SPECIFICATIONS DEFINITION OF POWER SUPPLY QUALITY MONITORING SYSTEM

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INTRODUCTION

In 1995 Milan Aem Spa entrusted CESI to prearrange a study for the definition of a monitoring system specifications for evaluating the quality of electrical supply, that exhaustively dealt with the following subjects:

- *Examination of normative context and its evolution*
- *Available tecnology state of the art*
- *Drawing up a document with formal requirements necessary for the conduction of bidding procedures necessary to realization of the system.*

Reasons that have made such a document necessary are the following:

- *Constraints imposed by the evolution of normative context*
- *Aspects due to energy market liberalization*
- *Importance of aspects related to the Power Quality in a metropolitan area characterized by an high density of population and energy consumption*
- *A particular attention to the customer, a characteristic of a multiutility company and traditionally linked to the territorial framework where it operates.*

1. AEM SPA ACTIVITIES

Milan Aem Spa operates in the following sectors:

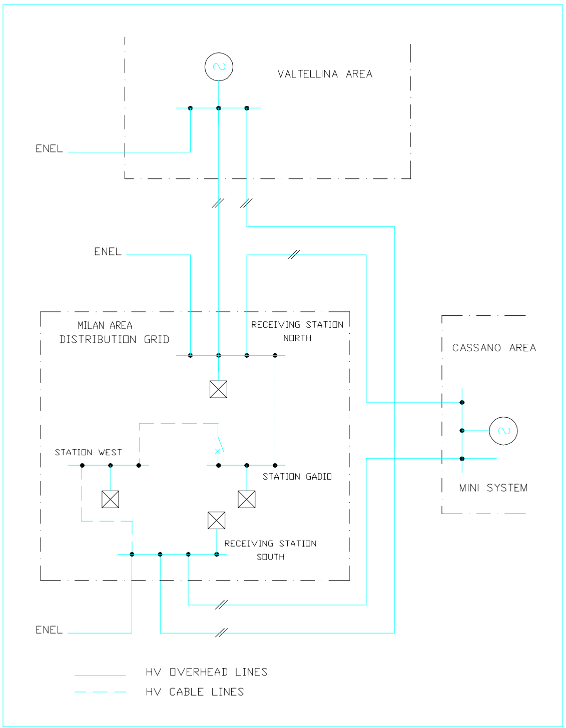
- Electricity
  Producing, transporting, distributing, and selling electric energy to 50% of the customers of the municipality of Milan and some neighbouring municipalities.
- Realizing and managing public lighting and traffic lights on behalf of the municipality of Milan
- Distributing heat and managing heating installations

2. THE AEM SPA ELECTRICAL SYSTEM

The Aem Spa electrical system is completely self-contained, and includes electric power stations of hydraulic and thermal type, high-voltage transporting lines, and an urban distribution grid. The system is interconnected with 3 high-voltage lines to the Enel national grid, so as to assure reciprocal emergency. Some data related to the consistence of plants are reported hereby.

- Production
  - Hydroelectric (Valtellina area) n.7 power stations for a total of 600 MW installed
  - Thermoelectric (Cassano area) n.3 units for a total of a 420 MW installed
- Transportation
  - 220 kV long-distance lines
  - 130 kV long-distance lines
- Distribution
  - HV/MV stations
  - 23/9 kV substations
  - MV/LV substations
  - MV and LV cable grids
  - Electrical customers number: 430.000
  - Characteristics of withdrawal
  - Peak power : 600 MW about
  - Energy sold : 3.000 GWh per year

From the point of view of the HV grid, the distribution system is constituted by four 220 kV load nodes.



3. THE DISTRIBUTION SYSTEM

Every 220 kV node supplies several 23 kV transforming stand-alone units.
Every 23 kV transforming stand-alone unit supplies:

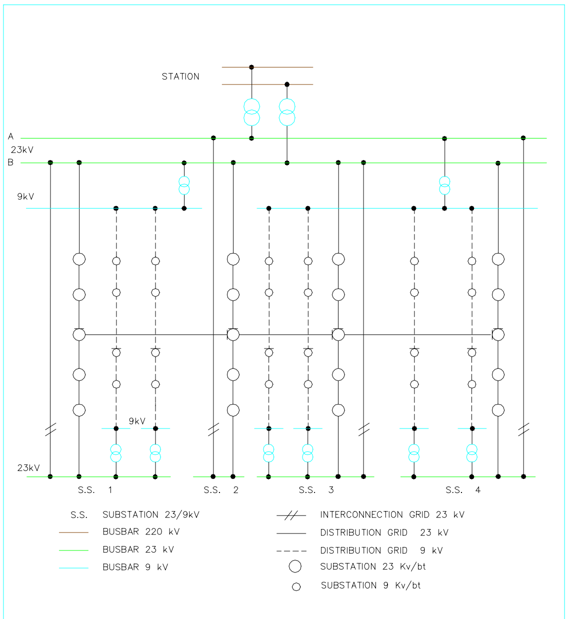
- The 23 kV primary interconnecting grid connected to 23/9 kV substations (1 or more substations for every stand-alone unit).
- The 23 kV secondary distribution local grid

- One or more 9 kV transforming stand-alone units supplying the 9 kV secondary local distribution grid.

Every substation supplies :

- The 23 kV secondary local distribution grid
- One or more 9 kV transforming stand-alone unitis supplying the 9 kV secondary local distribution grid.

Thus 2 voltage levels for MV secondary distribution, one 23 kV and the other 9 kV exist; in general in the old side of the city the 9 kV grid prevails, in the new side the 23 kV grid prevails. System architecture for 23 kV stand-alone units in a typical station is represented in the following diagram. Two 23 kV transforming stand-alone units, and eight 9 kV transforming stand-alone units are noted in this example.



4. NORMATIVE CONTEXT FOR THE PQ DEFINITION

The principle EU draws its inspiration in the definition work of electric voltage characteristics starts from the electric energy definition as a "product", free to run such as other goods or services, regulated by legislations harmonized in various nations.

For this purpose CENELEC has drawn up standard EN 50160 (translated into CEI 110.22 in Italy), in which frequency, amplitude, waveform, supply voltage symmetry in low and medium voltage grids are examined.

Its purpose is to provide main characteristics of the energy supplied, so that the quality of the product traded may be evaluated with the aid of adequate measures.

The standard has been drawn up with the objective to define a product having reasonable costs and characteristics adequate to the correct operation of customers equipment.

Characteristics have been defined considering:

- present quality standard of the product supplied in Europe (generally these levels allow a satisfying apparatus operation);
- cost implications of the product, on both the distributor grid, and on the design of apparatus.

We need to outline that standard EN 50160 is evolving, in particular as far as quantitative phenomenon definition is concerned, such as outages and voltage dips, that, among all conducted disturbances classified withing low frequency electromagnetic compatibility are by far the most important.

It is right to suppose that standard EN 50160 will evolve with more imposition than the present one, for example sanctioning the distributor's obligation to assure quality standards of the electric product described in standard EN 50160. A continuous monitoring system installed in the electric grid proves to be the only way that allows the distributor to "prove/certify" quality of the product supplied.

5. OBJECTIVES OF PQ MONITORING SYSTEM

Service quality expectation in a metropolis within an industrialized nation is pretty relevant.

From a preliminary result analysis of a sample measurement program on conducted disturbances in the Aem grid we have verified that service quality is averagely very satisfactory, in both normative terms, and in terms of expectation satisfaction by most of the connected customers.

Of course particular situations exist, above all due to a well defined category of disturbances, voltage dips and outages, and to particular customers, manufacturing and service-producing sector, to which a particular attention needs to be paid.

The requirement to monitor disturbances in connection with particular customers proves therefore to be an already present requirement.

Similarly, PQ monitoring also in non critical nodes, allows to maintain service within the standards achieved, emphasizing anomalous growth trends in time.

Considering this, the main objectives to achieve through a monitoring system are:

1. To evaluate in real time the quality of the product supplied through a continuous monitoring; furthermore this allows to dispose of data related to nodes supplying critical customers (both disturbed and disturbing).
2. To monitor disturbance growth trend in the grid so as to prevent critical situations in time, adopting necessary provisions in advance.
3. To diagnose incompatibility situations between mainfeeder and sensitive loads.
4. To dispose of an instrument for measuring power "withdrawal quality" from the costumer, other than, generally, "the service quality" supplied by the distributor.

To satisfy such objectives, the system shall be configured as an instrument network managed by a central unit.

6. MAGNITUDES OBJECT OF PQ MONITORING AND MAIN INDICATIONS FOR MEASUREMENT

Magnitudes to monitor will have to cover all characteristics of voltage reported in standard EN 50160.
The magnitudes presently considered in accordance with the standard and related characteristics of low and medium voltage supplied by the distribution grid, measured in normal working conditions, are listed hereby.

Frequency:

- Nominal value:50 Hz
- Measurement interval :10 sec
- Limits of arithmetic mean value of fundamental frequency:
  - 49.5 to 50.5 during 95% of one week;
  - 47.0 to 52.0 during 100% of one week.

Amplitude:

- Nominal value : Vn = 230 V (LV)
- Stated value : Vc = 23 kV or 9 kV (MV)
- Measurement interval : 10 min
- Limits of the arithmetic mean value of voltage r.m.s. values
  - 0.9 to 1.1 x V during 95% of one week

Flicker:

- Long-term severity level of the flicker:
  $P_{lt} \leq 1$ p.u. for 95% of one week
  where $P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{i=1}^{12} P_{sti}^{3}}$
  Pst = amplitude measured by flickermeter in a 10 min window.

Harmonic distorsion:

- Measurement interval : 10 min.
- Limits of percent values (With respect tonominal voltage8 of every voltage harmonic component for 95% of one week:

Odd harmonics				Even harmonics	
not multiple of		multiple of 3			
ord. h	volt. %	ord.	volt. %	ord. h	volt. %
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	.5	6 .. 24	.5
13	3.0	21	.5		
17	2.0				
19	1.5				
23	1.5				
25	1.5				

- Total harmonic distorsion index:

$$THD = \frac{1}{U_1} \cdot \sqrt{\sum_{i=2}^{40} U_i^2} \leq 8\%$$

Symmetry:

- Measurement interval : 10 min
- Limits of r.m.s. mean values of the inverse sequence component.
  0÷0.02 x U (direct) for 95% of one week

voltage dips and outages:
There is a set of electromagnetic phenomena which prove to be described only in general terms, moreover non quantitative in accordance with EN 50160. Such phenomena are:

- voltage dips, defined as a (sudden) decrease of r.m.s. value of the supply voltage to a value included between 90% and 1% of rated voltage (or stated) value;
- outages (short or long, accidental or programmed) defined as conditions in which voltage at supply terminals is lower than 1% of rated or stated voltage.

The quality of electrical service mainly depends on the two above mentioned phenomena. Results of a voltage dips and outages measurement program of a duration lower than a minute are provided in the UNIPEDE framework.
Results at 95% are reported in the table, averaged on three years' monitoring, in 9 different nations involved for a total of 126 measurement points (frequency occurring per year with a probability of 95% not to be exceeded).
It is outlined that values in the table must be inteded as mean values coming from electrical situations (neutral state, and type of MV distribution, if overhead or in the cable) and lightning discharge situations extremely different from each other, and they may be pretty far from values that can be verified for example in an urban grid with insulated neutral cable distribution like that of Aem.

Depth		**Duration**					
% of rated V		**(ms)**	**(ms)**	**(s)**	**(s)**	**(s)**	**(s)**
from	**up to**	**10 < 100**	**100 < 500**	**0.5 < 1**	**1 < 3**	**3 < 20**	**20 < 60**
10	30	111	68	12	6	1	0
30	60	13	38	5	1	0	0
60	99	12	20	4	2	1	0
99	100	1	12	16	3	3	4

UNIPEDE recommends to classify samples observed over one year for voltage dips and outages according to tables hereby reported:

Classification of voltage dips for duration and depth

Duration(t) Depth_ p%)	10 ms ÷ 0.1 s	0.1 s ÷ 0.5 s	0.5 s ÷ 1s	1 s ÷ 3s	3 s ÷ 20s	20 s ÷ 1min
10 ÷ 15	N_{11}	N_{21}	N_{31}	N_{41}	N_{51}	N_{61}
15 ÷ 30	N_{12}	N_{22}	N_{32}	N_{42}	N_{52}	N_{62}
30 ÷ 60	N_{13}	N_{23}	N_{33}	N_{43}	N_{53}	N_{63}
60 ÷ 99	N_{14}	N_{24}	N_{34}	N_{44}	N_{54}	N_{64}

Classification of outages for duration

Outage duration	**< 1 s**	**1 s ÷3 min**	**> 3 min**
Outage number	N_1	N_2	N_3

Overvoltages:
Limits are not specified, the recommended classification is illustrated in the table:

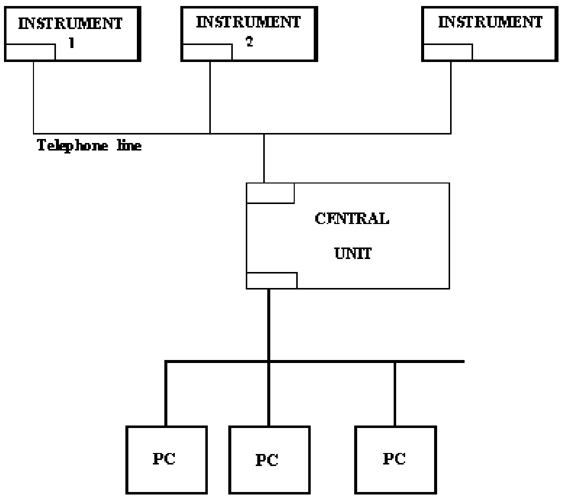
Duration (t) Amplitude (A%)	t < 1 s	t 1 s ÷ 1 min	t > 1 min
110 ÷120	N_{11}	N_{21}	N_{31}
120 ÷140	N_{12}	N_{22}	N_{32}
140 ÷160	N_{13}	N_{23}	N_{33}
160 ÷200	N_{14}	N_{24}	N_{34}
>200	N_{15}	N_{25}	N_{35}

Interharmonics
Limits are not specified, nor a measurement method regognized as a standard is settled; moreover it is a phenomenon normally neglectible.

Signals intentionally injected into grid
Limits are specified; presently they are not present in Aem grid.

7. MONITORING SYSTEM ARCHITECTURE

The following figure represents as a principle the proposed system architecture



The single measuring instruments communicate through a conventional telephone line with the central unit, from which they receive measurement setting parameters, and to which they send, once the measurement has been carried out (or with an appropriate time imposed by the user), data collected. Most instruments only measures a triad of voltages, while in some cases more complete instruments realize the measurement of one triad of voltages, and one triad of currents. The system also provides some portable measuring instruments. Communication via telephone cable is made possible by the presence of a modem on each instrument and on the central unit.

8. CENTRAL UNIT FUNCTIONS

The central unit must perform the following functions:

1. Instrument network remote-management
2. Data-base for measurements made, with data filing and statistical processing functions, with the following basic objectives.

a) processing of all acquired magnitudes, so as to verify, on a weekly basis, fulfilment of limits imposed by the standard: the system might compile automatically a report on the quality of the service supplied by the grid over a week, emphasizing further excesses of imposed limits;
b) possibility of emphasizing the trend of differrent types of disturbances recorded in the grid in pretty long time periods, in the order of months, quarters or years, in connection with each of monitored nodes and/or as an average global data of the grid.

9. CHARACTERISTICS OF MEASURING INSTRUMENTS

The instrument whose main characteristics are outlined hereby is devoted to the measurement of low-frequency conducted disturbance present on electric grids.
The instrument will be installed in fixed locations, that can be enquired, configured and however managed by a central station, via telephone modem.
The instrument will prove to be thought for a permanent monitoring usage, and designed in a manner conforming to environmental characteristics (of electromagnetic and climatic nature) of the environment where it will be operating.
Three different instrument versions will be provided, each having the characteristics listed here with:

1. instrument for fixed installation devoted to the measurement of one triad of voltages (phase to neutral or voltages between lines).
2. instrument for fixed installation devoted to the measurement of a triad of voltages and one of currents;
3. portable instrument devoted to the measurement of a triad of voltages and one of currents.

The instrument will be equipped with a rechargeable internal battery to allow to operate also in the absence of auxiliary supply: it is regarded that the autonomy should assure the instrument to operate for 2-3 hours without supply. In case of particulary long outages, the apparatus, equipped with battery-powered calendary clock, switches off recording the start time and, upon restart, recording the event and its duration for time differences. The length of maximum outage in which the instrument remains on could be programmable. The instrument will have to be equipped with a non volatile memory support in which collected data are saved for a maximum of 1 week non stop measurement.
The apparatus will have to communicate the collected data when enquired by the host via modem and further it must be possible to remotely program the measurement program.It will also be possible to obtain real-time instantaneous measurement data from remote programming.

Due to the type of connection required for voltage (100Vrms for MV and 230Vrms for LV) is sufficient to dispose of two fixed measurement ranges that can be selected, or one wider range provided that converter dynamics is such to assure the necessary accuracy.

10. DEFINITION OF RULES PRESIDING AT THE CHOICE OF MONITORING SITES, AND CHOICE OF SITES

The principle to which we draw our inspiration is to check a sample, through which quality control on full-scale productions is typically made. We need to define the rules presiding at a choice of measurement sites in such a way that we may consider that quality image detected by them is, with a sufficiently elevated grade of confidence, representative of the quality supplied by the overall grid in average.
The choice of nodes must thus be limited to all those nodes to which particular users do not result connected, not representative of a diffused load typology in the grid, characterized by a potentially considerable impact on the grid, or by an emphasized sensitivity to disturbances not shared by other connected loads. For this typology of load, and for nodes they result connected to, monitoring takes a different purpose, it becomes punctual (thus it cannot participate in the definition of mean disturbance value in the grid), it is performed operating the control of a number of magnitudes higher than the minymum one foreseen by standard EN 50160, and especially it is realized by monitoring current absorption by the load.
We will provide hereby for the criterion with which nodes must be chosen to define a monitoring designed to evaluate quality of the service averagely supplied by the grid . A first choice criterion of sites is based on the voltage level : as previously explained, medium and low voltage grids will be kept under control since we have the definition of characteristics in european standard EN 50160 only relatedly to them. At least in a first phase, 30 instruments are predicted to be utilized.

10.1 Choice criterion of sites for characterization of the quality supplied in average to low-voltage connected users

In general, a statistical survey to characterize the quality offered in average on low voltage should be conducted, differentiating the result according to the following situations:

- typical categories of customers
  - residential
  - service/producing sector
  - handicraft/industrial
  - commercial
  - mixed (if none of the previous categories exceeds 60 % of the total)
- different electrical distance of the MV/LV substation from the station that supplies transforming stand-alone units.

Such a requirement is due to the fact that for most disturbances, the entity of disturbances decreases with the increase of the node short-circuit power. Normally, the disturbance expected at MV/LV transformer primary results progressively increasing with increase of the MV/LV substation electrical distance from the station supplying it : as the disturbance measured on LV is the effect of the composition of the disturbance existing on MV (where-even though in a different manner-, all MV/LV substation and deliveries in the transforming stand-alone unit depend on) with that effectively originated on LV, to characterize the quality of the service supplied to a specific category of load it will be necessary to examine LV grids supplied in points collocated at a various distance - electrically intended - from the station.

- necessity to distribute uniformly LV measurement points in various MV transforming stand-alone units. It is intended that MV/LV substations where the monitoring instrument is installed are connected on both 23 kV level and on 9 kV level.

The typical installation point of a monitoring instrument on low voltage will be directly the MV/LV transformer secondary.
The number of instruments to consecrate to LV monitoring must be not lower than 18 (thus 60% of the instrumentation total), considering that:

- on LV grid a significant share of the load supplied by Aem is concentrated,
- on LV grid an emission characterization of different classes in which the users are subdivided is possible (on the contrary it is not possible in MV grid, at least not in the same terms).

Having separated 4+1 categories of LV grids, we think we need to subdivide the number of instruments in order to evaluate (in some way) the importance of category, for number of users and/or for absorbed energy. This number of instruments should be collocated as uniformly as possible on the whole grid, subdividing in various transforming stand-alone units, preferring-even if little-those MV/LV substations supplied by the 23 kV system (subdivision might be 10-11 instruments in the 23 kV system, and 8-7 instruments in the 9 kV system).
Let's suppose to assign:

- 5 instruments for checking domestic category,
- 4 instruments for checking tertiary category,
- 3 instruments for checking industrial category,
- 4 instruments for checking mixed category,
- 2 instruments for commercial category;

Such instruments are to be distributed in the grid, in MV/LV substation collocated at a various distance from HV/MV stations.
Therefore the 18 instruments can be distributed in 23 kV and 9 kV grid substation according to the diagram of the following table. (where 1 = 0÷1.5 Km, 2 = 1.5÷3 Km, 3 = > 3 Km)
An appropriate statistical analysis to be made at the end of the data acquisition relating to service quality protracted for a significant period (some months), will highlight the statistical consistence of the sample detected. Once the statistical consistence of the acquired sample has been verified, the processing system of data collected will:

- characterize the quality of the service supplied to different typologies of customers,
- compare the values detected,with both the values foreseen in the standard EN 50160,and with the grade of customers satisfaction served,
- monitor, for different disturbances analyzed, further growth trends of mean value in time,
- check events associated with the quality service in single sites monitored, emphasizing further anomalous deviations from values measured with respect to mean value.

	Syst	Category	St. al. unit	Distance
1	23 kV	Residential	North A	1
2			South B	3
3			Gadio A	1
4		Service prod sect	Gadio B	3
5			South B	1
6		Industrial	West B	2
7			North B	3
8		Commercial	South A	3
9		Mixed	West B	3
10			North A	2
11	9 kV	Residential	North B	1
12			West A	3
13		Service prod sect	North A	2
14			West A	3
15		Industrial	South B	1
16		Commercial	Gadio A	2
17		Mixed	Gadio B	2
18			South A	1

10.2 Choice criteria of sites for service quality monitoring in 23 kV and 9 kV medium voltage grid

23 kV : two of the 23 kV system stand-alone transforming units may be chosen on which to operate a monitoring dedicated to both determine a mean value of the quality supplied, and to identify disturbance propagation mechanisms between the different voltage levels (HV/MV/LV). Further MV loads particularly critical for disturbance injection entities (or for an outlined sensitivity) for which we want to set a punctual monitoring are, of course, an exception: such loads may also not to belong to MV stand-alone units considered into account. We find interesting to evaluate the quality of the service on 2 transforming stand-alone units that may represent two substantially different situations:

1. the first one supplies one of the most extensive grids in terms of Km of cable, with a higher short-circuit power at bus-bars, with the major number of 9 kV transforming stand-alone units supplied, and serving an area comprising the north side of Milan and neighbouring villages, probably with a prevailingly domestic and industrial load;
2. with the most moderate short-circuit power at bus-bars, the number of 9 kV stand-alone units supplied is intermediate, with a prevailingly commercial load

9 kV : for the purpose of investigating disturbance propagation laws, between the different voltage levels, we choose to limit the analysis to grids supplied by one 23 kV stand-alone unit between the two units above considered. It is useful to examine 9 kV grids supplied by one of the substations being part of the stand-alone unit 23 kV nr.1. It would be desirable to measure phase-earth voltage on the HV bus-bar, or current at the transformer secondary, the measurement of voltages between lines. Taking measurement points of LV chosen in MV stand-alone units into account, in some substation it would be necessary to measure voltages at MV/LV transformer primary and secondary: this is done for the purpose to characterize disturbance transfers from MV to LV and -which is the same-the proper disturbance of LV. It would be worthwhile to consider at least one substation in which there is also a delivery to MM.(Metropolitana Milanese), in such a way that we can evaluate the impact of undergound traction converters on grid disturbance. For this type of substation there would be the measurement of two triads of voltages (MV/LV transformer primary and secondary) and the triad of absorbed currents by MM converters.
Substations investigated for monitoring are the following:

- 23 kV system
  - stand-alone unit n.1
    - one instrument on LV bus-bars in the station North
    - one instrument on MV bus-bars
    - one instrument along an output feeder from one of the substations belonging to the stand-alone unit, in a medium-distance MV/LV substation (1.5 to 2 Km)
    - one instrument along an output feeder from a second substation in a medium-distance MV/LV substation, on the LV side
  - stand-alone unit n.2
    - one instrument in a MV/LV substation supplying a big tertiary load, distance 7 Km
    - one instrument in a cabin supplying a big load for underground traction, distance 1 Km
- 9 kV system
  - specified the substation, 23 kV stand-alone unit n.1, in a MV/LV substation at 2 Km distance
  - same 23/9 kV substation, 9 kV stand-alone unit n.2, in a MV/LV substation (MV bus-bars) at the back of the feeder
  - instruments monitoring particular customers : n.2.