An On-Line Real-Time Monitoring Method for Locating Natural Triggered Events on Medium Voltage Power Grids

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Why Cable Diagnosis?

500 000 KM ALONG THE FRENCH RAILWAY NETWORK

500 00 KM HIGH VOLTAGE LINES

500 KM IN A CIVIL AIRCRAFT

5 KM IN A MODERN CAR

NEW CHALLENGES ARE COMING

MARINE RENEWABLE ENERGY

Fault Diagnosis in Power Networks

The Fault

Transmission and distribution lines are always prone to short circuit for many reasons such as wind, falling trees, animals, etc.

Power Outage

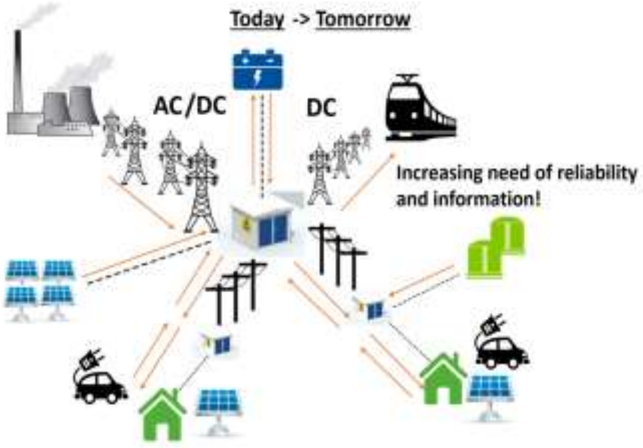
When there is a fault, a part of the network might experience power outage that can last a few minutes to a few hours.

Fault Location

The duration of the power outage mainly depends on the required time for fault location, reparation, and restoration processes.

"One estimate shows that outages caused by faults led to a $150 Billion losses in the USA alone in 2018"

- **Active Distribution Networks (ADNs)**
  - The accuracy of the existing fault location methods are affected by the presence of Distributed energy resources (DER).
  - Due to the restricted power quality constraints, there is a need for fast and reliable fault location systems.



- **Complex AC/DC network topologies (e.g., Multi-terminal HVDC grids)**
  - The fault location and protection is one of the major challenges to realize HVDC grids.

Need for reliable fault location system

Fault Diagnosis in Power Networks

Fault location methods

Travelling waves-based methods are more suitable ones for ADNs and MTDCs.

1. **Phasor-Based Methods**

   Use of voltage/current phasors
   - ✓ Straightforward application
   - ✓ Low-bandwidth measurement systems
   - o Need for multi-end measurements.
   - o Impact of DERs, fault impedance, system pre-fault condition.

2. **Travelling Wave-Based Methods**

   Use of fault-originated high-frequency signals
   - ✓ Higher accuracy
   - ✓ Immune to the pre-fault conditions
   - o Need for multi-end measurements for complex systems.
   - o Require more sophisticated analysis.

3. **Knowledge-Based Methods**
   - o Need for extensive trainings

Norms adopted to assess the performance of fault location methods

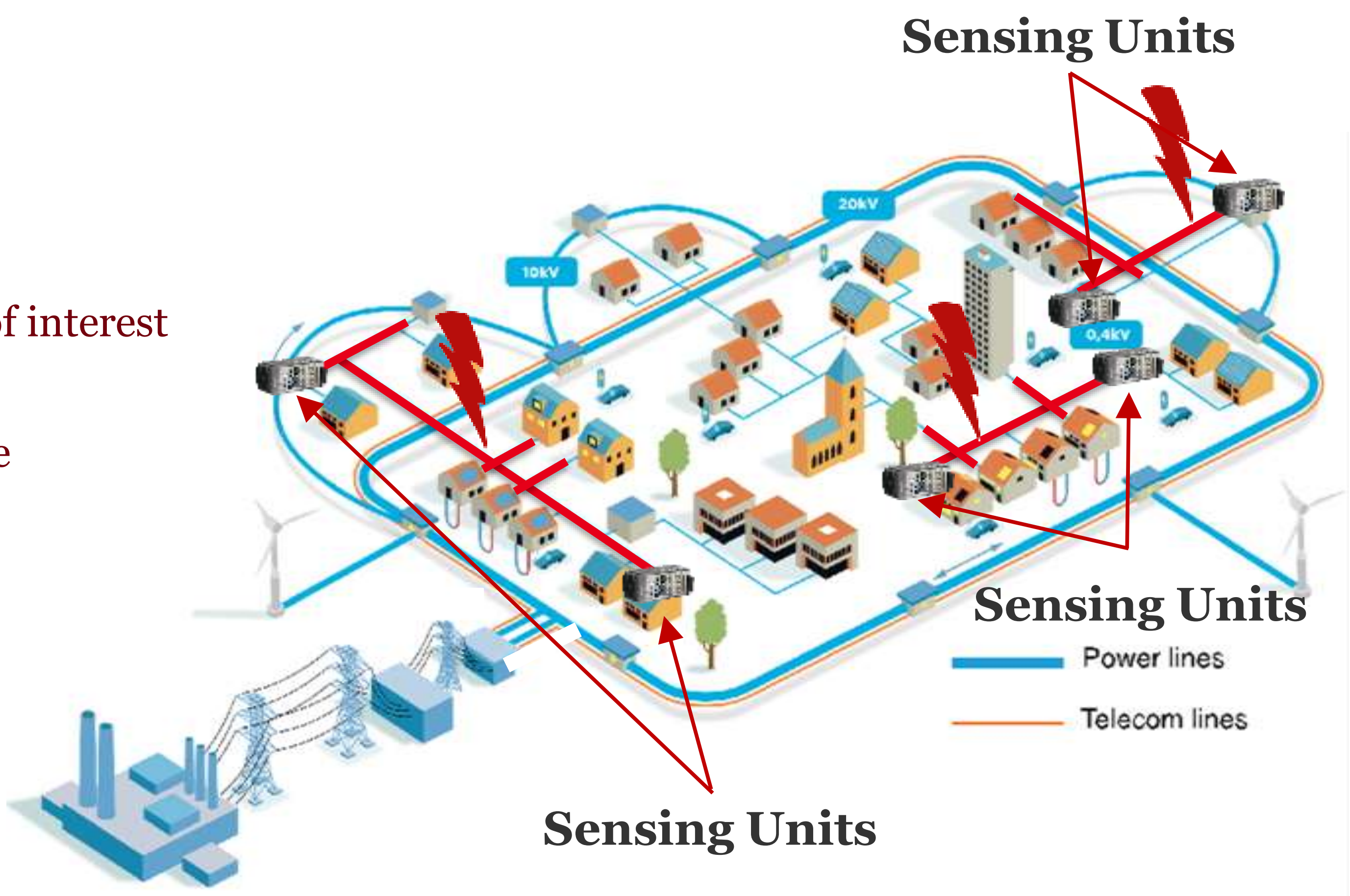
- ❑ Location accuracy
- ❑ Computational complexity affected by:
  - ❖ number of measurement points
  - ❖ pre-fault system state
  - ❖ Reliability of communication link (for the case of multi-end methods)
  - ❖ (unknown) fault impedance
  - ❖ presence and amount of noise in measurements

Need of deploying a given fault location method in low-cost, embedded and ruggedized hardware

Fault Diagnosis in Power Networks

The Proposed Technology--FasTR

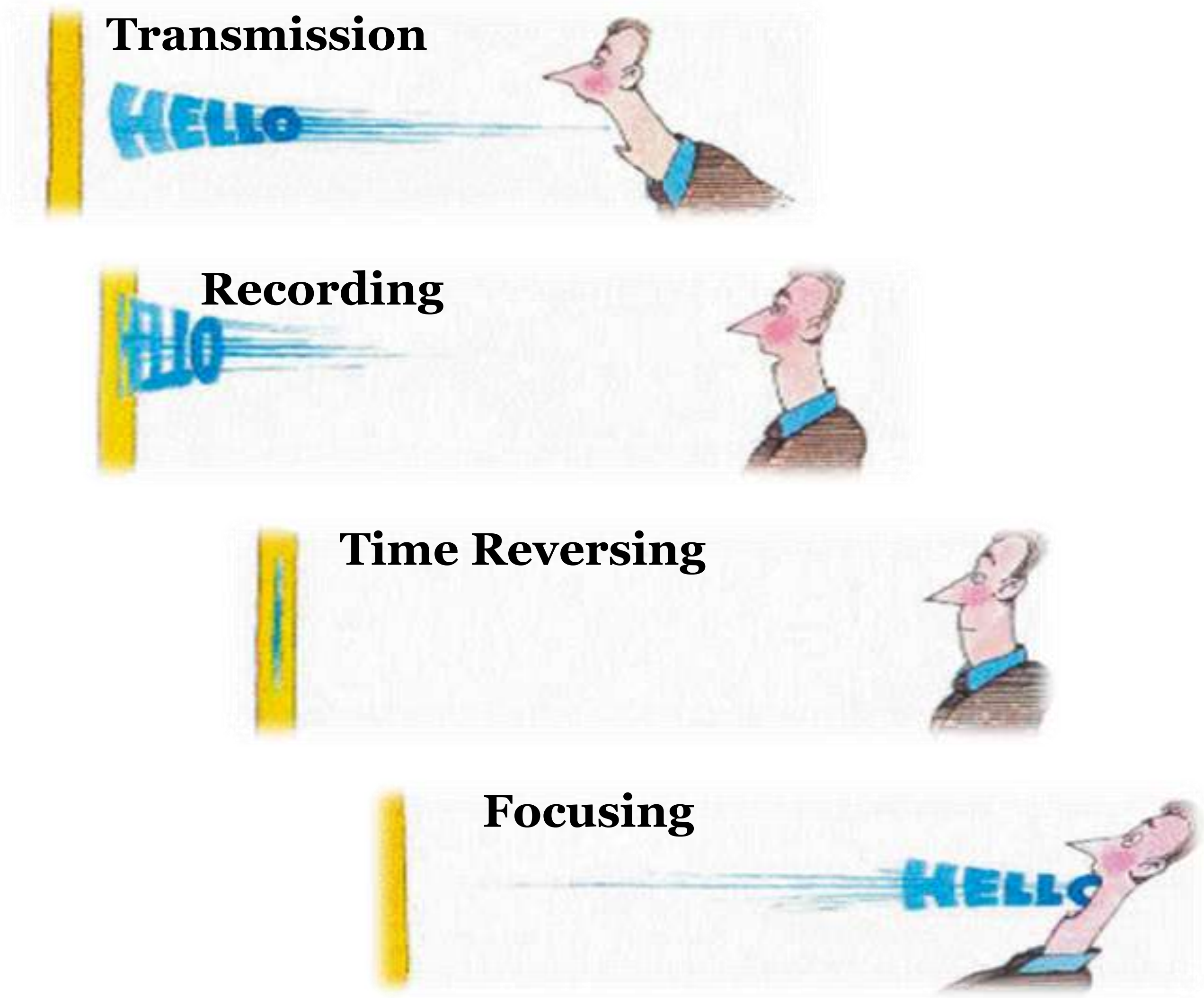
- Divide Network into subnetworks of interest
- Several Sensing units per grid zone
- Precision of a few meters
- 1 minute



Time Reversal Theory

Fault Diagnosis in Power Networks

Time Reversal TR Concept



Time Reversal TR Applications

- Ultrasonic focusing through the skull
- Geophysics and geoscience
- Detecting buried objects
- Nondestructive testing
- Remote inspection
- Hyperthermia
- Lithotripsy
- **Power Networks**

FasTR Algorithm for Power Networks

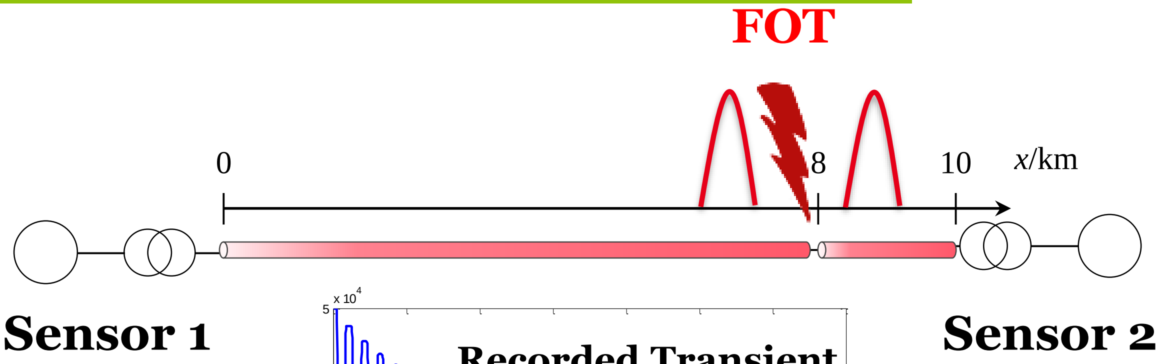
FasTR Algorithm

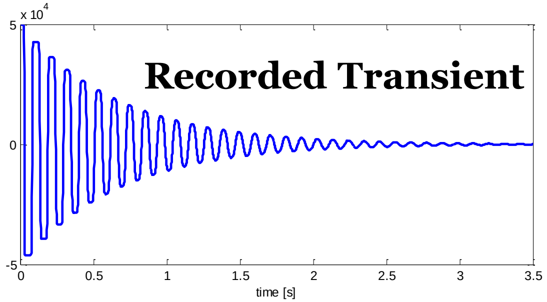
1 The fault-originating transient (FOT) is measured at predefined nodes of the network under test (NUT) where sensors are placed

2 The recorded measurements are time-reversed and numerically re-injected into a simulation model of the network

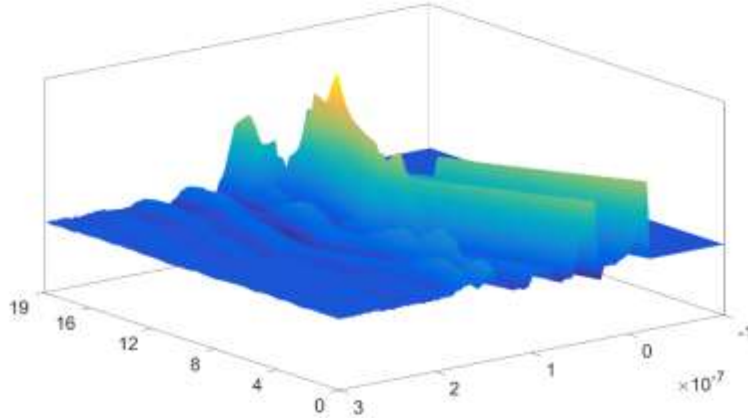
3 A cost function **F**(**x**; **t**) is constructed which aims at estimating the signal corresponding to the superposition of the back-propagated time-reversed signals, at each instant **t** and position **x** of a point in the network

4 A searching mechanism for detecting the extremum of **F**(**x**; **t**) is finally launched, thanks to a wide selection of optimization algorithms (Genetic, Particle Swarm, etc.)

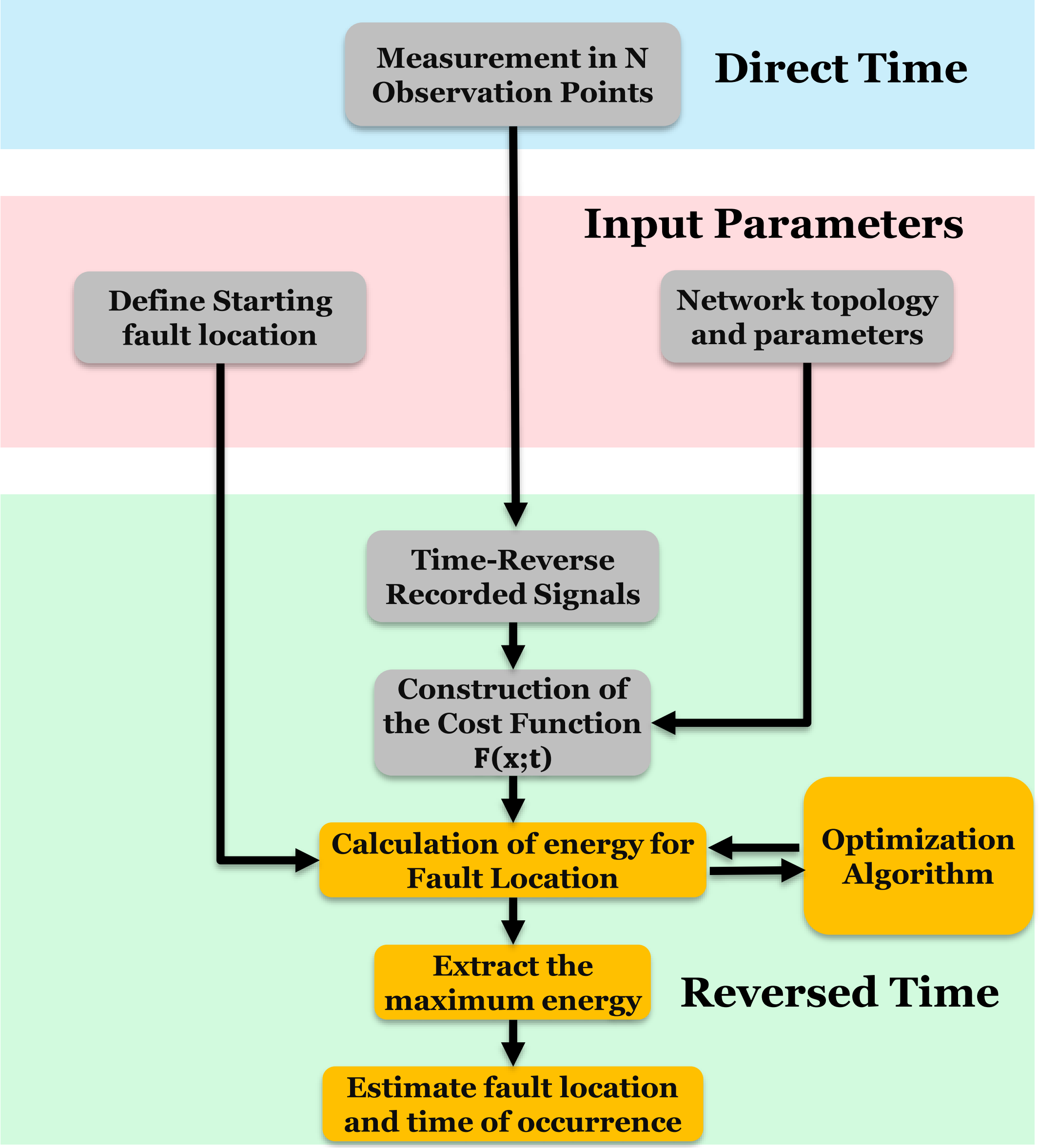




$$\mathbf{F}(\mathbf{x};\mathbf{t}) = \sum_{n=1}^{n_r}\left[\mathbf{Sr_e}\left(\mathbf{x}, \mathbf{t} - \frac{\mathbf{d}(\mathbf{x},\mathbf{x_e})}{\mathbf{v_{b_i}}}\right) \times \frac{\mathbf{e}^{\alpha^{\mathbf{b_i}}\mathbf{d}(\mathbf{x},\mathbf{x_e})}}{\mathbf{C_e^{b_i}}}\right]$$



FasTR Algorithm for Power Networks

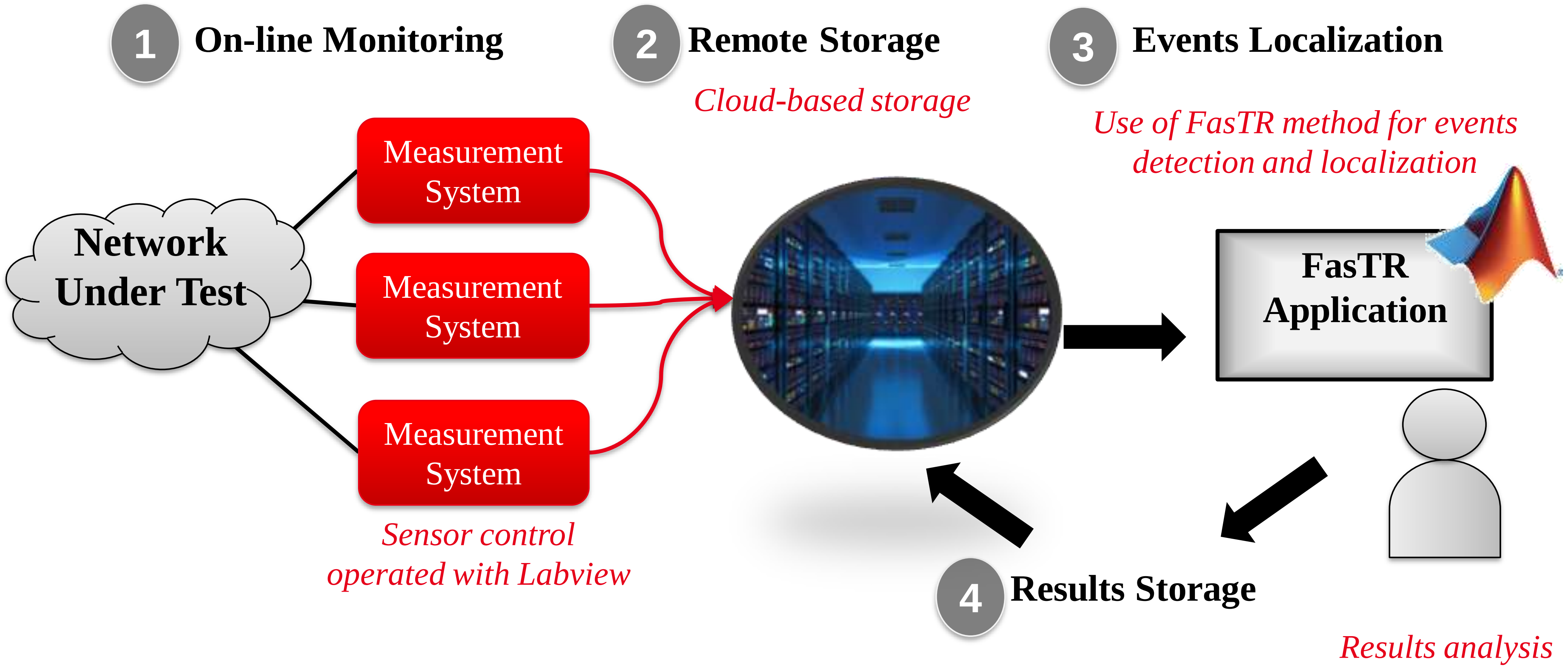


Flow Chart of the FasTR algorithm

$$F(x;t) = \sum_{e=1}^{n_r} \left[Sr_e\left(x, t - \frac{d(x,x_e)}{v_{b_i}}\right) \times \frac{e^{\alpha^{b_i} d(x,x_e)}}{C_e^{b_i}} \right]$$

- GA Genetic algorithm
- PSO Particle Swarm Algorithm
- SG Surrogate Optimization Algorithm
- SA Simulated Annealing algorithm

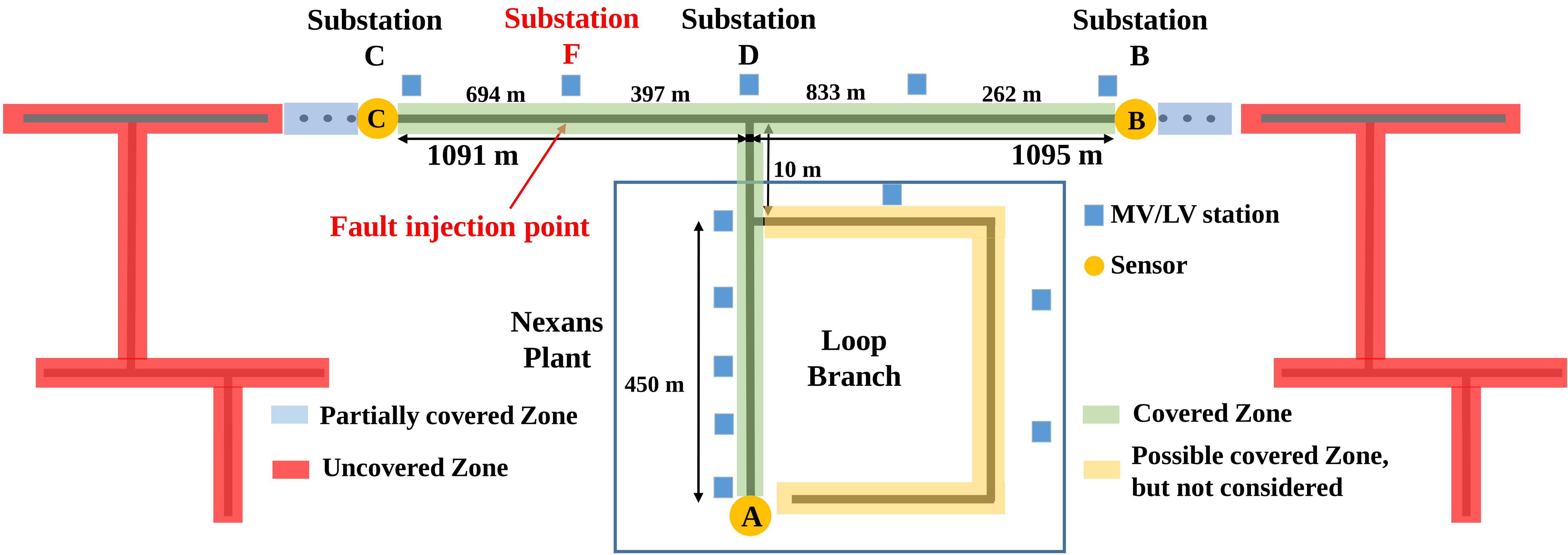
FasTR Fault Location Global Testing Setup



Tested Power Network

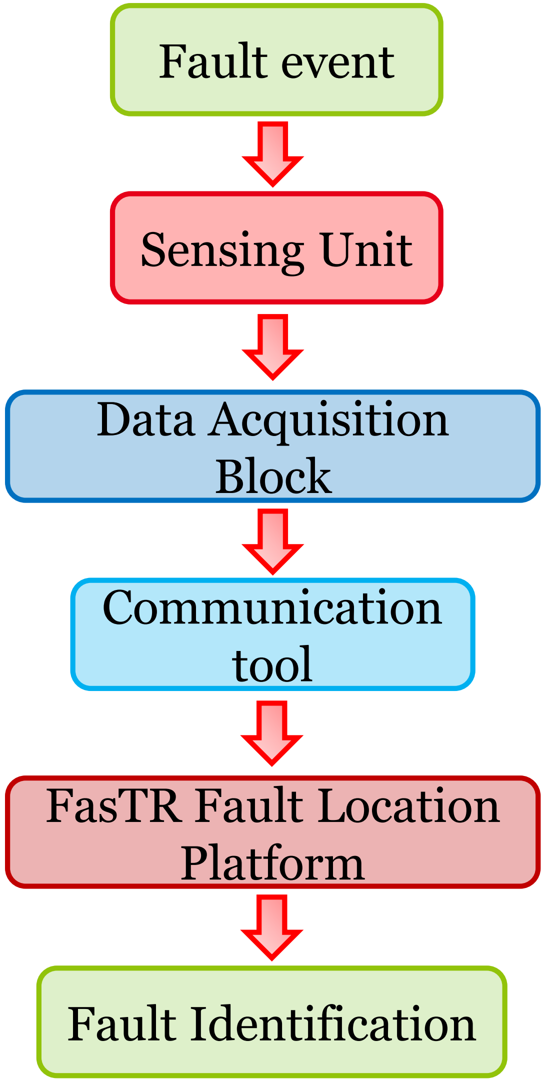
FasTR first pilot test on a realistic power networks under normal operating conditions

2.6 km energized three-phase 20 kV buried underground medium voltage (MV) pilot network



Faults considered are manually triggered single-phase-to-ground fault occurrences

Fault Location System Implementation



Fault Event

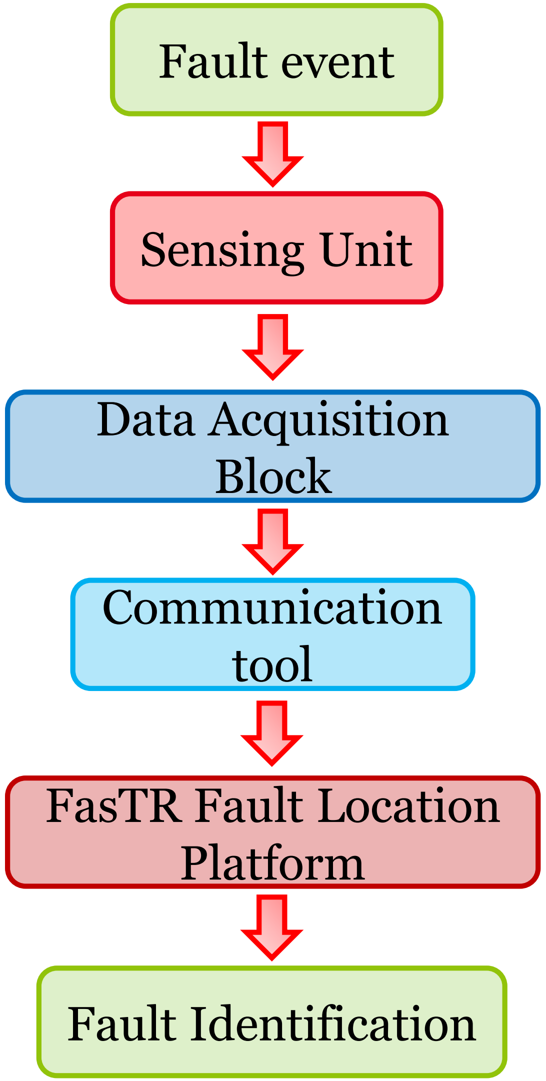
The pilot tests were carried out by an artificially triggering FOT generator which is composed of three elements:

- a disconnection system composed of a circuit breaker (CB) that allows to short-circuit one of the three phases of the SNUT's cable with the ground;
- an adjustable water resistor with values of 30 and 60 ;
- a spark igniter to give a better control over the instant of the arc occurrence.

The corresponding fault generator system has allowed the possibility of producing several types of faults depending on the combination of elements used. In our study we considered the following cases:

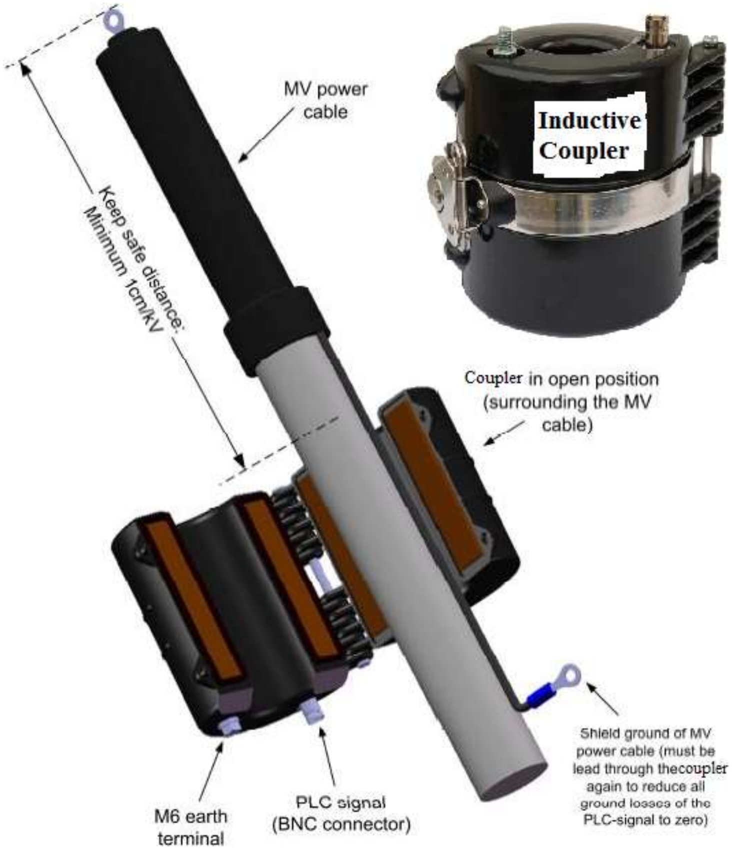
1) CB;
2) CB + spark igniter;
3) CB + 30Ω ;
4) CB + 60 Ω ;
5) CB + spark igniter + 60 Ω.

Fault Location System Implementation



Sensing/measuring unit

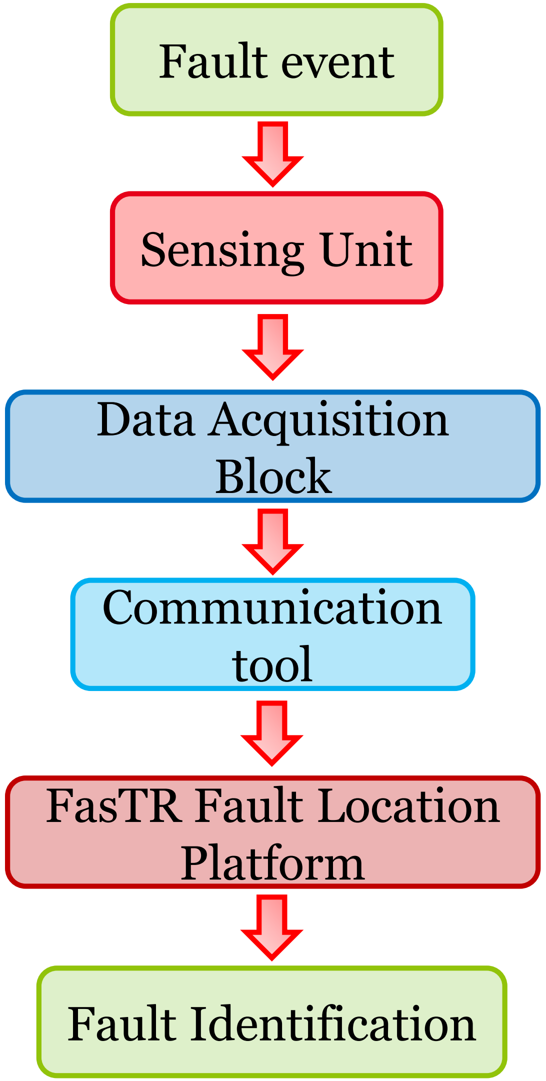
A high-frequency high-voltage Inductive Coupler:



- Perfectly isolates the high voltage low frequency component on MV networks so as not to damage the connected equipment
- Have sufficient bandwidth to cover the frequency spectra of the EM transient signals--frequency range of 30-500 KHz
- Transform the fault responses (more than ten kV) to the withstand voltage level of the signal cables as well as the data acquisition block
- The acquired FOTs are transferred to the acquisition block where a threshold triggering criterion is implemented so as to decide whether a fault-related event has eventually occurred or not.

Fault Location System Implementation

Each acquisition system is deployed on distant predefined observation points on the tested large MV power network.



Data acquisition block

Responsible of acquiring the measured FOTs from the defected MV power network that will be further sent to a server where the FasTR processing is applied

The acquisition system is assembled by National Instrument (NI) products and is composed of four main modules consisting:

- Controller module (on-board PC)
    - High performance Intel processor
    - System bandwidth up to 8 GB/s
- Acquisition module
    - High resolution oscilloscope that allows continuous data transfer at the speed of 400 MB/s to the PC memory
    - Sampling frequency of 100 MS/s real-time and up to 2.0 GS/s equivalent-time
- GPS module (including the antenna)
    - Enables timing and synchronization features capable of synchronizing PXI and PXI Express systems using the GPS, IEEE 1588, etc.
- Clock synchronization module
    - Synchronizes of all modules installed in the chassis.

Fault Location System Implementation

Each acquisition system is deployed on distant predefined observation points on the tested large MV power network.

Fault event

↓

Sensing Unit

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Data Acquisition Block

↓

Communication tool

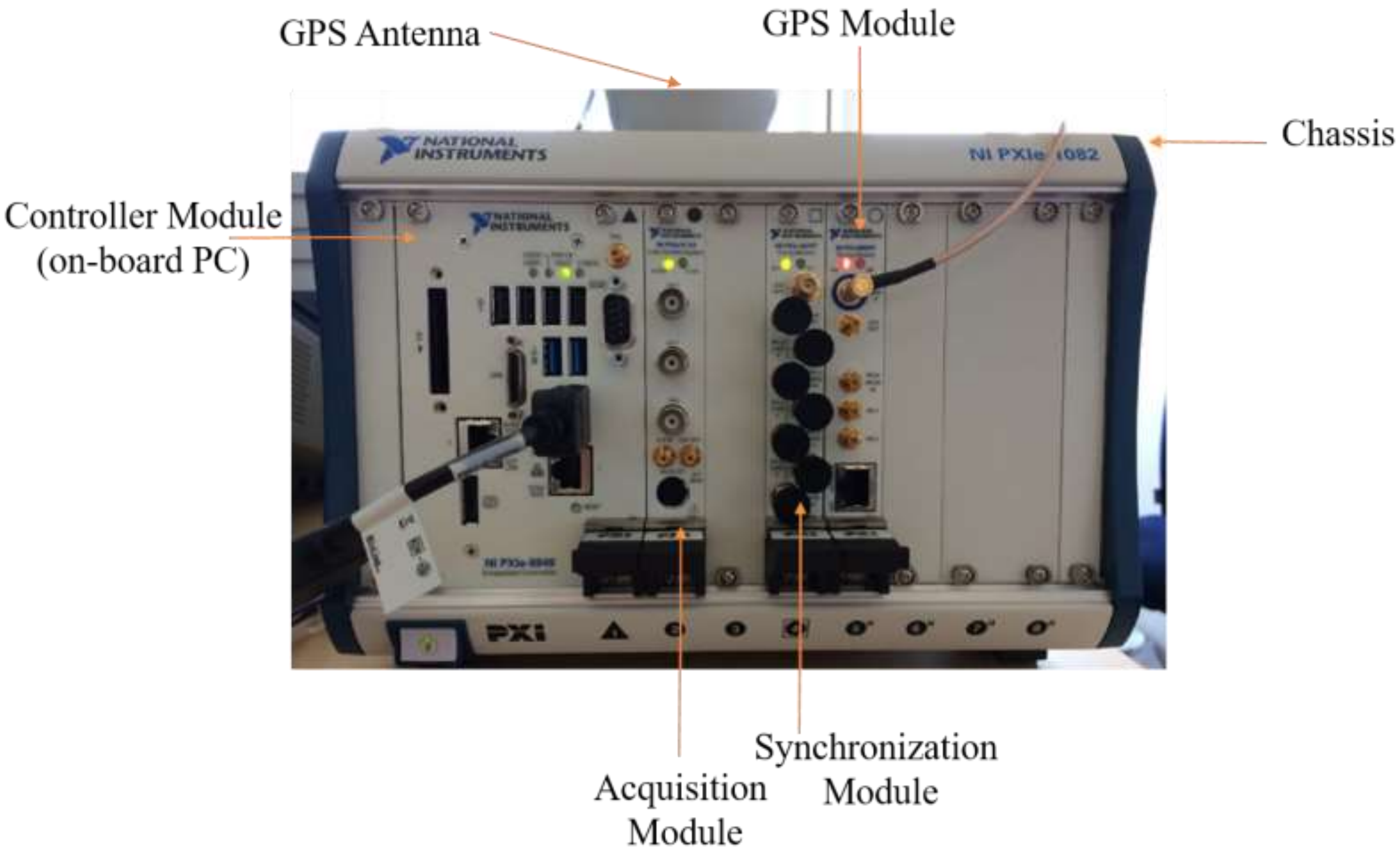
↓

FasTR Fault Location Platform

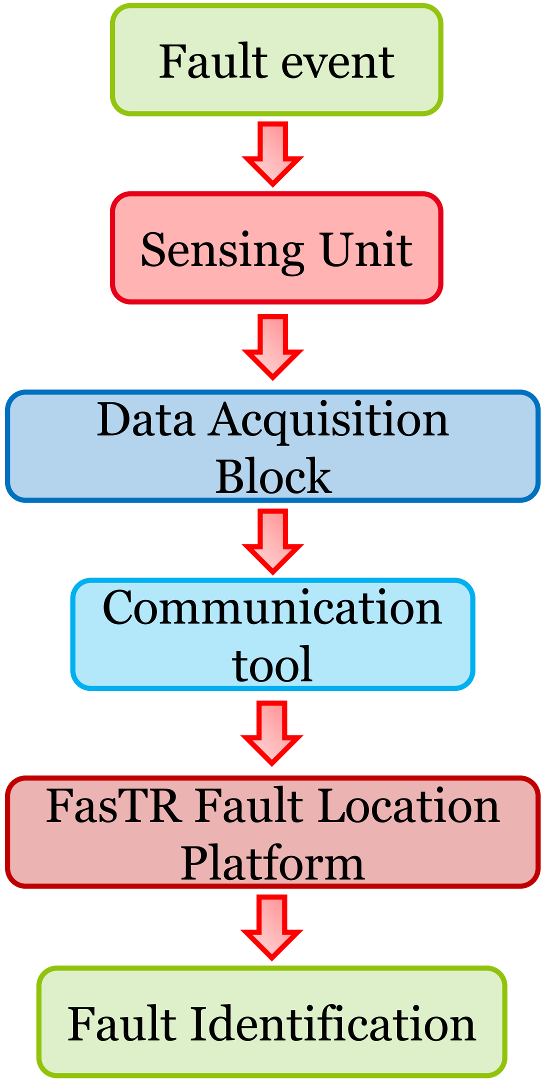
↓

Fault Identification

Data acquisition block



Fault Location System Implementation

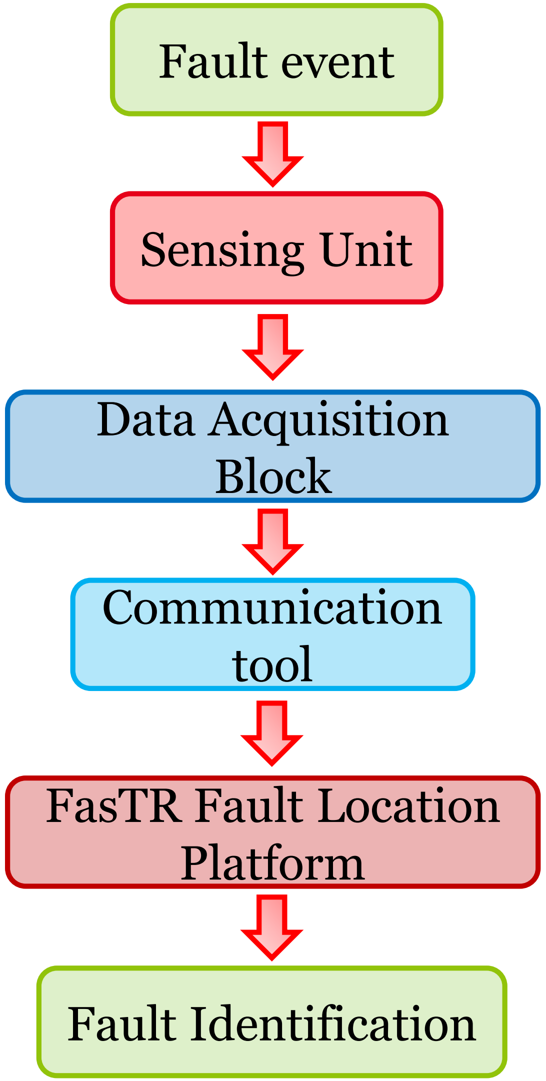


Communication Tool

To facilitate the process of handling, reading, and transferring event-related data, a remote control solution is implemented

- A communication tool based on a 4G network is installed
- It enables the communication of each data acquisition system with a central server
- Once a FOT is detected, recorded and time-stamped at the level of each acquisition system, a scripted code implemented on the system checks in real-time if new data were added to the windows folder
- The 4G connection to the internet sends the data to a distant server

Fault Location System Implementation



FasTR Fault Location Platform

The fault location platform comprises a server employed as a database for saving the recorded events and a computer unit to apply the FasTR algorithm for processing.

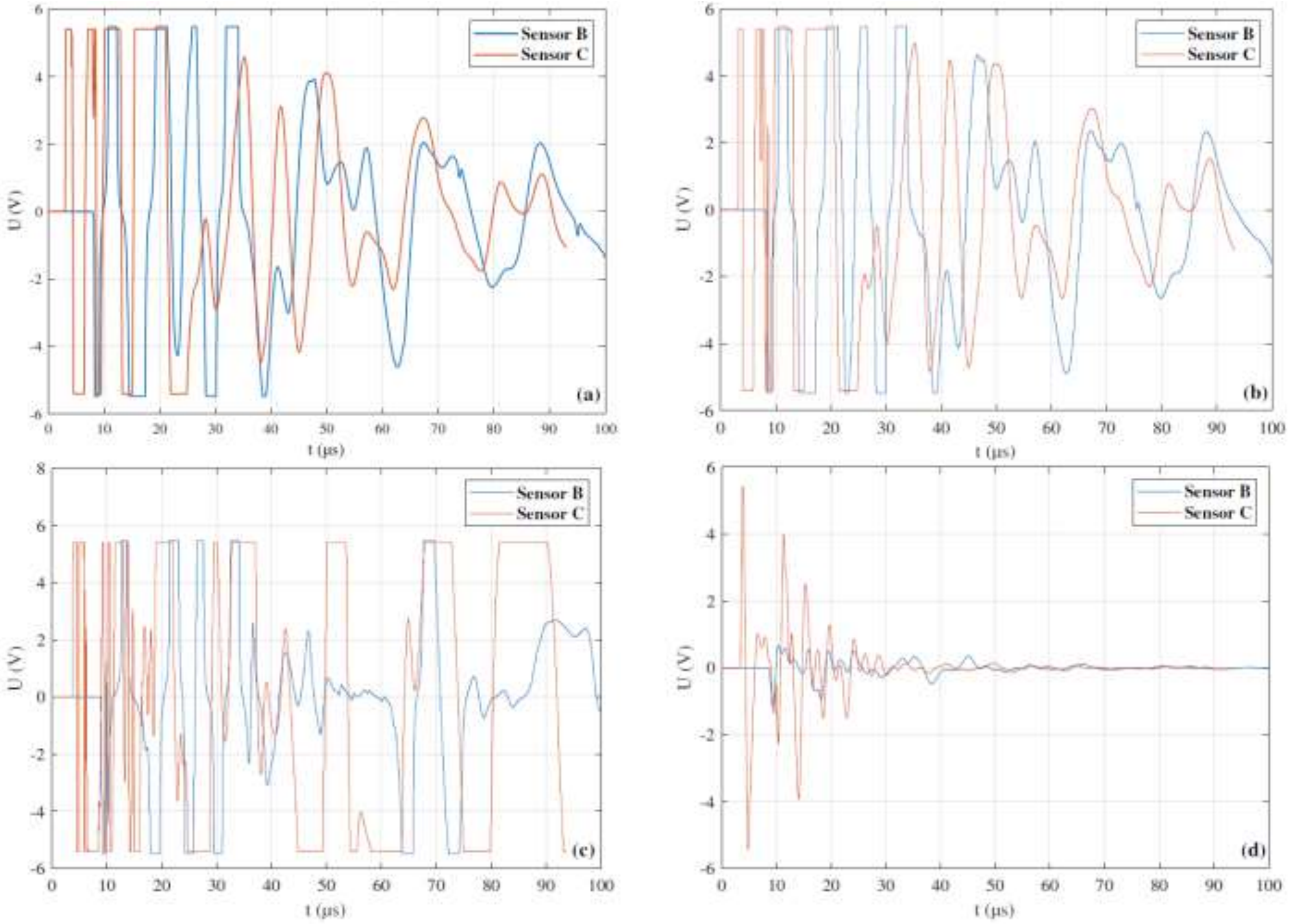
- All data arriving to the server are stored with meta information to ID them individually.
- As soon as new data arrives, a computer unit harnessing an executable version of the FasTR algorithm MATLAB code is launched for analysis.
- It interrogates the database and repatriates all data of the selected test and performs the calculus which can be done on any PC having the FasTR executable file and the right login info.
- Once an event is detected, the corresponding information (fault position, location, and time of occurrence) is saved on a file and sent using the communication network back to the server.
- An immediate warning approach could be also implemented where an email or a text message could be sent to the nearest operation center and/or technician for urgent intervention.

FasTR Results

Amplitude of the FOTs' voltage as measured by sensors B and C for the faults triggered by

CB + 30Ω

CB + 60Ω



CB +spark ignitor

CB + spark ignitor +60 Ω

Sensor A was not capable of recording any signal

A Computation time of less than one minute

Right Faulted Phase Located

	Actual triggered		Retrieved estimated		
Test	Phase	Location	Phase	Location	Time
Scenario 1	L3	694 m	L3	667 m	55 s
Scenario 2	L3	694 m	L3	667 m	57 s
Scenario 3	L3	694 m	L3	643 m	54 s
Scenario 4	L3	694 m	L3	640 m	60 s

An Average error of 40 meters

Conclusion on FasTR Method

- **Fault location accuracy**
  - A position accuracy ranging from a minimum error of 27 m and maximum of 54 m which is satisfying for locating powerful transient signals' source locations.
  - With a better method of precise calibration and a more accurate GPS system, the result should be greatly improved.

- **Network Coverage**
  - Sensor A wasn't capable of detecting any high-frequency signal during the tests
  - FasTR algorithm was still capable of operating with incomplete or missing data
  - The presence of sensors covering the direct path where an event occurs is enough to enable locating its position

- **Response time**
  - The total execution time of the developed system realizing the FasTR methods is less than a one minute

- **FasTR method advantages compared to existing methods**
  1. Several sensing units without the need for communication channels, irrespective of the size and complexity of the network
  2. Capability of pinpointing the precise fault location rather than the fault passage
  3. Applicability to inhomogeneous networks composed of overhead lines and underground cables
  4. Applicability to networks with presence of active injections associated to Distributed Energy Resources (DERs).

THANK YOU FOR YOUR ATTENTION

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