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Glossary

AMI	Advanced Metering Systems
CHP	Combined Heat and Power
DER	Distributed Energy Resource
DSO	Distribution System Operator
EB	Electric Boiler
ENS	Energy Not Supplied
ENG	Energy Not Generated
EV	Electric Vehicle
GMon	Grid Monitoring (application)
HMM	Hidden Markov Model
HP	Heat Pump
LC	Loss Calculation (application)
LL	Line to Line
LN	Line to Neutral
ODet	Outage Detection (application)
ODiag	Outage Diagnosis (application)
OGM	Observability Grid Model
OHL	Over Head Lines
OLTC	On-Load Tap Changer (transformer)
Pit	Flicker severity
PLC	Power-Line Communication
PM	Preventive Maintenance (application)
PV	Photovoltaic Solar
RES	Renewable Energy Sources
RFG	Reference Grid Model
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
SO	System Operator
THD	Total Harmonic Distortion
TPICM	Three Phase Current Injection Method
TSO	Transmission System Operator
Un	Nominal Voltage
WT	Wind Turbine
WF	Wind Farm

1 Executive Summary

This document contains the preliminary design of the grid models and a state of the art of the five observability applications of Net2DG, which had been identified to be of high priority in Deliverable 1.1.

Chapter 2 introduces the topic and relates the work of Work Packages 2 and 3 with the common goals of the Net2DG project; it introduces the distinction between two different grid model types that are used in Net2DG: the Observability Grid Model that is associated to observability applications and ICT Gateway, and the reference grid model which is used for assessment and testing.

The necessary background on distribution grids starting from their typical topology and structure is reviewed in Chapter 3 and covering in addition relevant assets, faults in distribution grid, voltage quality issues, grid losses. Chapter 3 also presents the analysis of grid simulation tool and the first foundation of the Net2DG Reference Grid Model.

Chapter 4 reviews the available estimation techniques for operational states of the distribution grid which are the candidates for use in the Observability Grid Model.

In this public version, Chapter 5 contains an overview of the state of the art and of adapted requirements of the grid observability applications for Outage Detection, Outage Diagnosis, Loss Calculation, Preventive Maintenance and for Grid Monitoring.

2 Introduction

Capturing properly a given distribution grid at a given moment in time is a challenging tasks both for DSOs but also for research purposes. Grid topologies may change during the operation. Several section cables may be installed in parallel. The parameters of the cables, transformers and other power systems components are degrading in time while datasheets available in DSO's archives are providing parameters' values with standard deviations as coming from manufacturers. Operating conditions at different loading hence different temperatures will also influence these parameters. Distance between junction boxes and house or cable lengths to the metering point in low voltage grids are not known exactly, thus this length is typically missing in DSO's database. The distribution grids might also have multiple grounding points of the neutral (at the secondary substation, along the feeder, at customer connection points of TN grids, etc.), and the value of this parallel impedance can vary significantly for a given area. Thus, the neutral voltage displacement may impact the measured values especially in unbalance situations, but also deviations in simulation results. Smart Meters and other measurement devices are complying with standard accuracy classes however the actual accuracy of a particular device is not known exactly. All these issues have a large impact on the Net2DG's observability/domain applications and therefore the actual operating conditions need to be captured properly by using appropriate models. Two different models are defined in this document namely the Reference Grid Model (RGM) and the Observability Grid Model (OGM) as shown in Figure 1.

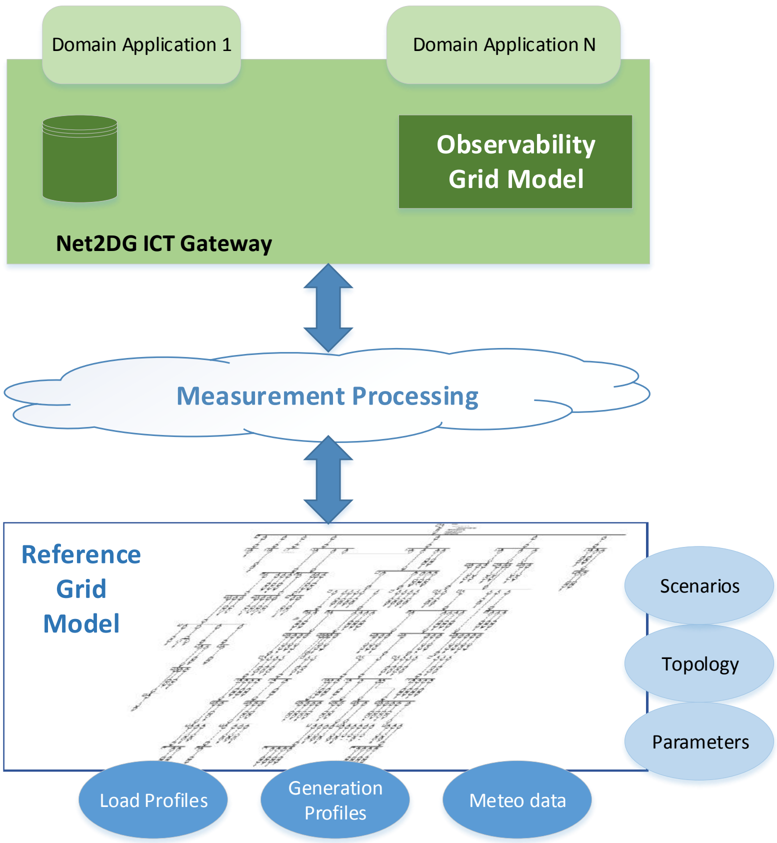

Figure 1: Reference Grid Model versus Observability Grid Model.

The Reference Grid Model is a representation of the real world used to reproduce events and operational challenges similar to daily operation of distribution grid. All parameters are known with a minimum uncertainty and all variables are ideally available without accounting for measurement errors. This model will be implemented in a selected simulation tool that will support the research activities in WP2 – WP4 in Net2DG. A special implementation of RGM is to be achieved in WP5 for large scale laboratory demonstrations using RT-HIL approach.
The Observability Grid Model is the one available in the Net2DG ICT Gateway which is built based on various information sources available at DSO level. Typically, the information available to characterize a given distribution grid is available in various formats and data bases. This model is the basis for supporting the observability applications taking into account only the information available but also considering some feasible technical assumptions when information is missing. All observability applications will be compared with the Reference Grid Model that will provide all the information assuming perfect knowledge and availability of data, measurements, etc.

3 Modern Distribution Grids

3.1 Typical topology and structure

Traditionally, the purpose of distribution networks was to deliver power from the transmission network to customers (end-users), although nowadays, the inclusion of distributed generation causes bi-directional power flows. Such distribution grids are classified according to the voltage level, however, discrepancies exist in the EU; for instance, in the UK distribution is considered up to 132 kV [2] whereas in Belgium is only levels under 30 kV [3]. In this project, distribution is considered below 36 kV as defined in [40]. The reliability requirements of the grid decreases along with voltage level, for example; a 33kv connection is expected to have less than a few minutes of outages per year, while a 230 V connection in a rural area (individual domestic consumer) expects at least an hour. The difference in reliability level is typically caused by the fact that, in general, lines with higher voltages have more redundancies and ring or mesh topologies, while low voltage grids are typically operated in radial topology. Figure 2 to Figure 4 present the topologies radial, ring and mesh in an increasing order of reliability. Also, rural and urban areas can be distinguished, since urban areas usually present radial or mesh topologies and underground cables, due to the high concentration of users, which makes it cost effective, while rural areas are dominated by radial feeders and Over-Head Lines (OHL). Finally, it is also worth mentioning that, since distribution grids are traditionally designed on the basis of extreme conditions (worst case scenario), there is very little active management (control) [2] [3] [4] and [6].

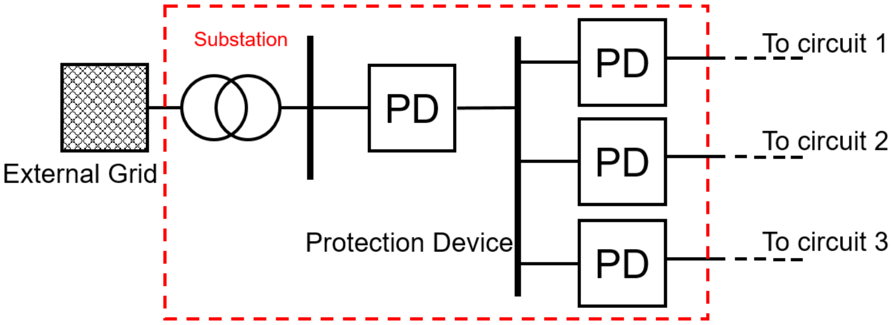

Figure 2: Typical radial topology [6]

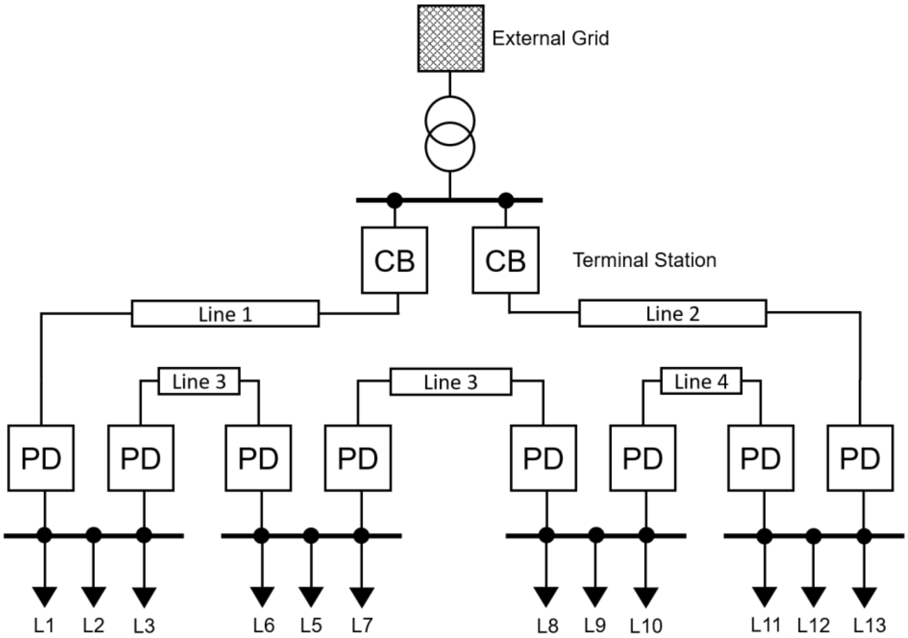

Figure 3: Typical ring topology [6]

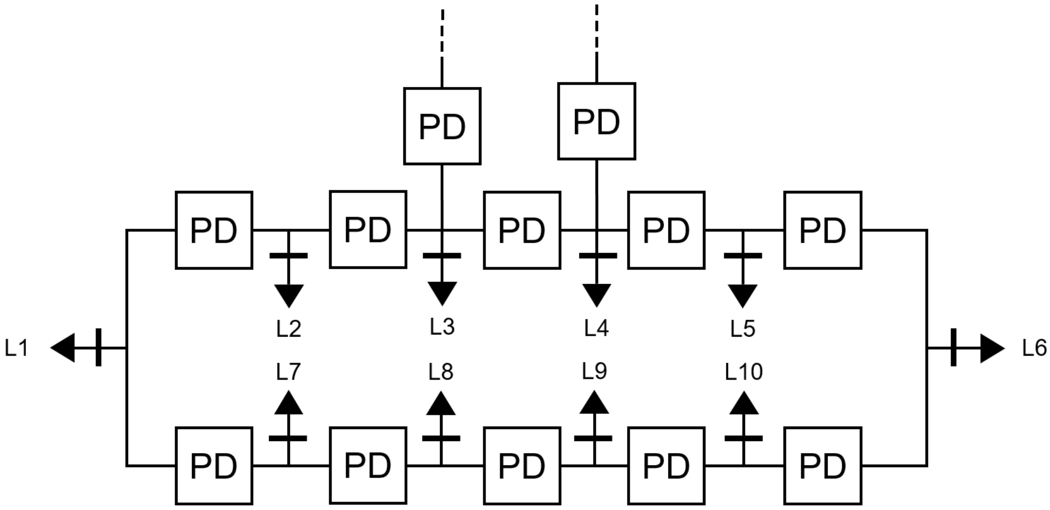

Figure 4: Typical mesh topology [6]

A comparison between the project's two areas of interest, Denmark and Germany, is presented in Table 1. [7]

Table 1: Comparison of the areas of interest [7]

	Denmark	Germany
MV	Radial & Mesh topology. Underground Cable.	Radial & Mesh topology. 75 % Underground 25 % OHL
LV	Radial, limited redundancies. Underground Cable.	Radial, despite being able to operate as mesh.
DG	Wind (especially in rural areas) and PV.	High PV penetration.

3.2 Assets

In this section, basic descriptions of the assets involved in the grid to be modelled are covered. In this case, the term asset refers to any kind of generation unit, loads or measurement devices, Remote Terminal Units, etc., which are connected permanently to the electrical grid infrastructure i.e. connection boxes, terminal busses or bus-bars. It is worth mentioning that there can be more devices and measurement devices installed temporarily in the grid, like mobile PQ measurement units, which are typically used to identify reported issues in a given area. However, these units will not be considered in modelling of the RGM.

3.2.1 Production & Consumptions Units

3.2.1.1 Loads

There are 4 basic types of loads namely residential, commercial, industrial and agricultural common to any distribution grid below 60 kV. These types of loads can be briefly described based on [9] [10] and [11] as:

- Residential consumptions comprise diverse loads varying from compressors (fridges, air-conditioner, etc.) and lighting equipment to sensitive devices such as computers and microwave ovens. A single phase device is limited to a maximum 16 A in Denmark. Devices with more than 16 A shall be connected on two or three phases. Standard junction boxes are allowing 25A per phase.
- Small Commercial Customers: Businesses like restaurants or laundromats are considered to fall within this category. Thus the type of load depends on the activity, being more resistive for the first ones while more inductive for the lasts, due to the motors involved. A higher variation of power is perceived in those consumers with constant impedance (e.g. restaurant) while motor driven ones keep a constant current load model. These customers are typically directly connected to a secondary substation or have their own secondary substation. The installed capacity of these loads is up to tens of kVA.
- Large Commercial Customers: Businesses like hotels, hospitals or high schools fall within this category, where heating, cooling and lighting loads largely contribute. These customers are typically directly connected to MV distribution grid by a secondary substation. The installed capacity of these loads is up to hundreds of kVA even couple of MVA.

- Industrial Customers: These type of consumer are typically sawmills, workshops, glass factories, etc. Disregarding the activity, in general, most of the large loads found on their premises are motors, small arc furnaces, welding machineries, etc. Typically the installed capacity varies from tens of kVA to hundreds of kVA. Hence they can be directly connected to a secondary substation or have their own secondary substation.
- Agriculture: it contains loads such as animal farms, irrigation systems, milking machines, etc. which represent high consumption, but are used during relatively short periods of time, causing load spikes. Most of these loads represent motors, lightning and heating or air-conditioning systems, but they usually have domestic loads also included. It should also be mentioned the high seasonal load variations, for example grain drying consumes a lot of energy during late summer; corresponding to the highest consumption peaks of the year. The installed capacity is in the range of hundreds kVA. Most of the agriculture loads are connected to the MV distribution through a dedicated secondary substation.

Regarding the type of connection, most residential loads as well as small commercial customers in Germany are three-phasic (3ph) due to the extract unbalance limits; although some of them might be monophasic (1ph); while in Denmark they are always 3ph. On the other hand, large commercial and industrial consumers are always 3ph. In other European countries the criteria varies substantially. In France, for example, households are single phase connected as long as the expected load is less than 18 kVA (80 A / 230 V) [12], while the connection can be monophasic up to 14,49 kW (63 A / 230 V) in Spain [14], and up to 10,35 kVA (45 A 230 V) in Portugal [12] [13].

The typical daily aggregated profiles for different consumer types at the LV transformer level are presented in Figure 5 to Figure 8 based on available measurements in a distribution grid located in Northern Jutland, Denmark [14] and [16]. Figure 5 presents an aggregated industrial consumer load profile while Figure 6 presents the aggregated demand profile of a group of 133 residential households; subsequently Figure 7 presents the aggregation profiles of commercial consumers i.e. supermarket and, finally, Figure 8 represents the aggregation of five agricultural loads connected radially. These profiles are included to point out the hourly differences in utilisation of each load type. Finally, it is worth mentioning how the expected trend is to increase the loading of all the consumers, especially after the inclusion of the units described in Section 3.2.1.3 [15].

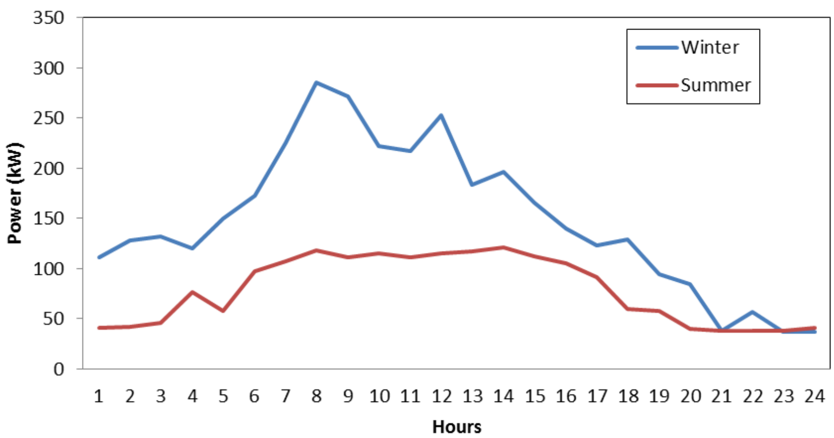

Figure 5: Aggregated Demand Profile – Industrial [15]

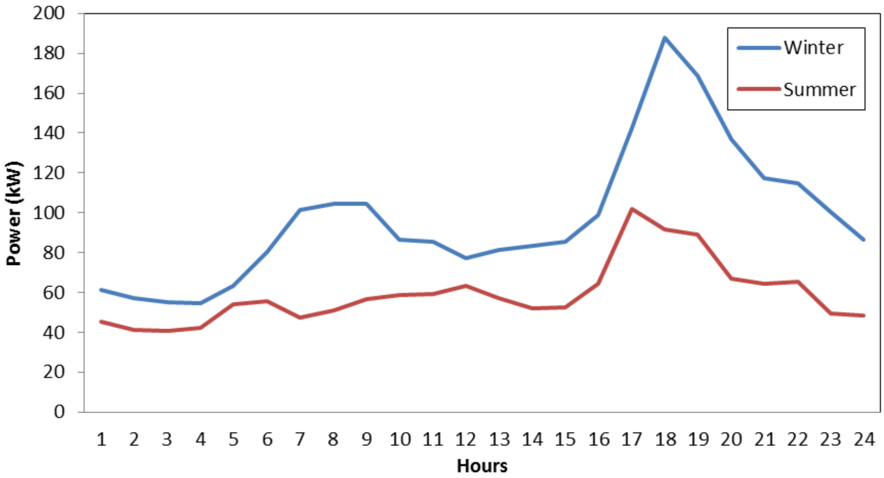

Figure 6: Aggregated Demand Profile – Residential [15]

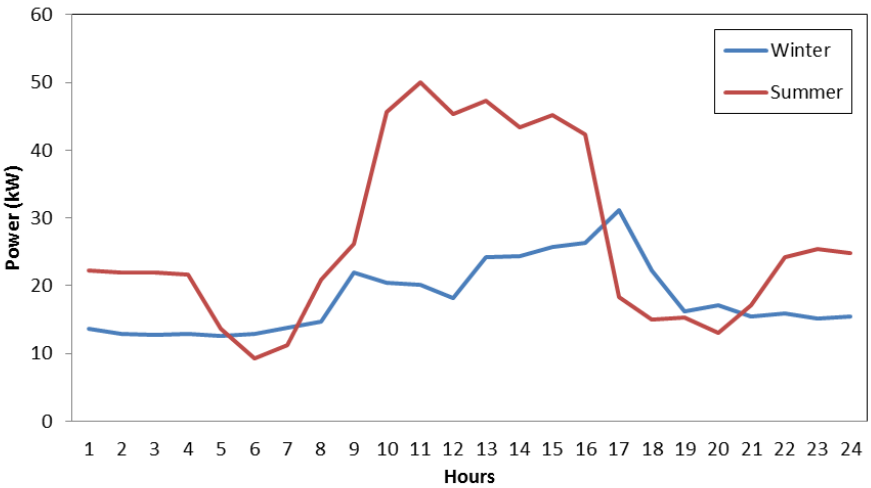

Figure 7: Aggregated Demand Profile – Commercial [15]

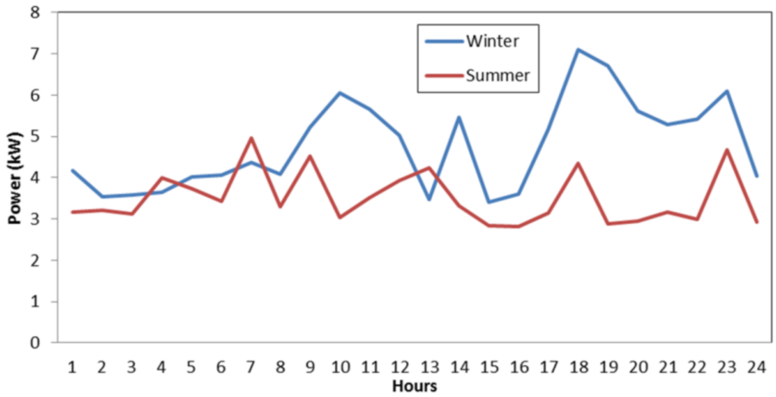

Figure 8: Aggregated Demand Profile – Agriculture [15]

Perspectively, it can be mentioned, that time-variable energy market prices are increasingly available even at the level of residential customers. Enabled by the rollouts of smart metering, innovative electricity retailers (such as the Austrian start-up aWATTar GmbH, https://www.awattar.com/) pass day-ahead spot market prices on to their customers, providing significant incentives to shift flexible loads (such as heat-pumps, EV charging etc.) to times of low or even negative energy prices. On the one hand, by leveraging new flexibilities this contributes to more liquid and thus efficient energy markets, but on the other hand, this could increase the simultaneity of loads and thus conflict with DSO assumptions on simultaneity factors.

3.2.1.2 Renewable energy sources

The typical renewable energy sources found in the European grids are solar photovoltaics (PV) and Wind Turbines (WT). Both of them are connected to the grid by means of a power electronic device. It is important to distinguish between utility scale and prosumer installations. The utility scale ones are in the range of MW and usually connected at medium or high voltage grids. The prosumer ones are up to tens of kW and connected directly to low voltage distribution grids. Combined Heat and Power (CHP) should also be mentioned, since they can be powered with hydrogen, biogas or biofuel; corresponding to a renewable or CO2 neutral source of energy. Regarding PV installation trends, the EU is experiencing a solid 3 % rate since 2015 as according to [17] and it will continue at least until 2020 as shown in Figure 9. Particularly, Germany represented the fourth highest installation growth in 2016, while also being the country with highest PV capacity per inhabitant, it's worth mentioning that Italy is fifth and third respectively in those same lists [18]. In that same document, the issues caused by PV installation are highlighted with selected cases mostly in Asia; such issues are relevant in the Net2DG scope, as they are to be minimised or avoided by European DSOs. On the other hand, Denmark, Sweden, Germany, Ireland and Portugal are world leaders in wind power installed capacity per inhabitant, which resembles the high penetration of this source in European grids [18]. However, considering available data from Germany and Italy, only between 5 to 7 % of the installed wind power is connected at distribution level in these two countries, which are the ones with highest installation of small scale wind turbines [19] [20]. Regarding Denmark, nearly the 24 % of the installed wind turbines are connected to the low voltage grid and their number is being exponentially increasing since 2016. However, they only represent about 0.3 % of the total wind power installed capacity [21].

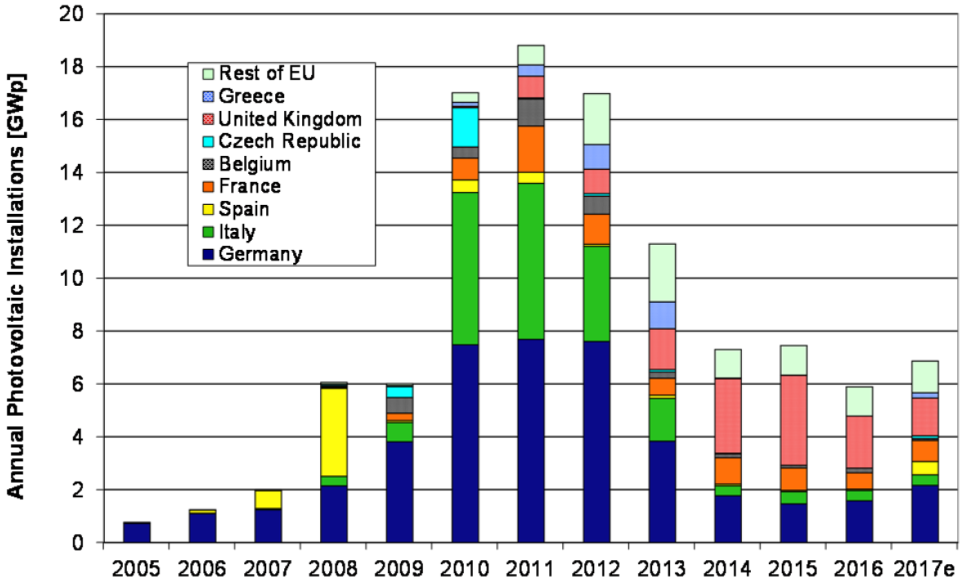

Figure 9: Annual PV installation in the EU [17]

In Germany as most of the EU, PV penetration in distribution grids is relatively high, while in other countries such as Denmark or Italy, small WTs can also be found. The typical installed power of a PV panel ranges from 150 to 300 W, thus, they are usually installed in PV plants reaching 3 to 15 kW; while the WT are between 10 to 30 kW and are usually installed individually. It is expected that the installation of such devices will be steadily increasing in the following years, nevertheless Fronius has already detected semi-urban areas where the penetration of PV reaches 80 to 100 % in relation with the secondary substation size [22]. Also, it is worth mentioning that it is possible to connect small WTs and PV units to the LV grid, while bigger ones are required to use MV connections. On the other hand, micro-CHP sizes range from 1 to 7 kW, although their evolution is more difficult to predict, since it is directly influenced by the deployment of Heat Pumps (described in the following section); in short, both micro-CHP and HP are used in households for heat production, CHP requires fuel, while HP uses electricity.

Regarding grid codes regulations specifying connection requirements, Energinet (Denmark) states that installations over 11 kW can only have 3-phase connections; while registered capacities lower than 11 kW may be 1-phase connected to power grid. However, the maximum current of 16 A for households shall never be exceeded. In other countries like Ireland, generators up to 6 kW are to be connected single phase, while a 3-phase connection is used for units up to 11 kW which is the maximum allowed in distribution networks. [21]

3.2.1.3 Other Prosumers/Controllable Loads/Special Units

In this category can be included units with particular characteristics, the most relevant ones are Electric Vehicles (EV), Heat Pumps (HP) and Electric Boilers (EB).

- EVs: There are three different kinds attending to their configuration: Battery Electric Vehicles (fully electric), Hybrid (only charge the battery by means of regenerative braking) and Plug-in Hybrid (bigger battery, it is possible to charge it by connecting it to the grid). With a penetration rate expected to continue growing in the following years, they represent the same installed power of a typical household, around 7,5 kW [24]. Thus, if widely spread, the existing grid will not be able to supply the demanded power unless smart charging procedures are used. Also, the possibility of discharging them during particular periods of time, opens the possibility of providing ancillary services. The charging rates vary depending on the connection which can be at regular outlet or at a public charging station. At a regular outlet, power ranges from 2 to 8 kW while in a charging station it does from 25 to 135 kW while, ultrafast chargers reach 400 kW. [25] [26]

- HPs: Basically, it is a device that uses electricity to transfer heat from a colder source to a higher level of temperature. There are three main types attending to the heat source: air, water and ground. The rate of use of this devices in Northern Europe is quite high. Demand response strategies can be applied to this loads in order to better allocate the demand according to the local generation among other factors, boosting efficiency and also reducing electricity bill. Although, this strategies must take comfort factors into consideration by utilizing the stored heat capacity of the house as buffer. Their power range from 1 kW in a household-size HP to MW in industrial ones. [27]
- EBs: Shortly, they are devices that transform electricity into heat by means of Joule effect. A resistor is heated up by the electricity and it transmit such heat towards a fluid (usually, water, oil or air). They are used in several countries to move consumption into night controlled by tariff and load control mechanism in the smart meter

Industrial consumers can sometimes be remotely controlled by agents (i.e. DSO, retailers, aggregators, ESCO, etc.) will usually offer billing reductions in exchange for temporarily reducing the consumption of a user. Typical types of industries involved in such demand response activities are: metals (aluminium and steel), cement, refrigeration, chemical and electrochemical [28]. Depending on the individual agreement between company and DSO the load reduction can be up to 100 % [29]. Beyond such individual agreements, commercial and industrial consumers typically see significant incentives from grid tariffs (kW price) to reduce peak loads. With the rollouts of smart metering, such incentives are likely to also be extended to residential customers. Additionally, reduced grid tariffs might apply to metering with interruptible loads.

3.2.2 Smart Meters

Driven by EU and national legislation, smart meters are installed at household and commercial level, but also at secondary substations. Both households and commercial smart meters provide 5 to 15 min. intervals of updated information regarding mainly the energy values for billing purpose. However other measurements e.g. voltages, active and reactive power as well as messages triggered by various events in the grid may be available internally in logger. Furthermore, different DSOs across Europe are in the process of deploying them in all substations. These meters provide measurements of energy, voltage and current with 15 minutes intervals on 3 phases. Although, it is important to differ between logged values and updated values in the database. Smart meters can typically log 5-60min values of voltage, power etc. but they typically only readout 1-4 times a day. [7]

The data from the smart meters can be divided into billing, analysis logger, voltage quality and occurrence logger. Billing data is related to consumption measurement, divided into registers for positive and negative values. On the other hand, the analysis logger can record voltage, current, power, THD and frequency (only average). Lastly, the voltage quality and occurrence logger records information about specific events with detailed information about the time and parameters of the event. Examples of such events are: Long and short-term voltage deviations, outages, sags, swells, rapid voltage changes, THD and neutral faults [7]. Table 2 gives an overview of typical measurements and calculations from a Kamstrup's three phase SM .

Table 2: Typical Kamstrup's smart meter output

Output		
Signal	**Update Rate**	**Comments and Remarks**
RMS Voltage	5-15 min	Individual phase values
RMS Current	5-15 min	Individual phase values
Active Power	5-15 min	Individual phase values
Reactive Power	5-15 min	Individual phase values
Phase sequence	5-15 min	Considering phase A as reference (0°), it measures the relative angles: $\widehat{AB}$ and $\widehat{AC}$
Energy	5-15 min	Individual values for each phase, distinguishing between produced and consumed; active and reactive.
THD	5-15 min	Individual assessment per phase in voltage and current

The accuracy of voltage and current measurements is defined in standard IEC 62052-11 [8] and IEC 62053-11 [9]. At substation level, transformer operated meters with class 0,5 are installed, while direct connected meters with class 2 are used at household level. Table 3 and Table 4 present the expected errors in % for each meter, distinguishing between mono and polyphase devices, but also the kind of load being supplied.

Table 3: Error limit in Class 0,5 transformer operated meter. [9]

	Value of Current	Power Factor	Error [%]
1ph and 3ph feeding balanced loads	0,02 In ≤ I < 0,05 In	1	± 1
	0,05 In ≤ I < Imax	1	± 0,5
	0,05 In ≤ I < 0,1 In	0,5 inductive 0,8 capacitive	± 1,3 ± 1,3
	0,1 In ≤ I < Imax	0,5 inductive 0,8 capacitive	± 0,8 ± 0,8
	0,1 In ≤ I < In	0,25 inductive 0,5 capacitive	± 2,5 ± 1,5
3ph Feeding 1ph loads	0,1 In ≤ I < In	1	±1,5
	0,2 In	0,5 inductive	±1,5
	In	0,5 inductive	±1,5
	In ≤ I < Imax	1	-

Table 4: Error limit in Class 2 direct operated meter. [9]

	Value of Current	Power Factor	Error [%]
1ph and 3ph feeding balanced loads	0,05 Ib ≤ I < 0,1 Ib	1	± 2,5
	0,1 Ib ≤ I < Imax	1	± 2,0
	0,1 Ib ≤ I < 0,2 Ib	0,5 inductive 0,8 capacitive	± 2,5 -
	0,2 Ib ≤ I < Imax	0,5 inductive 0,8 capacitive	± 2,0 -
3ph	0,2 Ib ≤ I < Ib	1	± 3
	0,5 Ib	0,5 inductive	-
	Ib	0,5 inductive	± 3
	Ib ≤ I < Imax	1	± 4

Different requirements for calculation of Total Harmonic Distortion (THD) exists in practice. EN 50160 standard is typically used for distribution grids and defines the harmonic content up to the 25th order. IEC 61000-2-4 standard is defining the harmonic compatibility levels for voltage and current up to 50th order for different classes of industrial plants connected to voltage levels up to 35 kV.
According to [4] harmonics should be recorded as 10 minutes mean rms values of the voltage. On the other hand, [5] distinguishes between long and very short-term effects of the harmonics; being the first mainly thermal effects on cables and electrical machines while the second, disturbances in electronic equipment. It is worth mentioning how, [5] has the same calculation requirements for long-term effects as [4], while uses 3 second averages for short-term. However, dismissing transients. Regarding the scope of Net2DG, long-term harmonics are to be surveyed with 10 minutes rms averages. In Net2DG project EN 50160 is to be used as reference for evaluation of THD.

3.2.3 Inverter Subsystem

Most of the installed inverters are three phase in Germany and Austria due to grid code limitations regarding unbalances. However, this is not the case in Denmark, where the inverters can be both single or three phase connected to the distribution switchboard inside the house as long as the maximum 16 A limit per phase is satisfied. Regarding penetration levels, semi-urban areas could reach values of total installed power over transformer capacity close to 100 % in Germany and Austria, although the exact value is not known [18]. Thus, several penetration ranges are to be considered in the different scenarios. [7]
Despite of the fact that many inverters currently deployed would require a hardware update in order to include remote readout or control capabilities, they can be used to provide ancillary services like reactive power support even without any external communication [30]. Since they implement local regulations and particular DSO requirements, they result in an interesting tool. They are capable of measuring AC voltage, current and power, frequency, DC voltage and power. Also they are capable of detecting abnormal values according to the particular requirements of each DSO in any of those parameters and record them. Apart from electrical interface protection features (e.g. overvoltage trip

limits), inverters are capable of voltage and frequency control functionalities – either local-only, or remotely-controlled.

After the inverter installation, the operator might decide to register it on a monitoring platform. It is estimated that around 45 % of the operators do register their units since there are interested in knowing about their unit's performance. Additionally, software updates and some other services are only available to registered inverters. On the other hand, if the inverter is not registered, the unit keeps measurements locally for a certain time which are then overwritten. However, some aggregated values are stored and updated over the whole lifetime such as overall power production and operating hours. Therefore, the information can only be accessed on a server level when the inverters are registered, otherwise the data can only be retrieved with a local unit sending requests to the system.
Server and field levels can be distinguished regarding data availability from different sources. However, sever level is used as the main communication path for Net2DG since new grid control features will be available within the project duration.

- Server Level:
    - Historical data: Usually updated every hour, down to a 5 minute average values. Different data points such as DC voltages, RMS AC voltages or apparent power. However, the update rate can be modified by the user. All the information is stored in a data-hub; in the case of Fronius is Solarweb (https://www.solarweb.com).
    - Online data: It consists of instantaneous values refreshed approximately every 10 seconds. However, it has a limited range of data points, particularly active power flows.
- Field level: Recorded by inverter local Modbus TCP interface (a master-slave based communication protocol), in Net2DG this interface could be connected to a local field level RTU. The instantaneous values are recorded every second and belong to a large range of different data points similar to the ones mentioned as historical data at server level.

Apart from certified fulfilment of electrical interface protection requirements (e.g. over-frequency behaviour, over-voltage trip limits, etc.) the inverters are not officially calibrated to conform to a measurement class. However, some indicative values are provided by manufacturers summarized in Table 5. However, such values have to be assumed for all the range of operation of the unit since there is no information available.

Table 5: Typical measurement errors for Inverter subsystems [7].

Signal	Measurement Error [%]
AC voltage	±1
AC current	±3
AC frequency	±0,1
Active Power	±3,4

3.3 Faults

3.3.1 Characterization of Fault Types

A fault is the deviation of voltages and currents from the nominal values or states which ensure the safe operation of the system. Briefly, two types of faults can be distinguished attending to the way nominal values are modified: open-circuit and short-circuit. [31]
The term open-circuit refers to a fault in which the circuit is interrupted or disconnected which causes an abnormal operation of the system, i.e. blackout, unbalanced voltages. Whereas, short-circuit describes the conductive connection of at least two circuit points, which are normally at different potentials, through a low impedance path; which cause electrical equipment to suffer unacceptable mechanical and thermal stresses, leading to the interruption of power supply and to the shortening of their operational lifetime, sometimes even causing immediate destruction. [30] [31]
The cause of open-circuit faults is a conduction path to be interrupted. This might happen in different ways, for example, melted fuse, malfunctioning circuit breaker, OHL falling down, joint failures, broken conductor (due to vandalism, works, earthquakes, etc.). On the other hand, short-circuits are caused by insulation failures (animal bites, material ageing, voltage displacement due to a distant ground fault, overvoltages, etc.), overloading of equipment, lighting surges, mechanical damage (branches or tress falling over OHL, erosion or abrasion of the insulation in underground cables, etc.). [4] [31]
Additionally, faults can be classified as symmetrical and asymmetrical attending on how the phases are affected. Symmetrical are those faults in which all the phases are affected equally (roughly 5 %), whereas unsymmetrical are those in which they are not. A list of the most common short-circuits classified according to their symmetry is presented in
Table 6. [4] [31]

Table 6: List of short-circuits.

Type	Name	Code
Symmetrical	Three phases to ground	3ph2gnd
	Three phases	3ph
Unsymmetrical	Two phases	2ph
	Two phases to ground	2ph2gnd
	One phase	1ph
	Phase to ground	1ph2gnd
	Neutral to ground	neutral

The typical voltage and current ranges recorded during faults depend on various factors. In an open-circuit fault, the voltage and current of the affected line will drop to 0, while a voltage raise will be noticeable on the non-faulty phases if any. Whereas if a short-circuit occurred, the current will spike to dangerous levels (around 10 times the nominal), while the voltage level drop to values close to 0, except in the case of a 2ph fault, when it will be reduced to half of the nominal value.
Figure 10 presents the pre and post-fault waveforms of current and voltage in a line to ground fault. It can be seen how the voltage in one of the lines drops to values close to zero, while its correspondent current spikes to values more than 3 times bigger than the nominal. Particularly, Figure 11 presents

again voltage and current before, during and after a lightning strike. It can be seen how the wave form of the voltage is slightly altered during a fraction of a cycle, while the current suffers an inrush around 2,5 kA; the whole fault lasts around 10 ms.

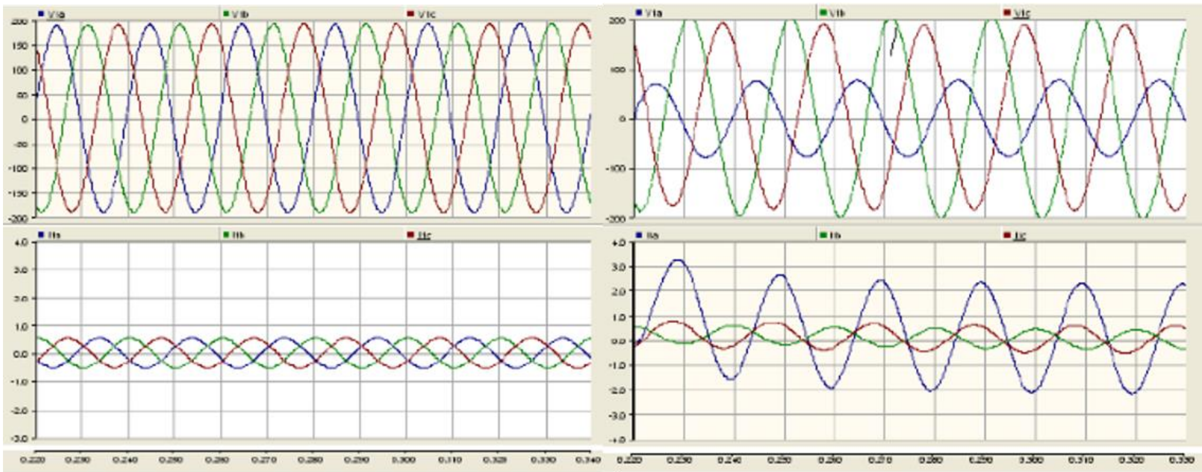

Figure 10: Voltage (above) and current (bottom) pre (left) and post-fault (right) – Line to Ground [32]

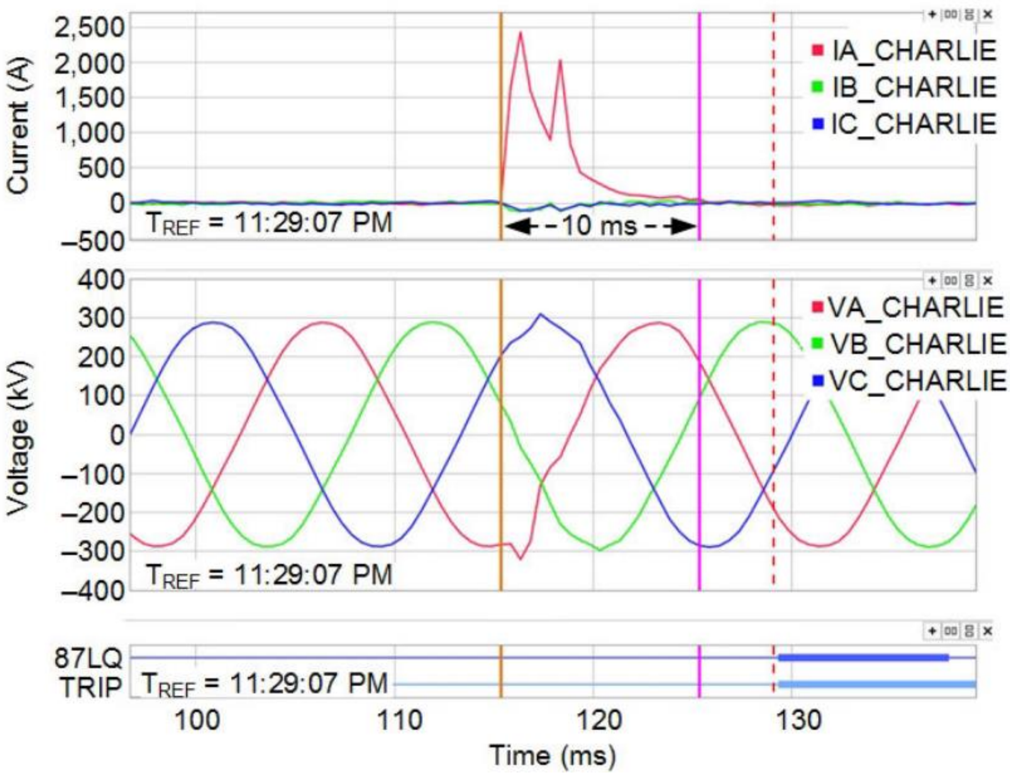

Figure 11: Voltage and current pre and post-fault – Single Phase lightning strike [33]

Regarding propagation, power transformer winding connection has major influence on how faults spread through the system. They can be divided into four categories regarding its influence: [34]

- Type A: Transformers that do not change anything from primary to secondary. Thus the fault spreads freely. The only type included in this category is the Star-star connection with both star points grounded (YGyg).
- Type B: Transformers that remove the zero-sequence. Examples of this are the star-star with one or none sides grounded (YGy, Yyg, Yy) and the Delta-delta (Dd).
- Type C: Transformers that swap line and phase voltages. In this case, each secondary side voltage equals the difference between two primary side ones. Examples are the Delta-star (Dy), Star-delta (Yd) and the Star-zigzag (Sz).
- Petersen coil or also known as Arc Suppression Coil (ASC), is used to compensate the capacitive earth fault currents supplied by outgoing feeders at a substation. The compensation can be either centralized or distributed. With the centralized design (most commonly used in the context of the project), one ASC unit will handle the compensation of all of the outgoing feeders. The centralized ASC is connected between the system neutral point and earth, typically between the neutral of a star-connected transformer and earth. If the transformer is delta-connected, the earthing transformer can be used to create the connection point.

It should be stated that, even though some transformers have difference phase shifts between primary and secondary, i.e. Yd1, Yd11; the rotation of phasor pre and during-fault can be seen as shift in zero point on the time axis. Subsequently not having any influence in the propagation. Finally, Table 7 presents the propagation of voltage signals in types B and C, since type A has no influence.

Table 7: Voltage propagation through transformers during faults. [34]

Fault	Primary	Secondary	
		Type B	Type C
Single Line to Ground (SLG)	C 1, A, B 1	0.88 c 0.33 a, 0.88 b	1 c, 0.58 0.58, b a
Double Lines to Ground (DBG)	C 1	0.66 c, 0.33 a, b	0.58 c, 0.58 a
Double Lined (DB)	0.5 1 A, B,C	0.5 1, b, c a	0.87 0.87, b a
Three phase (TF)	0.5 C 0.5 A, B 0.5	0.5 C 0.5 A, B 0.5	0.5 C 0.5 A, B 0.5

3.3.2 Examples of Recordings

An example of a single phase cable fault in the TME low voltage grid is shown in Figure 12. The fault was dicovered due to the connectivity loss of the smart meter when checking the data during the up-load process in the national data-base. A post fault analysis using the information from SMs revealed how the fault evolved from an alarm to a complete outage of one phase. A grid loss calculation in the faulted area correlated with the received alarms is shown in Figure 13. Minumum voltages from SM loggers up and around the faulty location are shown in Figure 14. It is whort mentioning that the meter detects when the voltage surpasses a threshold, logs the time when the event starts and ends and the minimum/maximum value within this period (under/overvoltage event).

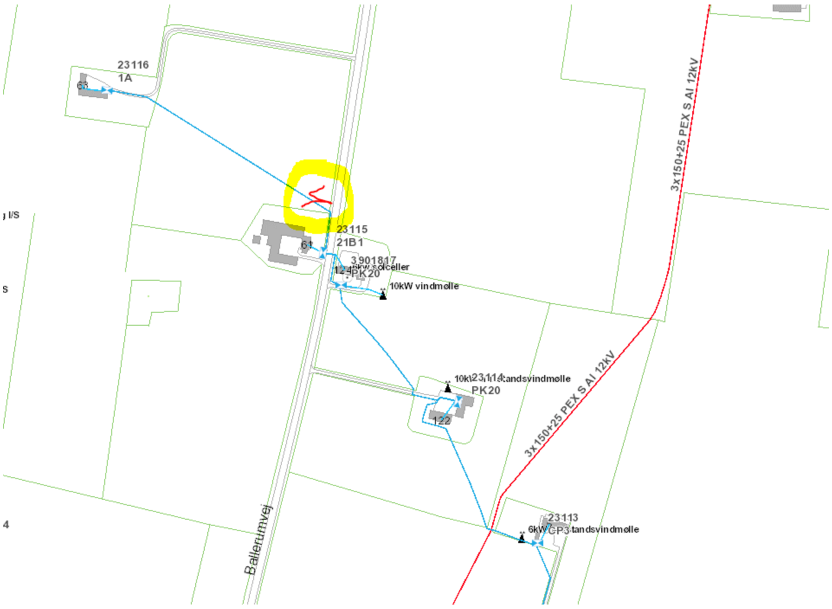

Figure 12: Affected area by a single phase fault [7].

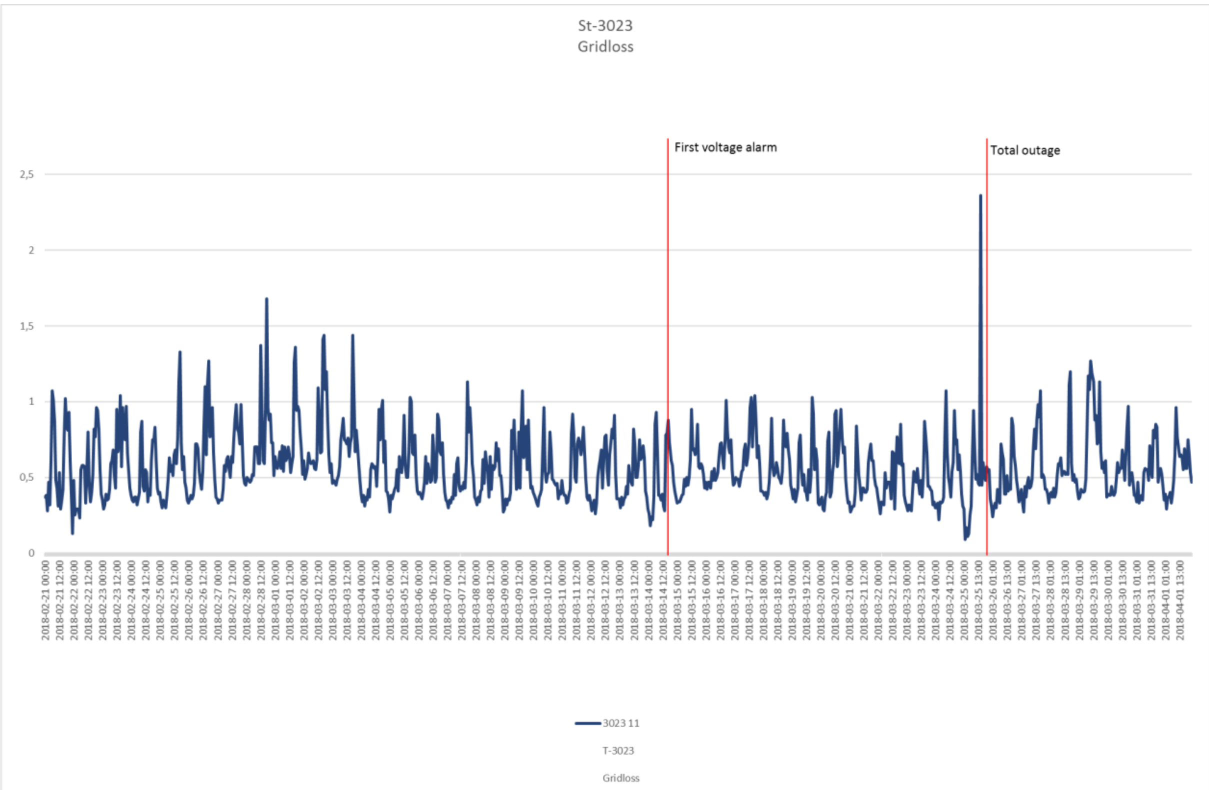

Figure 13: Calculated grid loss up to and around the cable fault [7]

Figure 14: Measured minimum voltages up to and around the cable fault [7]

3.3.3 Statistics

A complete overview of faults in distribution grids at European level is not available based on the authors' knowledge. However, some statistics for Nordic countries at both transmission and distribution level are given in [35] such as:

- Most of the events are located in OHL.
- Most of the faults occur on 132 kV grids.
- The most common fault is the single phase to ground.
- Voltage drops down to 0,75 last several cycles, while those down to 0,25 last up to minutes.

Figure 15 present the fault trends from 1996 to 2015 in the Scandinavian countries. Such graph shows how the tendency is towards an increase in the number of faults, especially in the last years, when more distributed generation is being included in the systems. [35]

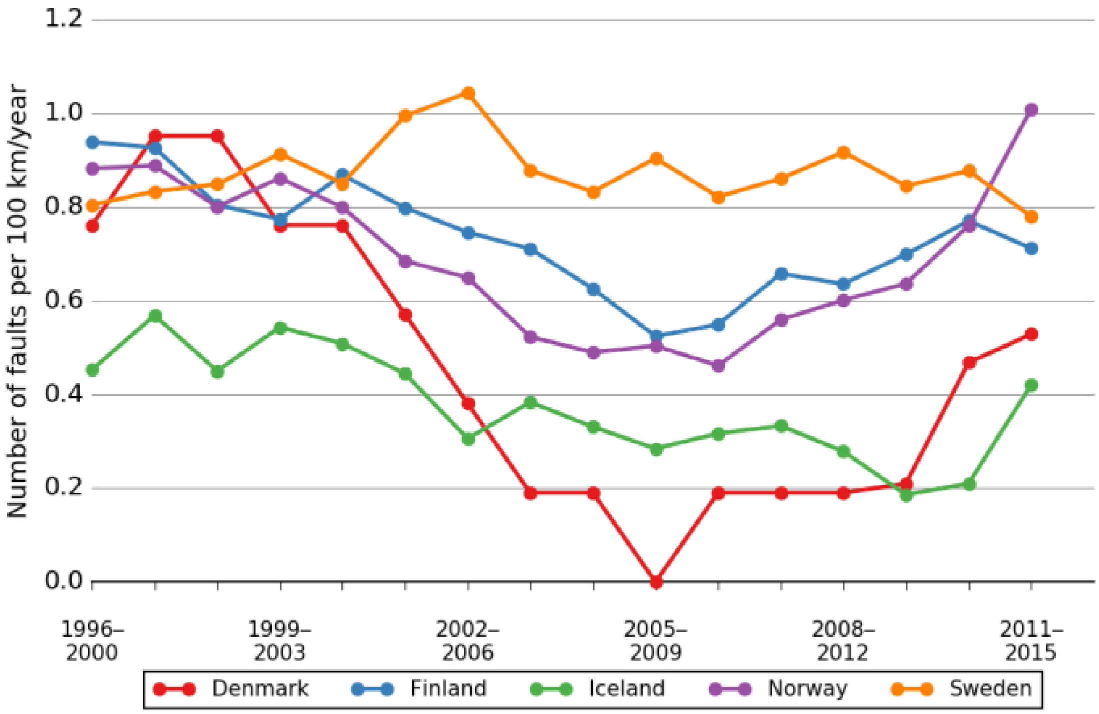

Figure 15: Fault trends as five-year averages for OHL in the Scandinavian countries [36]

In [36] is stated that around 80 % of the outages occur at distribution level (< 25 kV) while the rest are registered at higher voltage levels. Also, it points out the reduction of outages suffered after the conversion towards underground cables. Figure 16 presents the average outage minutes per consumer per year in the Nordel system (Scandinavia and Baltic countries), while Figure 17 classifies each individual fault according to the cause.

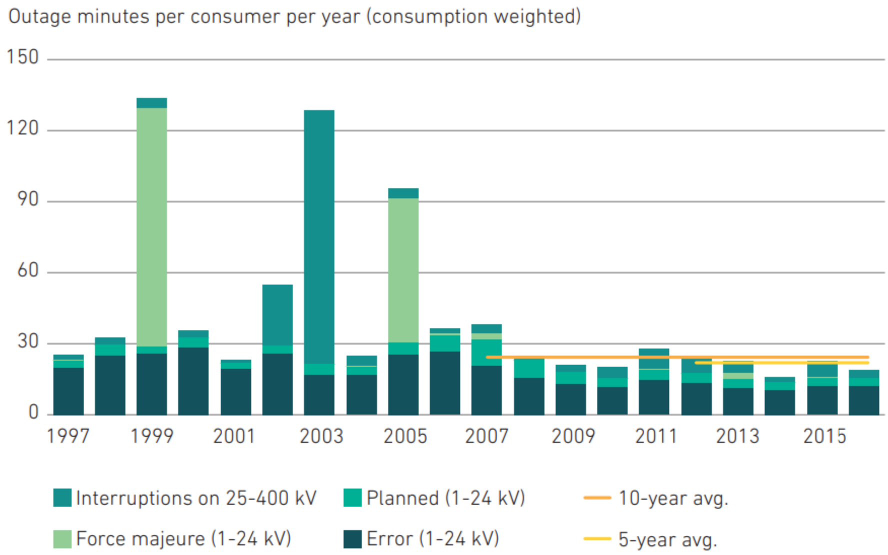

Figure 16: Outage minutes per consumer per year in Nordel [37]

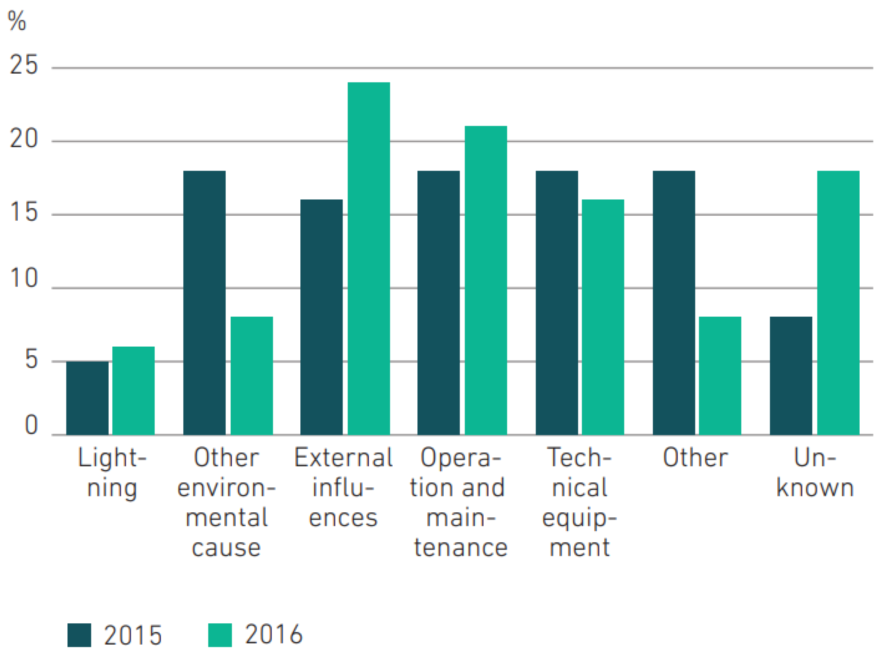

Figure 17: Outage Causes in Nordel during 2015 and 2016 [37]

3.3.4 Reliability in Distribution Networks

Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered. The so called, level of reliability is considered appropiate when the cost of avoiding additional interruptions exceeds the consequences of the failure. Particularly, reliability is evaluated in terms of outage rate, duration and costs; such factors depend upon: reliability of individual equipements items, network configuration, automation, load profile, available transfer capacity, grid length and loading.

Usually, SOs calculate indices based on the number of customer per outage and its duration; being System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) the most important ones. Such indices are defined by equations (1) and (2). A graphical representation of such indices for the European countries can be found in Figure 18 and Figure 20.

$$SAIFI = \frac{Total\ Number\ of\ Affected\ Customers}{Total\ Number\ of\ Customers} = \\ = \frac{(No\ Customer\ Interrupted\ per\ Interruption)(Number\ of\ Interruptions)}{Total\ Number\ of\ Customers} \tag{1}$$

$$SAIDI = \frac{Aggregated\ Customer\ Interruption\ Duration}{Total\ Number\ of\ Customer} = \tag{2}$$
$$= \frac{\sum(Outage\ Duration)(Number\ of\ Customer)}{Total\ Number\ of\ Customer}$$

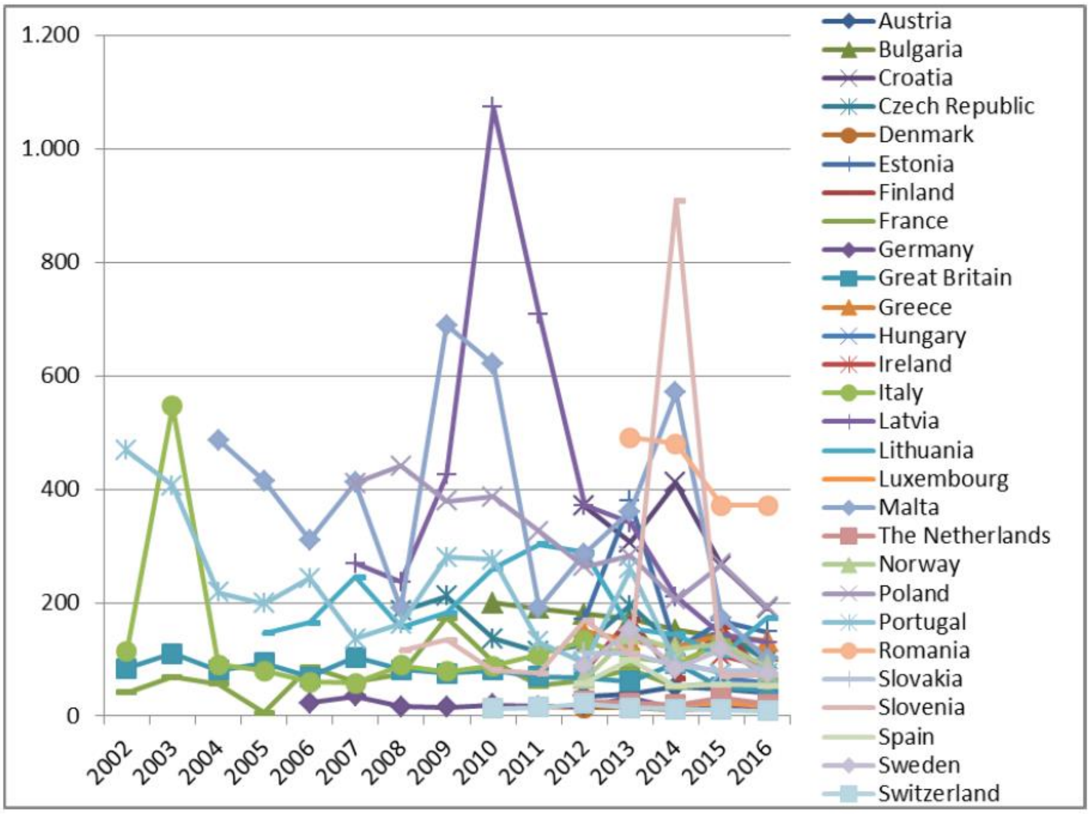

Figure 18: Unplanned SAIDI, including exceptional events (minutes per customer) – time series and min-max [38]

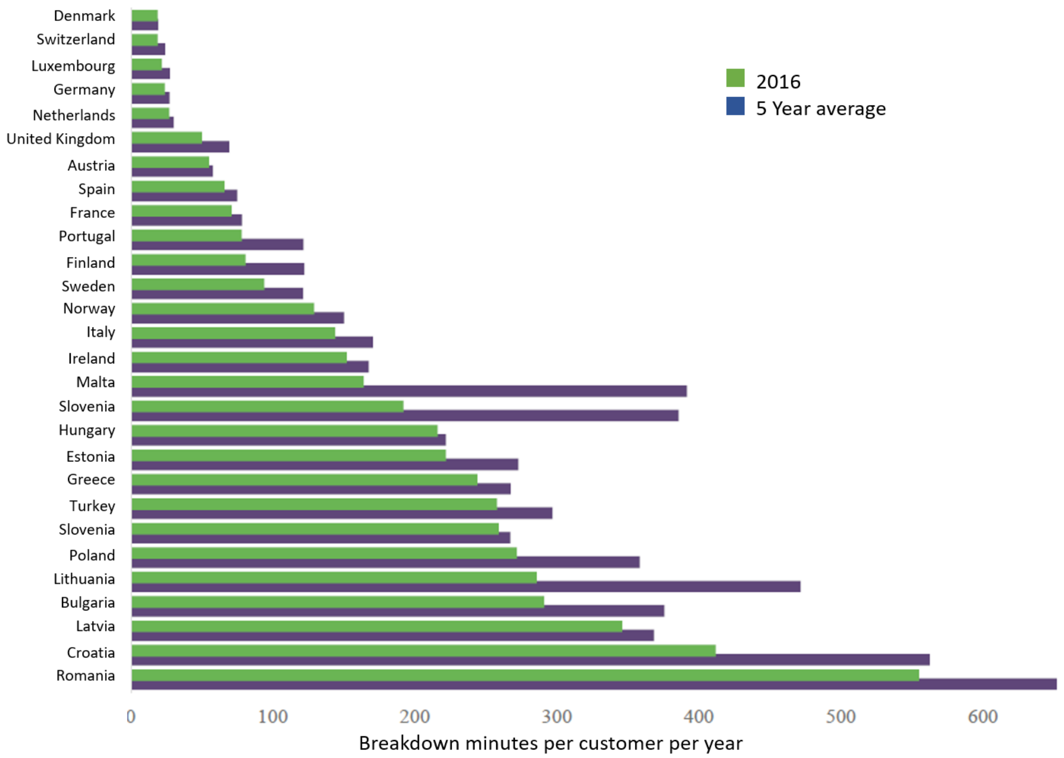

Figure 19: Breakdown minutes per country [38]

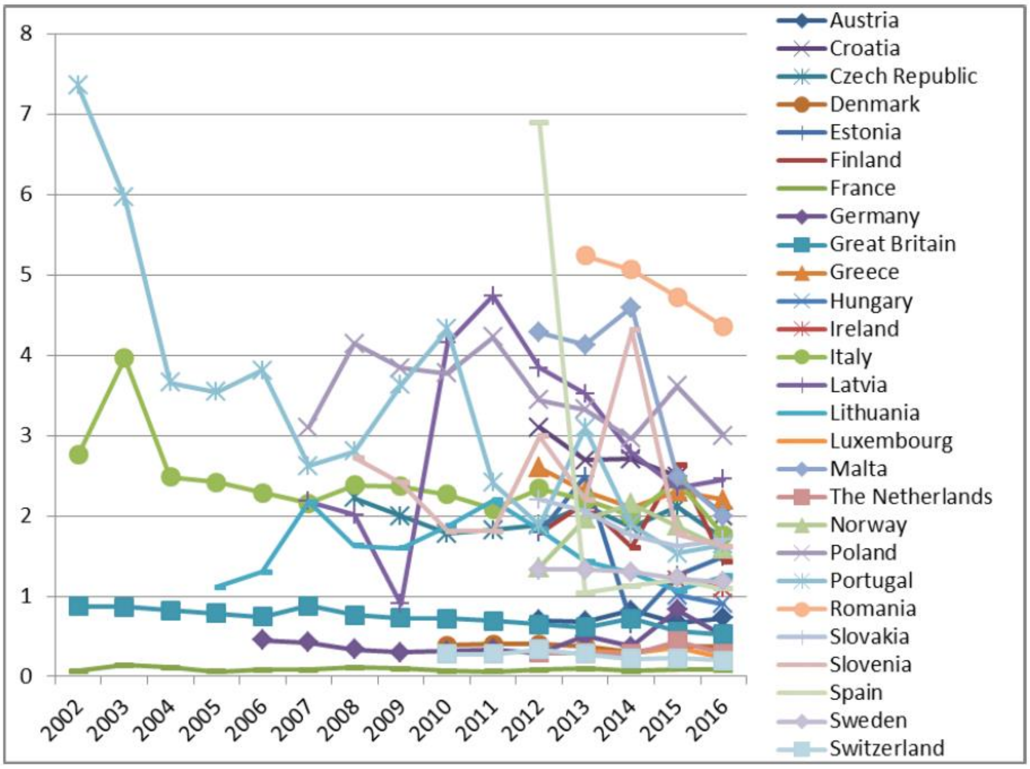

Figure 20: Unplanned SAIFI, including exceptional events (interruptions per customer) – time series and min-max [38]

Moreover, Energy Not Supplied (ENS) is many times used as a reference to be able to understand the impact of an outage in terms of energy and, hence, its related costs. The index calculates the energy in accordance with the duration of the outage being the total energy not supplied to the load points affected by the failure event under consideration. The value is dependent on the total installed power in the affected area and, when no detailed information is available, a simultaneity factor and a load factor are used with typical values (DSO dependent). The calculation can be done by using the formula given by [39]:

$$ENS = \frac{TIEPI \times ES}{T}\ [MWh]$$

where ES is the energy (in MWh) supplied to the MV network and T is the predefined period of time (in hours). TIEPI index indicates the equivalent time of interruption of the installed power, regarding long interruptions, over a predefined period of time (e.g. one year) and can be calculated by:

$$TIEPI = \frac{\sum_{j=1}^{y}\sum_{i=1}^{x}\left(DI_{i,j} \times PI_j\right)}{\sum_{j=1}^{y}\left(PI_j\right)}\ [min]$$

where DIi,j is the duration (in minutes) of the long interruption i in the delivery point j; PIj is the power installed (in kVA) in the delivery point j; y is the total number of delivery points in the MV network and x is the number of long interruptions at the delivery point j in the predefined period of time.

The economic impact of power outages is logically extensible to the DSOs. Besides the Cost of Energy Not Supplied (CENS), depending on the regulatory framework, the DSO may be responsible for paying a compensation to customers and even a possible Incentive to Quality of Service penalties to the regulator. According to [39], there are three categories in which the economic costs can be divided: faulted and damaged components repair or replacement costs; compensations paid to customers and penalties paid to regulators; and loss of revenue because of the ENS. The first category depends on the type and location of the fault and the damage components. The second category depends on the rules and laws established to regulate the DSO operational activity. The third category depends exclusively on the amount of affected load and on the effectiveness of service restoration.

3.3.5 Net2DG Scope

Regarding faults, the main relevant Net2DG identified scenarios are:

- Detect and diagnose energy supply interruptions to the consumer: Such open-circuit faults are caused by blown fuses 75 % of the time [3]; they can be all phases, phase-phase, phase-neutral; both in substations and in connection boxes. Also, there is interest in identifying slowly developing faults i.e. isolation lost in a cable, which eventually might cause a single phase-ground fault. Another possibility are loose connections. Therefore, there are two main objectives, first to identify immediate faults like the blown fuse, but also detect slowly developing ones like phase to ground by monitoring seasonal and weather dependent variations related to the phase-ground leakages. Finally, since such pre-conditions of long term faults can be detected, the ultimate goal is to identify the pre-conditions that lead to an outage, thus establishing preventive maintenance according to historical data and recorded events.

- Detect voltage drops in junction boxes based on active and reactive power measurements: Currently this is being done by using manpower during periodic maintenance or after a consumer complains about flicker or short-term transient outages. Therefore, the target is to reduce outage occurrence and duration by systematic pre-outage detection. In this way, the repairs can be planned and addressed in advance, avoiding customer dissatisfaction, additional payments to staff (due to night hours or weekends) while also avoiding fault escalation. It should be stated that, contrarily to voltage dips which are voltage reductions of short duration (fraction of a second up to a minute), drops are considered long term or even permanent (from minutes to hours).
- Fault detection and identification without relying on customer feedback and visual inspection: Additionally, the DSOs would see some value in being able to automatically notify the user that there is a problem in the grid and that they are working to solve it, in order to avoid handling incoming calls. However, due to the reduced amount of this types of faults, the priority is quite low. The evaluation of the Net2DG solution will consider: time from fault occurrence until certain percentage of the users has power restored, potential impact on tariffs, manpower working hours, customer satisfaction.

Summarizing, the fault related objectives are:

- Identify and handle open-circuit faults remotely (according to UC FM-1 FM-5 [7]).
- Identify and locate short-circuit faults and neutral loss remotely (according to UC FM-2 FM-4 [7]).
- Improve predictive maintenance tools (according to UC FM-3 [7]).

The expected advantages are:

- Increase customer satisfaction.
- Reduce manpower hours.
- Reduce outage time.
- Improve predictive maintenance tools.

3.4 Voltage Quality

3.4.1 Disturbance Sources

The considered voltage issues are Dips, swells and transient over-voltages. First, dips are defined as < 90% of Un, while swell as > 110% of Un. They are classified according to the residual voltage and the time length of the event. While dips are caused by faults, swells' origin are switching operations, connections and disconnections of both loads and generators. Finally, transient over-voltages are generally caused by lightning or switching. They are distinguished from swells because of their different origin, magnitude and length; since the first ones tend to be more intense and longer. Lastly, Figure 21 presents the typical waveform of voltage dip and swell. [40]

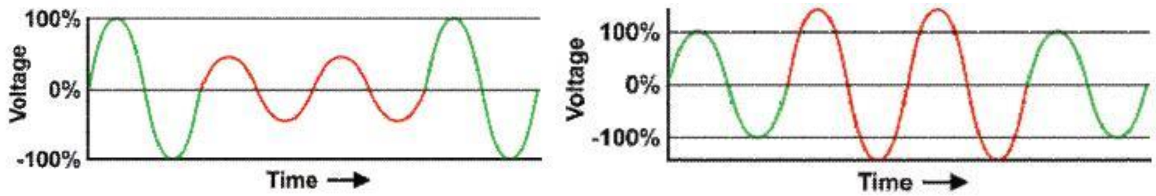

Figure 21: Voltage dip (left) and swell (right) [41]

As stated in [40], the main impacts of modern assets such as renewable energy and power converters, are an increase on the THD, but also in voltage dips and swells. The increase of THD is mostly caused by the power electronics, due to the switching operations of the semiconductors, while the dip-swell increase is caused by the variable production (random connection disconnection) of the renewable energy.

3.4.2 Metrics for Voltage Quality

Summarizing, EN50160 recommends to monitor: Frequency, magnitude, waveform and symmetry of the voltage. Here is presented a summary of the most relevant parameters in LV and MV. Note that the reference for Section 3.4.2 is [40].

3.4.2.1 Frequency

Its nominal value is 50 Hz, during normal operation, the mean value of the fundamental measured over 10 seconds should be within 50±1% Hz for 99,5 % of the year and 47 Hz < f < 52 Hz during the whole time.

3.4.2.2 Nominal Voltage (Un)

Under nominal operation supply voltage variations should not exceed ±10 % of the nominal Un. Regarding measurement, there are different conditions for LV and MV:

- LV: 10 min mean RMS values should be kept within Un±10% for 95 % of the time during week period [40]. Also, all the values should be kept within:

  (Un - 15%) < Un < (Un + 10%).
- MV: 10 min mean RMS values should be kept within Un±10% for 99 % of the time during week period [40]. Also, all the values should be kept within Un±15%.

3.4.2.3 Flicker Severity (Pit)

Pit ≤ 1% during 95 % of the time.

3.4.2.4 Supply Voltage Unbalance

Under normal operation, the values of the negative phase sequence fundamental, should be between 0 and 2 % of the positive phase sequence; during 95 % of the time (weekly intervals); measured in 10 min mean RMS.

3.4.2.5 Harmonic Voltage

THD (up to 25^{th} order) should not exceed 8 % at any moment, although there are specific requirements for each individual harmonic. Such conditions are to be met during 95 % of each week period and measured in 10 min mean RMS values. Extension to the 4oth harmonic order is under consideration in EN50160

3.4.2.6 Interharmonics

It is acknowledged to be increasing due to power converters, but there is not recommended levels yet. Even though EN50160 does not include them, IEC 6100-2-4 series does.

3.4.2.7 Signalling Voltages

Signalling voltages are limited according to a shape, however this falls beyond the scope of this project. Since all communication is expected to be hold in dedicated hardware, not on the lines.

3.4.3 Voltage Events

The voltage events are in the following classified according to [4].

3.4.3.1 Supply Interruptions

They are very unpredictable and variable from place to place and time to time. They are classified according to length, being considered Long Interruptions when lasting more than 3 minutes while short when lasting less than a few seconds (never more than a minute).

3.4.3.2 Dips and Swells

A Dip is identified as a 10 % reduction from the nominal while a Swell is a 10 % increase over the same value. Dips are usually caused by faults occurring in the public network while swells are typically caused by switching operations and load disconnections. Regarding measurement, Table 8 presents the proper protocol as according to the standard. However, if statistics are collected, the measurement should be performed as according to EN 61000-4-30. Such standard also explains the evaluation, which depends on the purpose. Typically for LV networks polyphaser aggregation and time aggregation are applied to three phase systems. Polyphaser aggregation consists on defining an equivalent event characterized by a single duration and residual voltage, while time aggregation consists of defining an equivalent event in the case of multiple successive events (additional rules are provided in IEC/TR 61000-2-8). Finally, it should be mentioned that given the dependence of voltage dip duration on the protection strategy adopted, their duration is not easily predicted.

Table 8: Guidelines when measuring or detecting dips and swells. [4]

Type according to conductor and phase	Monitored Voltage
4 wire – 3 phase	Line to neutral
2 wire – 3 phase	Line to line
Single phase connection	Supply voltage (line to line or line to neutral)

3.4.3.3 Transient Overvoltages

Transient overvoltages located at the supply terminals are generally caused by lightning, induced overvoltage or by switching manoeuvres. Their duration covers a wide range from milliseconds to less than a microsecond therefore being out of the Net2DG scope.

3.4.4 Examples of Voltage Issues

Figure 22 exemplifies the voltage quality issues caused by the integration of PV units at distribution level while at the same time presenting how such quality is improved after reinforcing the grid. As it can be seen, in the reinforced system, there is no need for power curtailment, but also, voltage fluctuation is considerably reduced. On the other hand, Figure 23 presents the typical voltage waveform during the occurrence of flicker phenomena.

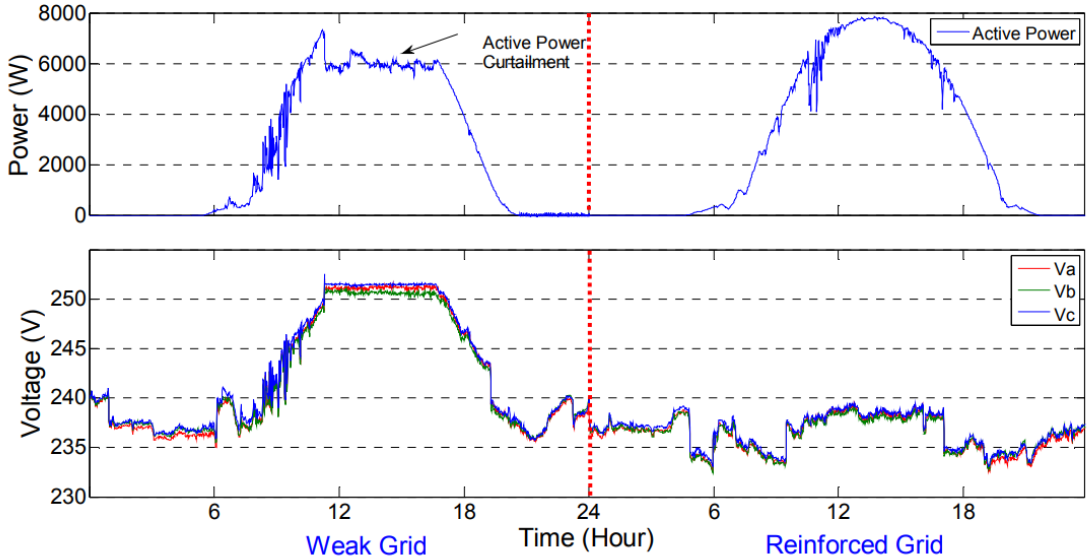

Figure 22: Effect of PV in Voltage Quality of Distribution Grids. [42]

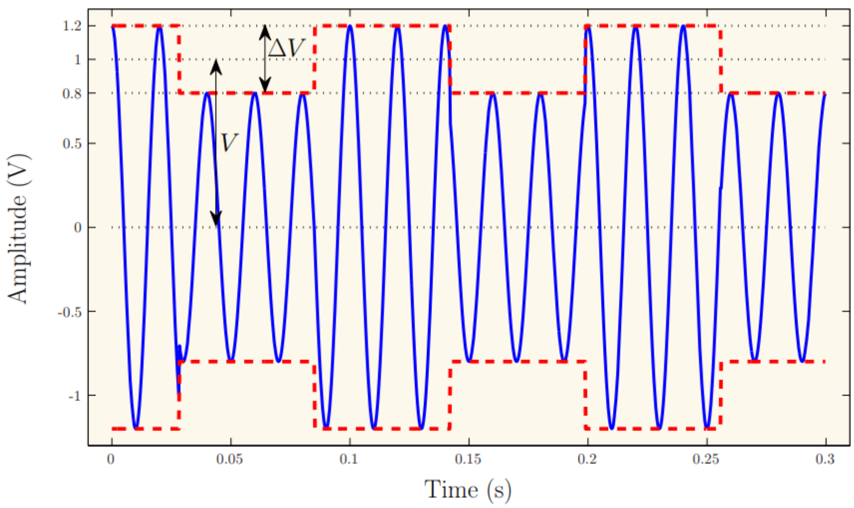

Figure 23: Example of Flicker in Distribution Grids. [43]

3.4.5 Existing Practice

In general, the existing practice when identifying voltage issues is to wait for consumers to call complaining about alarms from equipment, apparel not working, or blinking lights. Most of the time,

it is linked to incorrect TAP settings (80 %) and low transformer or substation capacity. If the issue doesn't fall under such categories, an analyser is installed in order to check the parameter EN50160. If such parameters are not fulfilled, field technicians continue to trace the error. [7]
On the other hand, when a customer requests connection of generation units, an evaluation is performed to ensure the proper functioning of the system. First, P and Q are recorded over a period of two weeks, although voltage is not properly monitored. Then a simple grid model is used in order to consider whether it is necessary to reinforce the grid. However, no continuous measurement of voltage at customer level is available, this will change after the smart meter installation. The targeted improvements are: investment reduction, since grid reinforcement will be calculated based on actual voltage measurements, increase renewable hosting capacity and reduce damages of customer equipment; tariffs considering demand response, avoid voltage variations and dips. [7]
Currently, the already installed smart meters and inverters are capable of detecting and reporting (when demanded) whether the user is receiving power from the public grid or not, but also if they are supplying or consuming; thus helping in the simplistic diagnose already in practice. [7]

3.4.6 Net2DG Scope

Briefly, the scope regarding voltage quality includes using the data monitored by the smart meters and smart inverters to improve the quality of the assessments performed by the DSOs. Since such devices allow to monitor voltage quality parameters as defined by EN50160, rising flags whenever the standard is not fulfilled.

3.5 Losses in Power Grids

3.5.1 Sources

Part of the energy flowing through the distribution grid, from the transmission grid, or generated by distributed generation (connected at distribution level), is lost in various ways in distribution systems. Electrical losses are an inevitable consequence of the transfer of energy across electricity distribution networks. On average, more than 7% of electricity transported across local distribution systems in Europe is reported as electrical losses (IEA Statistics, OECD/IEA 2014). This imposes a substantial financial cost on society both in terms of the costs of producing the electricity that is lost and the costs of transporting these units over the transmission and distribution networks.

Generally speaking, losses affect a utility's economics in two ways. Firstly, they increase the power and energy demands, and thus increase the overall cost of purchasing and/or producing the total power requirements of the utility. Secondly, system losses increase the load flows through individual systems components, which then lead to additional costs being incurred due to the extra losses associated with the increased load flows. Last but not least, extra costs can also be incurred in having to increase some component ratings to cater for the additional current caused by these losses.

The recorded losses can be broken down into three main categories: variable losses, fixed losses and non-technical losses. Variable losses, often referred to as copper losses, occur mainly in lines and cables, but also in the copper parts of transformers and vary in the amount of electricity that is transmitted through the equipment. Fixed losses, or iron losses, occur mainly in the transformer cores and do not vary according to current. Both variable and fixed losses are technical losses, in the sense that they refer to units that are transformed to heat and noise during the transmission and therefore are physically lost. Non-technical losses, on the other hand, comprise of units that are delivered and consumed, but for some reason are not recorded as sales. They are lost in the sense that they are not charged for by either the suppliers or the distribution businesses. In recent time, non-technical negative losses might result from non-measured surplus infeed from (very) small generators (in Austria, infeed fom generating units <800 W is not measured) or from non-registered DER units.

Variable losses on a network are approximately proportional to the square of the current. This means that, for a given capacity, a 1% increase in load will increase losses by more than 1%. Therefore, greater utilisation of the network's capacity has an adverse impact on losses. Consequently, there is a trade-off between the cost of financing surplus capacity and the cost of losses. Therefore, cost of losses is highly relevant on OPEX and the operation strategy of the distribution system must constantly envisage its optimization/minimization.

The sources can be divided in fixed and variable. The first ones are always present in any grid and correspond to Joule losses, capacitive losses and oversized transformers (operating out of the most efficient point of operation). While variable ones might or not be present; they include: theft, unnecessary high consumption, large reactive consumption, unbalance, THD, faults and other unidentified sources. [7]

3.5.2 Existing Practice

The losses estimation is based on the measurement of energy flows at substation level and manual reading of electricity meters at consumers and small generators. Missing readings are extrapolated if any. Then, such value is multiplied by the annual average energy price in order to estimate the economic losses. [7]

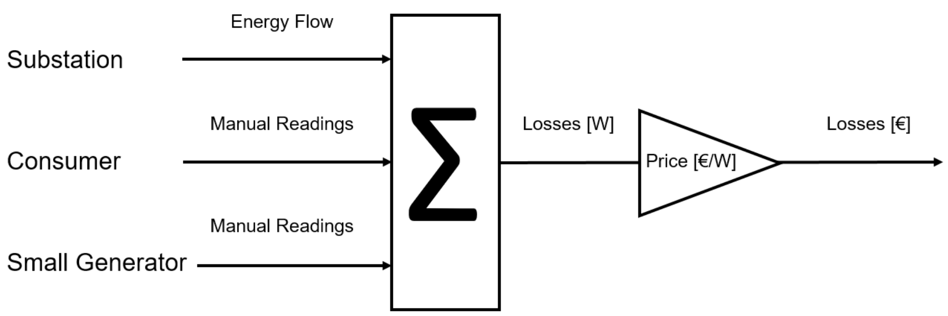

Figure 24: Losses estimation concept

3.5.3 Net2DG Scope

While the principle of the loss calculation in Net2DG is the same as described in the previous section, i.e. substraction of the consumed energy from the injected energy into a certain part of the grid, Net2DG will go beyond a yearly energy loss calculation for the full distribution grid as follows:

- Resolution in time: The Net2DG solution will use high resolution measurements in time down to intervals of 15 minutes. Therefore, a time-series of losses will be obtained which allows the detection of anomalies by correlation of this time series e.g. with consumption data or total energy flow.
- Spatial resolution: The Net2DG solution will allow to calculate losses in parts of the distribution grid, e.g. for the LV grid connected to a secondary substation, for a single feeder, or even below a junction box. That way inefficient or anomalous sub-grids can be identified.
- Robustness to inaccurate, erroneous or missing input data: The Net2DG Loss calculation solution shall be able to work with incompletely measured grids, e.g. in scenarios of 80% Smart Meter deployment. Grid models built from the existing data will be used to extrapolate missing measurements. The measurement errors and clock synchronisation together with the grid estimation procedures will be used to quantify errors of values used for the loss calculation, so that confidence intervals for the absolute and relative loss metrics will be obtained. These confidence intervals subsequently allow to identify whether changes in loss behaviour are significant or fully explainable from the variability of the input data.

By following the aforementioned losses estimation method, the source is not identified. Thus, the first objective is to estimate losses based on the information available from smart meters and taking into account distribution grid characteristics (topology, parameters, etc). A second objective is to propose advanced methods to identify unregistered consumers, and other undesired consumptions in the grid. An advanced Net2DG use-case (loss minimization – which will be discussed during Year 2) will automatically recommend one or more loss reduction approaches for the LV grid, which include the following measures:

- Identification and removal of prosumers behaving outside of specification
- Static limitations of prosumers to certain maximum power
- Adaptations of the LV grid topology
- Out of scope here is the dynamic management of prosumers (which is a third Ne2tDG use-case, which will not be covered by the project any more)

3.6 Reference Grid Modelling

The Reference Grid Model is an accurate representation of the real world used to reproduce events and operational challenges similar to daily operation of distribution grid. This model will be implemented in a selected simulation tool that will support the research activities in WP2 – WP4 in Net2DG. A special implementation of RGM is to be achieved in WP5 for large scale laboratory demonstrations using RT-HIL approach.

3.6.1 Type of Simulation

Regarding the preferred type of simulation, RMS (phasor) is chosen over EMT. Briefly, the disturbances affecting power systems are classified as: electromagnetic and electromechanical transients. Figure 25 compares both transients; the main different from the point of view of the simulation approach is the necessary sampling time, which for EMT is about 10-100 μsec while 10-20 msec for RMS. Thus, despite of the fact that EMT is more accurate, the hardware necessary to run a simulation is comparatively bigger than the RMS equivalent. Also, RMS' time step allows to simulate large power grids with thousands of busses and generators at very high speed, thus; the result from a RMS simulation is the phasor value and not the exact waveform.

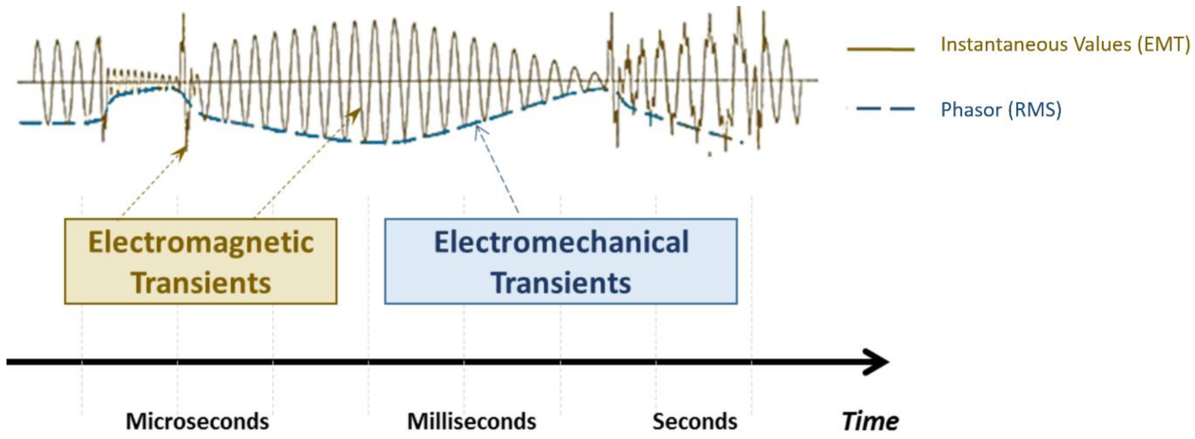

Figure 25: Electromagnetic vs Electromechanical Transients [45].

In conclusion, the reference grid model should be able to provide RMS values of voltages, currents, active and reactive power, phase angles per phase for a 3-phase low voltage grid at time resolution of maximum 1 second. Also, it should consider the particularities of transformers, OHL, cables and substations. Finally, it should be able to simulate short- and open-circuit faults as well as consider the effects of degraded behaviour of components.

3.6.2 Assumptions and Limitations

The following assumptions and limitations are considered for RGM:

- A radial LV grid behind a secondary substation is in scope.
- Medium voltage network is modelled based on Thevenin equivalent and is characterized by Short Circuit Ratio (SCR) and Grid Impedance Ratio (X/R).
- LV grid layout is fixed in all penetration scenarios for AMI and Inverter.
- A four wire representation of the distribution grids is considered in order to account for asymmetrical faults and voltage unbalances.
- The electrical grid representation is assuming a 50 Hz grid frequency.
- Harmonic studies and the associated THD calculations are not in scope.
- A manual Tap-Changer in secondary substations is considered.
- An On-line controllable Tap-Changer will be considered in primary substations only.
- A fault in a cable is modelled by an equivalent impedance according to fault type inserted in a given location and respective affected phases
- A fault in a connection box is modelled by switching off the faulted phases of a given radial.
- Geographical distribution of wind speed and solar irradiation is not considered. An equivalent wind speed and solar irradiation is used for all generating units in the area.

- Update rate for equivalent Wind speed and Solar Irradiation is from 1 second to maximum 10 seconds in order to support power/voltage quality studies.
- Wind Turbines and PV systems are modelled as constant power sources with a given time response in active and reactive power delivered to the grid.
- All loads behind a household are aggregated per phase according to general rules for low voltage installation. Lightning and outlets are typically in one phase, washing and dishwasher machines as well as refrigerators are in another phase while cooking plates and electrical oven on the remaining phase.
- All electrical loads will be modelled as constant equivalent current sources per phase.
- EVs, HPs and EB are included as regular loads inside of the household.
- Update rate for constant equivalent current sources is at least 1 second up to 15 min. Specific power/quality studies may not be performed with min level current injection from electrical loads.
- Measurement of electrical variables provided by SM or Inverter Subsystems will include a probabilistic error per signal as specified in Section 3.2.

3.6.3 Requirement Specifications

Table 9: Summary of specifications.

External Grid SCR	5 to 10
External Grid X/R	5 to 10
Installed capacity of Secondary substation	< 1250 kVA
Minimum Number of consumers	1
Maximum Number of customers	400
Grid layout	Radial
Maximum Installed capacity for household loads	35 A or 24 kW
Installed capacity of single phase PV system	
Installed capacity of thee phase PV system	<= 400 kW
Installed capacity of WT	10 to 25 kW

3.6.4 Operational Scenarios

The selected test cases should be relevant in present and future scenarios of the European grid, therefore, different levels of penetration regarding renewable energy and AMI should be analysed in this research.

The Renewable Penetration Level (RPL) is defined as:

$$PL\,[\%] = \frac{\sum Installed\ Renewable\ Power\ [W]}{Transformer\ Size\ [VA]}\,100 \quad (3)$$

While the AMI Penetration Level (AMIPL) is:

$$AMIPL\ [\%] = \frac{Number\ of\ users\ with\ AMI}{Total\ number\ of\ users}\ 100 \quad (4)$$

Firstly, renewable penetration nowadays ranges from 1 % in countries like Netherlands to nearly 50 % in Denmark [47], also, researchers claim that penetration over 25 % starts to create issues [48]. Therefore, several levels should be tested, i.e. 0, 25, 50, 75 and 100 %. Secondly, AMI penetration is quite inconsistent trough the EU, but it is expected to reach 80 % at the end users by 2020 [49], therefore, the scenarios could reflect for example 50, 80 and 100 %.

Seasonality is another factor to take into account, summer and winter scenarios determine meteorological parameters which are key to renewable production and faults (more incidences are recorded in winter). Also, consumers act differently both in summer and winter but also weekly, since the consumption patterns change a lot from a weekend to a week day. Finally, Table 6 presents all the possible permutations defining the scenarios according to the considerations exposed in this section.

Table 10: Operational Scenarios.

<table>
<tr><th>Renewable Energy</th><th>AMI/PVI</th><th>Season</th><th>Week</th></tr>
<tr><td>0</td><td rowspan="2">50</td><td rowspan="3">Summer</td><td rowspan="3">Regular</td></tr>
<tr><td>25</td></tr>
<tr><td>50</td><td>80</td></tr>
<tr><td>75</td><td rowspan="2">100</td><td rowspan="2">Winter</td><td rowspan="2">Weekend</td></tr>
<tr><td>100</td></tr>
</table>

3.6.5 Simulation Tools

Each WP has different needs, requirements and preferences regarding simulation tools, however, the fact that WP5 will gather all the developed work and test it into the laboratory facilities of AAU must be taken into account. Thus, since WP5 will need to adapt models developed by experts in other scientific areas, such modifications should be kept at minimum in order to avoid errors and incompatibilities. Therefore, Matlab/Simulink is the tool selected for the final running version of anything that needs to be tested in WP5.

Secondly, priority should be given to any free software available when compared against a paid one. Each WP can, therefore, choose their own simulation tools as they please as long as the ultimate application is developed in Matlab/Simulink in order to allow implementation in the laboratory set up of AAU.

WP2 main objective is to develop observability algorithms for distribution grid which must be able to run on top of the ICTs from WP3 and coordinate with control algorithms from WP4. Finally, the combined work of those WP is integrated and tested in WP 5.

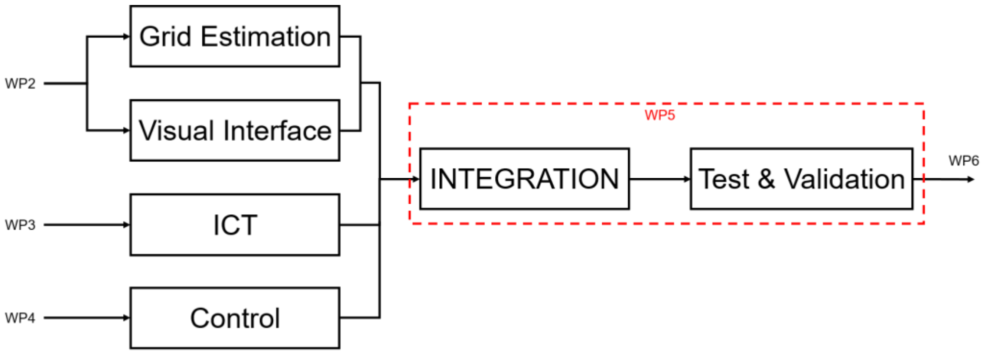

Figure 26: Schematic of the WP integration.

Table 11: Simulation tools capabilities overview.

Type of Modelling	Purpose	Study Types	Examples of Software Packages
Steady state power system analysis	Assessment of voltage and thermal conditions, fault levels	Load flow, voltage step, fault level contribution of DG	DIgSILENT, DINIS, ERACS, ETAP, IPSA, Power World, PSS/E, SKM Power Tools, OpenDSS
Dynamic power system analysis	Assessment of the transient and dynamic behaviour of equipment e.g. generators, DFIGs, and/or the network	Transient stability, critical clearing time, dynamic voltage step/control, fault ride through	DIgSILENT, DINIS, ERACS, ETAP, IPSA, Power World, PSS/E, SKM Power Tools
Harmonic analysis	Assessment of harmonics, distortion levels and identification of resonances	Impedance scan, harmonic load flow (including impact of VSC)	DIgSILENT, ERACS, ETAP, IPSA, PSS Sincal, SKM Power Tools
Electro-Magnetic Transient (EMT) Analysis	Assessment of eletro-magnetic transients and phenomena	Insulation coordination (lightning, switching), HVDC/ FACTS equipment design, sub-synchronous resonance (SSR)	ATP-EMTP, EMTP-RV, PSCAD/ EMTDC
Real Time Simulation (RTS)	Closed loop and scenario testing in real time	Real time simulations, protection testing, control system testing	RTDS, Opal-RT
Hybrid Simulation	Assessment of multiple models/ programs in the same dynamic simulation environment	Dynamic analysis of the interaction between two systems	ETRAN (PSS/E and PSCAD)
Multi-Domain Analysis	Assessment of multiple systems and their interactions	Study of interactions between electrical, power electronic, mechanical and fluid dynamic systems	MATLAB (including Simulink and SPS/Simulink), DYMOLA

Typical EMT simulations tools are handling a limited number of electrical nodes while RMS ones are used for large scale simulations. Considering the size of a distribution grid with tens of primary substations and thousands of secondary ones an RMS simulation tool is the only feasible candidate. A number of 66 different power system analysis software tools were reviewed in order to identify suitable candidates to be used in Net2DG project. This detailed review is presented in Annex A – Available Software.

Table 13 presents the top 5 software tools that are relevant for supporting Net2DG project. The main criteria for evaluation are:

- Open source - Net2DG aims in providing solutions to small and medium DSOs that may not afford cost related to licenses
- Maintenance - The software shall have continuous updates and an active community behind.

- Support – the software shall have an on-line helpdesk with a quick response in maximum 2 working days
- Load Flow – the software shall be able to perform classical load flow studies
- Control – the software shall be able to run time domain simulations where control algorithms can react and provide setpoints based on measurements in the electrical grid
- Fault Level – the software shall allow user to define characterization of external grid i.e. stiff or weak but also unbalanced fault studies.
- PerPhase Analysis – the software shall be able to model 4 wire electrical circuits

This analysis points to OpenDSS as being the simulation tool which is capable of addressing the electrical grid studies that supports the observability applications in Net2DG project.

Table 12: Top 5 power system simulation tools.

Name	BCP Switzerland	DIgSILENT (PowerFactory)	MathWorks (SimPowerSystems)	OpenDSS	PowerWorld
Open Source	No	No	No	Yes	No
Maintenance	Yes	Yes	Yes	Yes	Yes
Support	Yes	Yes	Yes	Yes	Yes
Load Flow	Yes	Yes	Yes	Yes	Yes
Control	Yes	Yes	Yes	Yes	Yes
Fault Level	Yes	Yes	Yes	Yes	Yes
Per Phase Analysis	Yes	Yes	Yes	Yes	No

3.7 Summary

In this chapter, modern distribution grids are analysed from different perspectives. First, topologies, generators, loads and data sources are overviewed; not only on their current state, but also future trends. Then, the greatest identified issues, namely: faults, voltage quality and losses; are covered. Such analysis consists on a short theoretical background, followed by statistic studies pointing out to the relevance of each challenge, followed by the existing practices from DSO dealing with such issues and finalising with the Net2DG scope. Finally, the modelling of the reference grid model is thoroughly discussed; pointing out the necessary assumptions, limitations and simulation approach needed. This leads to the definition of requirements and specifications for the model, ultimately defining the relevant scenarios to be studied. The last section analyses and selects the suitable software tool in which the model should be developed. Such selection is made after reviewing most of the available power system analysis software packages. The next chapter deals with the mathematical techniques used to survey and study the grid.

4 Estimation Techniques for Operational States of the Distribution Grids

4.1 Load Flow

Load Flow or Power Flow is the basic traditional approach when analysing power systems in steady state; its target is to determine voltages and currents under given load conditions. It is used to obtain voltages, currents, active and reactive losses, therefore it is the basic tool in planning, operation, economic scheduling, exchange of power between utilities and contingency analysis.

Equations defining power flow studies are non-linear, thus it is not possible to obtain an analytical solution. An iterative numerical algorithm is required to solve such equations. Commonly used numerical algorithms are: Gauss-Seidel, Newton-Raphson, Backward-Forward method and Three Phase Current Injection Method.

- Gauss-Seidel: Is the slowest method, no longer in use in commercial applications.
- Newton-Raphson: Is faster and more efficient than Gauss-Seidel, more suitable for system with few nodes.
- Backward-Forward: Performs better in radial distribution systems when compared with Newton-Raphson, especially if distributed generation or transformers are included. It is straightforward to implement and is very fast for radial or weakly meshed distribution systems. The overall speed arises from the low computational burden to perform each iteration. [51]
- Three Phase Current Injection Method (TPCIM): when large scale medium and heavy loaded systems, highly meshed topologies or if voltage control devices are included in the system, the number of iterations required by this method does not increase significantly, whereas Backward-Forward demands a much larger number of iterations. [52]

According to literature the Backward-Forward and TPCIM seems to be the relevant algorithms to be considered for Net2DG observability applications when the execution time is critical. Nevertheless, a basic load flow is sufficient for any other study. However, it should be pointed out how [50] [51] and [52] already present execution times higher than one second for fairly small network topologies. Finally, Table 13 presents the pros and cons of load flow studies as grid analysers.

Table 13: Advantages and disadvantages of load flow studies.

Advantages	Disadvantages
Commonly used both in academia and industry.	Slow method, difficult to implement in Real Time control applications of medium and large girds.
Proven technology	Not suitable for transitory analysis.
Multitude of tools available	Uses assumed values in the calculation (i.e. voltages) instead of measurements.

4.2 Kalman Filters – Linear Quadratic Estimation

Kalman filtering, also noted as linear quadratic estimation (LQE), is a mathematical algorithm that uses a series of measurements observed over time to produce estimations of unknown variables. The main novelty of this method is that the measurements contain statistical noise and inaccuracies, then it uses a joint probability distribution over the variables for each timeframe; producing more accurate values than those based on single measurements. [53]

The algorithm consist in two steps or stages; prediction and update. In the prediction stage, the algorithm estimates the current state variables along with their uncertainties. Then, in the update stage, the outcome of the next measurement is observed and, since it contains a certain amount of error and noise; their value is updated using a weighted average with more weight applied to estimates with higher certainty. Finally, it should be pointed out that, the algorithm is can run in real time, using only the present input measurements and the previously calculated state and its uncertainty matrix; no additional past information is required. [53]

Table 14: Advantages and disadvantages of Kalman Filters.

Advantages	Disadvantages
Handles time changing measurements [54]	Bigger error than Weighted Least Square [56]
Strong against interferences and noisy data [54]	Assumes linear system and observation models [57]
Reduced computing time and storage necessities compared to Power Flow [54]	Gaussian output assumption leads to obtain impossible states [53]
Simple, easy to implement in on-line, continuous monitoring of dynamic stability indexes [54]	Leads to errors if you start with exact knowledge of the state and perfect measurements [53]
Supports past, present and future state estimation even without knowing the precise nature of the modelled system [55]	Slow reaction speed in rapid change situations [53]

4.3 Weighted Least Square Method – State Estimation

This method determines the most probable state of a system by using certain measured quantities. In short, The WLS method minimizes the sum of the weighted squares of the residuals. Such weights represent the certainty of the measurements, being higher for accurate values. It is based on certain assumptions:

- The measurements follow a normal distribution.
- The mean value of the measurement errors is zero.
- The errors are independent.

In this method, the state estimation fully depends on the choice of the initial state. The best choice is to refer all the calculations to one voltage measurement with the lowest error as possible. In the case of a distribution grid, this is usually the voltage level at the substation.

The reference book covering this mathematical method is [59].

Table 15: Advantages and disadvantages of Weighted Least Square Method.

Advantages	Disadvantages
Handles time changing measurements [54]	Relatively weak against noisy data [54]
Smaller error than Kalman Filters [54]	Dependant on initial state [57]
Reduced computing time and storage necessities compared to Power Flow [54]	Calculation time increases at least quadraticly with the number of measurements or states [57]
Most widely used algorithm in power system estimation. [58]	Poor initial state selection leads to divergence[57]
	Generally slower than Kalman Filters [57]

4.4 Bayesian Estimator

The Bayesian estimator is a probabilistic approach able to estimate an unknown probability density function recursively over time using a mathematical procedure based on measurements.

This algorithm calculates the probabilities of multiple beliefs to allow a system to infer its estate. Essentially, Bayes allows to continuously update their most likely estate within a map of possibilities based on the most recently acquired measurements. Such algorithm is recursive and consists of two parts: prediction and innovation. Finally, it should be pointed out that if the variables are linear and follow a normal distribution, the Bayes approach is equivalent to the Kalman filter.

Table 16: Advantages and disadvantages of the Bayesian estimator.

Advantages	Disadvantages
Faster than WLS in monophasic analysis [60]	No information about three phase systems [60]
Capable of finding global optimum. [61]	Unsuitable for handling huge amounts of data [62]
	No practical applications have been developed [60]
	Never used in Real Time applications [60]

4.5 Summary

Figure 27 presents a comparison between Power Flow and Estimation techniques regarding the data, inputs and outputs needed for their implementation. The main advantages of estimation over power flow is the computational speed which makes them suitable for real time implementation, but also the fact that they use real measurement, not assumed values.

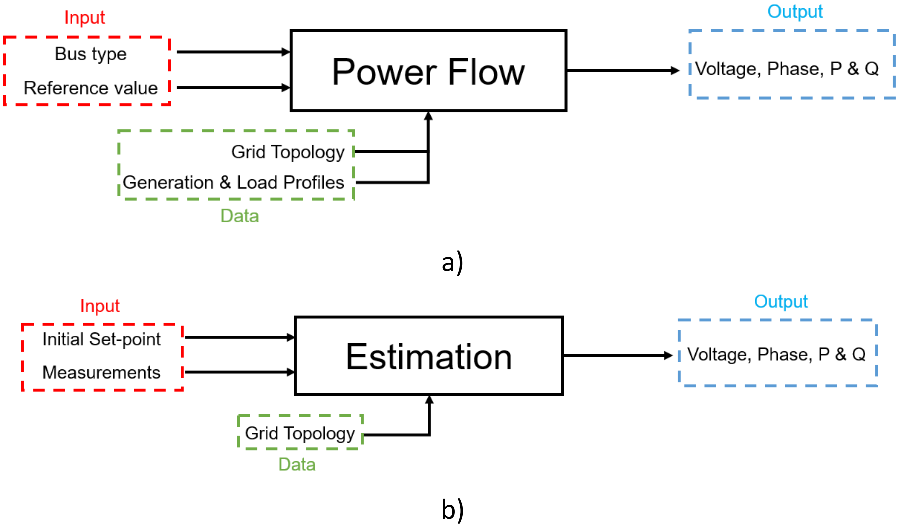

Figure 27: Input Output comparison between Power Flow (a) and estimation (b) techniques.

Due to the fact that WLS is the most widely spread, the estimator most likely will follow that algorithm. Otherwise, Kalman filters seem also suitable.

5 Observability Applications – Design

5.1 Overview

The following subsections present the Observability Applications that will be developed within WP2. In this public version of the deliverable, the description concentrates on the state of the art and requirements of each of the applications.

The applications were selected according to future trends and the prioritization list from [7]. The use-cases, the name of the corresponding applications, and their priorities obtained in [7] are listed on Table 17. The bold faced ones, Priority 1-5, have been selected for the first design in WP2.

Table 17: Net2DG Use-cases and prioritization [7].

Use case ID	**Name of the application**	**Priority**
UC FM-1: Outage Detection	**ODet**	**1**
UC LM-1: Loss calculation and recording	**LC**	**2**
UC FM-3: Preventive maintenance (asset management)	**PM**	**3**
UC FM-2: Outage Diagnosis	**ODiag**	**4**
UC VQ-1: *LV Grid Monitoring*	**GMon**	**5**
UC FM-5: Neutral fault diagnostic and location		6
VQ-2: Automatic Voltage Regulation → WP4	AVR	7
UC RE-1: Calculate and Visualize energy/power exchange in interconnection points to TS and overall in DS grid		8

UC FM-4: Neutral fault detection		9
LM-2: Loss Minimisation via grid reconfigurations		10
UC RE-2: Recommend improvements to the DS grid to minimise energy exchange from TS Grid		11
LM-3: Loss Minimisation using interaction with flexible energy resources		12

5.2 Assumptions for the Application Design in Release 1

The design and development of applications in Net2DG WP2 is done in multiple releases. This deliverable addresses Release 1. A set of simplifying assumptions are taken for this release. These are listed in the following:

- Single LV area served by one transformer: All applications focus on the LV grid only, i.e. they work on the delimited grid topology from the secondary substation trafo to the DSO customers in the LV grid. Release 1 thereby designs the applications to be executed for a single LV area, which is served by a single secondary transformer. Multiple application instances may be run in parallel to cover multiple LV grids at the same time.
- Radial LV grids only: LV grids operated in meshed topology are not considered in Release 1.
- Only measurements of electrical variables and of ICT reachability of measurement devices are considered in Release 1. Further sensors, e.g. providing temperature, are not considered.
  - o The electrical variables considered in Release 1 are voltages, currents, active power, reactive power.
- Fixed and aligned measurement interval durations: All electrical measurements refer to intervals of same duration, which in Release 1 is fixed to 15min. These 15min intervals are aligned in time, i.e. start and end of these intervals are assumed to be exactly the same for all measurements containing any time instant of this interval.
- Fixed LV topology during analysis intervals: Each application will update its grid topology view when it has been initiated. Topology changes during the runtime or topology changes that occurred during any of the analysed 15-min measurement intervals are not assumed to happen in Release 1.
- Single grid fault only: Only a single grid fault is assumed to happen in one LV grid within the period analysed by the applications.

Furthermore, Release 1 design focuses only on the functional behaviour of the application. Non-functional requirements like execution performance, scalability or application SW stability are out of scope in Release 1.

Release 1 assumptions regarding the interaction of the application with the Observability Grid Model: Generally, applications can either use an application-specific Observability Grid Model or a ‘common’ Observability Grid Model that is accessed via the ICT Gateway. The assumption for Release 1 of the applications is that the common Grid Observability Model provides values of average voltage for all grid nodes, average current for all cables, and average active and reactive power at all cable

ends. This Release 1 Observability Grid Model is used by ODiag, LC, PM, and GMon. ODet is designed to operate without any Observability Grid Model in Release 1.
The design of the Release 1 applications does not make any specific assumptions regarding the specific type of field measurement devices and neither regarding a certain minimum penetration of field measurement devices. The assumption from the application design is that the observability grid model can fill in missing values when required in specific applications (such as in LC).

5.3 Outage Detection (UC FM-1)

The use-case with the highest priority is the Outage Detection, which will be implemented by the ODet application.

For the Release 1 design, the following assumptions specifically for this application are taken in addition to the general Release 1 assumptions in Section 5.2:

- There is no isolated (micro-grid like) operation of parts of the LV grid: distributed generators in the LV grid detach when there is no power supply at their connection point coming from the relevant secondary substation
- All cables (including the ones at customer site that are represented in the topology) are 4-wired cables, so connecting all three phases.

5.3.1 State of the Art

This subsection looks at existing products and research publications regarding outage detection. In addition, other ongoing research projects are covered generally in the annex in Sect. 0.

Existing Products - Outage Detection in existing Smart Metering Systems: The provided AMI system detects all voltage outages, disregarding whether they are happening on one, two or three phases and all events are registered in the voltage quality logger as two events; one for outage of the voltage and one for reestablishment of the voltage. The voltage detection depends on the event. If the outage is on one or two phases (i.e. the meter is still powered by the third) the registration level is a configurable value between 50-160V. If the power outage is on all phases power outage is detected when the voltage drops below 160V. The detection levels are illustrated in Figure 1. It is possible to configure the time the voltage outage should be present before the event is logged. The value can be configured in the interval 0 sec. to 30 minutes. All detected voltage outages are also registered in one of two occurrence counters that register the number of voltage outages. The occurrence counters are accessed on the scheduled read-outs from the smart meter. According to EN50160, voltage outages are divided into short voltage outages (≤3 minutes) and long voltage outages (>3 minutes) and every voltage outage is registered in one of the two categories.

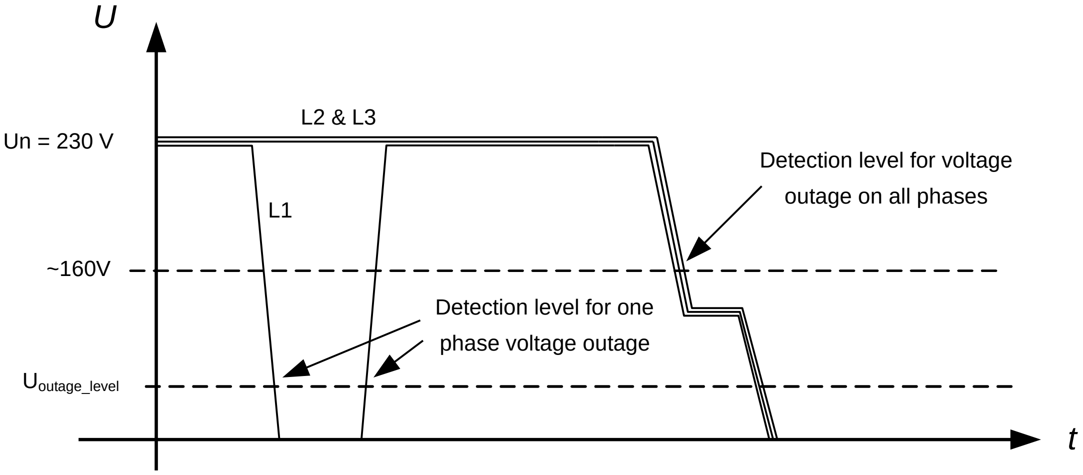

Figure 28: Detection levels for one phase and three phase voltage outages [1]

Outage detection based on Smart Metering Systems is also already currently performed by Distribution System Operators in a manual process. The communication network management tool of existing smart metering systems allows in many cases to visualize the status of the communication paths to individual or multiple Smart Meters. This communication path status is normally visualized on top of the communication network topology, which only in case of PLC communication has some resemblance to the LV grid topology.

Existing Products – Outage detection and anti-islanding functions in DER inverters:
International interface protection requirements for DER inverters operated in grid-tied mode usually require an inverter-internal protection against unintentional islanding. The corresponding feature is called anti-islanding which may be subdivided into active and passive anti islanding. In unintentionally islanding grid segments, voltage and frequency will exceed permissible conditions with a very high probability. At such abnormal conditions at the electrical interface, the inverter automatically disconnects according to the specified trip limits of abnormal voltage or abnormal frequencies. In addition to these passive protection limits (voltage and frequency), international standards such as [63 (Utility-interconnected photovoltaic inverters – Test procedure of islanding prevention measures) require DER inverters to feature active protection against unintentional islanding. The related standards do specify the required behavior, whereas it does not determine the controller implementations, which are consequently up to the manufacturer of the DER inverter.
Fronius implementations, for example, include an active anti-islanding detection method based on a reactive current component injected by the inverter. The injected current changes periodically between a capacitive and an inductive pattern (resulting in zero reactive power on average). The reaction of the frequency on this reactive current pattern is being continuously measured and analyzed. In case of an interconnected grid, the change in reactive current will not result in any related frequency response. Whereas in case of an islanded grid situation, the reactive current pattern will cause a change in frequency. The analysis of the measured frequency pattern clearly indicates the electrical island and the inverter trips within 5 seconds.

Related published research work on fault detection:

Using the taxonomy of the dependability community [64], a grid outage is a service failure. Detecting this grid outage can then be seen as a special case of a fault- or error detection, see e.g. [65],[66]. The input to fault detectors can be inconsistent, ambiguous, incomplete, missing or delayed [67], [68], e.g., inconsistency may originate from multiple observations providing conflicting information. In addition, measurement errors may occur and influence the observations. A measurement error is the difference between the measured quantity value and the true value of the considered measurand [69], [70]. In a distributed environment, several sources of measurement errors exist, including also examples of drifting clocks and low clock resolution and clock synchronization uncertainty , or intrusiveness of the measuring system [71]. In the context of Net2DG, measurement error that may affect the fault detection and later also the fault diagnosis accuracy.
Performing diagnosis under unreliable observations has been handled using various techniques and with different objectives in existing detection and diagnosis work including threshold-based heuristics [74] and probabilistic methods [72] .

Related published work on outage detection in distribution grids:
Part of the research work looks at the detection of complex fault scenarios that do not directly lead to outages, e.g. due to meshed grids [73], local generation or recovery actions by active components in the distribution grid [75]. The approach of the first reference uses change detection on the distribution of incremental changes of voltages. It then uses the co-variance of the voltage change distribution of different measurements to detect whether both measurement points are affected by the outage. The second reference proposes an algorithm to generate and evaluate multiple hypothesized fault causes for such scenarios and the optimal reaction to the fault. The scenario of missing Smart Meter information is taken into account via so-called credibility values. The latter inspires the used concepts in Net2DG to work with outage probabilities as outcome of the detection.

A second group of papers considers outages that are caused by simultaneous faults [76]. Some of the related work uses approaches based on machine learning:
[77] uses a probabilistic version of a genetic algorithm to identify the set of faulty lines in scenarios with multiple simultaneous line outages. The algorithm uses a model of the grid which has as input the line reactances, the measured power and the measured phase angles (motivated by a scenario of PMU placements).
[78] considers the scenario of multiple simultaneous line faults (motivated by extreme weather events) and proposes a machine learning algorithm that uses the distribution grid topology and the last gasp messages from the AMI system in order to identify such simultaneous line faults. The impact of the timing and of the reliability of the reception the last gasp messages are not analyzed in this work.

The idea to use multiple heterogeneous measurement sources for outage analysis has been previously considered. [79] categorizes the outage analysis into four different types and discusses qualitatively a use-case for each of the different outage analysis types based on the utilization of multiple data sources. However, no specific algorithms are defined or evaluated.

[80] uses a simple algorithm based on direction information from different fault indicators, which are not designed or described in detail, in order to identify the feeder segment in which the fault occurred. It also provides a simple algorithm for fault-isolation. The analysis of these algorithms is very preliminary.
[81] defines an evaluates an approach to distinguish persistent and temporary outages based on smart meter events: outage notifications, tamper notifications, ping responses from smart meters. The approach uses simple probabilistic models and fuzzy rules; while it also proposes to use measurements about power availability at intermediate nodes from the SCADA system in order to localize the fault. Both proposed directions are inspirations for the chosen Net2DG design.

Conclusions for Outage Detection in Net2DG: The Net2DG solution benefits from the fusion of measurement and ICT reachability information from different, heterogeneous subsystems, in particular including Smart Meters, Smart Inverters, measurement devices at substation. The assumption of radial topologies and generators that disconnect when the grid is in outage are simplifying the outage detection scenario for Net2DG in Release 1 on one hand. The main challenges for Net2DG Release 1 is to provide accurate outage detection despite the unreliability of ICT in outage scenarios, i.e. implying that measurements of electrical variables may not be available for all existing measurement devices in the LV grid.

5.3.2 Requirement Specs

Initial requirements for the ODet application have already been derived in [7]. Due to the further evolution of the Net2DG architecture and based on prioritization decisions within WP2, some changes to these requirements did occur. The original requirements stated in [7] and the changes (in bold-faced) are introduced here and the rationale for the changes is explained:

- ODet appl. must be able to subscribe to events (such as relevant alarms from AMI or PV systems) coming from the ICT Gateway
- ODet appl. Must be able to request the LV ~~and MV~~ grid topology from the ICT Gateway
  - **Rationale: First version focuses on LV grid only**
- ODet appl. must correlate the received events and use the communication device and measurement device status to distinguish between
  - ICT fault
  - Grid outage of single customer
  - Grid outage of multiple customers
- The ODet application should be able to take decisions on additionally needed information and request this information from the data Gateway
  - **Rationale: Although this is an optional requirement, it is kept already for the first design iteration, as it is expected that the ODet application will achieve a much better performance when implementing this optional requirement. Note that this implies that the ICT GW makes a device model, that can express the capabilities of field devices and hence the applicability of requesting additional data.**
- The ODet application must be able to communicate its result to the ICT Gateway

- By processing the grid topology and measurements, the ODet application should calculate number of affected clients ~~and energy not supplied (ENS)~~ and store this in the ICT Gateway.

Rationale: Calculating ENS requires to determine the duration of the outage; this functionality is moved to the Outage Diagnosis use-case; ODet should only detect the occurrence of an outage, whether it is single-phase or multi-phase, and how many customers are affected

5.4 Outage Diagnosis (UC FM-2)

5.4.1 State of the Art

Many methods for outage diagnosis use the information of fault passage indicators located along the feeders [83] [84] [85], so that the DSO is able to identify the feeder section where the fault occurred. These methods are based on the mapping of fault indicators that are deployed along the feeders. These can detect fault currents on single or three-phases and are usually mapped on the topological model of the grid within a GIS or DMS at the DSO's central systems. When a fault occurs (and a subsequent outage), an event is communicated and a correspondence to the branch where it occurred is signalled. The references [83] [84] [85] describe the operational setup and configuration of such a method.

These methods are quite accurate and provide an effective way to locate the fault. However, these are very much only considered for HV and MV grids. Moreover, not only they do not contribute much for the root cause analysis of the fault but also are very dependent on CAPEX for the acquisition and deployment of the sensors. Furthermore, there is also a high dependence of communication of each sensor to the DSO central systems.
An alternative method for outage location is by using a functionality that some of the modern digital protection relays have of analysing the fault current shape against the short circuit characteristics previously set at the device for that specific feeder [86]. This method is based on reactance calculation to assess the equivalent distance [87]. A radius is then virtually drawn and the possible locations are signalled by the intersection of that radius with the feeder branches/sections.

Here, the strong dependent on the use (and correspondent needed investment) on high end protection relays is a factor that might delimit a common use of this approach. Also, these relays are only adequate for HV and MV grids.

Lastly, there are methodologies specific for earth faults [88]. These faults occur where the power carrying cable or conductor breaks and gets into contact with earth or any conducting material in contact with earth. Locating earth faults in electrical distribution grids is essential to the operation of the electrical grid. With the localization of an occurring earth fault, technical teams can be dispatched to resolve the fault, normally by repairing a failed grid component or link. Obviously, visual inspection by human technicians is not sensible, given that an electrical distribution grid can encompass underground cables or hundreds of kilometres of overhead lines and the time to repair the fault is

critically important. Furthermore, compensated electrical distribution grids have specificities that hinder prior art localization methods.
The existing protection system at the Primary (HV/MV) substation can detect the occurrence of Earth Faults, but not its exact location. The deployment of so-called Peterson coils allows the continued operation of the MV grid despite the fault. However, the grid is not operating in the optimized conditions any more with consequences of lifetime reductions of electrical components and often resulting in subsequent faults, which then cause power outages at customers.
Thus, there is a need for methods for locating earth faults in electrical distribution grids, in particular in LV electrical distribution grids.
To tackle these challenges, GridData has developed and registered a patent for an application that uses use a pattern matching algorithm towards grid measurements at high time resolution immediately after the fault and a customized grid model to identify likely locations of the fault.
The basic idea for the technical approach for the Earth-Fault Localization is to use current and voltage measurements with high time resolution immediately after the fault occurred. The method automatically locates earth faults in electrical distribution grids, in particular for compensated electrical distribution grids. It has been surprisingly found that time-domain signals immediately ensuing the earth fault contain sufficient information to locate the earth fault in electrical distribution grids, even in large and complex compensated electrical distribution grids.

Furthermore, an electrical outage can also be diagnosed by the status of the communication with sensors. If there is an outage, either the sensor is offline or it can emit alarms before shutting down, while the battery power is still powering the communications module of that sensor. In the case of an all phase power outage an alarm denoted "Last Gasp" is generated. It will be generated if the meter for some reason is no longer supplied by the main voltage grid. The all phases power outage alarm is a supplement to the existing power outage registration in the smart meters' Voltage Quality logger, which can be read out by the AMI system as usually, when the system is restored. The meter has back-up power to send out one, but only one, alarm before it powers . The all phase power outage alarm is sent as a broadcast massage to the surrounding meters/concentrators. A meter that receives an alarm will repeat/forward the message in the RF-mesh, unless it is impacted by all phase power outage itself. When the power to the meter restores, the meter will send a "power restoration" alarm to the rest of the system.

In Figure 29 a simplified RF-mesh topology is outline were a number of meters are installed on the same radial of electricity supply. The present RF routing network is shown as dotted lines. It shows how some meters are using other meters as repeaters/forwarders to reach the concentrator. Note that meter number 5 is a point-to-point meter using a 2G/3G/4G modem.

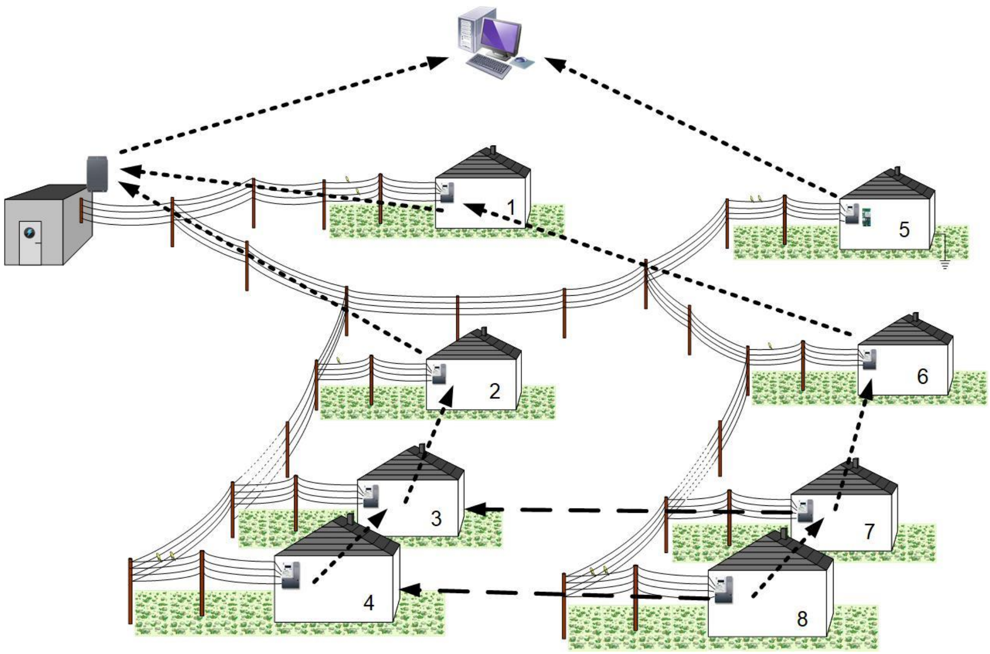

Figure 29: Simple RF-mesh topology. Note meter 5 is using a GSM modem

In the case were a full power outage appears from the main electricity supply all relevant meters will each send out one alarm to indicate that the power is no longer applied. As an alarm from one meter cannot be forwarded by nearby meters if these meters are also impacted by the power outage, only the alarms from meter number 1, 2, and number 5 will be received in the system. This example is illustrated in Figure 2.

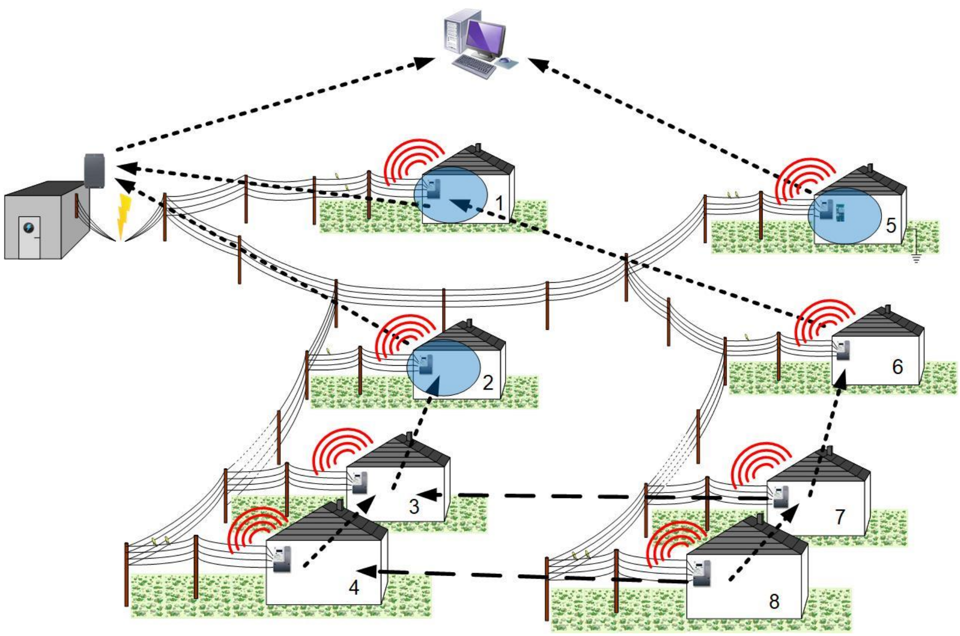

Figure 30: How a “last gasp” alarm is transmitted through the system if a full power outage occurs. The “lightning” on the left-hand side of the figure indicates where the brake on the power lines is located. Note meter number 5 is using a GSM modem.

In the case where an all phase power outage alarm is received by a meter that is not impacted by the power outage, this meter will repeat the alarm in the RF network. This is illustrated in Figure 31, where the brake of the power line is introduced on the radial connecting the right-hand side of the grid. The system will receive alarms from meter number 5, 6, 7, and number 8.

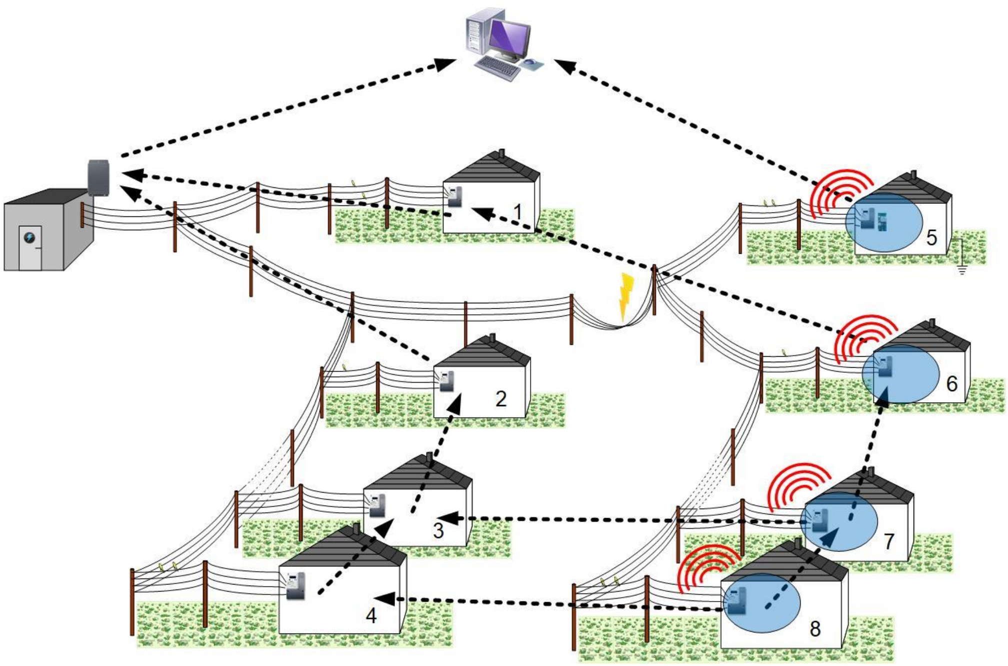

Figure 31: An all phase power outage in one section of the grid. The "lightning indicates where the brake on the power lines is located. Note meter number 5 is using a GSM modem.

5.4.2 Requirement Specs

Initial requirements for the ODiag application have already been derived in [7]. An adaptation of these is included bellow where further details have been added to specifically meet the objectives of WP2:

- ODiag appl. must be able to be triggered by the ICT Gateway based on detection events from the Outage Detection application
- ODiag application must be able to obtain the result from the Outage Detection application via the ICT Gateway
- ODiag application must be able to request the detailed grid topology and additional measurement data from the affected LV (on release 1 of the application) and/or MV grid region (on release 2) from the ICT Gateway
- ODiag appl must process the received data and reachability information in order to calculate the likelihood of the following causes of the outage:
    - Blown fuse
    - Cable Fault
    - Bad connection in junction box
    - Short circuit
    - Outage of phase on MV level of secondary substation

    - Others (unknown)
- The ODiag application must be able to communicate its result to the ICT Gateway
- ODiag appl. must be able to subscribe to events from the GUI (events being input provided by the user) coming from the ICT Gateway

Additional optional requirement:

- The ODiag should be able to be triggered by a GUI event.

5.5 Loss Calculation and Recording (UC LM-1)

Purpose of the Loss Calculation (LC) application is to obtain an estimate of the time series of losses in a LV grid. The first design of this application is outlined in the following.

5.5.1 State of the Art on Loss Calculation

The loss calculation application in Net2DG is an automatized and extended version of the current manual procedure for loss calculation that is applied by some DSOs, see Sect. 3.5.2.The loss in the low voltage grid is calculated by continuously comparing energy leaving the substation with the amount of energy measured by the smart meters at the underlying costumers:
LV gridloss [kWh] = kWh substation – ΣkWh costumers

This current approach is one method of the implemented loss calculation methods in Net2DG. Net2DG will extend this approach by (1) adjustments for correct treatment of generation scenarios; (2) inclusion of the data quality of measurements for calculation of confidence intervals of this loss calculation; the former includes also the impact of time interval alignment errors due to clock synchronisation [89] in later Releases. (3) approaches to handle missing measurements; in later releases also faulty measurements.

Loss calculation through the use of simulation models has been part of many research projects:
The Austrian project "DG DemoNet – Smart LV Grid" (2011-2014) obtained losses by simulation/calculation in PowerFactory based on models of real LV field test grids. The project investigated the impact of inverter-based reactive power controls (e.g. Volt/VAr or Q(U) control), targeting increased DER hosting capacities, on losses in the grid. Findings include that properly designed and efficient reactive power controls can multiply reactive currents when active, while increasing annual total losses in the range of a few percent. [87]

A large number of research papers uses loss calculations obtained from simulation models. [91] points out that in practice missing data makes it difficult to break down the losses into technical and non-technical losses. Simulation experiments of real grid topologies from Northern Germany and France in [92] show strong differences of the contribution of the share of losses from the LV grid (42% of the losses in Northern Germany are on LV grid level, while in France only 14%), arguing that detailed LV grid loss analysis is highly relevant. The need for simple engineering rules (not requiring detailed grid simulations) for loss calculation has been pointed out and addressed in [93].

Loss reduction has also been considered as target metric in the Energy Balancing use-case in the FP7 project SmartC2Net [6]. The approach in SmartC2Net distributed the adjustments of active power between multiple generation units in an MV grid and showed that losses can be reduced by approximately 10% with such method. The losses were obtained from simulation models using a similar formula as stated above for the LV grids. Other work, e.g. [94] investigated the impact of placement of distributed generation in distribution systems on losses.

Losses are also used in the context of fault-detectors: for instance, [95] uses rule-based decision making with fuzzy rules on load profile measurements from AMI systems in order to detect fraud (non-technical loss) and faults. It applies the approach exemplarily to a single-phase-to-ground fault of the Medium Voltage Grid with subsequent restoration in an underlying meshed LV grid by circuit-breakers.

5.5.2 Requirement Specs

Initial requirements for the LC application have already been derived in [7]. Due to the further evolution of the Net2DG architecture and based on prioritization decisions within WP2, some changes to these requirements did occur. The original requirements from Ref. [7] and the changes (in bold-faced) are introduced here, and the rationale for the changes is explained:

- The LC application must be executed periodically with configurable period
- The LC application must be able to obtain the grid topology ~~**and its evolution over a specified time interval in the past**~~ from the ICT GW.
    - *Rationale: Release 1 assumes that topology changes in the LV grid do not happen in the considered time intervals.*
- The LC application must be able to obtain all available energy (active and reactive) measurements, the corresponding time intervals, and the accuracy of the measurements and time intervals from the ICT GW.
    - *Remark: The requirement as stated above feeds one of the possible ways of calculating losses. In case of missing measurements, this may however not be the preferred one. Net2DG will analyze this by comparing with another approach that uses the cable currents for loss calculation. Therefore, another requirement is added to feed the second way of loss calculation:*
- **Alternative: The LC application must be able to obtain averages of all cable currents during the 15min time intervals, and the accuracy of the current values and the accuracy of the time stamps from the IG.**

- ~~*The LC application must be able to obtain other measurements such as voltages from the IG, in order to use them for extrapolation of missing energy measurements*~~
- ~~*The LC application must be able to extrapolate missing energy measurement points from a grid model.*~~

    Remark: The previous two requirements depend on how the grid model is triggered and by whom. Release 1 follows the approach in [96], in which the application does not *need to care about whether a value is from a measurement* or from the Observability Grid Model.

- The LC application must be able to correlate the energy (active and reactive) measurements and measurement time intervals in order to obtain a series of values over time intervals of
  - Absolute loss of energy (in kWh and kVArh) in LV grid parts below a substation or junction box and accuracy of this loss calculation
  - Relative loss of energy and accuracy of this relative loss for two different normalizations: (1) relative to total energy flow through the junction box/substation and (2) relative to sum of generation and import in the considered LV grid area.
- The LC application must be able to write back the calculated sequence of loss values and time intervals to the ICT GW.

5.6 Preventive Maintenance (UC FM3)

5.6.1 State of the Art

The installation of smart grid equipment, such as smart meters, data concentrators, inverters and other measurement devices, contributes to increase the monitoring and control capabilities of low-voltage grids. However, advanced software functions are needed to fully explore the information collected by the different devices. A new paradigm is the preventive control of distribution grids, where a key input is information about a certain asset of the distribution grid is used to detect potential technical problems. For this purpose, many platforms from manufacturers and software companies exist today dedicated to asset management. These can be quite complex, incorporating the digital models of the assets which are fed by several sensoring information for that specific asset. If there is no intrinsic sensor information, then no information can be calculated or estimated.

Furthermore, current SCADA systems collect substantial amounts of real-time information but it is not at all frequent to find specific application where the historical operational information from a specific asset is analysed and included on the decision process of the utility.

Another current predictive maintenance techniques based on asset analysis are currently being used by utilities [97]. These bring on-site results and required teams availability to inspect the asset (here considered are transformers, cables, lines, junction boxes):

- Power System Assessments – These are conducted by professional electrical engineers trained in power system analyses. Power system assessments provide visual inspections of the existing power distribution system. Defects, deficiencies, deteriorations, hazards, or weaknesses in existing system installations are identified as part of the assessment.
- Infrared (Thermographic) Inspections in transformers – Infrared inspections use a specialized camera to detect anomalies not noticeable to the naked eye. In an electrical setting, infrared inspections identify hot spots, which can be a precursor to equipment malfunction, which leads to unplanned downtime.
- Online Temperature Monitoring – This technology provides 24/7 access to critical connection points where traditional thermography cannot be used. Continuous monitoring provides the

means to evaluate the equipment's current condition and detect abnormalities at an early stage. During a planned outage, wireless temperature sensors are installed in low-voltage and medium-voltage equipment areas not accessible to an infrared camera.

- Insulating Fluid Analysis – This approach measures the physical and chemical properties of oil in an oil-filled transformer. An oil analysis can detect the breakdown of the oil paper insulating system. Common tests performed on electrical insulating oils include readings for moisture content, acid levels, dielectric strength, power factor, and dissolved gas analysis.
- Partial Discharge Monitoring – A partial discharge is a localized electrical discharge in an insulation system that does not completely bridge the electrodes. As insulation systems age, they become more susceptible to these types of breakdowns.
- Circuit Monitor Analysis – Circuit monitors record data relating to voltage, current, and power. They help facility managers and engineers understand where and when dangerous and destructive transients, sags and swells occur.

The research area is quite active on this field. Again, there is a heavy dependence of the methods developed and the sensoring information the asset originates. Focusing on similar methodologies as the one proposed within NET2DG where the deployment of other sensors in the assets is not the focus, research is usually taking approaches based on estimation methods or profiling techniques. In [104], the method developed within the UPGRID European project is described which is based on net-load forecasts for each LV node, including PV generation and self-consumption, which are then used to predict power flows. This allows to foresee in advance (for ex.1 day ahead) the possible grid constraints and the stranded assets. It is therefore a planning tool and not so much a asset focused method and hence with a different aim than the envisaged here with the PM application despite the potential to use measured net-load for LV nodes.

Another approach to asset management is having a similar method as it is used on the finance industry. A risk management method coupled with a life-cycle cost method is proposed in [105]. The bulk of costs in electrical grids can be found in costs for maintenance and capital depreciation. A comprehensive approach for an asset management in transmission systems thus focuses on the "life-cycle costs" of the individual equipment. The objective of the life management process is the optimal utilisation of the remaining life time regarding a given reliability of service and a constant distribution of costs for reinvestment and maintenance ensuring a suitable return. However, the fact that the Net2DG project focuses on LV grid where many assets are less critical, there is few sensors dedicated to a single asset and where the utilities are considering these assets as a commodity, the risk based approach is not so applicable to Low Voltage. And hence, the importance of leveraging the information available to achieve improvements, on a preventive maintenance perspective, which is the aim of this project.

Patent: MILA - Meter Impedance Learning Algorithm - WO 2018/122160 A1: The present invention relates to an electricity meter adapted to measure electricity consumption in an electricity distribution network with three phases, wherein the electricity meter comprises a measuring circuit for measuring

voltages and currents for each of the three phases, a microcontroller unit configured to calculate the electrical energy supplied from the electrical distribution network via the phases and an impedance learning algorithm unit for estimating impedance values of the electrical distribution network as seen by the electricity meter. The impedance learning algorithm unit is arranged to continuously calculate symmetrical components of the three phases based on at measured voltages and currents from the three phases and to estimate zero- and negative sequence impedances as a ratio between a summation of a changes in the zero- and negative sequence voltages and a summation of the changes in the zero- and negative sequence currents, respectively.
In an electrical distribution network supplying energy to a number of consumers, the electric power provider needs to be able to measure the electrical energy consumed by or delivered to the individual costumer. Each consumer has an electrical meter installed measuring the electrical energy delivered to the connection point of the consumer. The electrical network is usually divided into two levels, a transmission network level and a distribution network level. The transmission network is operated at high voltages above 60kV and the distribution network is operated at voltages below 60kV. Most consumer are connected to the distribution network below 10kV; the majority are in fact connected at low voltages below 1000V. In the transmission network, the grid, i.e. cables, transformers, generator, etc. are well defined with known impedance, allowing the Transmission System Operator (TSO) to simulate load flows based on knows parameters. Whereas, when looking at the distribution network often only parameters of main components are known. This makes it difficult for Distribution System Operators (DSO) to predict overload and system stability. When it comes to overloads and faults, it is important to know the short circuit currents (SC-currents), which may occur during faults. Today, SC-currents are determined by calculations with input data from transformer-, radial-, and service wire impedance. Alternatively, impedance for calculation SC-currents may be measured with special equipment installed near or at the point of supply. In the first instance, SC-currents are based on theoretical measures only and the actual SC-current may differ in case of incorrect input data. In the second instance, expensive and specialized equipment have to installed and manually operated which is labour and cost intensive and only provides momentary impedance data. Electricity meters of the prior art have the drawback that they only provide the DSO with information about voltages, currents, and power consumption at the point of use. An object of the present invention is to provide a cost-effective electricity meter providing additional information about impedance of the electricity distribution network as seen by the electricity meter.

5.6.2 Requirement Specs

An adaptation of the application requirements already described in [7] were used to detail the main requirements of the PM application. The main goals are stated as follows:

- The solution should be able to detect short-term transient outages or anomalies in the voltages or energy losses that are caused by loose cable connectors, aging cables, cable damages such as scrapped off insulation.
- The solution could try to identify and localize grid assets under abnormal operating conditions that might evolve into grid outages.
- The solution should reduce manual work involved.
- The solution should minimize false detections and faulty localization and diagnosis outcomes.

Adapting from [7] requirements:

- PM must be able to receive measured voltage and currents from smart meters, inverters, measurement devices and substations via the ICT Gateway.
- PM must be able to request the LV and MV grid topology from the ICT Gateway
- PM must be able to update the missing parameters (calculated/estimated by GMon) for the grid model nodes that do not have information accessible
- PM must store all calculated values in the ICT Gateway marked as estimated.
- PM must be able to detect and identify any asset within the LV grid that requires maintenance based on the historic data measured by any sensor collecting relevant information from assets (voltages, THD level, currents, temperatures, etc.) and the estimated state.
- PM must be able to persist any deviations from normal operational conditions asset management purposes in the ICT Gateway.
- PM must be able to monitor the frequency of events related to a specific asset and detect significant changes on the pattern, indicating possible maintenance needs. In case the measured values are outside the limits, the priority of maintenance intervention is increased.
- PM must generate a report including a description of the asset needing maintenance, the position, the problem and what caused the detection.

5.7 LV Grid Monitoring (UC VQ1)

5.7.1 State of the Art

Testing of voltage quality is usually initiated by a call from a customer complaining about flashing in the light, dimmers that behaves strangely or short life of lightbulbs. There may also be complains about small turbines or PV inverters that indicates over- or undervoltage.

As a current practice and following the example of TME, for voltage quality testing, initially, the voltage quality logger in Kamstrup's AMI is observed to quickly investigate whether the voltage has been within +/- 10% of rated voltage. Then a historical file is retrieved for the smart meter analysis logger where we can see average values for the voltage in 15-minute intervals.

If a more detailed analysis is required, a voltage quality logger (Gossen Metrawatt) is installed in the switchbox. It has much higher resolution and shorter log intervals than the smart meter.

This tool, with the included software Dran-Viev, can generate a report that shows whether the grid complies with EN50160 according to voltage quality.

This is an example of what modern AMI systems may already be capable of. Depending on the capabilities of those systems, graphical interfaces may help locating the smart meters that have detected voltage problems in a more or less automatic way.

Todays' automatic meter reading (AMR) meters are not only used for providing accurate billing information (hourly consumption data) to utility, but they may be also used for electricity distribution network planning and management. The AMR meters using advanced metering infrastructure (AMI) identifies the voltage problems (voltage imbalance, outage, and power quality) and generates alarm signals for the operation centre based on threshold voltages.

Examples of these modern systems which are available on the market can be referenced [99] [100][101]. However, these systems revolve around a complex architecture and demanding infrastructure.

In [102] use cases are designed and mapped into smart grid architecture model (SGAM) with a focus on power quality. The use case is useful to understand the activities involved in low voltage monitoring process as it defines the steps or interaction of actors (smart meters, distribution system operator), and information systems (at control centre) with respect to requirements in different scenarios. It exemplifies the process between actors and systems for sending alarms from smart meters to operation centre and how this information is applied for managing those problems. The communication systems, supporting protocols, the breakdown of data at the operation centre, actors, integration of different information systems (supervisory control and data acquisition (SCADA, distribution management system (DMS), etc.) and type of information are described and depicted for the use cases of outage management and power quality in form of SGAM and present a good structure to be adapted for use within Net2DG.

Distribution operators have long had poor visibility on the low voltage grid compared to its heavily automated and real-time monitored high and medium voltage networks. Seeing a smart meter as just a measurement tool for the meter-to-cash function is a wasted opportunity and this perspective is shared between the Net2DG project and also in [103]. Smart meters are seen as a communication and distribution sensor, which when combined with power line communication (PLC) and analytics software is capable of making distribution companies “grid aware”. One function of smart meters is to measure energy but they have another possibility - to monitor power. DSOs that have deployed advanced metering infrastructure (AMI) supported by PLC or wireless communications can leverage the technology to monitor power voltage, power factor, average values and power flow. The benefits have the potential to extend to grid topology mapping to a DSOs business and operational functions are immense, from updating geographic information system (GIS) records to the identification of phase imbalancing. In a European three-phase context, distribution companies can use AMI to map the voltage on feeder lines from the transformer to smart meters with the added benefit of overlaying the voltage profile. Essentially smart meters can offer a phase view of the grid by measuring the power flow on each line rather than a grand average allowing the DSO to identify assets that are being under or over utilized.

The success of leveraging an AMI system to monitor the LV grid depends on three factors. First, having a highly available and sufficiently stable PLC or wireless communication infrastructure, resistant to interferences in the grid. Second, having up-to-date and precise LV grid schematics down to the single meter/single smart device. And third, financing. DSOs will need to find enough investments for a state of the art NMS and advanced LV supervision.

5.7.2 Requirement Specs

The main requirements of the GridMon application are:

- The solution should be able to visualize quality issues in the LV grid and diagnose causes of the voltage problems.

- The system should monitor voltage profiles from smart meters, inverter and sensor data
- The solution must be able to detect values which are outside a window of values previously defined and which can be customized.
- The solution should create warnings for the operator and indicate visually where the problem(s) was detected
- The operator must be able to use the solution to assess if the problem was corrected and remain resolved.
- The solution should be able to identify whether inverters operate in a configuration that is compatible to the connection requirements reflect by the individual contract between DSO and plant operator

The solution should notify the Grid Operator when the voltage quality does not fulfil EN50160 in certain points of the grid.

6 Conclusions and Outlook

Modern distribution grids present high rates of renewable energy installations along with power electronics coupled generation, which creates a number of challenges to be added on top of already existing ones. However, the smart grid concept presents control and observability possibilities never seen in distribution grids. Technologies like AMI can potentially change the way these grids are operated and conceived without additional big investments as this is already a commitment European countries have and in a relatively short period of time. Although, first it is necessary to study which problems are already in place, which ones are expected to appear and finally see what it is exactly the data available to tackle all these problems.

The present document has covered a number of topics from background to identification of issues and challenges. Then the scope of Net2DG has been aligned and defined to a number of different applications aiming to fill the technological gap of the industry with modern technologies and methods. As presented in Chapter 3, the amount of available data is much more than before, however it is still limited to perform highly technological applications that might require per-phase measurements. Nevertheless, Net2DG will develop applications suitable to be implemented with current available technologies and methods to be able to estimate the operational parameters from available measurements from the field. Then, Chapter 4 focuses on estimation techniques as well as the objective to be able to detect possible erroneous information on the original data set from measurement devices or the GIS system. Furthermore, in case of missing data or time synchronisation problems, the methods here described also address this challenge. In Chapter 5, the concrete applications are specified and designed taking into account the possible growing features to be presented in future releases, after certain advances are done in those solutions. The focus here is on the five priority applications derived from the use cases described within WP1 which are Outage Detection and Diagnostic, Losses calculation, Preventive Maintenance of assets and LV grid monitoring. All these applications will be based on a strong interface with WP3 and WP5 and will introduce unique characteristics to the Net2DG solution. This public version of the deliverables focuses on the state of the art for these five applications.

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8 Annex A – Available Software

This Annex presents a list of the available power system simulation tools. Table 19 presents a system of tick boxes that make easy to evaluate and identify possible options for Net2DG, note how Table 18 presents the color code legend.

Table 18: Colour code legend.

Colour	Meaning
(red)	Discarded because of various reasons
(orange)	Discarded because of mail inquiry
(yellow)	Discarded because it is a paid tool, but capable of solving everything
(green)	Selected

Table 19: Review of the simulation tools.

Name	Open Source	Maintained	Support	Load Flow	Control	Fault level	Per Phase Analysis	Remarks
Advanced Grounding Concepts (WinIGS)	No							Grounding and shortcircuit tool not a general one
AMES	YES	YES	YES	?	No	?		It is a generalistic program not power system specific
ASPEN	YES	YES	YES	YES	No	YES	?	OneLiner and Power Flow can handle with ease networks with over 100,000 buses. DistriView can handle radial or looped distribution feeders with up to 32,000 nodes.
ATP-EMTP	No	YES	YES					It is listed as free, but it is not
BCP Switzerland (NEPLAN)	No	YES	YES	YES	Yes	YES	YES	Short answer pointing to download and try. Control seems tricky.
Commonwealth Associates (Transmission 2000)	No				No			
CYME	No	YES	YES					Tailor made not generalistic
DCOPFJ	YES	No	No					Too "home made" not reliable to have support on the future
DIgSILENT (PowerFactory)	No	YES	YES	YES	YES	YES	YES	
DiSC	YES							Developed for the SmartC2Net in AAU, matlab based
DNV GL (SynerGEE Electric)	No	Yes	Yes	?	?	?	?	They don’t provide much information

Dome	No	No	No					
EasyPower	YES	YES	YES	YES	NO	YES	?	The control capabilities described in the website are not enough. They are limited to motor on/off
Electrocon (CAPE)	No	YES	YES					Not suitable for distribution according to website
Elplek	YES	No	No					Doesn't look propprely maintained
EMTP-RV	No	No	No					
Energy Advice (EA-PSM)	No			YES	No	YES		
Energy Computer Systems (SPARD)	No			YES	No	YES		
EPFL (SIMSEN)	No	No	No					
ERACS	No				No			
ETAP	No	YES	YES	YES	?	YES	?	NO REPLY FROM MAIL INQUIRY
GDF Suez (Eurostag)	No	No	No					no updates since 2015
GE Energy (PSLF)	No							from general electric
GridCal	YES	-	-	YES	No	No	No	
GRIDLAB-D	YES	Maybe	Maybe		No			Doesn't specify anything about control, it´s support is limited to a fund that might get withdrawn
GridPACK	YES	NO	NO					
InterPSS	YES	No	No					
IPSA Power	No	YES	YES	YES	No	YES	?	
KEPCO (KW-PSS)	No							From a company like Siemens
Manitoba HVDC Research Centre (PSCAD)	No	YES	YES					From a company like Siemens
MatDyn	YES	YES	No					
MathWorks (SimPowerSystems)	No	YES	YES	YES	YES	YES	?	
MATMOR (PADEE)	No							Everything is in Spanish
MATPOWER	YES	No	No					
MicroTran	No	No	No					not reliable support
MILSOFT (Windmil)	No				No			
Minpower	YES	No	No					is only maintained by one guy, looks like a hobby thing
Mosaik	YES	YES	YES	YES	NO	?	?	
NEMO	YES							Market tool, not technical
Nexant (SCOPE)	No				No	?	?	
OpenDSS	YES	YES	YES	YES	YES	YES	YES	Quick response pointing at where to find useful information
pandapower	YES							Most of the support is in German

Phase to Phase (Vision Network Analysis)	No				No			
Power Analytics (EDSA)	No	Yes	Yes	Yes	Maybe	Yes	?	Quite shady website, difficult to find answers
PowerGAMA	YES	No	No					Market analysis
PowerModels.jl	YES				No	No		
Powertech Labs (DSATools)	No							Confusing options
PowerWorld	No	YES	YES	YES	YES	YES	No	Short response within a reasonable time frame, does not perform per phase analysis
PRDC (MiPower)	No							website is hacked, doesn't seem reliable
PSAT	YES	No	No					
PYPOWER	YES	NO	NO					
PYPOWER-Dynamics	YES	NO	NO					
PyPSA	YES	Yes	No					Focused on transmission, unconfortable interface
RAMSES	YES	No	No					
ReticMaster	No	No	No					closed website
RPowerLABS	YES	Yes	Yes	Yes	No	Yes		webbased
SES & Technologies (CDEGS)	No							meant for protection testing
Siemens PTI (PSS/E and SINCAL)	No	-	-	-	-	-	-	It is better to avoid this kind of commercial software
SIMPOW	No	No	No	-	-	-	-	
SKM (Power*Tools for Windows)	No				Not clear			Extremely Expensive, low limit for buses
SmartGridToolbox	YES							Not for windows
TEFTS	YES	No	No					
Tom (PASHA)	No	No	No					
UWPFLOW	YES	No	No					
vSPD	YES	No	No					
Xendee	No				No			It has control, but not suitable for the applications we want

9 Annex B: Additional Information regarding State-of-the Art of Applications

The following list of research projects deals with topics that may be relevant for the applications in Net2DG. As most of these projects are ongoing, a detailed analysis is at this stage not possible. Instead, these projects are put on a watch list and monitored in half-yearly time intervals to assure that any cooperation benefit for Net2DG is going to be detected. The text in the following list is partially obtained from the project web sites:

- UnitedGRID project – currently limited information available.
- Storage4GRID - http://www.storage4grid.eu/pages/publications.html
- http://upgrid.eu/ - 4 pilots were about: Smart grid monitoring and operation, advanced grid maintenance, distributed energy resources and active demand management integration, and active consumer awareness and participation with cost efficiency
- http://www.integridy.eu/ - Among other the inteGRIDy will integrate innovative smart grid technologies, enabling optimal and dynamic operation of the distribution system's assets within high grid reliability and stability standards. Validate innovative Demand Response technologies and relevant business models. Utilize storage technologies and their capabilities to relieve the DG and enable significant avoidance of RES curtailment, enhancing self-consumption and net metering. Provide predictive, forecasting tools & scenario-based simulation, facilitating an innovative Operation Analysis Framework.
- https://www.wisegrid.eu - WiseGRID InterOperable Platform: Scalable, secure and open ICT platform, with interoperable interfaces, for real time monitoring and decentralized control to support effective operation of the energy network. The objective of the platform is to manage and process the heterogeneous and massive data stream coming from the distributed energy infrastructure deployed.
- WG COCKPIT a micro control room: Cockpit for DSOs or microgrids Operators in order to control, manage and monitor their own grid, improving flexibility, stability and security of their network, considering an increasing share of distributed renewable resources. By means of the cockpit, the DSO will be able to detect faults, self-protect and self-reconfigure the network in a robust way to restore the power system without the intervention of a central intelligence (self-healing).
- http://zaphiro.ch/ - SynchroGuard is a highly flexible and customisable solution for smart distribution grids, offering combined monitoring, control and fault management in one single solution
- https://www.sogno-energy.eu/ - DSOs need to use services increasing their flexibility to adapt and reducing their need for fixed investments. SOGNO will address this challenge by combining the application of deep intelligence techniques, industry grade data analysis and visualisation tools, advanced sensors, an advanced power measurement unit and 5G based ICT to provide fine grained visibility and control of both MV and LV power networks using end to end automation in a virtualised environment.