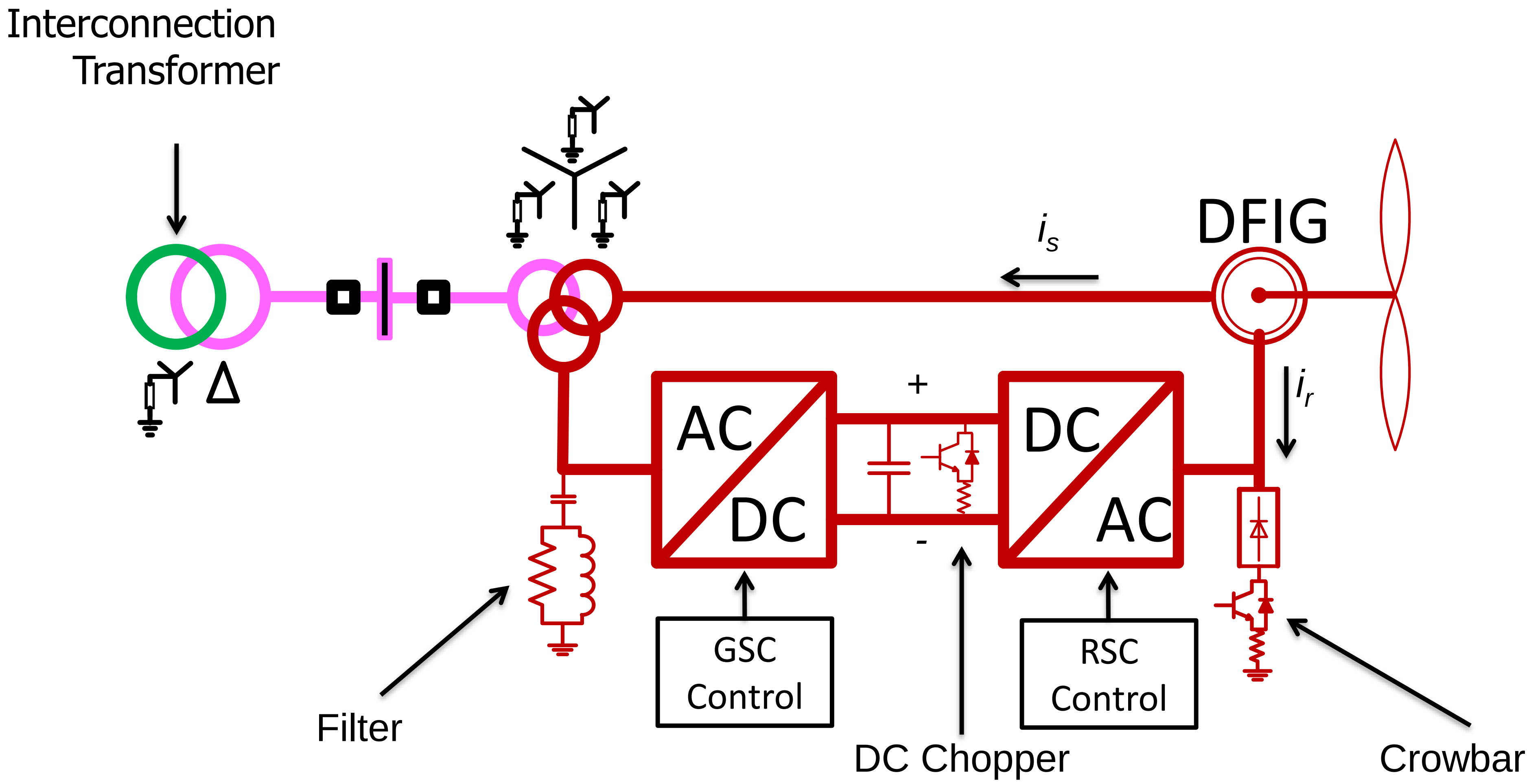
INTRODUCTION

- TASK 4.1: Accurate models for desktop protection studies and HiL tests
  - Benchmark system with high PE penetration.
  - Accurate converter models and their control systems.
- TASK 4.2: Assessment of the existing protection functions/solutions under high PE penetration
  - Capability of existing short circuit protections.
  - Short circuit magnitude different from SGs depending on:
  - Penetration of PE-based renewable electricity generators
  - Grid interfaces (high penetration of inverter-connected units)
  - HiL (Hardware-in-the-Loop) techniques.
  - Performance verification of present protection schemes.

INTRODUCTION

- ❑ TASK 4.3: Development and test of new protection solution when reached high PE penetration
  - Providing solutions to the shortcoming of existing protection systems by introducing new protection and technologies.
- ❑ TASK 4.4: Proof of Concepts
  - The feasibility (technical & economical) of the proposed solutions will be assessed by further HiL tests.
- ❑ TASK 4.5: Power system design for a secure system with high PE penetration
  - Recommendations

TASK 4.1 DFIG SYSTEM



TASK 4.1 DFIG CONTROLS

Crowbar And Chopper Protection

Chopper (Voltage limit)

Crowbar (Current limit, Time action, Impedance)

Converters (Grid Following Control)

Gsc Control Strategies

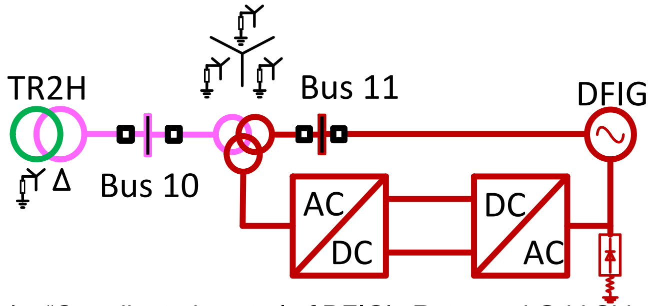
(Positive: DC voltage, Reactive power supply)

(Negative: 2ω minimization)

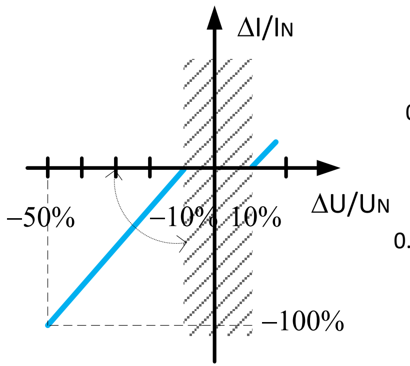
Rsc Control Strategies

Positive: Reactive power support, MPPT

Negative: 2ω minimization

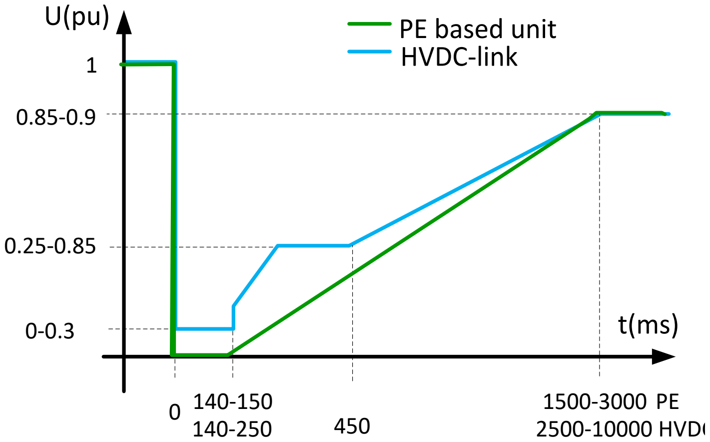


L. Xiu, "Coordinated control of DFIG's Rotor and Grid Side Converters During Network Unbalance" *IEEE Trans. Power Electronics,* Vol 23, No 3, 2008.



Reactive current static:

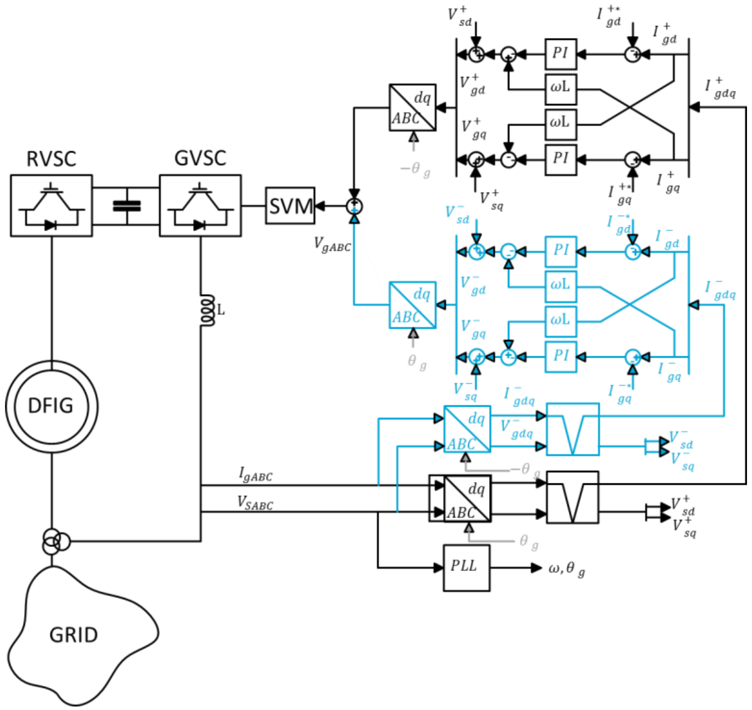
$k=(\Delta I/I_N)/(\Delta U/U_N)$



TASK 4.1 DFIG CONTROL

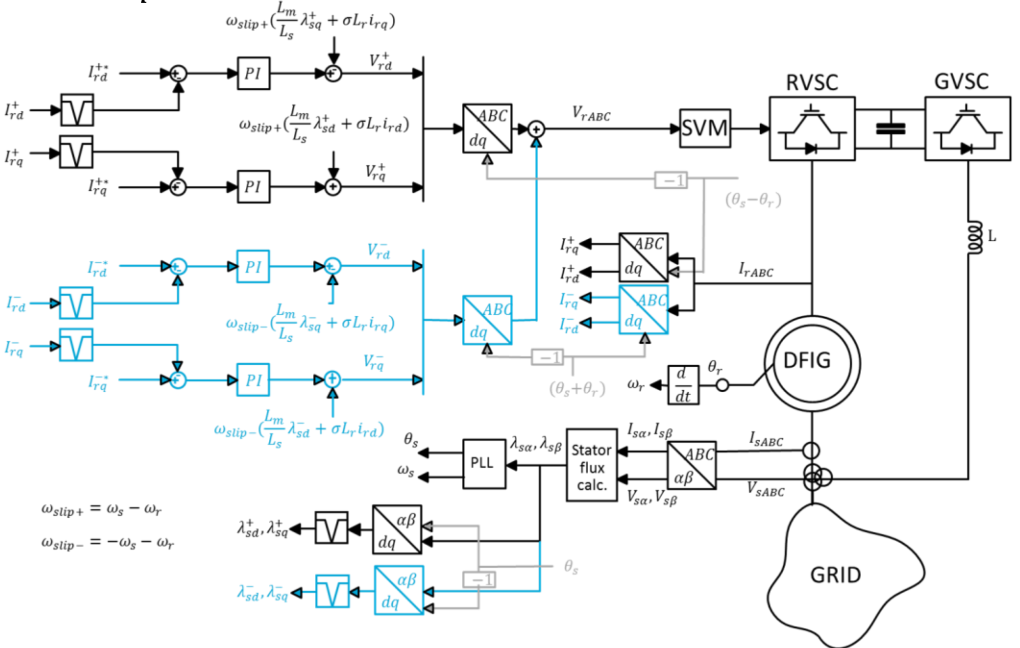
– **Positive Frame:**

- **GSC reference**:
  – I_{gd}^{+*} by DC voltage regulator
  – I_{gq}^{+*} by Grid Code at PCC
- **RSC reference**:
  – I_{rd}^{+*} by the Grid Code at PCC
  – I_{rq}^{+*} by optimal power reference calculation



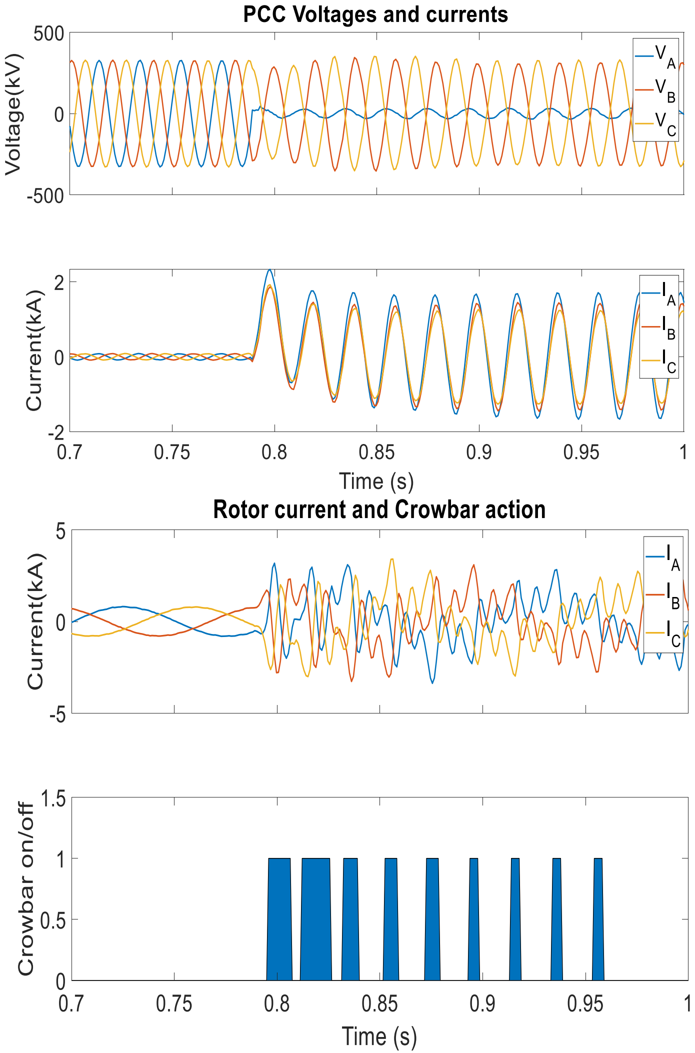
– **Negatieve Frame:**

- **GSC reference**:
  – Stator and GSC active power harmonics components equals.
  – I_{gd}^{-*} Zero active power pulsation ($P_{gcos2} = P_{ecos2}$)
  – I_{gd}^{-*} Zero active power pulsation ($P_{gsin2} = P_{esin2}$)
- **RSC reference**:
  – Harmonics components of active power set to zero
  – I_{rd}^{-*} Torque oscillation minimization ($P_{ecos2} = 0$)
  – I_{rq}^{-*} Torque oscillation minimization($P_{esin2} = 0$)

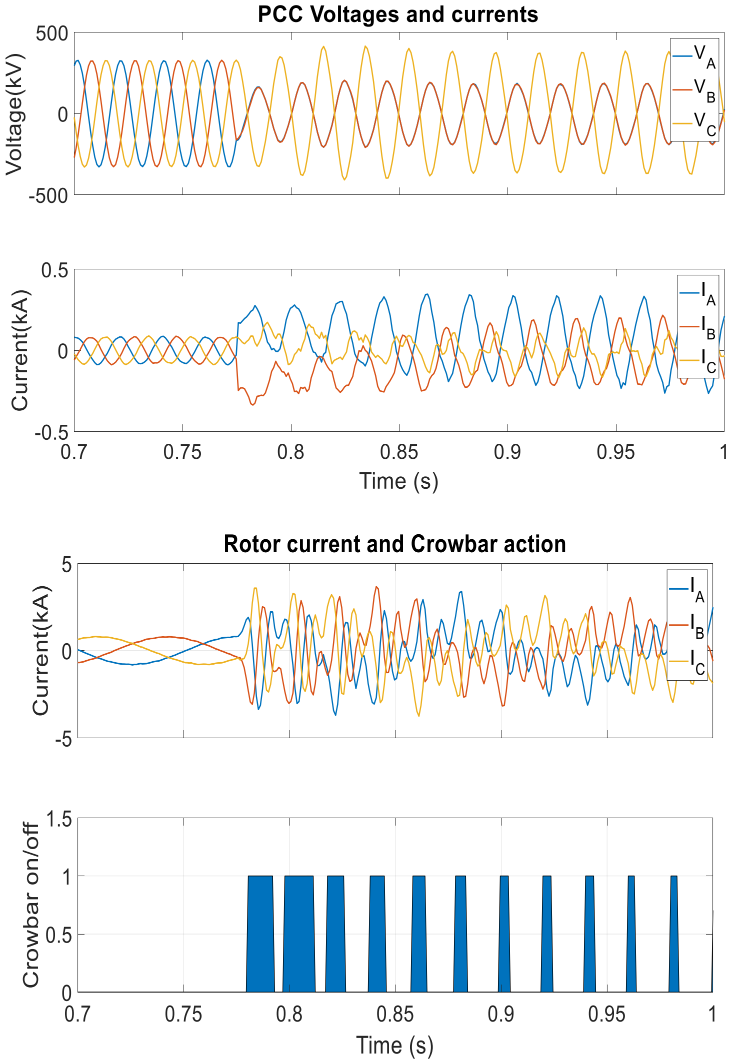


TASK 4.1 SIGNALS DURING A FAULT

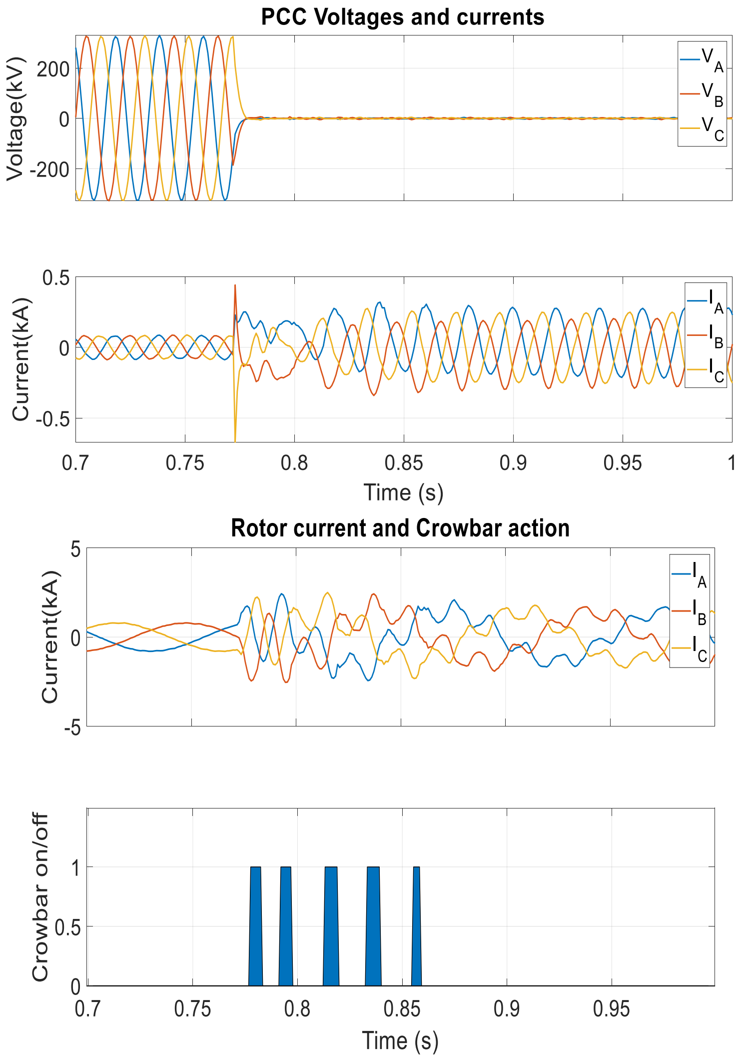
LN fault



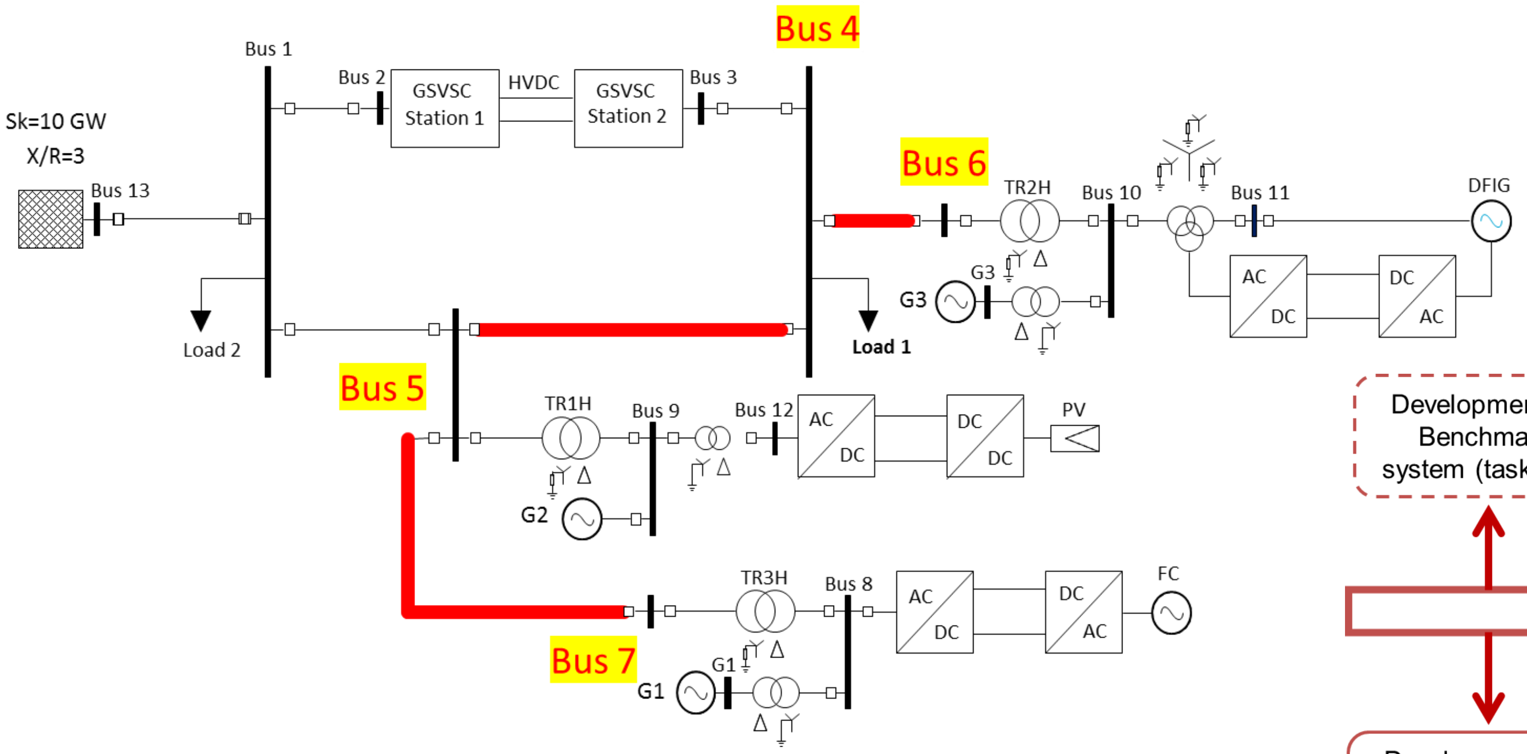
LL fault

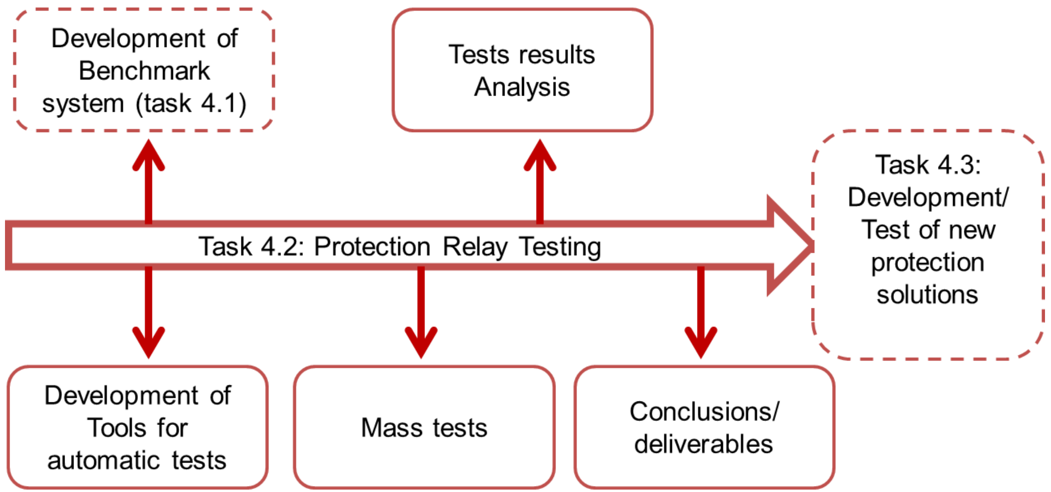


LLL fault



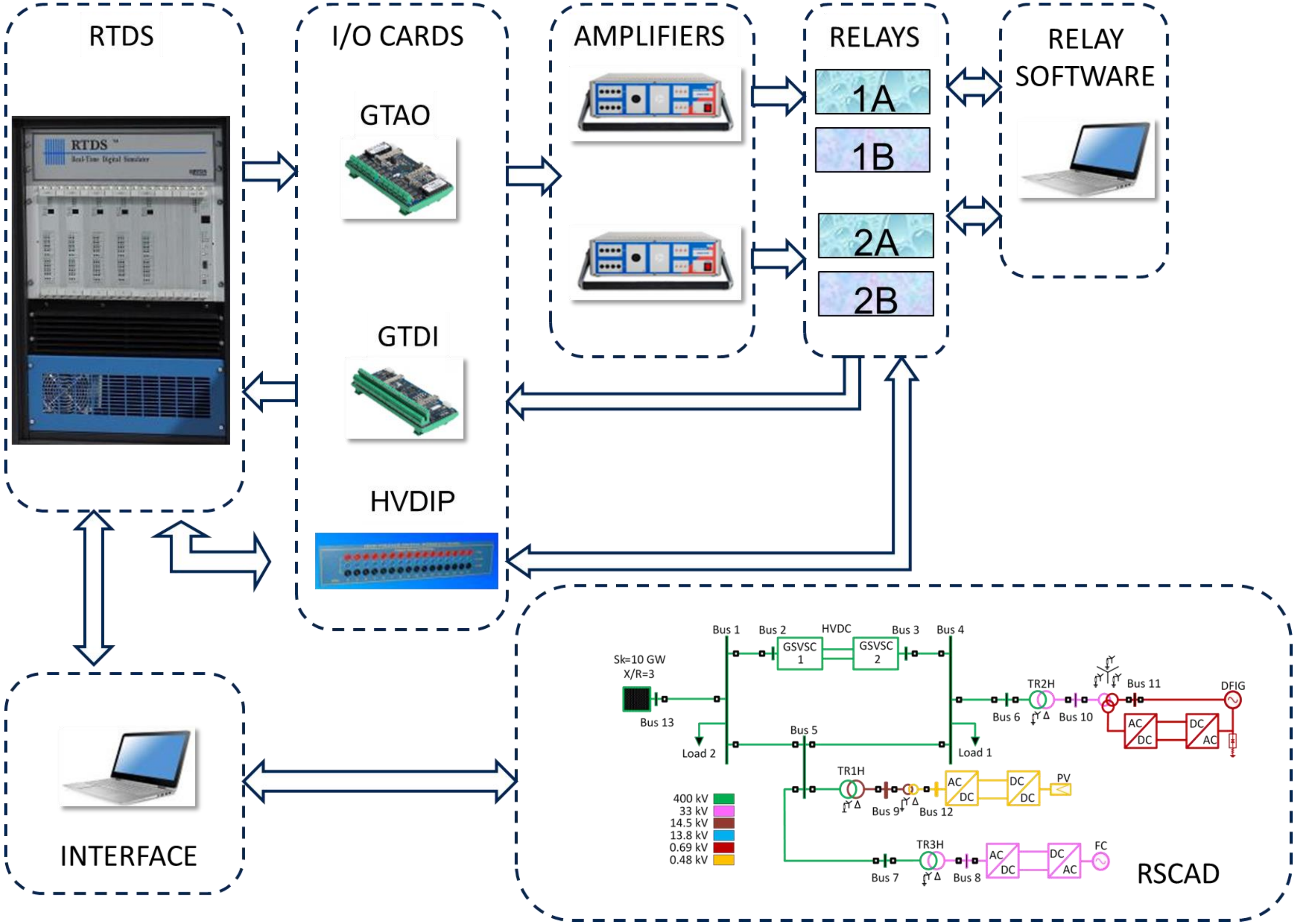
TASK 4.2 SHORT CIRCUIT TRANSMISSION LINES

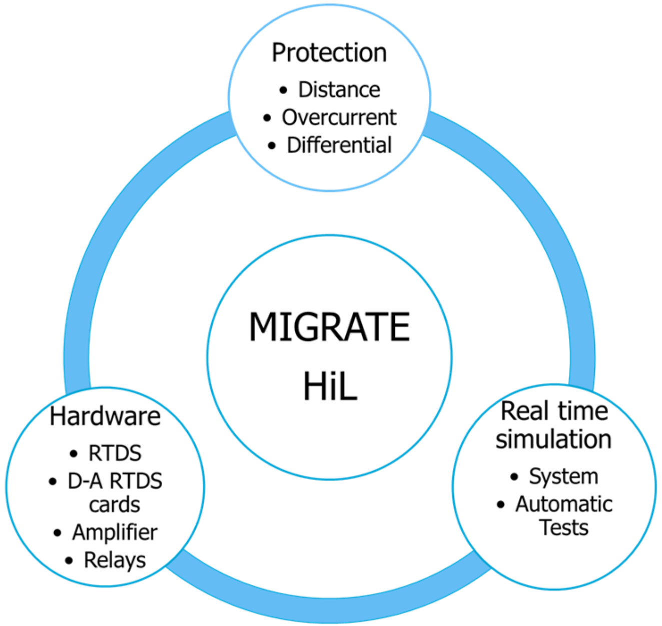




- Faults at Line 4-6, 5-7 and 5-4
- The Benchmark model developed reproduces potential problems for protections due to high level of penetration of power electronics

TASK 4.2 HARDWARE IN LOOP



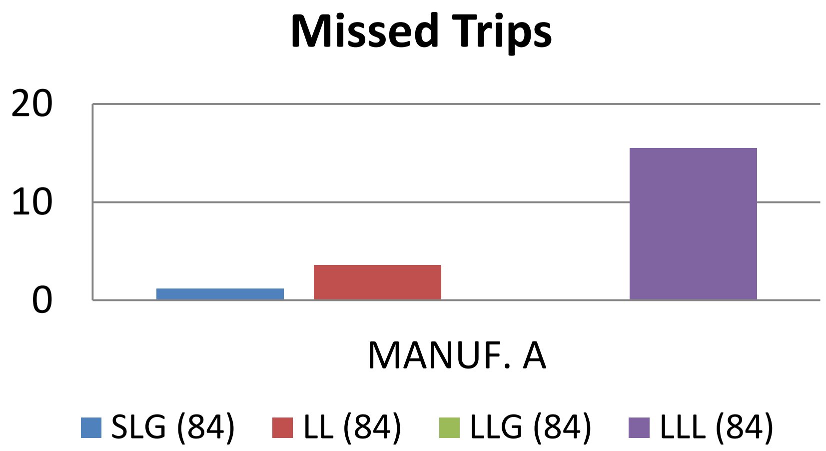


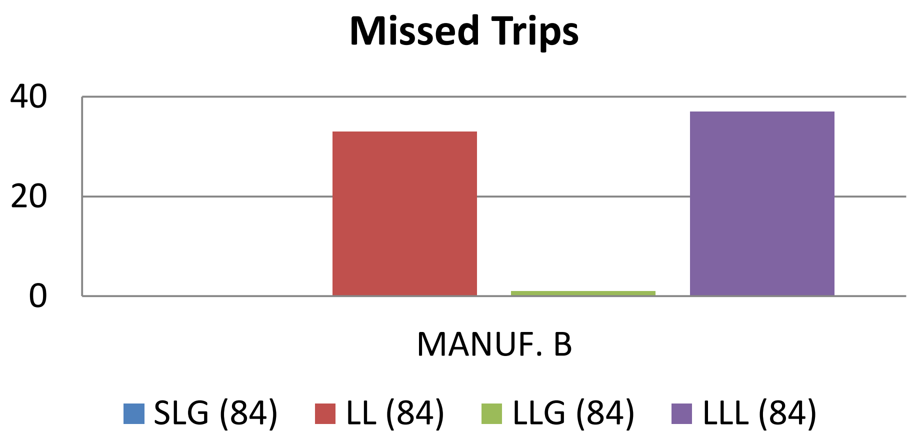
TASK 4.2 HIL TESTS

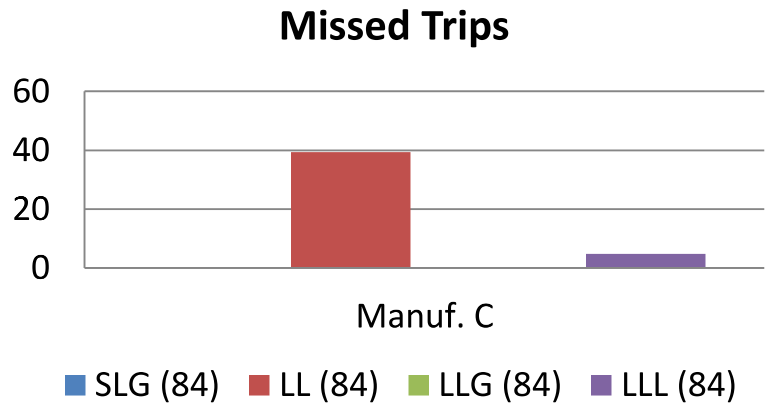
Priority	COMBINATIONS	DIFFERENTIAL PROTECTION	DISTANCE PROTECTION	DIRECTIONAL PROTECTION	TOTAL NUMBER OF TESTS
1	Protection functions under test	1	1	1	
2	Number of lines	3	3	3	
3	Scenarios	6	6	6	
4	Generation Level	2	2	2	
5	Point of the line	3	7	2	
6	Type of fault	4	4	4	
7	Fault Resistance	1	3	3	
TOTAL NUMBER OF CASES		432	3024	864	**3456**

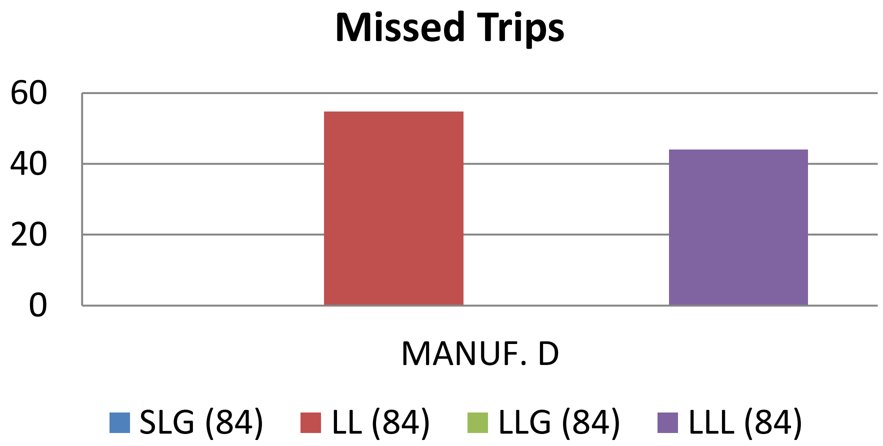
1- protection function
2- number of lines 4-6, 4-5 and 5-7
3 – scenarios (weak and strong grid)x(PE, SG and PE&SG)
4- generation level 40 MW and 200 MW
5 – points of line – 0%, 50% and 90%
6 – type of fault – LG, LLG, LLL and LL
7 – fault resistance 0 ohm and 1 ohm

TASK 4.2 MISSED TRIPS. LINE 4-6 100% PE SCENARIO

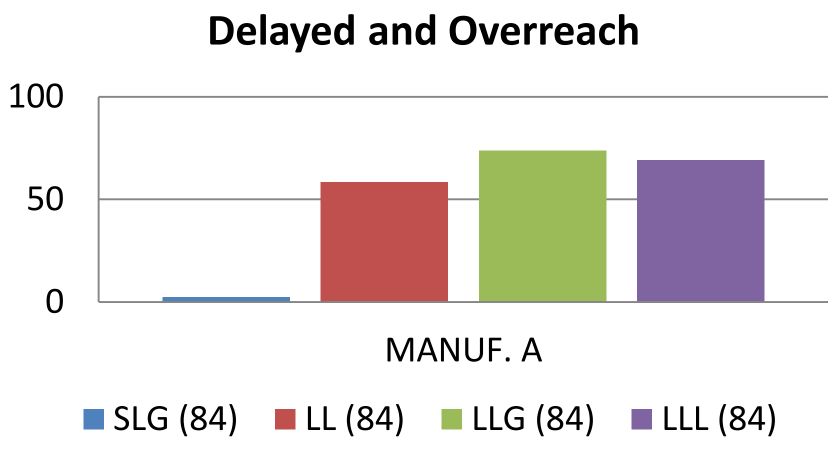


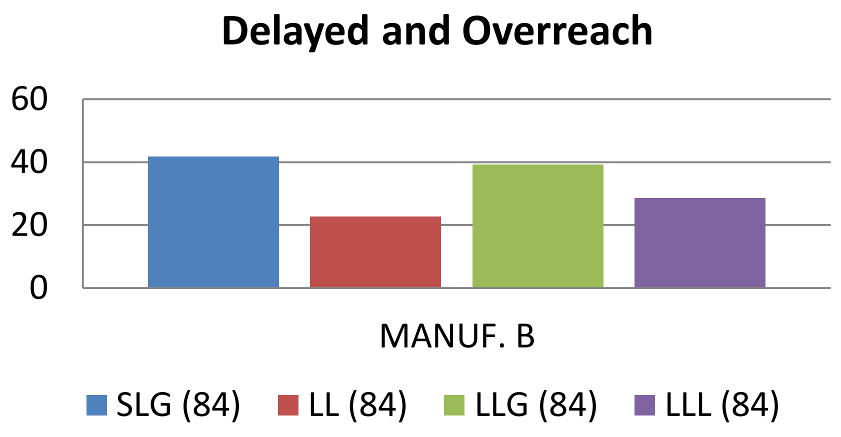


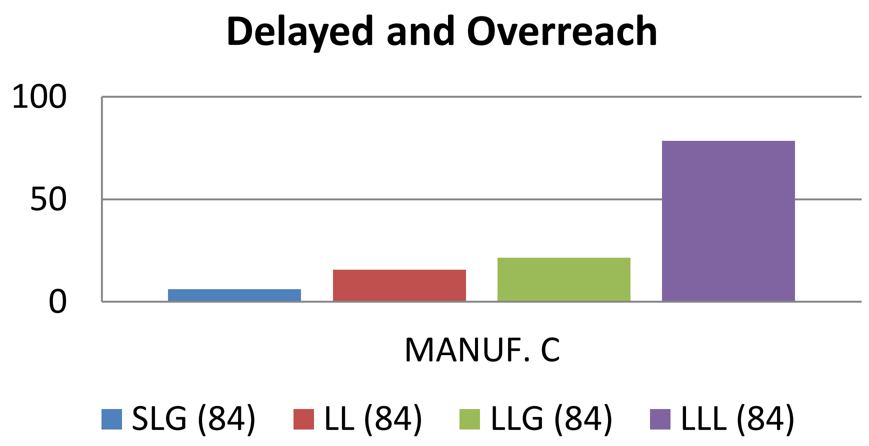


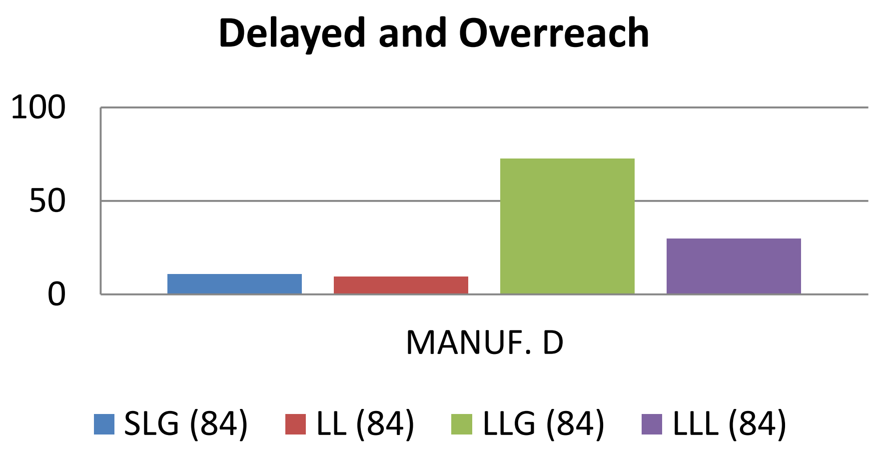


TASK 4.2 DELAYED TRIPS. LINE 4-6 100% PE SCENARIO









TASK 4.2 SUSPICIOUS CASES

						Tripping times			
Test repeated	**Test number**	**Point of the fault**	**Type of fault**	**Generation level**	**Scenario**	**Relay-A**	**Relay-B**	**Relay-C**	**Relay-D**
1	6471	70.0%	LL	40MW	RW_SG	0.031	1.500	1.500	1.500
2	6400	50.0%	LL	40MW	RW_WG	0.177	1.500	1.500	1.500
3	6484	70.0%	LL	200MW	RW_SG	0.035	0.125	0.168	0.026
4	6845	95%	LL	200MW	RW_WG	0.134	1.500	0.267	1.500
5	6692	90.0%	LLG	40MW	RW_WG	1.500	0.580	0.457	0.444
6	6777	95%	LLG	200MW	RW_SG	0.037	0.065	0.468	0.237
7	6852	95%	LLL	200MW	RW_WG	0.338	0.312	0.218	0.194

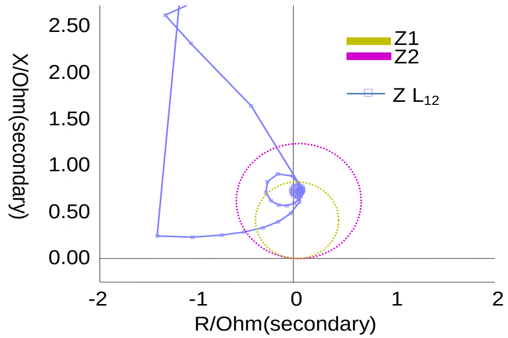
No operation

Suspicious operation

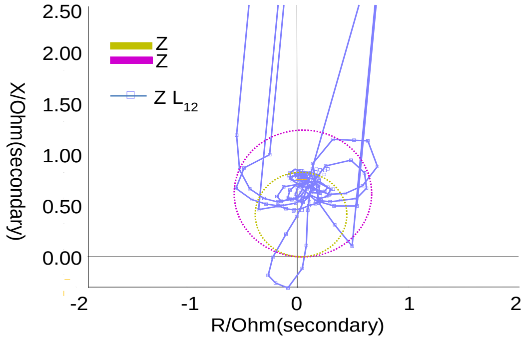
TASK 4.2: IMPEDANCE TRAJECTORY AND RMS CURRENT

LL FAULT at 70% TL 0Ω

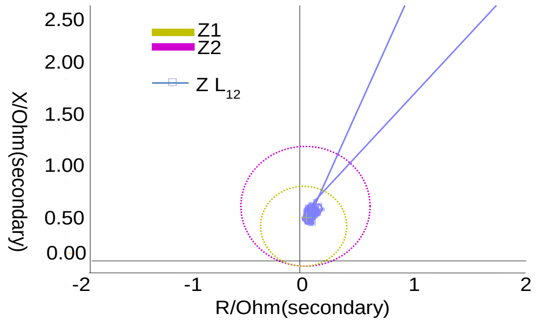
SG 40MW

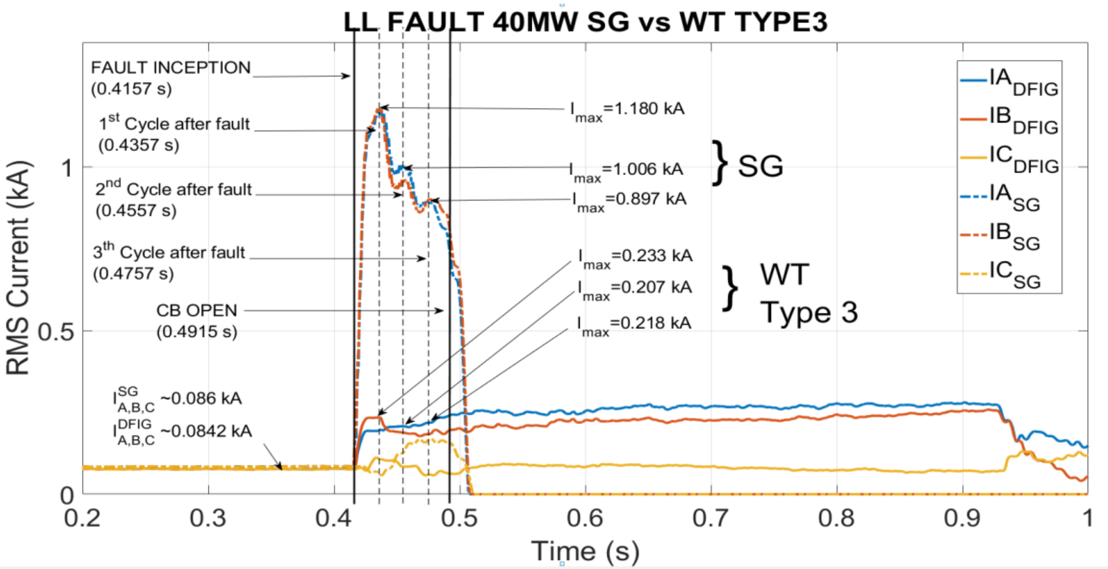


DFIG 40MW

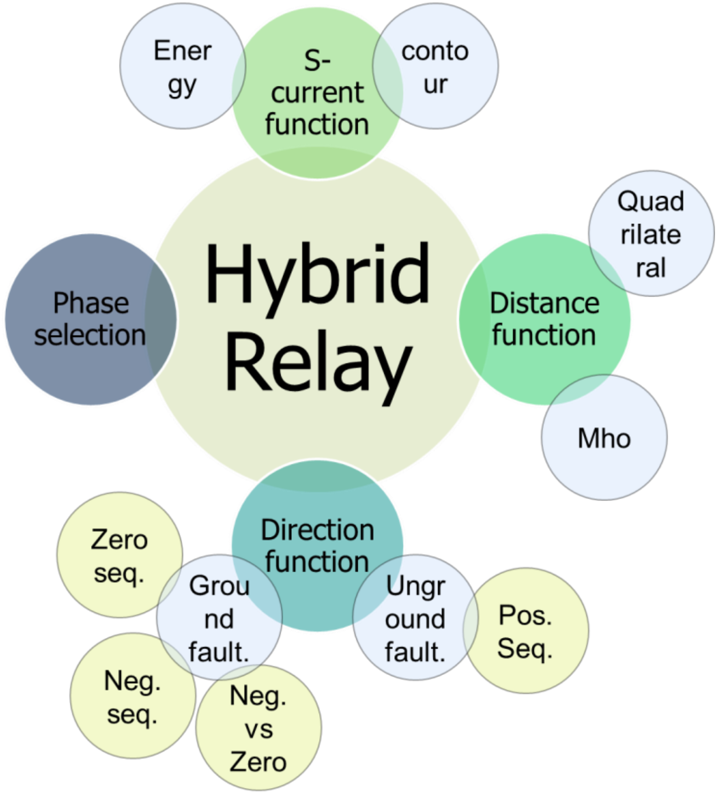


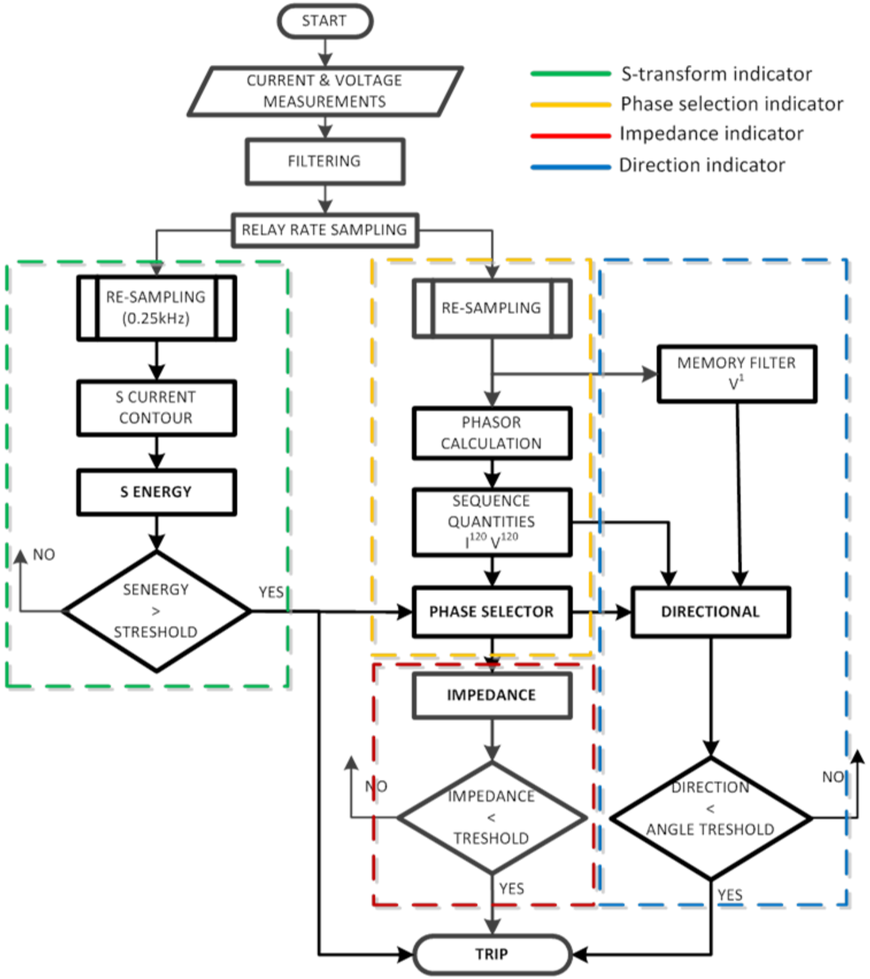
DFIG 200MW



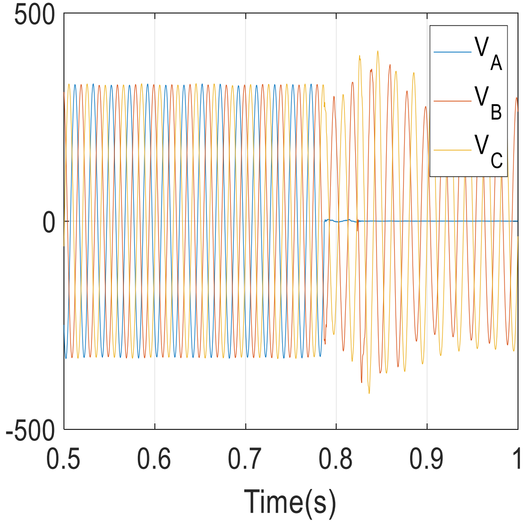


TASK 4.3 HYBRID RELAY BASED S-TRANSFORM

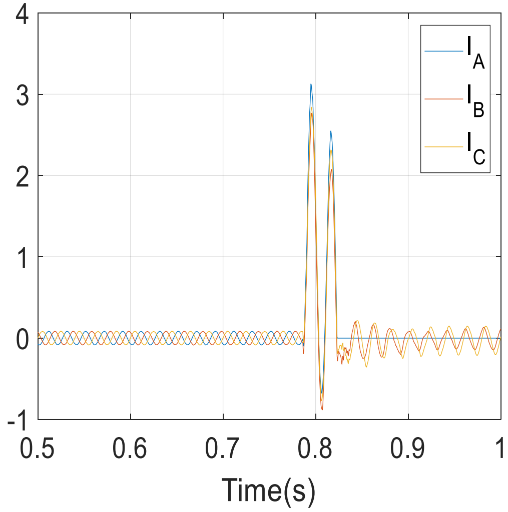




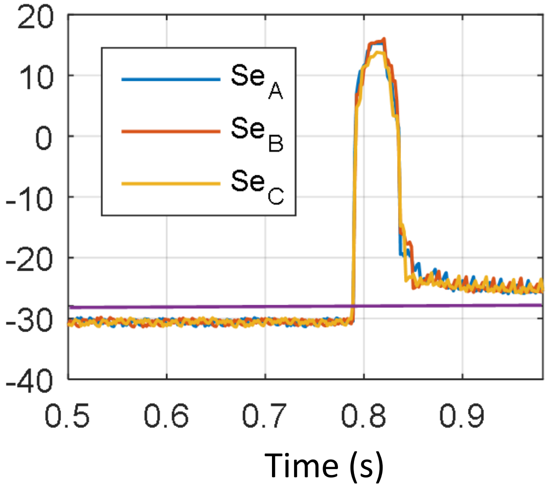
TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID.
FAULT: **LN**, 70%, 0Ω



Voltage (kV)



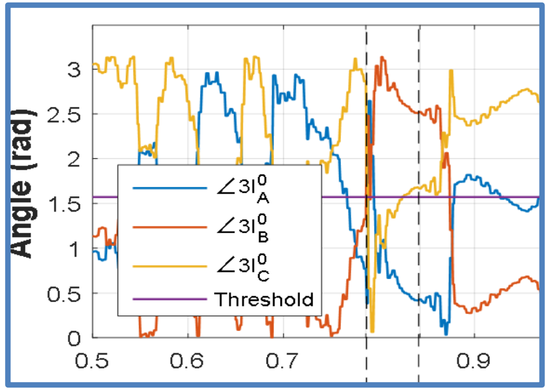
Current (kA)



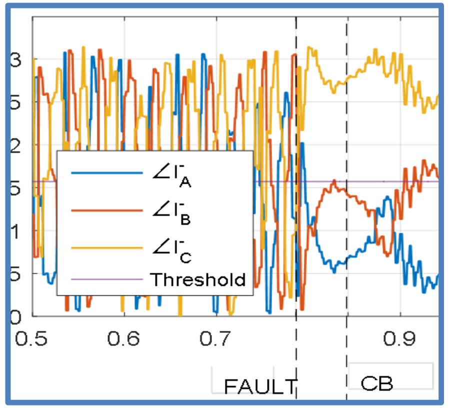
S-Energy (dB)

TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID.

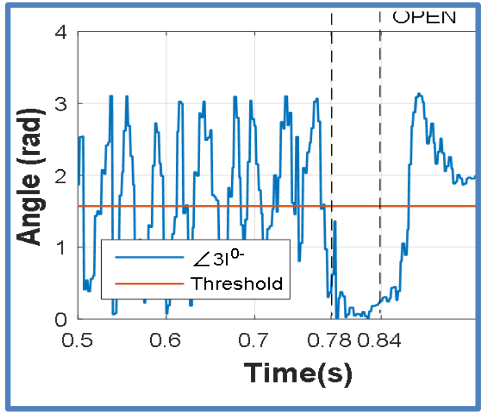
FAULT: **LN**, 70%, 0Ω



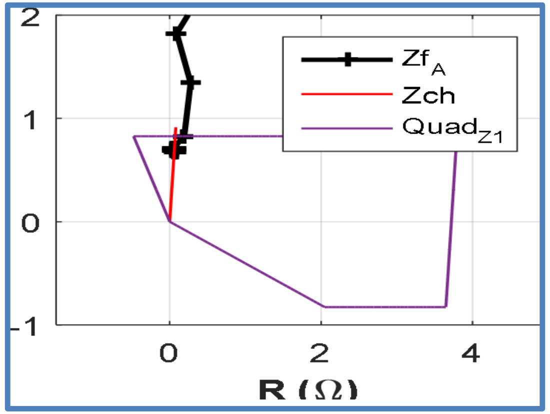
Zero sequence(rad)



Negative sequence(rad)

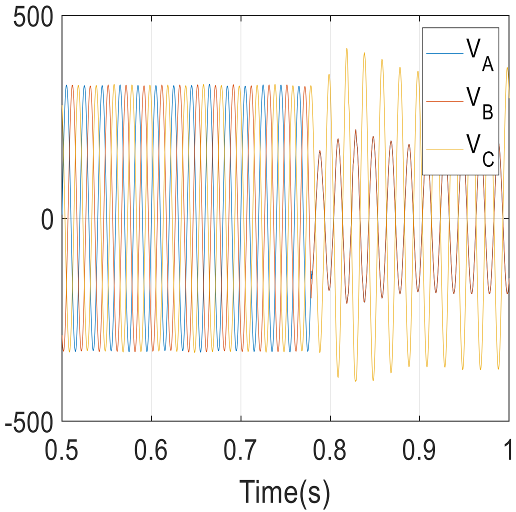


Zero vs Negative (rad)

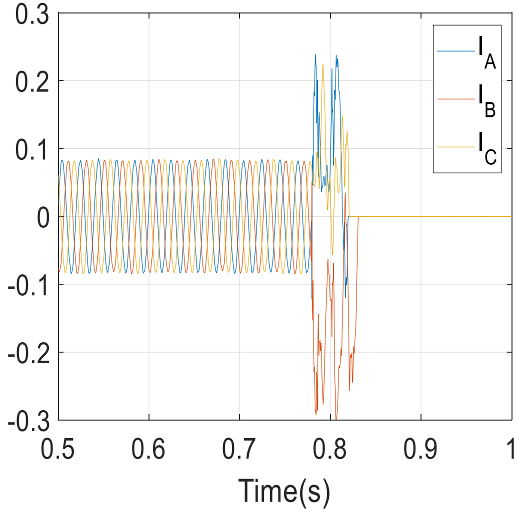


Impedance locus

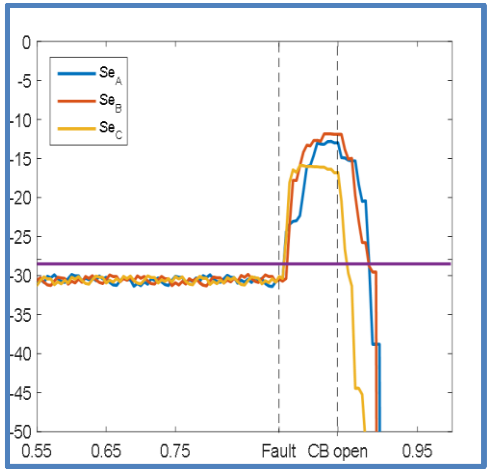
TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID.
FAULT: **LL**, 70%, 0Ω



Voltage (kV)

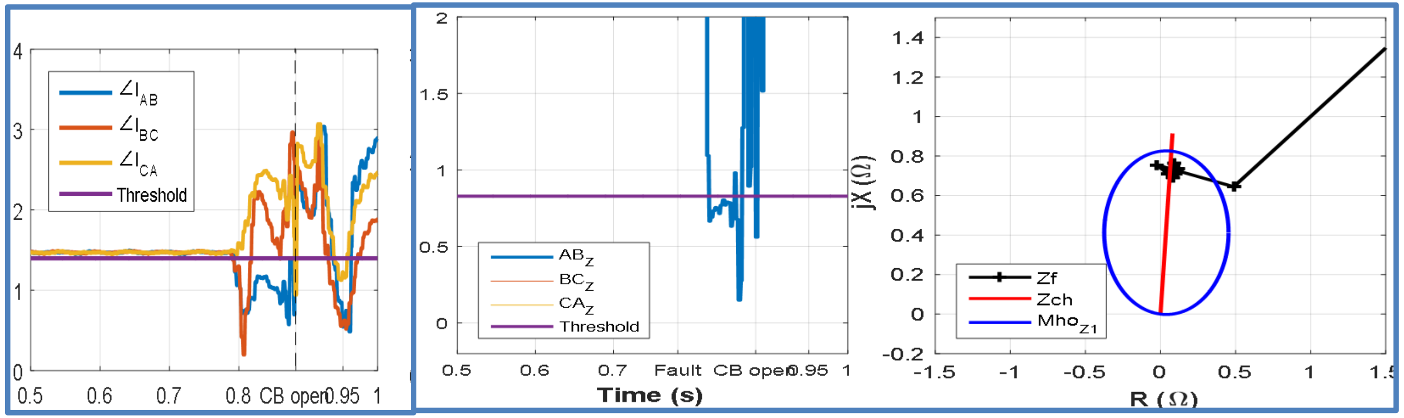


Current (kA)



S-Energy (dB)

TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID.
FAULT: **LL**, 70%, 0Ω

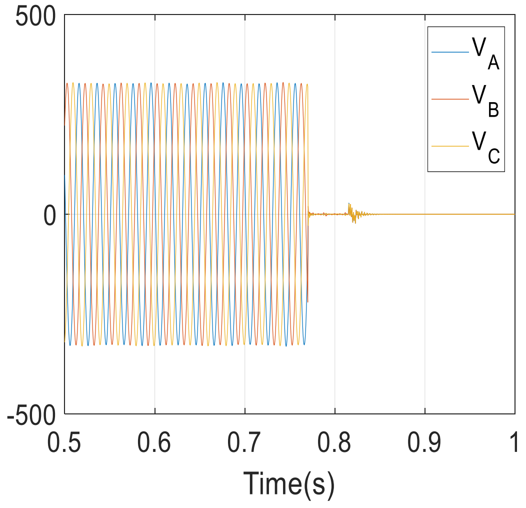


Positive sequence(rad)

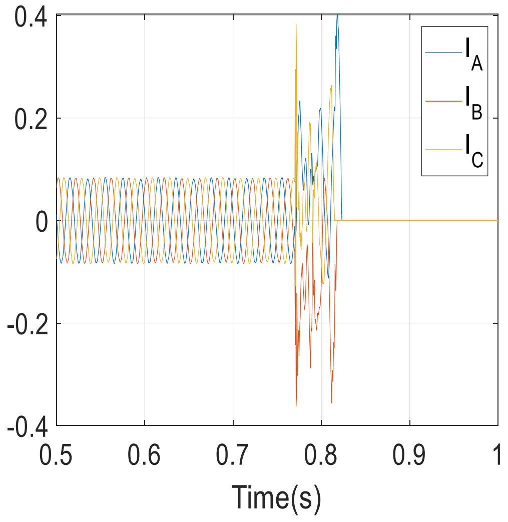
Impedance

Impedance locus

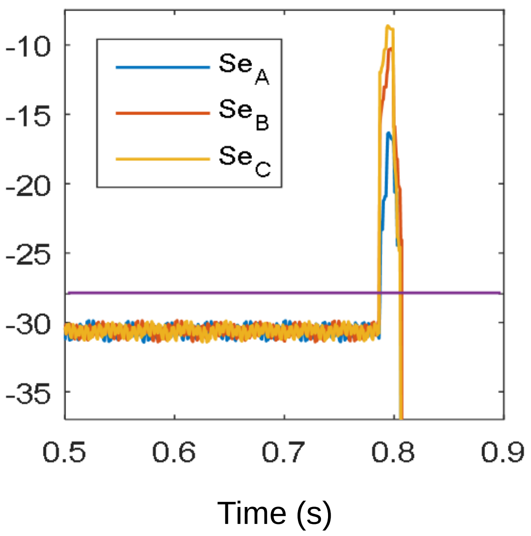
TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID. FAULT: **LLL**, 70%, 0Ω



Voltage (kV)

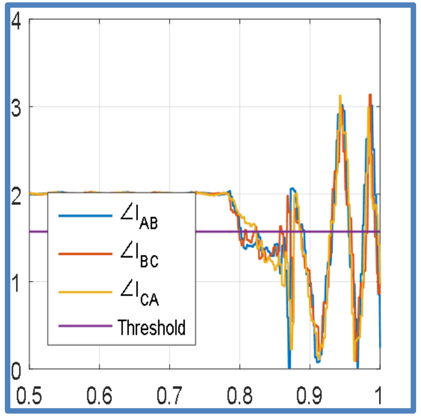


Current (kA)

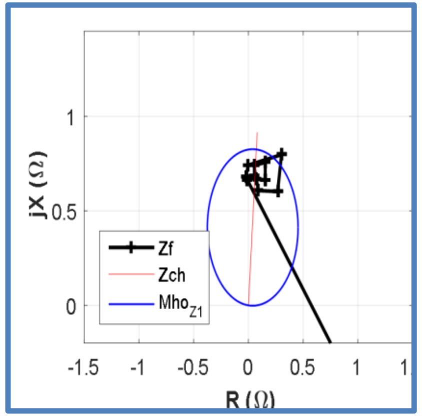


S-Energy (dB)

TASK 4.3 CASE 1: DFIG-40MW, STRONG GRID. FAULT: **LLL**, 70%, 0Ω



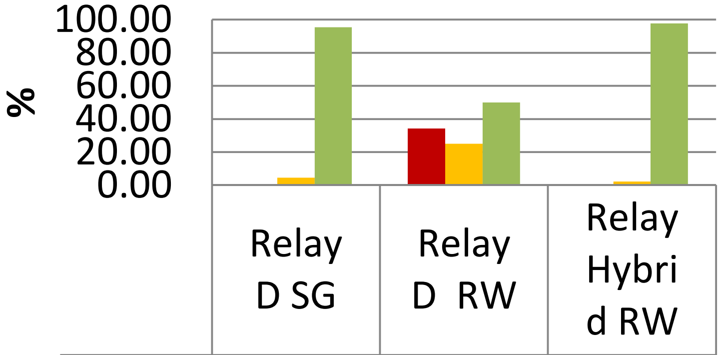
Positive sequence(rad)



Impedance locus

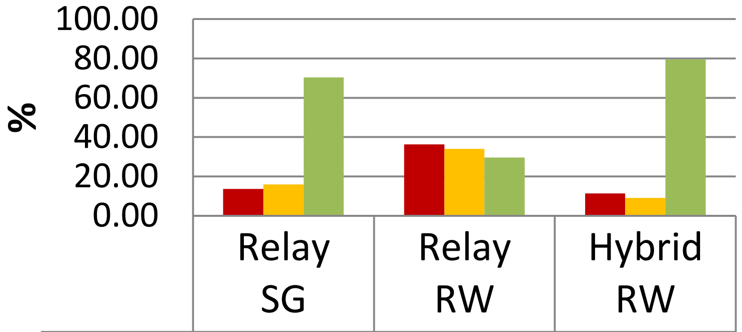
TASK 4.3 PERFORMANCE COMPARISON

0 Ω fault



	Relay D SG	Relay D RW	Relay Hybrid RW
Error	0.00	34.09	0.00
Delay	4.55	25.00	2.27
Ok	95.45	50.00	97.73

1 Ω fault



	Relay SG	Relay RW	Hybrid RW
Error	13.64	36.36	11.36
Delay	15.91	34.09	9.09
Ok	70.45	29.55	79.55

Priority	Variables	
1	Number of lines	2
2	Scenarios	6
3	Generation Level	2
4	Point of the line	6
5	Type of fault	4
6	Fault Resistance	2
7	Repetition	3
TOTAL NUMBER OF CASES		3456

CONCLUSIONS

- An advanced algorithm based on FDST is presented

  - Can be used to enhance the performance of distance protection
  - Fault detection is very sensitive and fast
  - Overcomes the difficulties that present commercial relays perform during the detection of ungrounded faults
  - Low computation burden used makes the algorithm suitable to be implemented in an actual distance relay
  - The S-energy indicator is not vulnerable to different fault types, fault inception angles and fault resistances.
  - In order to accurately identify any fault in the protected TL, the FDST should be combined with other indicators such as phase selection, directionality and impedance.
  - The results of the HR model are compared to the performance of four different commercial relays. The unexpected behavior like no trips, delayed trips or overreach are less than 0.12% when Wind turbines are near the relay.

PAPERS

M. Popov et al., "Enhancing Distance Protection Performance in Transmission Systems with Renewable Energy Utilization," *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, The Hague, Netherlands, 2020, pp. 181-185, doi: 10.1109/ISGT-Europe47291.2020.9248896.

J. Chavez, M. Popov, S. Azizi, V. Terzija: Protection Function Assesement of Present Relays for Wind Generator Applications, *International Conference on Power System Transients (IPST)*, Perpignan, 2019, Paper #: 19IPST029