CONPROVE

PERFORMANCE COMPARISON BETWEEN DIGITAL TWIN IEDs AND PHYSICAL DEVICES THROUGH CLOSED-LOOP TESTING

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INTRODUCTION

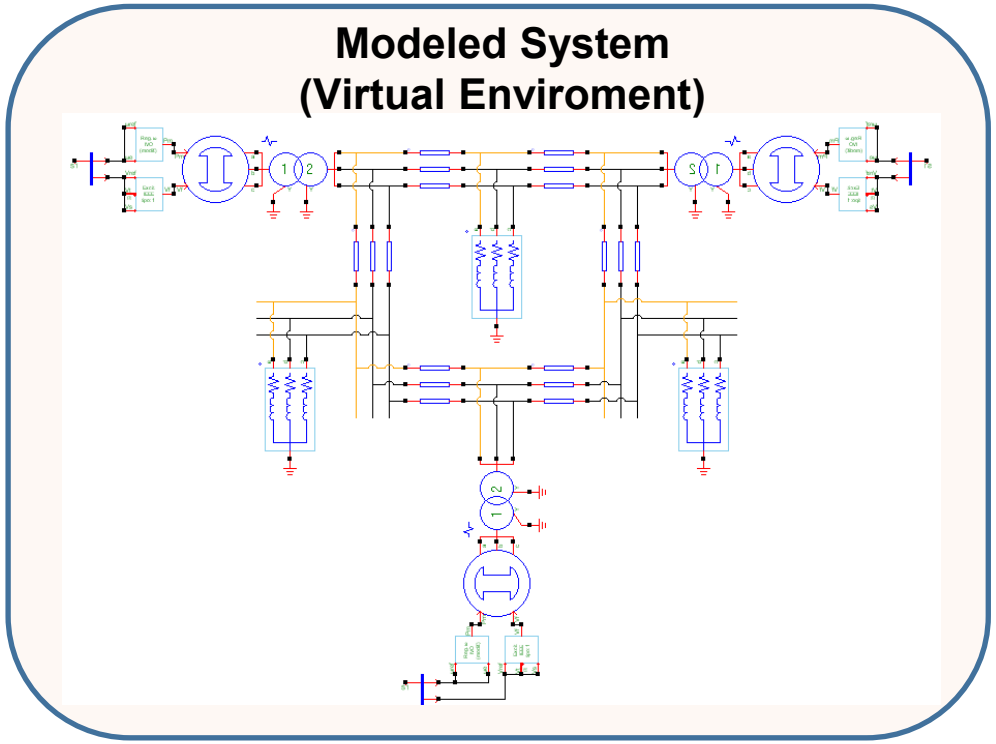
- **Advantages of a Digital Twin IED**:
  - **Early validation** of protection settings;
  - **Reduction** of FAT/SAT time;
  - Team **training**;
  - **Closed-loop** testing (API for partner ecosystem).

INTRODUCTION

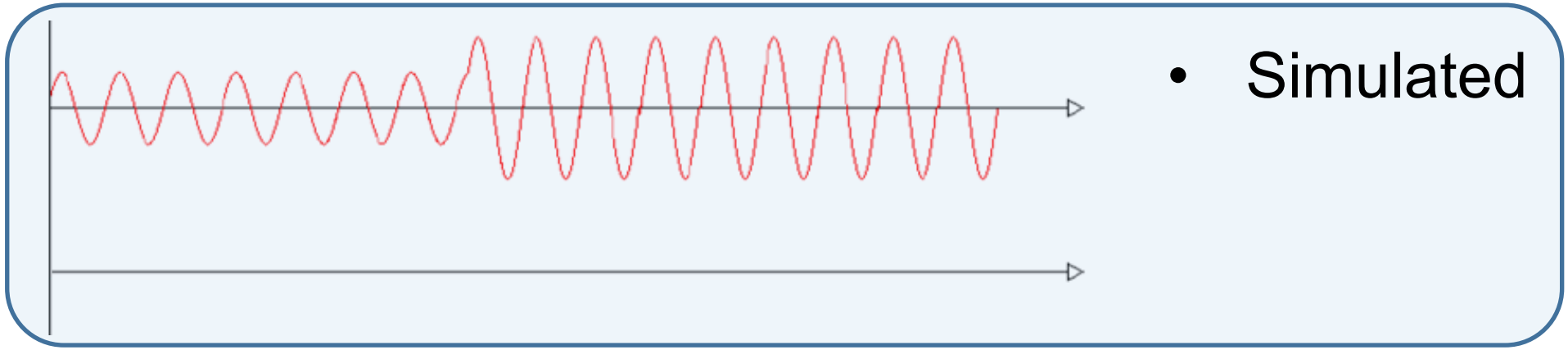
- **Digital Replica IEDs** are already a **reality**:
  - Hardware **independence**;
  - **Unlimited** number of signals.

- **EMT Software**:
  - **Simulates real-world scenarios**;
  - **Testing with virtual IEDs**;
  - **Open-loop / Closed-loop** testing;
  - **Step-by-step methodology**.

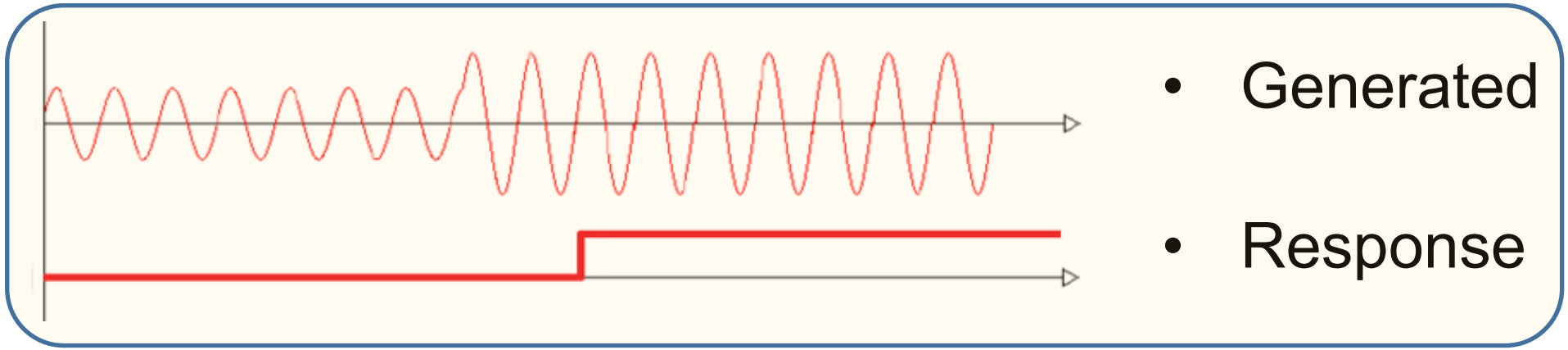
STEP-BASED CLOSED LOOP vs REAL TIME



STEP-BASED CLOSED LOOP

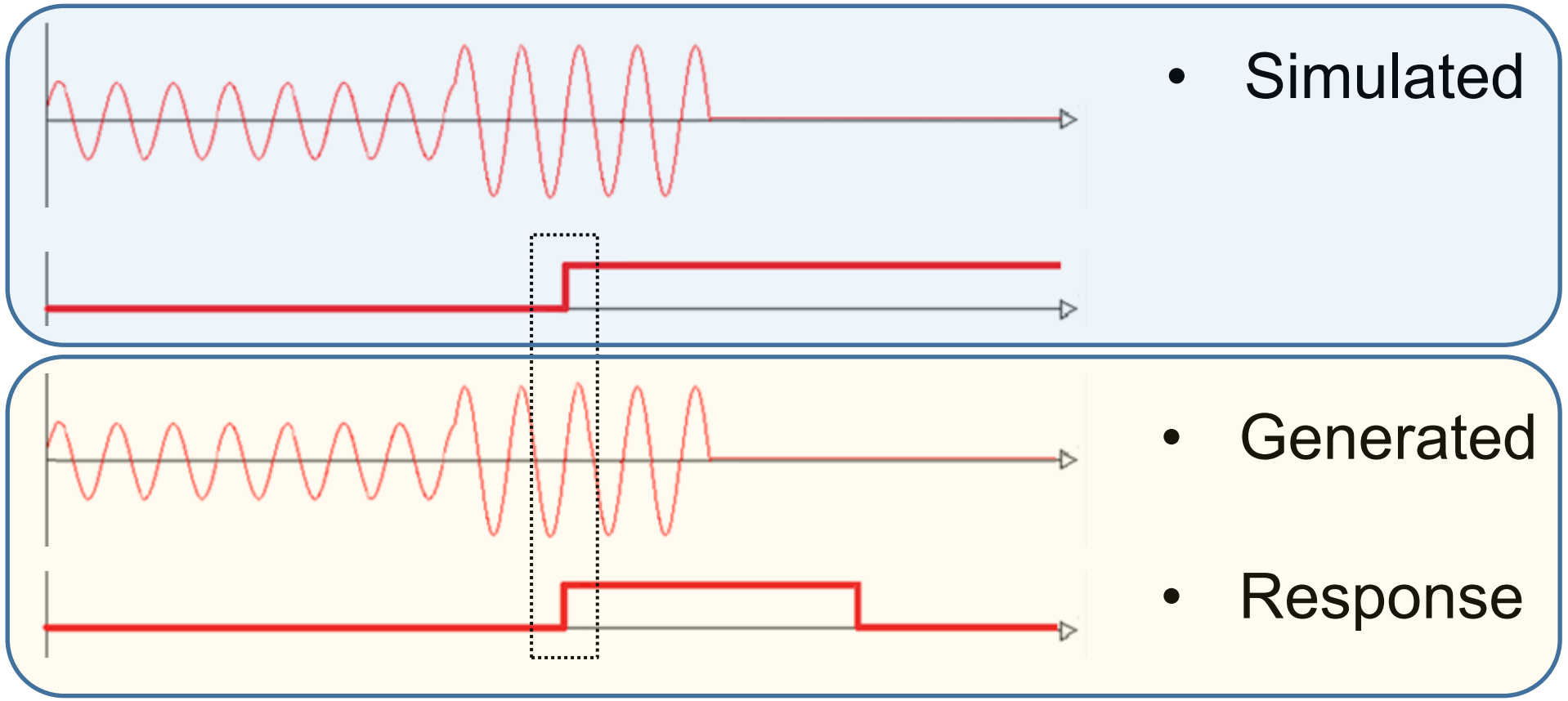


- Simulated



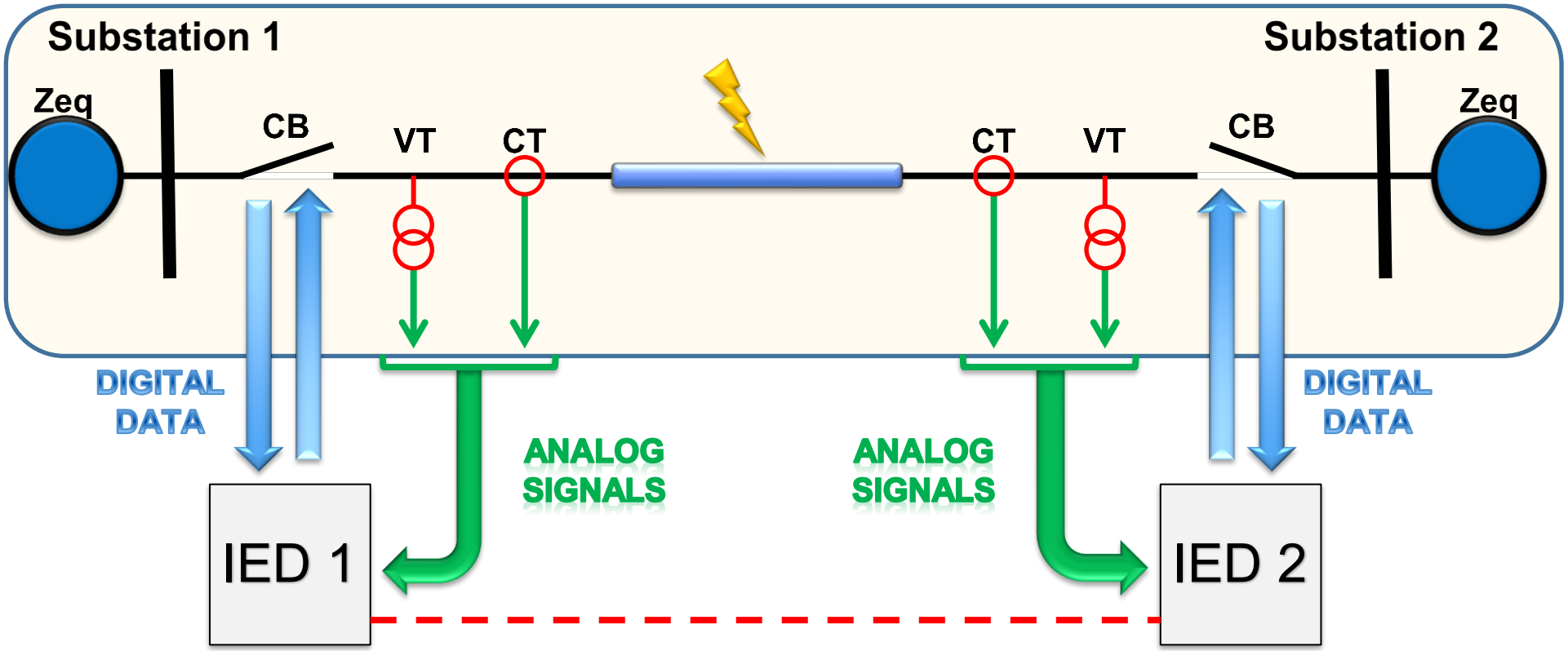
- Generated
- Response

STEP-BASED CLOSED LOOP

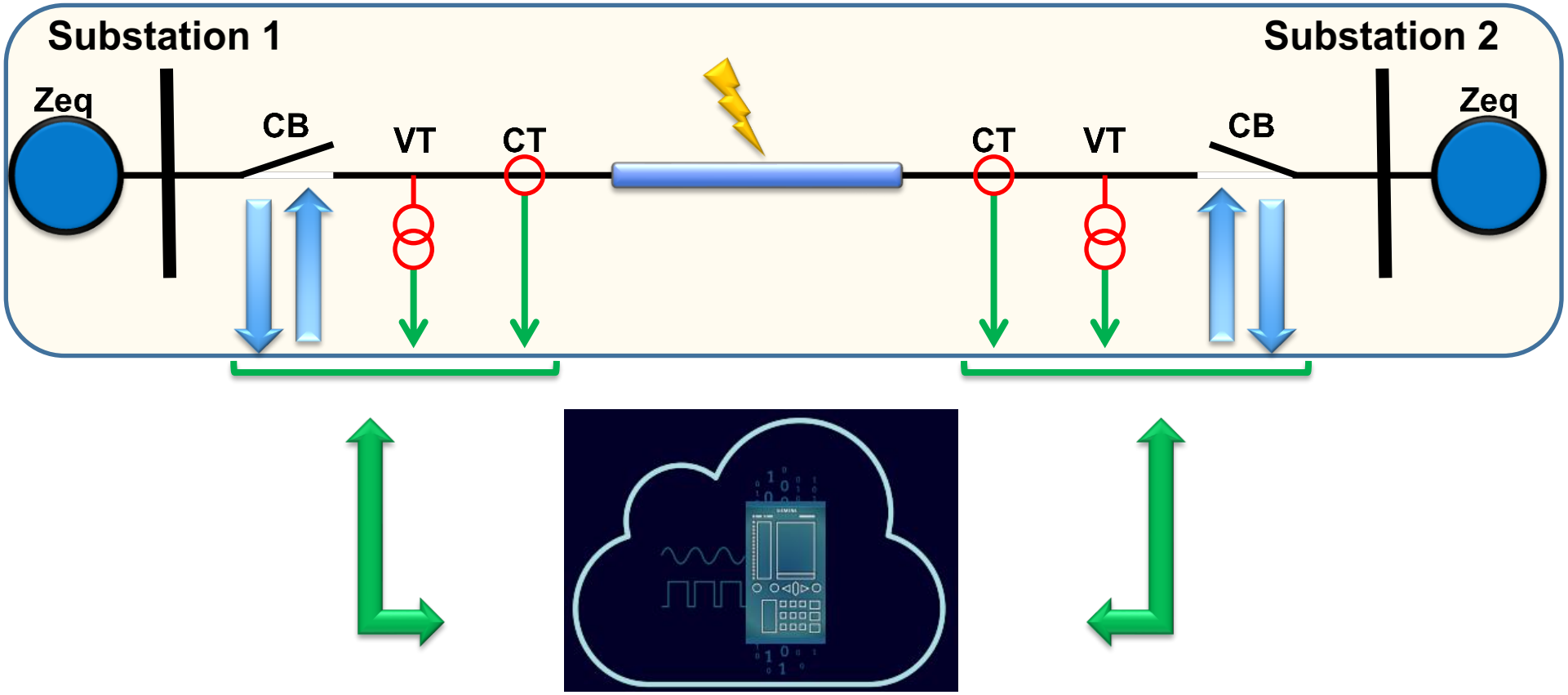


- Simulated
- Generated
- Response

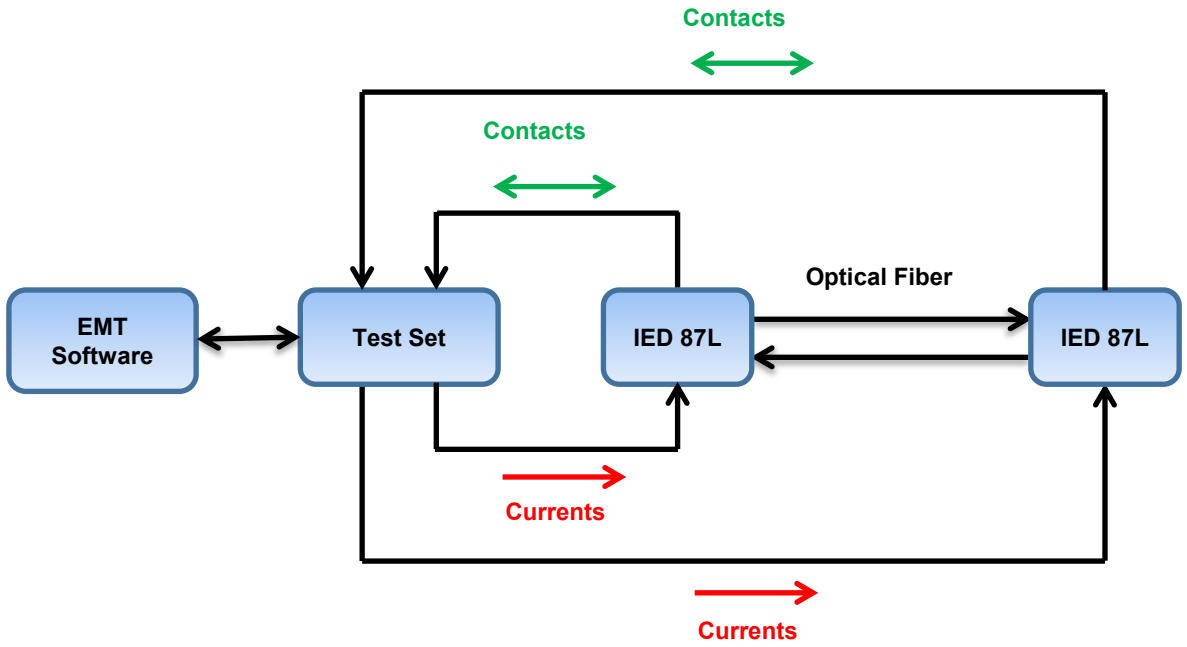
TEST DEVICE

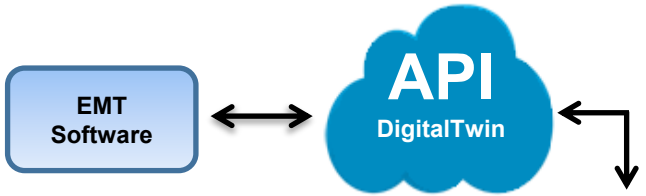

Substation 1
Substation 2
Zeq
CB
VT
CT
CT
VT
CB
Zeq
DIGITAL DATA
ANALOG SIGNALS
ANALOG SIGNALS
DIGITAL DATA
IED 1
IED 2

TEST DEVICE



METHODOLOGY



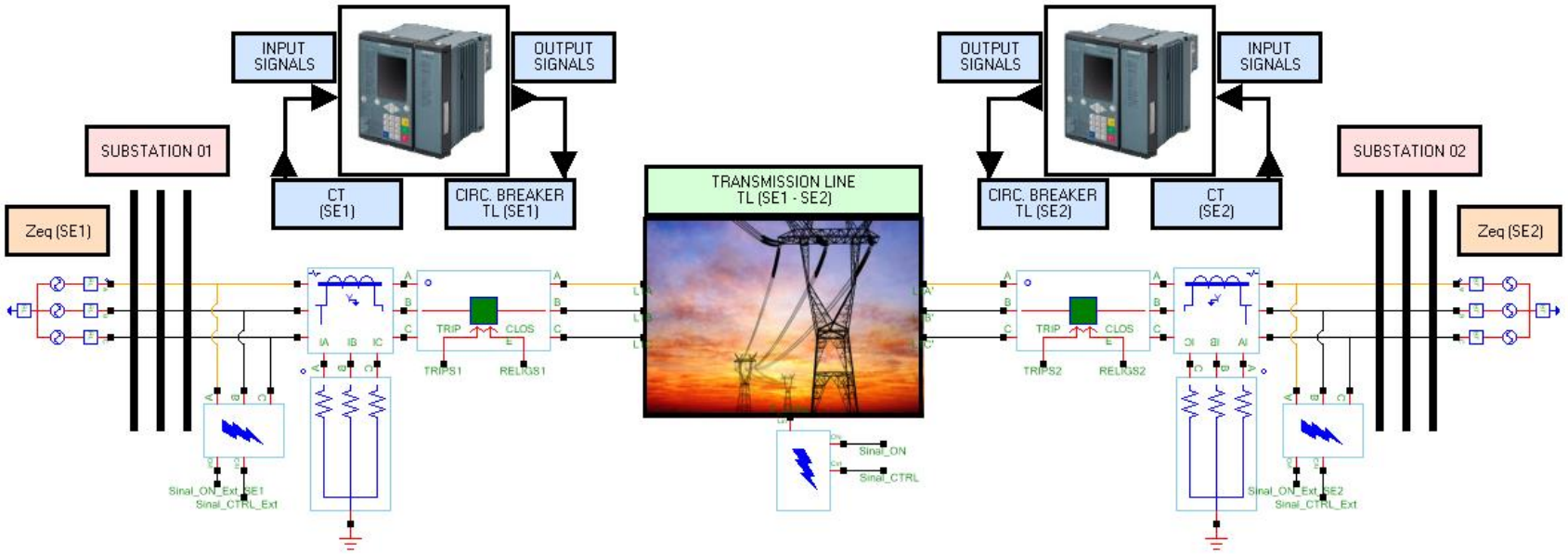


VIRTUAL vs REAL

- Is the virtual IED a faithful replica of the real IED?
- Does it exhibit the same behavior?
- Does it use the same algorithms and provide the same functionalities?
- Are the responses identical?

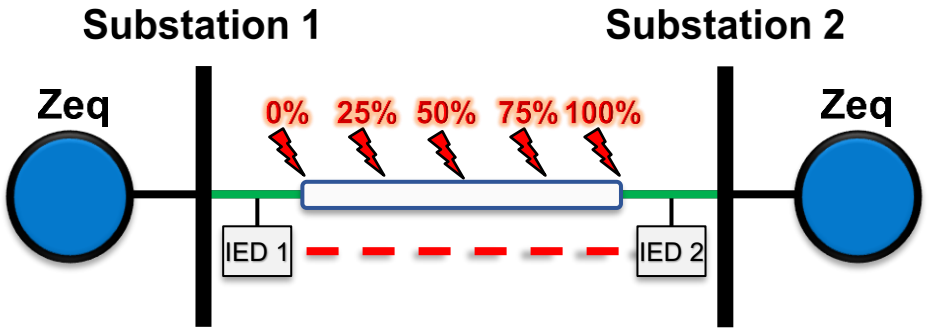
CASE STUDY

- Environment (Physical Device and Digital Twin)
- 500 kV, 87L Line Protection
- 260 test cases divided into 10 groups



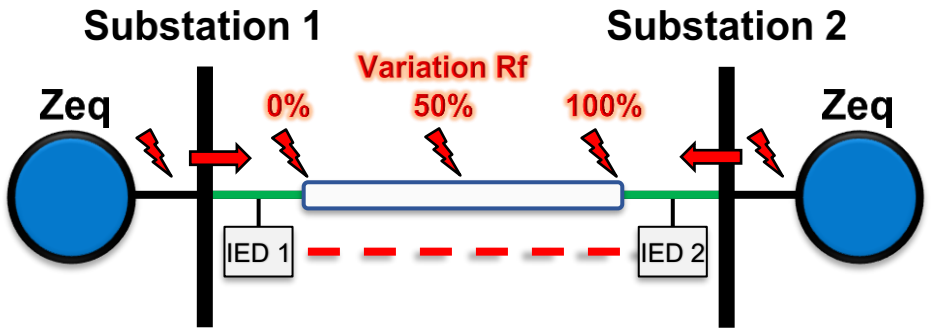
PERFORMED TESTS

50	**Internal faults** with incidence angles of 0° and 90°. **Three-pole reclosing, successful and unsuccessful**. Faults at: 0%, 25%, 50%, 75%, and 100% of S1–S2.
50	**Evolving internal faults** with incidence angles of 0° and 90°. **Tripolar reclosing with and without success**. Faults at 0%, 25%, 50%, 75%, and 100% of S1–S2. The evolution occurs **one cycle after fault inception**.



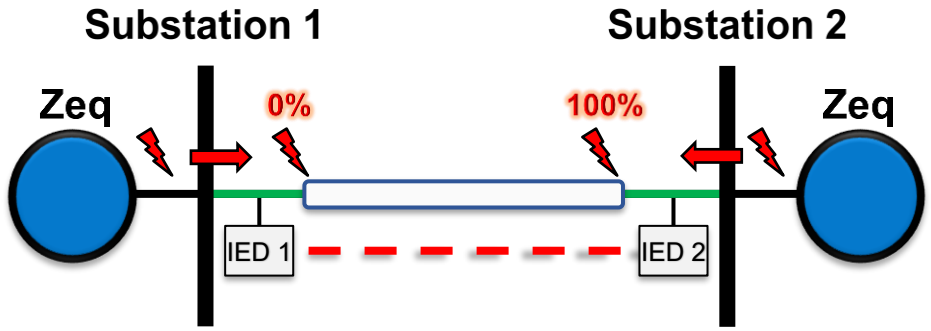
PERFORMED TESTS

30	**Internal faults with variation of the fault resistance** at the **midpoint** of the line. Incidence angles of 0° and 90°, with the fault resistance adjusted to values ranging from **5 Ω to 200 Ω**. **Successful three-pole reclosing**.
10	**External faults** in SS 1 and SS 2, with incidence angles of 0° and 90°. For these cases, the 87L function must not operate.
10	**External faults followed by internal faults (after 6 cycles)**, with incidence angles of 0° and 90°. For these cases, **successful three-pole reclosing** shall be verified.



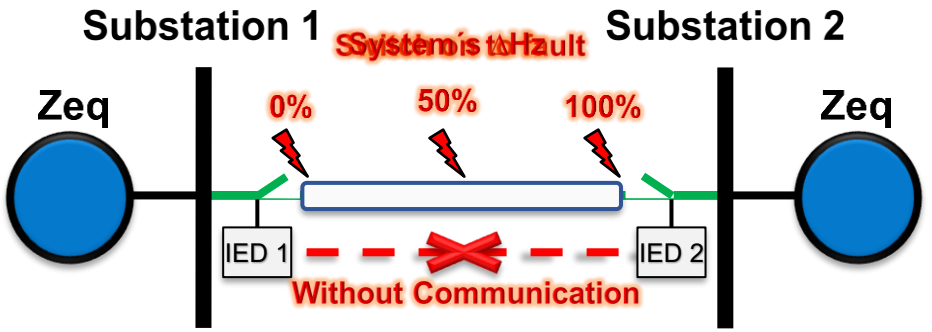
PERFORMED TESTS

40	**External faults with CT saturation** at SS 1 and SS 2, with incidence angles of 0° and 90°. For these cases, the 87L protection function must not operate. At each substation, different fault types were simulated for different **burden resistance** values, aiming to induce both mild and severe saturation conditions.
40	**External faults followed by internal faults (after 6 cycles)**, with incidence angles of 0° and 90°. For these cases, **successful three-pole reclosing** must be verified. Light and heavy saturations were induced by varying the **burden resistance**.



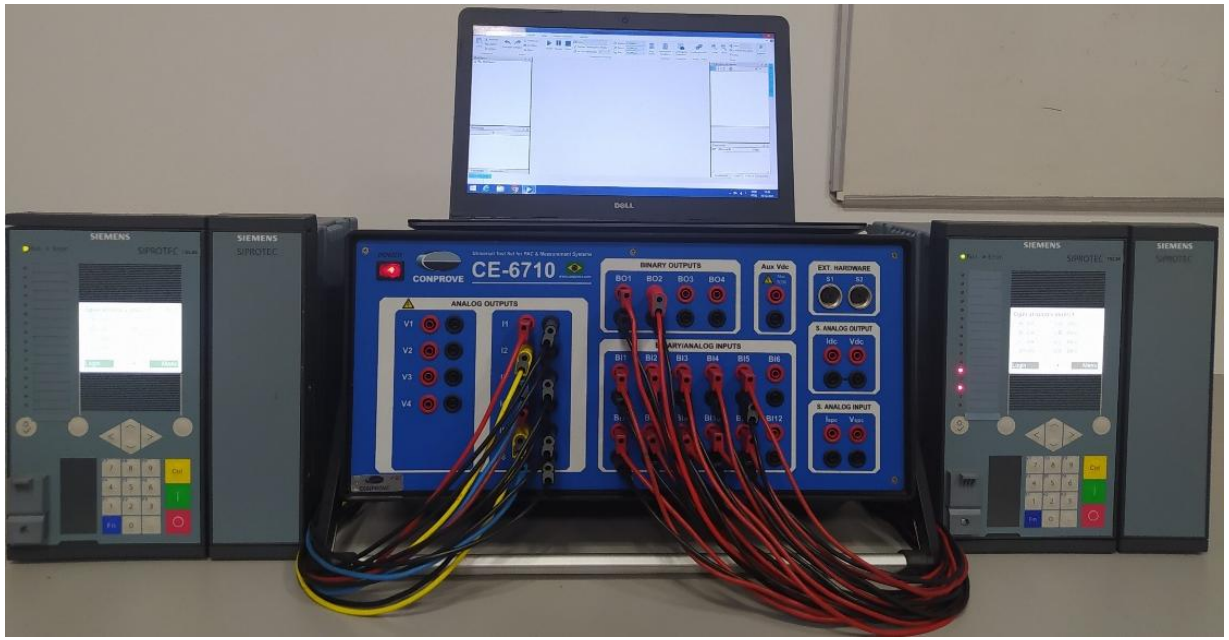
PERFORMED TESTS

12	Internal faults under the **"switch-on-to-fault"** condition, with inception angles of 0° and 90°: • SOTF with the SS 1 terminal open: 0% and 100% of SS 1; • SOTF with the SS 2 terminal open: 0% and 100% of SS 1.
10	Verify the relay response to **underframequency and overfrequency conditions (57 Hz and 72 Hz)**. Internal faults of **different types** at **50%**, with incidence angles of 0° and 90°. **Unsuccessful three-pole reclosing**.
8	Faults **without communication**, external and internal, at the 0% and 100% positions, with incidence angles of 0° and 90°. **Unsuccessful reclosing**.

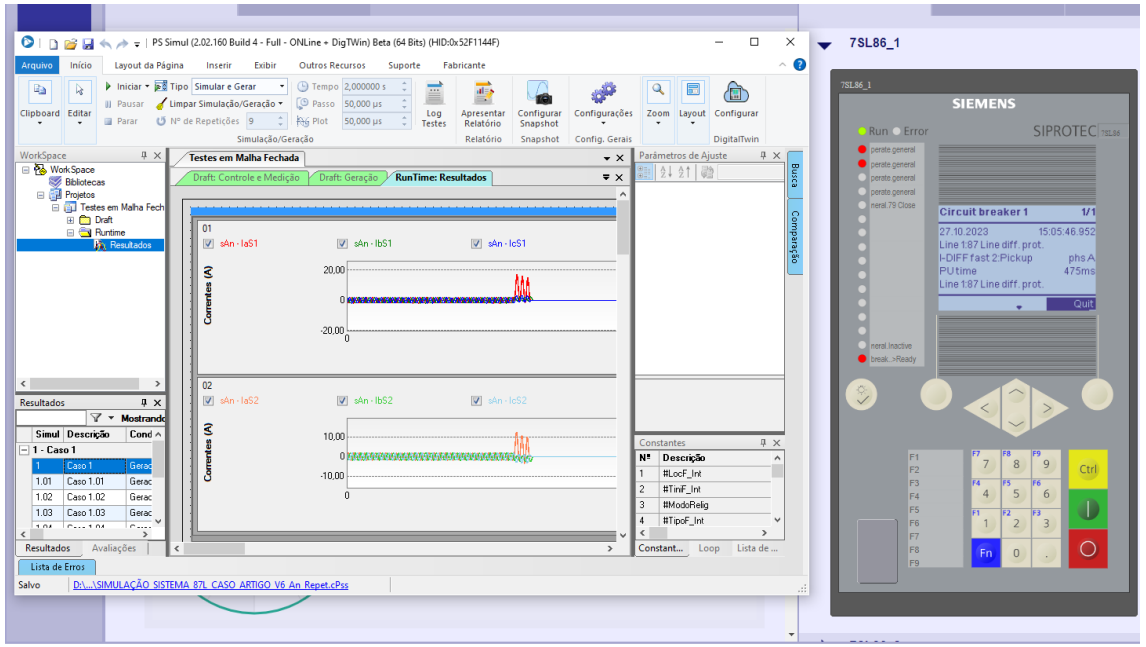


TEST SETUP

Conventional System:
Analog Signals and Binaries

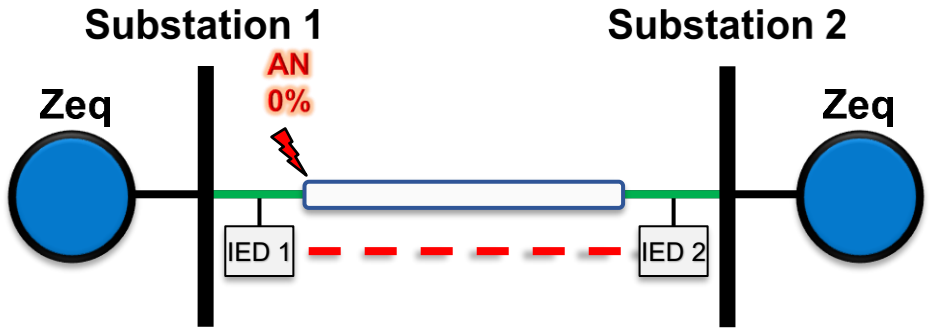


DigitalTwin:
COMTRADE -> API



COMPARISON

- **A-G fault** at **0%**;
- Incidence angle of **0°**;
- **Unsuccessful** reclosing;
- Repeatability **(20×)**.




Secondary CT Currents (Substation1)
sAn - G2 - IaS1
sAn - G2 - IbS1
sAn - G2 - IcS1
Currents (A)
20,00
10,00
0
-10,00
2,00
Secondary CT Currents (Substation2)
sAn - G2 - IaS2
sAn - G2 - IbS2
sAn - G2 - IcS2
Currents (A)
10,00
0
2,00
Binary Inputs (IED's Substation 1 and 2)
eB1 - 7SL86_1 - TRIP
eB1 - 7SL86_1 - DIF_87
eB1 - 7SL86_1 - SOTF
eB1 - 7SL86_1 - OC_50/51
eB1 - 7SL86_1 - REC_79
eB2 - 7SL86_2 - TRIP
eB2 - 7SL86_2 - DIF_87
eB2 - 7SL86_2 - SOTF
eB2 - 7SL86_2 - OC_50/51
eB2 - 7SL86_2 - REC_79

TIME COMPARISON (ms)

Signal	System	Physical Device				DIGITAL TWIN				Avg. ΔT
		Min. T	Avg. T	Max. T	σ	Min. T	Avg. T	Max. T	σ	
TRIP (7SL86_1)	BR	11.800	14.182	17.250	1.59	8.050	10.473	12.050	1.28	3.71
	AR	12.450	16.480	20.800	2.64	12.950	15.330	17.950	1.67	1.15
REC_79 (7SL86_1)	-	1032.4	1035.6	1039.9	2.25	1029.8	1031.7	1033.8	1.57	3.91
SOTF (7SL86_1)	BR	-	-	-	-	-	-	-	-	-
	AR	14.200	20.100	26.200	2.88	12.950	16.128	19.950	2.24	3.97
TRIP (7SL86_2)	BR	12.600	14.540	17.600	1.54	8.050	10.320	12.050	1.38	4.22
	AR	15.100	17.157	23.150	3.58	12.950	15.725	19.000	1.81	1.43
REC_79 (7SL86_2)	-	1031.3	1033.1	1035.2	1.16	1034.0	1036.4	1038.1	1.27	3.29
SOTF (7SL86_2)	BR	-	-	-	-	-	-	-	-	-
	AR	15.750	22.950	29.950	4.19	12.950	16.168	19.950	2.41	6.78

BR = Before reclosing
AR = After reclosing

CONCLUSION

- **520 contingency scenarios** were tested:
  - 260 – **Physical IED**;
  - 260 – **Digital Twin**.
- Trip **variations** between the methodologies → **physical contact** (relay);
- **Test tool** demonstrated;
- **Closed-loop**;
- Hardware **independence**;
- **Cost-effective** solution.

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THANK YOU!

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