European Metrology Network
Smart Electricity Grids

EURAMET

Strategic Research Agenda
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SMART ELECTRICITY GRIDS

Authorship and Imprint

This document was developed by the EURAMET e.V., European Metrology Network (EMN) for Smart Electricity Grids.

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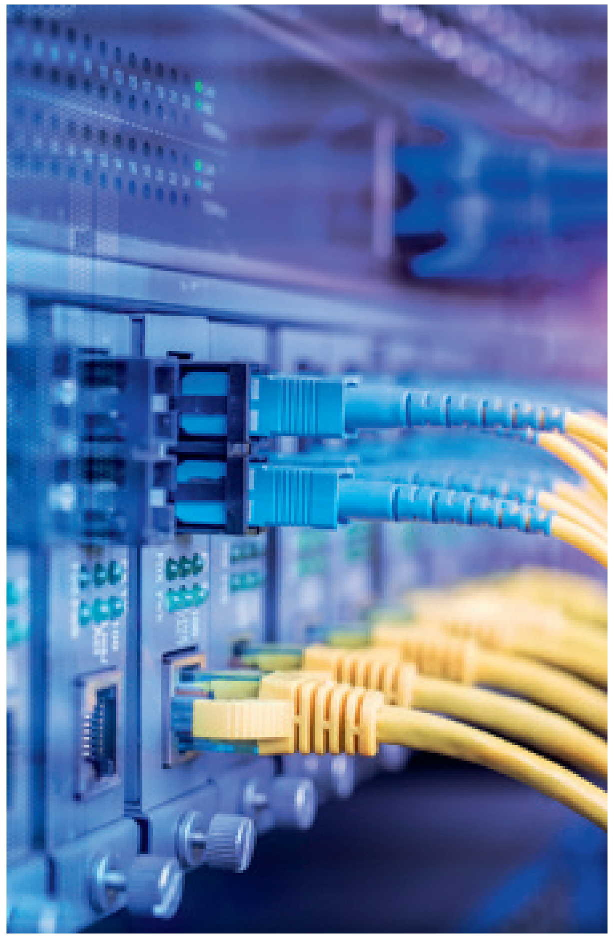
Further information
This is the first official version of the Strategic Research Agenda for EMN Smart Electricity Grids, which provides guidance towards industrial metrology needs and the technical challenges that need to be solved as a priority through collaborative efforts between National Metrology Institutes (NMIs), Designated Institutes (DIs) and stakeholders. This document will be revised every two to three years in accordance with arising needs and priority changes from the smart grid community.

For further information about this document, please contact your national contact person of the EURAMET European Metrology Network on Smart Electricity Grids (see https://www.euramet.org/smart-electricity-grids).



Chapter Images

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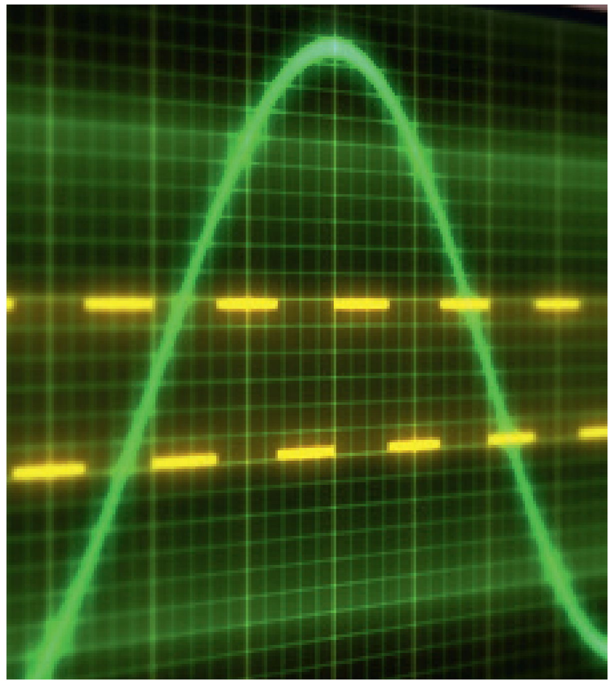
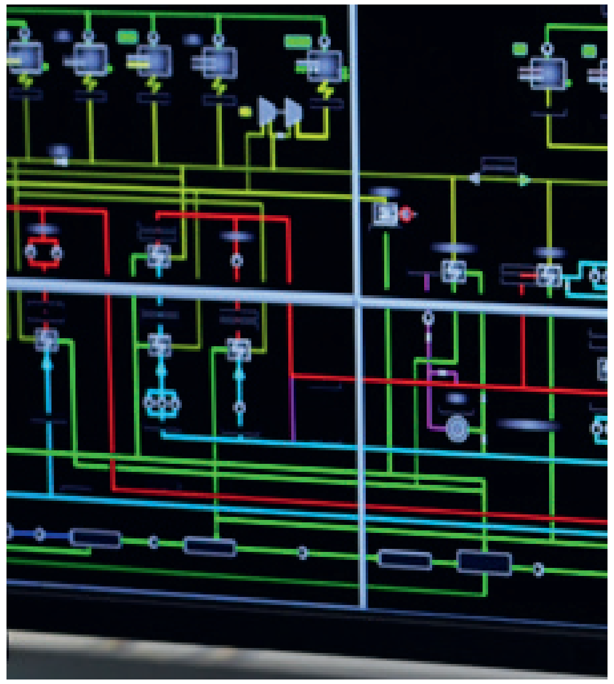




Management Summary

Recognising the strategic importance of the electric grid as the backbone of a secure, clean and efficient energy supply in Europe, the European Association of National Metrology Institutes established the European Metrology Network Smart Electricity Grid (EMN SEG) in 2019. The EMN SEG is a coordinated effort by European national metrology institutes to develop a sustainable structure providing close collaboration in measurement science and techniques in smart electricity grids. Accurate, reliable and traceable measurements are key to guarantee stability and flexibility of modern grids through monitoring and quality control in an increasingly volatile production and consumption environment.

This document is the first official edition of a Strategic Research Agenda (SRA) for the EMN SEG. It has been compiled following a broad consultation of representative stakeholders and specialists of the SEG community. Its purpose is to give an overview of the major metrological challenges faced by electricity grids in an era of major changes, driven by the need for a more sustainable energy supply. It presents a vision and ambition for Europe over the coming five to ten years for addressing needs expressed by stakeholders via further strengthening and coordinating a sustainable and effective research strategy at European level.

This SRA firstly introduces the rationale behind the institution of metrology networks and the specific case regarding smart electricity grids. Subsequently, nine themes identified as bearing particular relevance to smart electricity grids are explored in the core chapter, ranging from modern-day embodiments of revenue meters to digital substations, and emerging fields such as DC grids and efficiency. For each theme, outstanding measurement challenges are pinpointed and structured in implementation roadmaps.

- Revenue metering
- Power quality
- Digital substations
- Instrument transformers and sensors
- Grid monitoring and data analytics
- Efficiency
- High-voltage testing
- DC grids and application
- Grid integration

1. Introduction

1.1 Metrology in Europe

A quality infrastructure of a national or regional entity is often considered to consist of three pillars: metrology, standardisation, and conformity assessment. Metrology is the science of measurement, and is highly relevant to society, the economy, and science. It is based on common definitions of measurement units, their realisation in practice and their traceability to reference standards. Whilst science and metrology have nurtured each other, leading to great fundamental advancements, applied metrology has underpinned technological or industrial development and thus proved to be an essential pillar in the quality infrastructure of developed countries, besides standardisation and conformity assessment. Legal metrology is, as its name implies, the field linked to regulatory intervention of states in measurement affairs, wherever mandated by requirements for safeguarding the interests or protection of the citizen.

The ultimate goal of metrology is to underpin and foster confidence in measurements of all stakeholders, from the private party to the multinational corporation. Each country has therefore developed, to some degree of sophistication, a network of measurement institutions, laboratories or facilities, that sustain the metrological pillar of the national quality infrastructure. Governments usually delegate their competence in measurement matters to National Metrology Institutes (NMI).

EURAMET is the European Association of National Metrology Institutes [1]. Its mission is to develop and disseminate an integrated, cost effective, and internationally competitive measurement infrastructure for Europe, focused on meeting the needs of industry, business, and governments. Through its services, EURAMET supports its members in meeting their national requirements and establishes a balanced European measurement infrastructure. Enhancing the benefits of metrology to society is one of the highest priorities for EURAMET and its members.

1.2 R&D at EURAMET

To develop an integrated metrology system for Europe, EURAMET has always encouraged cooperation and knowledge transfer among its members and associates. EURAMET implements capacity building activities to improve the research and operational capabilities of its member institutes, coordinates and funds research projects to address grand challenges, whilst also supporting and developing the international system of measurement units.

The vision of EURAMET and its members is to ensure Europe has a world-leading metrology capability based on high-quality scientific research, and an effective and inclusive infrastructure that meets the rapidly advancing needs of end users. The EURAMET European Metrology Research Programme (EMRP, [2]) has enabled European metrology institutes, industrial organisations and academia to collaborate on joint research projects within specified fields includings industry, energy, environment, health, new technologies and fundamental metrology. The successor programmes, the European Metrology Programme for Innovation and Research (EMPIR) and the European Partnership on Metrology (EPM), continue to support measurement research projects in these fields [3-4].

1.3 R&D in smart grids

The European energy union strategy puts high priority on renewable energy, smart energy systems and energy efficiency in order to „build a low-carbon, climate resilient future" via „secure, clean and efficient energy" [5]. This strategy has a profound impact on electricity grids – the backbone of modern society. The upcoming low-carbon electricity generation is variable and often localised, stressing distributed networks and requiring additional capacity in transmission grids. The evolving energy demands and aims to incorporate renewables into Europe's energy mix necessitate a transformational change of Europe's electricity distribution and supply infrastructures. Consumers expect electricity supply to be reliable and secure, and their revenue meters to be accurate. Smart grids are a proposed solution to changing patterns of supply and demand, designed to be more flexible and responsive, and ensure reliable connectivity.
Grid stability and quality of supply are significantly affected by the massive uptake of renewable energy sources (RES) and grid energy losses need to be reduced in order to meet EU climate targets [6]. Many joint research projects under EURAMET administrated programmes since 1993 have so far provided crucial metrology and normative support to the development of smart electricity grids, with extensive stakeholder interaction and support [7]. These projects cover a large variety of topics: smart grid stability and quality, sensor networks, rate-of-change-of-frequency, power plants, HVDC transmission, ultra-high voltage and very fast transients, high-voltage testing with non-sinusoidal signals, non-conventional sensors, instrument transformers for non-sinusoidal signals, efficiency of solid state lighting, wind turbines, energy harvesting, hydrogen storage solutions, inductive charging of electric vehicles, losses in energy conversion, power transformer losses, electromagnetic interference on electricity meters, and supraharmonics emission limits.

To address specific needs expressed by international standard developing organisations, many of these projects have been developing metrological methods and techniques required for standardisation.

2. European Metrology Networks

2.1 Motivation

EURAMET's European Metrology Networks (EMNs) have been established as a new comprehensive, longer-term infrastructure, to analyse European and global metrology needs, and subsequently address these needs in a coordinated manner [8]. EMN members are to formulate common metrology strategies including aspects such as research, infrastructure, knowledge transfer and services. Members commit to contributing to the EMN, helping to establish sustainable structures that are strategically planned from the outset.

By providing a single point of contact for information, underpinning regulation and standardisation, promoting best practice, and providing easy access to project results, the EMNs aim to benefit stakeholders at large. This initiative yields creation and dissemination of knowledge, enhanced international leadership and recognition, and stronger collaboration across the measurement science community. Several EMNs have been established to date: Advanced Manufacturing, Climate and Ocean Observation, Energy Gases, Mathematics and Statistics, Quantum Technologies, Radiation Protection, Smart Electricity Grids, Smart Specialisation in Northern Europe, and Traceability in Laboratory Medicine [8].

2.2 EMN Smart Electricity Grids

Recognising that there is a significant need for a more coordinated approach on measurement issues related to the future of electricity grids, a European metrology network specifically dedicated to activities in this field was established. Hence there is now a specific entity named EMN SEG focussing on stakeholders' technological and strategic objectives in electricity grid metrology [9]. There are some overlapping interests with the EMN on Clean Energy, a new EMN that is currently under development that include, for instance, the interaction between renewable energy sources and the grid, power-to-X, electric vehicles, and novel energy storage concepts.

Five objectives have been formulated to accelerate the development of the EMN SEG activities:
1. To establish systems within the EMN to coordinate and align national R&D strategies.
2. To significantly enhance exploitation and uptake of research results.
3. To develop a plan for a joint sustainable European metrology infrastructure.
4. To create a widely visible identity as the voice of the European electricity grid metrology community and to establish liaisons with relevant European stakeholder organisations.
5. To set up an extensive knowledge transfer programme.

This document addresses the first objective. It is aimed at developing a European joint Strategic Research Agenda describing current and future metrology needs related to smart electricity grids, collected from stakeholders.

2.3 Involvement of stakeholders

The EMN SEG has developed its Strategic Research Agenda (SRA) in close cooperation with multiple stakeholders at national and European levels - including government and public institutions, utilities, Transmission and Distribution System Operators (TSOs, DSOs), industry associations or organisations (such as ENTSO-E, EDSO, EURELECTRIC and ESMIG), industries and manufacturers, standardisation organisations, and research centres. Stakeholder involvement through a series of consultations has not been limited to purely technical or scientific topics leading to SRA inputs, but also addresses socio-economic issues, collaborative knowledge build-up, and help to provide innovative solutions to ensure the usefulness and uptake of research.

2.4 Time frame of the SRA

The SRA has been compiled to cover a broad time span of five to ten years. It will be thoroughly reviewed every two to three years after its initial publication, in order to identify new research areas or fields of applications, and determine the extent to which the framework conditions have evolved.

3. Smart Electricity Grids

3.1 European Green Deal

On 11 December 2019, the European Commission unveiled its European Green Deal [10], a flagship initiative aiming for climate-neutrality by 2050. It outlines a long list of policy initiatives designed to put Europe on track to reach net-zero global warming emissions by 2050.

The transition to climate neutrality requires smart infrastructure. Increased cross-border and regional cooperation will help achieve the benefits of the transition towards clean energy at affordable prices. The regulatory framework for energy infrastructure will need to be regularly reviewed to ensure consistency with the climate neutrality objective. This framework should foster the deployment of innovative technologies and infrastructures, such as smart grids, hydrogen networks, carbon capture, energy storage, and enabling sector integration. Some existing infrastructure and assets will require upgrading to remain fit for purpose and climate resilient.

The Trans-European Networks - Energy (TEN-E) Regulation [11] is an EU law which aims to assist national governments and companies to better interconnect electricity and gas infrastructure across national borders. It sets out a new method for planning trans-European energy transmission infrastructure. It defines broad energy infrastructure priority corridors (e.g., north-south electricity interconnections) and thematic areas (e.g., smart grids) and is intended to help identify and implement the projects that are needed to improve these networks.

3.2 Electrical grid challenges

Electrical grids are an energy infrastructure that delivers electrical energy from producers to consumers. The electrical grid is a network comprising:
- generating plants: conventional – fossil-fired or nuclear, renewable – e.g., solar panels, wind turbines, geothermal, or both, hydroelectric.
- transmission and distribution grids: high-, medium- and low-voltage transmission lines and cables, AC and DC, power transformers, reactive power compensation schemes;
- energy delivery: neighbourhood substations, communication infrastructure;
- storage: dams, batteries, supercapacitors, power-to-X (power-to-gas), flywheels;
- consumers.

Due to new government initiatives, the European continent has been experiencing an ongoing development of its renewable energy sources (RES), alongside a corresponding increase of the RES share in the electrical energy mix. However, there are still key barriers present. Some of these are technical barriers with respect to energy storage capabilities, but there are also political ones with respect to reactions from the general public, for instance, public resistance against wind power stations in populated areas.

Modern grids are interconnected in a complex supranational mesh, optimised to meet the redundancy needed by each individual utility to guarantee reliable service. Interconnected grids are very complex systems that require high-level automation to ensure their stability in a highly-dynamic operating range.

The concept of smart grids uses information technology to adjust the electricity flow in real-time between suppliers and consumers. Renewable energy sources are highly volatile compared to traditional power plants. On a given grid scale, power flow can change direction owing to injection of renewable energy, something that had not been planned for in the traditional power-plant-to-consumer scheme.

With the steady introduction of new electronic equipment and a gradual switch from non-renewable non-electric to renewable electric energy, such as heat pumps and electrical vehicles, electrical energy consumption is steadily increasing. The resulting increased load on the grid has a deleterious effect on operational safety margins. Smart grids aim at mitigating such breakdown risks by means of improved monitoring and control, better management of the storage options and fine tuning of renewable sources. The advent of smart grid technologies comes at a very high investment cost and metrology can, in turn, contribute to mitigating these costs. Another challenge arises from the huge amount of data generated by smart grids, which may need to be stored and mined as well as kept confidential and private, protected from malevolent intrusions.

Modern electrical power grids therefore require real-time control and monitoring systems to ensure stability under increasingly complex conditions. The measurement and control systems must be managed through accurate and reliable time synchronisation, across wide areas. By collecting information on the state of the grid, it is possible to balance production, distribution and consumption. Smart grids aim at fostering and optimising:

- reliability, by improving efficiency and security of grids;
- flexibility, by striking a fine balance between production and consumption, using storage optimally;
- accessibility, by integrating renewable sources;
- consumption, by way of better management of the overall system and reduction of operational costs.

The concept of smart grids primarily concerns transmission and distribution networks, both nationally and internationally (pan-European). Smaller scale grid systems, operating to a certain degree on an autonomous level, interact with smart grids. For example:

- railways: trains, cars, catenaries, generation stations, interconnection to utilities;
- e-mobility: vehicles, private or public loading stations, storage, direct connection to renewable sources;
- from the smart house to the smart factory: prosumers interconnected to utilities;
- smart cities: group of smart houses and smart factories interconnected to each other and distribution grids;
- storage: networks with batteries, supercapacitors or novel storage concepts.

3.3 Grid measurement infrastructure

The reliable and cost-effective operation of electrical grids by utilities relies on a sophisticated measurement infrastructure developed and supplied by asset and equipment manufacturers.

Transmission and distribution system operators need to contribute to grid stability, safety and security while managing the interface to fellow actors relying on:

- current, voltage and frequency monitoring using instrument transformers,
- SCADA systems,
- monitoring the propagation of transient and disturbing phenomena,
- loss measurements,
- inter-utility and -operator metering and billing,
- fault management,
- asset management,
- community and corporate metering.

Low-voltage distribution networks need to address local issues such as:

- monitoring impedance, power flow, power quality,
- data communication,
- private and professional metering,
- efficiency of converters and inverters.

Furthermore, most European countries pose legal metrology requirements on electricity meters and instrument transformers. The advent of smart meters also comes with communication protocols for metered data and a wide range of measures regarding IT security.

4. Measurement Challenges in Electricity Grids

Various measurement methods and techniques have underpinned the implementation and continuous development of energy grids such as electricity grids. As factors like interconnection, interoperability, and power flow management have become increasingly complex, so have measurement methods aimed at ensuring reliability, flexibility, accessibility, and optimisation. The European Network of Transmission System Operators for Electricity (ENTSO-E), has identified 21 functional objectives in its Research & Innovation Roadmap 2017-2026 [12]. The achievement of these objectives requires making use of the appropriate relevant measurement tools:

Clusters	Functional Objectives	Comments
C2 Security and System Stability	T 5 Grid observability	Observability of the grid: PMUs, WAM, Sensors, DSO information exchange
	T 6 Grid controllability	Controllability of the grid: frequency and voltage stability, power quality, synthetic inertia
	T 7 Expert systems and tools	Decision support tools, automatic control and expert systems
C3 Power System Flexibility	T 11 Demand Response	Demand Response, tools to use DSR; Load profile, EV impact
	T 13 Flexible grid use	Flexible grid use: dynamic rating equipment, power electronic devices; use of interconnectors
C5 ICT & Digitalisation of Power System	T 18 Big data	Big data, data mining, data management
	T 20 Internet of Things	New communication technologies, Internet of Things
	T 21 Cybersecurity	Cybersecurity

Table 1: ENTSO-E objectives which can be supported by Metrology [12].

Based on knowledge collected through years of interaction between national metrology institutes and the industry and with the above objectives in mind, eight themes have been identified as bearing particular metrological relevance to smart grids. They are summarised in the following sub-chapters along with a ninth theme that is expected to become of increasing relevance in the coming years.

4.1 Revenue metering

Metering for billing purposes has always been crucial for fair trade and customer confidence. For many decades, conventional AC electricity meters have been based on the very reliable Ferraris concept, derived from a purely electro-mechanical transducer relating the metered electrical energy to counting the number of revolutions of a disc. Electronic meters use current sensors based on Rogowski coils, shunt resistors, Hall-effect magnetic sensors, or current transformers. As a result, they have no moving mechanical elements, but can rather be seen as an electronic board with sensors, a microprocessor, and an interface port.

Smart meters are electronic meters offering the possibility of recording detailed consumption and two-way communication between the meter and the measurement infrastructure, either by wireless link (mobile networks, radio) or physical link (Ethernet, fiber optic, power line carrier - PLC). They operate in conjunction with a gateway or a data concentrator on the other side of a two-way communication scheme and represent a network of IoT devices. In turn, this requires a high level of IT security to prevent malevolent coordinated intrusions from destabilising the grid control. This is subject to non-harmonised national legislation and, in many instances, remains underestimated.

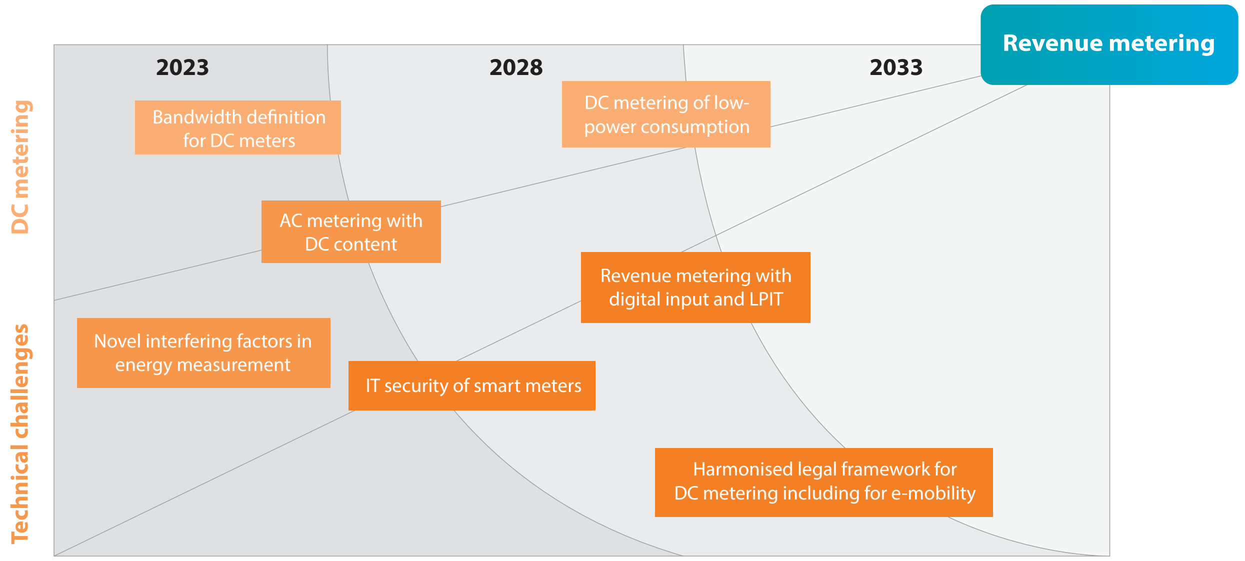
Recently, the current immunity requirements of the European Measuring Instruments Directive 2014/32/EU (MID) for electricity meters have been put into question. Electricity meters may be subject to much more electro-magnetic interference today, resulting from the use of solar panels and other renewable energy sources, amongst other things. Some electronic meters have shown vulnerability to these under specific circumstances. Research is underway to understand the (non-)immunity of several types of meters to these interferences, and to support the revision of European and international standards for electromagnetic compatibility.

Interest in DC active electrical energy metering is developing fast owing to solar PV energy generation, fuel cells, electric energy storage, transport systems, electric vehicles, and DC power distribution in IT networks and data centres. A key challenge will be the development of the required DC power metrology infrastructure and metrologically sound, harmonised legislative frameworks – possibly following similar principles as for AC active energy meters.

4.1.1 Measurement challenges - Revenue metering

- Development of a DC power metrology infrastructure, including a harmonised legal framework for DC active electrical energy metering
- Novel interfering factors in energy measurement, for instance related to dimmers, LEDs, etc.
- Revenue metering with digital measurements and low-power instrument transformers
- Metering of AC electricity in the presence of DC components
- DC metering of low energy consumption in the presence of DC offsets
- Definition of bandwidth in the case of DC energy meters
- Addressing IT security of smart meters

4.1.2 Implementation roadmap - Revenue metering



4.2 Power quality

Issues with the quality of electric supplies have been known since the beginning of electrification. The advent of power electronics, and more recently of inverters in connection with the multiplication of renewable energy sources, have led to an increase of non-linear loads and sources connected to the distribution grids. This produces harmonics of the 50 Hz sine waveform and, together with a wide range of other disturbances, can pose a risk to the safe operation of grids by stressing equipment connected to it. Hence, power quality (PQ) is sometimes referred to as the set of limits of electrical properties that aims at ensuring that electrical systems function in their intended manner without significant loss of performance or breakdown. Monitoring both the current and voltage contribution to power quality allows for the prevention of outages and damages, and for the analysis of issues in retrospect. The European standard EN 50160 specifies power quality in low- and medium-voltage grids, whereas the IEC standards IEC 61000-4-30, -4-7 and -4-15 define power quality quantities and methods.

Traditionally, power quality is analogue to electromagnetic compatibility but limited to 9 kHz. Disturbances of significant levels have been observed up to 500 kHz: supraharmonics up to 150 kHz and effects owing to narrow-band power line communication (PLC) up to 500 kHz. The low-voltage grid impedance is influenced by the impedance of devices or equipment connected to it, and as such is frequency dependent. This varying impedance has an impact on the grid stability, but also on the reliability of PLC signals, for instance, due to transmission losses. Even today, experimental instruments and methods that can precisely measure the line impedance are limited. Furthermore, various proposed methods tend to yield incompatible results. Consequently, there is a need to establish a metrological traceable grid impedance standard in order to compare different measurement techniques and open the road towards standardisation.

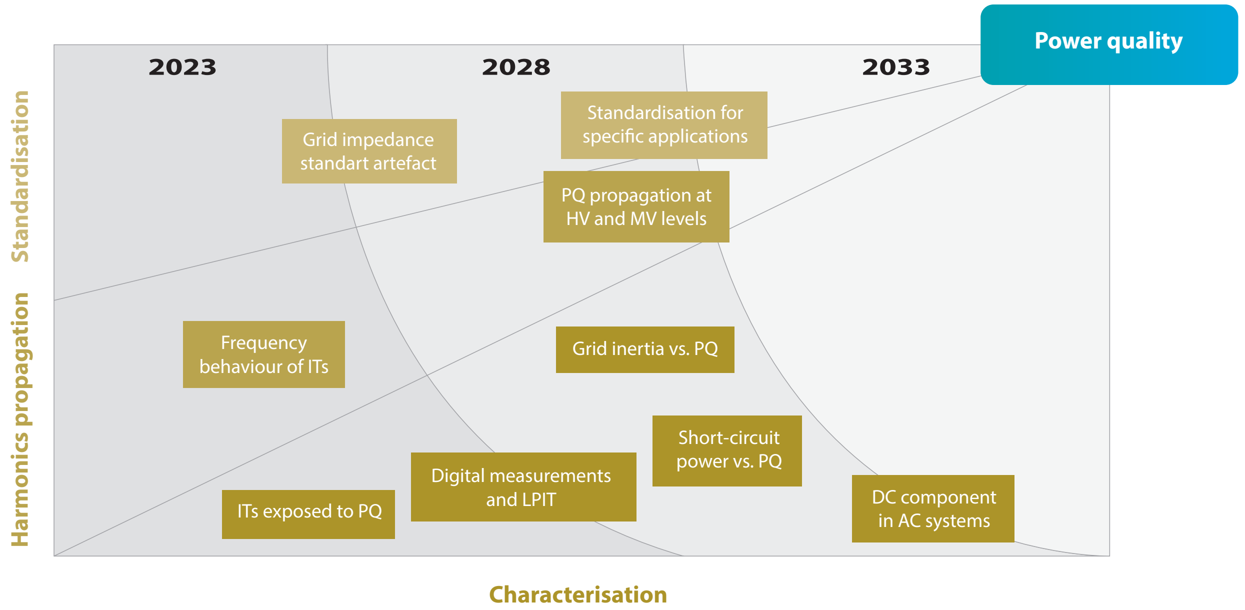
Some of the harmonic content of the power waveform is transferred to different voltage levels through power transformers. Instrument transformers that monitor current and voltage at power stations are designed for a nominal operation at 50 Hz and generally have an unknown frequency characteristic. It is assumed that some of the harmonics are transferred to the next voltage level, but this cannot be traced due to the inadequacy of instrument transformers. As these harmonics are not accounted for, they lead to uncontrolled parasitic power losses and a risk of premature aging of some sensitive components with limits designed for 50 Hz nominal operation. Typical components affected by harmonic energy content are transformers and shunt reactors, but this issue affects asset management more generally. Understanding propagation of harmonics is an important challenge to overcome when preventing detrimental effects. It requires the characterisation of the frequency transfer function of instrument transformers (see § 4.4).

Grids which are weakly coupled to the main grid infrastructure, e.g., in railway infrastructure, large ships, or electric vehicle charging stations, sometimes operate at different frequencies (DC, 16.7 Hz) with compatibility requirements at interconnection or border nodes. In railway grids, transients and inrush currents need to be monitored closely in order to maintain voltage regulation, inverters produce high levels of harmonic distortion and meters need to be able to handle various frequency systems. So far, neither commercial power quality analysers nor standards comparable to IEC 61000-4-30 have been developed for these specific applications.

4.2.1 Measurement challenges - Power quality

- Investigate the relation between RES-driven decrease of grid inertia and power quality
- Investigate the relation between RES-driven decrease of short circuit power and power quality
- Standardisation comparable to IEC 61000-4-30 for specific applications such as DC networks, railway infrastructure, and large ships
- Definition of a metrologically traceable grid impedance standard artefact and measurement method
- Measurement of propagation of PQ phenomena and events at HV and MV level and between voltage levels
- Development of characterisation methods for instrument transformer exposed to power quality phenomena
- Characterisation of the frequency behaviour of instrument transformers with investigation of propagation patterns of harmonics and other high frequency components
- Determination of the DC component in AC systems
- Power quality with digital measurements and low-power instrument transformers

4.2.2 Implementation roadmap - Power quality



4.3 Digital substations

Future electrical power grids will require real-time control and monitoring systems to meet increasingly complex and challenging conditions. Digital instrumentation will slowly substitute conventional analogue instrumentation. New standards in the IEC 61869 series address the digital communication of electronic instrument transformers, as well as stand-alone merging units (SAMU) and digitisers for analogue instrument transformers. Following the introduction of these new standards, the transition from traditional analogue instrumentation towards the new digital instrumentation technology is expected to gain speed, both on a transmission and distribution level. To support this change, new metrological tools and methodologies are needed as test systems for this new technology. They will also be required as test systems for the performance of intelligent electronic devices like digital energy meters or real-time critical all-digital PMUs, both for AC and DC.

To ensure synchronicity between digitally-equipped substations, accurate, secure and reliable time synchronisation over a wide area is necessary. This can usually be achieved by using Global Navigation Satellite Systems (GNSS). However, in mission-critical substations, satellite-independent time dissemination and synchronisation, based on Precision Time Protocol (PTP) or White Rabbit methods, are required to provide reliability of timekeeping.

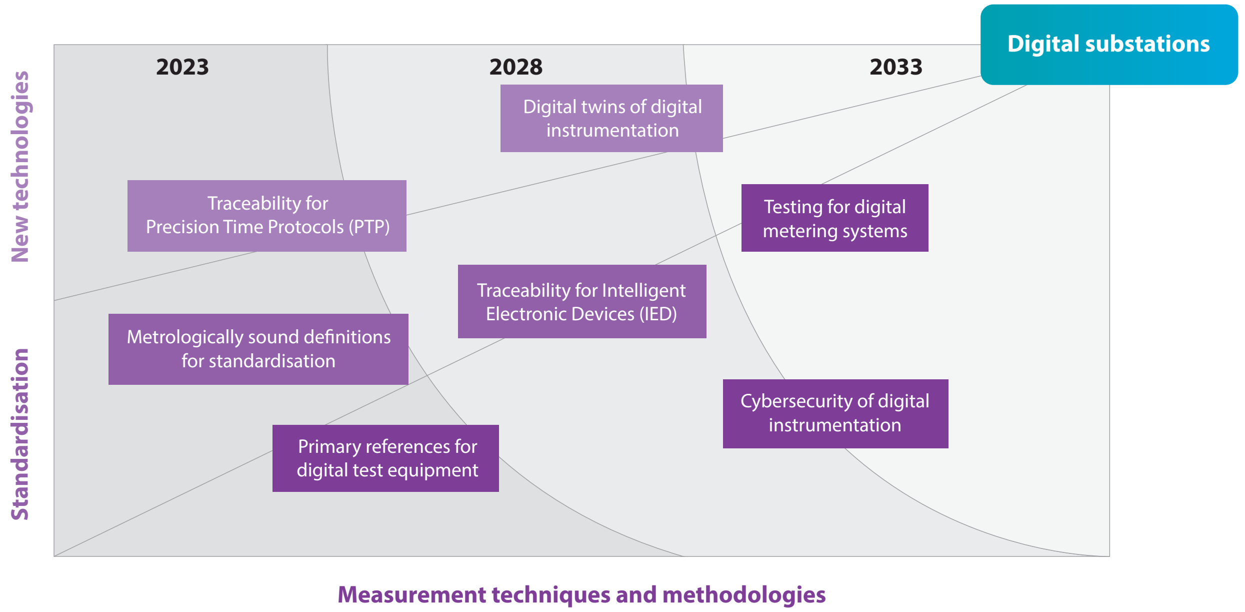
More precise synchronisation is needed within substations for SAMU timing. Providing traceable linking of timing of PTP and Pulse Per Second (PPS) signals is a challenge, as is providing the precise timing of SAMU sampling using the PTP protocol.
The deployment of digital instrumentation, along with the large-scale roll-out of smart meters, gateways and data concentrators (see § 4.1), is already ongoing in several European countries and requires enhanced cybersecurity requirements. Furthermore, these systems generate a wealth of unused data that might be useful for other applications, part of which is yet unknown.

Full understanding of digital substations with their new digital instrumentation, both at the system level and at the subsystem level, requires digital twins of these new components. Validation of these digital twins needs to be confirmed with real measurements.

4.3.1 Measurement challenges - Digital substations

- Investigation of PTP or White Rabbit methods for accurate time-stamping of data in digital substations
- Development and validation of digital twins of digital instrumentation
- Metrologically sound definitions for standardisation
- New metrological tools and calibration methodologies for intelligent electronic devices (electronic instrument transformers, SAMU, all-digital meters and PMUs)
- Testing methodology for complete metering arrangement in digital substations
- Primary references for digital test equipment
- Addressing cybersecurity of digital instrumentation at the proper level

4.3.2 Implementation roadmap - Digital substations



4.4 Instrument transformers and sensors

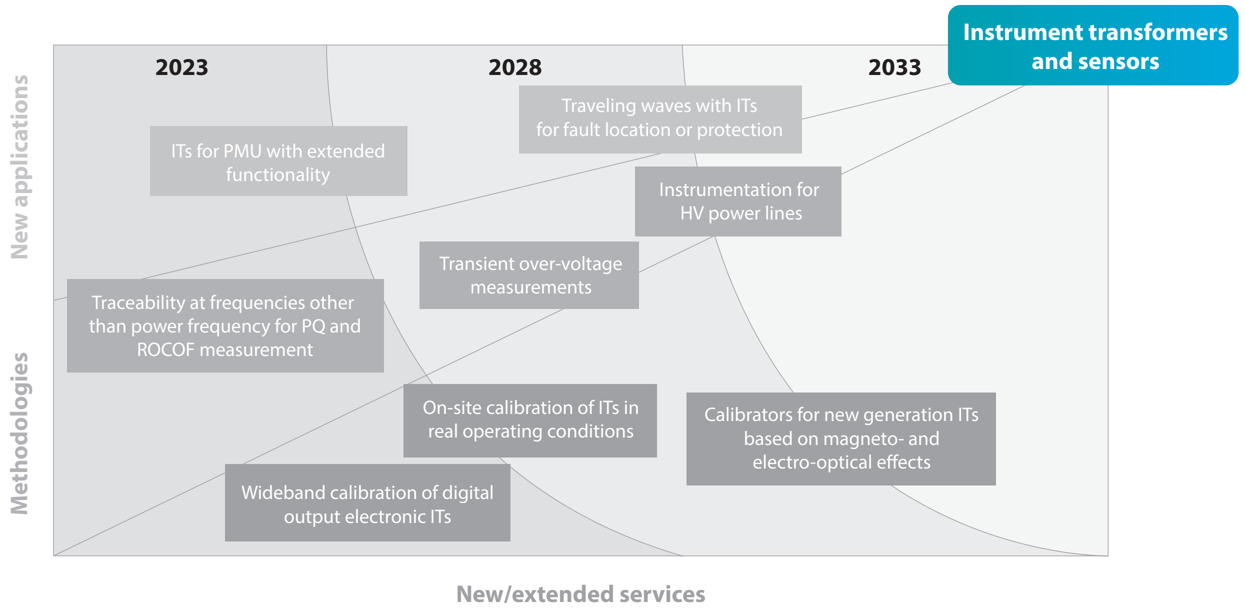
The safe operation and regulation of electrical grids requires a large number of grid sensors to monitor voltage and current at key grid nodes. High voltage and current are sensed through instrument transformers, high-accuracy electrical devices, which scale the grid voltage and current to fit the input levels of measuring instruments and secondary control circuitry - with the additional advantage of ensuring their galvanic isolation. The primary winding of the transformer is connected to the high-voltage or high-current circuit, and the measuring instrument is connected to the secondary circuit. Most instrument transformers are inductive, wire-wound transformers using an electromagnetic principle, but capacitive voltage transformers use a capacitor potential divider for operation at higher voltages.

Traditionally, traceability for instrument transformers is established for pure sine waves and at 50 Hz only. The presence of harmonics can impact the measurement accuracy of an instrument transformer, but this effect is not taken into account by the traditional calibration carried out at power frequency only. The limited measurement bandwidth and the lack of traceability for frequencies other than 50 Hz limits the possibility to analysing harmonic signals and interferences (power quality, see § 4.2). The limited bandwidth also impacts the possibility to measure transient over-voltages. Instrument transformers could also be used in association with the injection of traveling waves for fault location or protection or in conjunction with PMUs. Other wideband low-power-output passive or electronic instrument transformers, which operate on different principles such as Rogowski coils and dividers, are now commercially available. Instrument transformers based on magneto-optical or electro-optical effects of an optical fibre offer significant advantages over inductive and capacitor instrument transformers. Their bandwidth is much larger and their size is considerably smaller. Since the optical fibre is an electrical insulator, they are inherently decoupled from the power lines and almost immune to electromagnetic interference. They could support the instrumentation of high-voltage power lines for the application of dynamic line rating, monitoring, and modelling. Electronic instrument transformers permit the recording of a large number of dynamic parameters and they are usually fitted with digital outputs compliant with IEC 61850 and other standards, making them compatible with digital substations (see § 4.3). However, the metrology infrastructure for calibration and evaluation of (optical) electronic instrument transformers is currently incomplete.

4.4.1 Measurement challenges - Instrument transformers and sensors

- Extension of traceability at frequencies other than power frequency with characterisation of the frequency response for PQ monitoring and inertia (ROCOF) measurement
- On-site calibration of instrument transformers under real operating conditions for metering and monitoring purposes
- Assessment of instrument transformer accuracy performance in transient over-voltage measurements
- Application of instrument transformers in fault location and protection by injection of traveling waves
- Application of instrument transformers to measurements performed by PMUs with extended functionality
- Development of calibrators for new generation instrument transformers based on magneto-optical or electro-optical effects
- Qualified improved instrumentation for high-voltage transmission and distribution power lines
- Wideband calibration of electronic instrument transformers and low power instrument transformers with digital output

4.4.2 Implementation roadmap - Instrument transformers and sensors



4.5 Grid monitoring and data analytics

4.5.1 Monitoring of transmission grids

The stability of the grid requires sophisticated interconnected control loops for steady-state and dynamic system monitoring. Monitoring the parameters such as frequency, voltage, and phase is therefore key in avoiding shutdowns – e.g., if production exceeds consumption, the frequency increases, and vice versa. A fine balance must thus be struck for active power, in order for the frequency to remain constant, and having sufficient system inertia greatly helps to maintain this balance. The reactive power must be similarly well balanced to keep the operating voltage constant, which is referred to as the 'system strength' or 'short-circuit capacity'. Measuring the system inertia and the short-circuit capacity are both complicated tasks. The first commercial instruments have been developed and brought to market for monitoring these two parameters, but the reliability of these measurements is far from clear.

Grid control relies on a Supervisory Control And Data Acquisition (SCADA) system which measures power and voltage at key locations of the grid. Thanks to this infrastructure, energy flow in all parts of the grid can be monitored. The deployment of GNSS made it possible to achieve high synchronisation of the measurements. Phasor Measurement Units (PMU) enable an accurate measurement of voltage and current amplitude, phase difference at different nodes relative to UTC (Universal Time Coordinated), frequency, and rate of change of frequency (ROCOF). PMUs yield better state estimations with the possibility to observe long-distance oscillations with high refresh rates (up to 50 times per second compared to once every 15 minutes for SCADA). PMUs can be used to provide more information on a denser time scale, such as ROCOF, grid inertia from frequency and ROCOF, synthetic inertia, detection of sub-synchronous oscillations, fault location identification, dynamic thermal rating of overhead lines and cables, and remote instrument transformer calibration. PMUs have been deployed widely across North America, following spectacular grid blackouts [13], and now are becoming more generally introduced in the European transmission grid as well. However, verifying their measurement accuracy under all actual grid conditions is a challenging task.

4.5.2 Monitoring of distribution grids

The advent of renewable energy sources increases the variability and information density of distribution grids. One of the motivations of the large-scale deployment of smart meters is to provide fine geographical and time-resolved grid information to the utilities. This explosion in available data requires big data analytics in order to convert data to actionable information. Sensors are used to measure network current, voltage and frequency, with this data aggregated to form a view of the overall network state. However, distributed generation will need distributed sensor deployments. Methods for optimising sensor placement, the use of phasor measurement units (PMUs), and state estimation using aggregated smart meter data are just a few examples that could improve network management beyond the present SCADA systems. As an example, a 50 kV distribution network in the south-west part of the Netherlands provided data for comparing state estimation algorithms

applied to PMU data with SCADA data. The grid was equipped with a SCADA system already, whereas PMUs were installed as additional monitoring devices. To what degree and to which scale the granularity of PMU installation is useful in distribution grids is the subject of further research. For shorter monitored scales, observing amplitude and phase differences between different locations requires improved voltage and current accuracy as well as a higher degree of synchronisation.

Reduced grid inertia, caused by the increased integration of grid-following renewable energy sources, requires faster responses to system instabilities. The related shorter time constants and time scales in grid control demand higher reporting rates. Dynamic phasors might not be adequate to determine the varying low inertia in the presence of disturbances such as phase steps, frequency steps, phase modulations, and so other techniques - like Hilbert Transforms - need to be investigated. Potentially, other parameters might also be necessary to guarantee system stability, such as power stability rather than inertia.

4.5.3 Secure timing

Conventional power grids, typically equipped with centralised SCADA systems, receive state information from many substations only once every few seconds. Obviously, accurate timing for such measurements is not very crucial. However, future electrical grids will require real-time capable control and monitoring systems on a substation level for example exploiting PMUs to ensure stability under increasingly complex and challenging conditions. These PMUs and other digital measurement systems such as digital high-voltage sensors, stand-alone merging units, digital metering systems and digital intelligent electrical devices (IEDs) must be managed through accurate, secure and reliable time synchronisation across a wide area, both within and between substations. This has been achieved using GNSS where state-of-the-art IT security technologies, supported by independent back-up systems based on other technologies like PTP and white rabbit (see § 4.3), are necessary to protect against jamming and spoofing.

4.5.4 Modelling and data analytics

Measurement equipment deployed by grid operators provide significant potential for the real-time monitoring of abnormal grid dynamics and post-mortem fault analysis. This results in very significant data volumes, especially for high monitoring rates up to 50 readings/s. For grid improvement and maintenance to avoid repetition of issues, there is a need for appropriate visualisation and big data analytics to convert data into actionable information.

Network operators are interested in the detection of abnormal events in response to faults or changes to system dynamics. Data analytics techniques can be used to detect anomalies and atypical behaviour in power system operation and facilitate new alarm metrics for control room staff and protection systems. An example of grid instability is the build-up of oscillations in power systems due to the increasing difficulty of convertors locking onto a stable grid frequency and their intrinsic sensitivity to abnormal events. Hence, the need for early warning indicators based on fast data analytics. Another example is the change in grid inertia due to the relative increase of distributed generation with respect to traditional generation. Measurement and control of grid inertia is one of the most important issues facing system operators in future energy scenarios.

Measurement data from different origins, such as PMUs or other monitoring devices and even the sophisticated use of smart meter data, could therefore also be used to dynamically manage power flow in networks. As high levels of renewable energy sources and electrical vehicles are installed, parts of the grid are overloaded for short periods of supply and demand. Investing in the development of data analytics to manage power flow and rating management and consumption could result in lower investments in hardware related to rating over-dimensioning or substation reinforcement, and consequently enhance penetration of renewable energy sources.

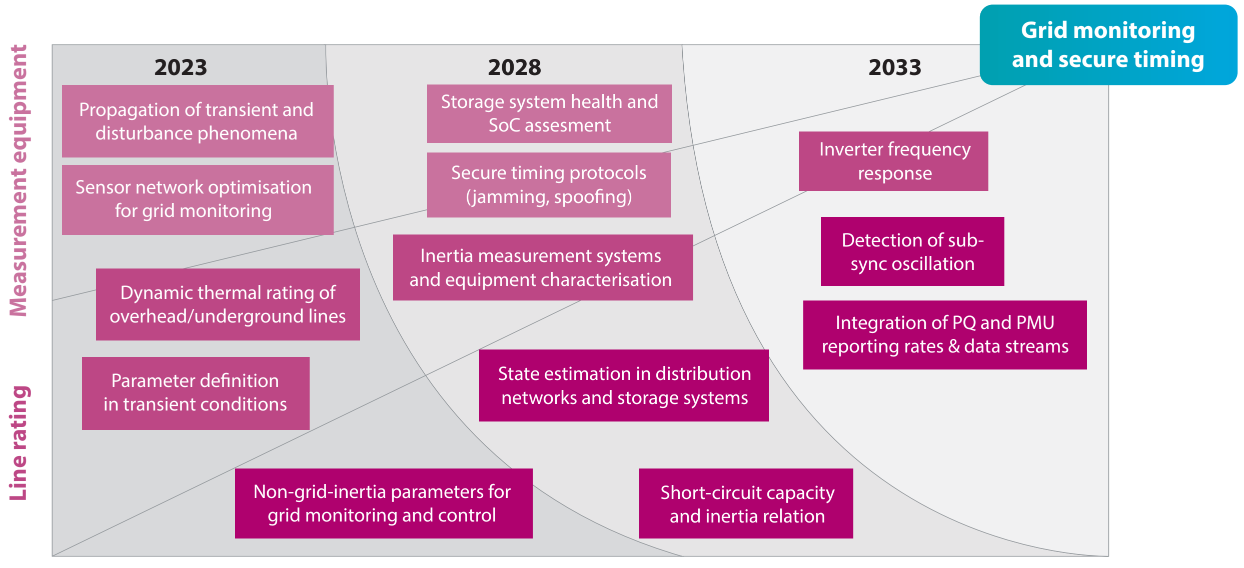
Modelling, for instance of virtual power plants for prediction before integration in a smart grid, plays an increasing role in planning phases. Measurement data can be used to validate or improve the models predicting the influence of installation on grid stability and power quality.

Conventional grid models typically assume a constant frequency for the whole network, whereas PMU measurements indicate that the frequency differs from place to place. Furthermore, the integration of new grid monitoring equipment with higher reporting rates will require models that can deal with different reporting rates. Measurement data is crucial to validate or improve new grid models, with respect to local frequency deviations as well as varied reporting rates.

4.5.5 Measurement challenges - Grid monitoring and secure timing

- Monitoring the propagation of transient and disturbance phenomena
- Novel definition of parameters in transient conditions
- Definition of grid inertia measurement from power, frequency and ROCOF including characterisation of dedicated equipment
- Investigate parameters other than grid inertia to monitor and control the grid
- Investigate the relation between short-circuit capacity and grid inertia including characterisation of dedicated equipment
- Characterisation of the frequency response of power inverters
- Detection of sub-synchronous oscillation
- Secure timing protocols protecting against jamming and spoofing
- Optimisation of sensor networks for grid monitoring
- Development of state estimation in distribution grids and storage systems
- Dynamic thermal rating of overhead lines and underground cables
- Integration of PQ and PMU reporting rates and data stream
- Assessing health and state of charge of storage systems

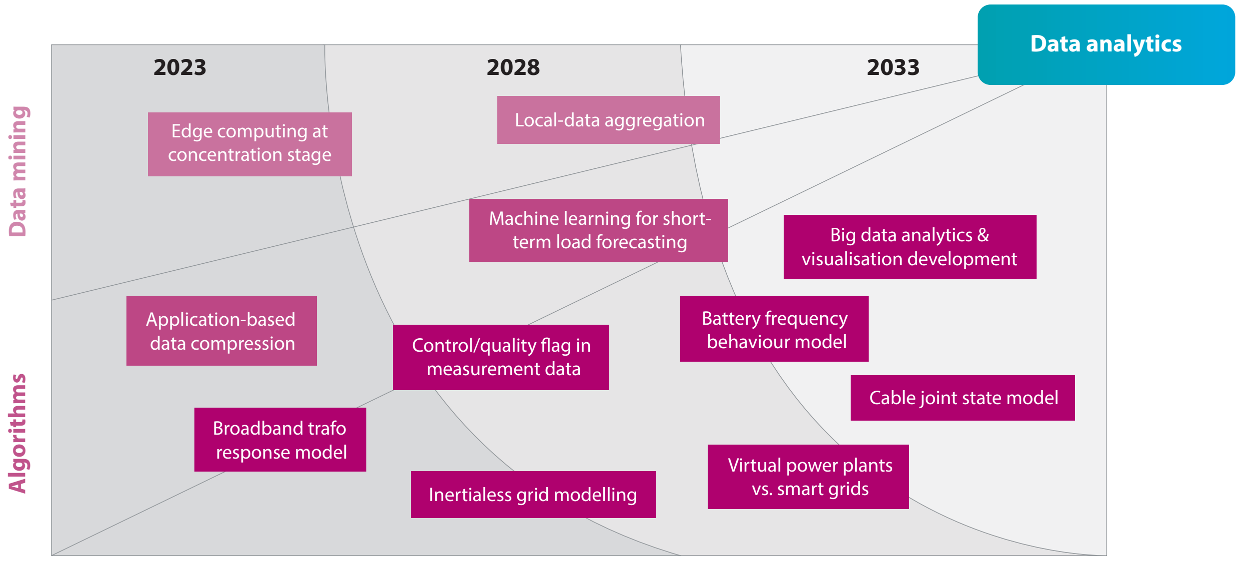
4.5.7 Implementation roadmap - Grid monitoring and secure timing



4.5.6 Measurement challenges - Data analytics

- Development of big data analytics and visualisation platforms with adequate evaluation of measurement uncertainty
- Local aggregation of measurement data streams coming from different sources and instruments
- Application-based data compression
- Edge-computing applications to be carried out at a preliminary aggregation level (e.g., at substation level, before being sent to control room)
- Development of machine learning algorithms for short-term load forecasting
- Validation of new grid models characterised by reduced inertia
- Modelling of virtual power plants interacting with smart grids
- Definition of suitable control and quality flags for measurement data streams to be aggregated
- Modelling of the broadband response of instrument transformer
- Definition of a model of the frequency response of energy storage systems and batteries
- Development of reference model for cable joints and possible faulty conditions for a prompt fault detection and location

4.5.8 Implementation roadmap - Data analytics



4.6 Efficiency

Much expectation has been placed in smart grids for achieving higher efficiency of all major current and future equipment, for the most part by enabling better power management of energy utilities and consumers and secondly by development of more efficient grid components. The latter so-called 'technical energy losses' are due to energy dissipated in transmission and distribution lines, transformers, converters and inverters, and are either permanent or variable, i.e., varying with the amount of electricity distributed.

Characterisation methods for wasted energy and energy efficiency of converters (rectifiers and inverters) still need development. Evaluation of efficiency has two major aspects. First, total input power versus useful power, the difference being the loss is best measured at fundamental frequency only. Second, during product development, identifying exactly where losses occur, which necessitates accurate wide-band measurement of active power instead of relying only on simulations. This can be exemplified by the case of an HVDC substation. The AC grid will supply AC power at fundamental frequency. The HVDC converter inevitably creates harmonics in its operation. If not completely filtered, these harmonics will be injected back into the AC grid causing power loss in the grid. Measuring converter input AC power with a wide-band measuring system will then measure the power of the fundamental drawn from the grid minus the power of the harmonics re-injected into the grid, causing losses elsewhere and leading to an optimistic figure on efficiency.

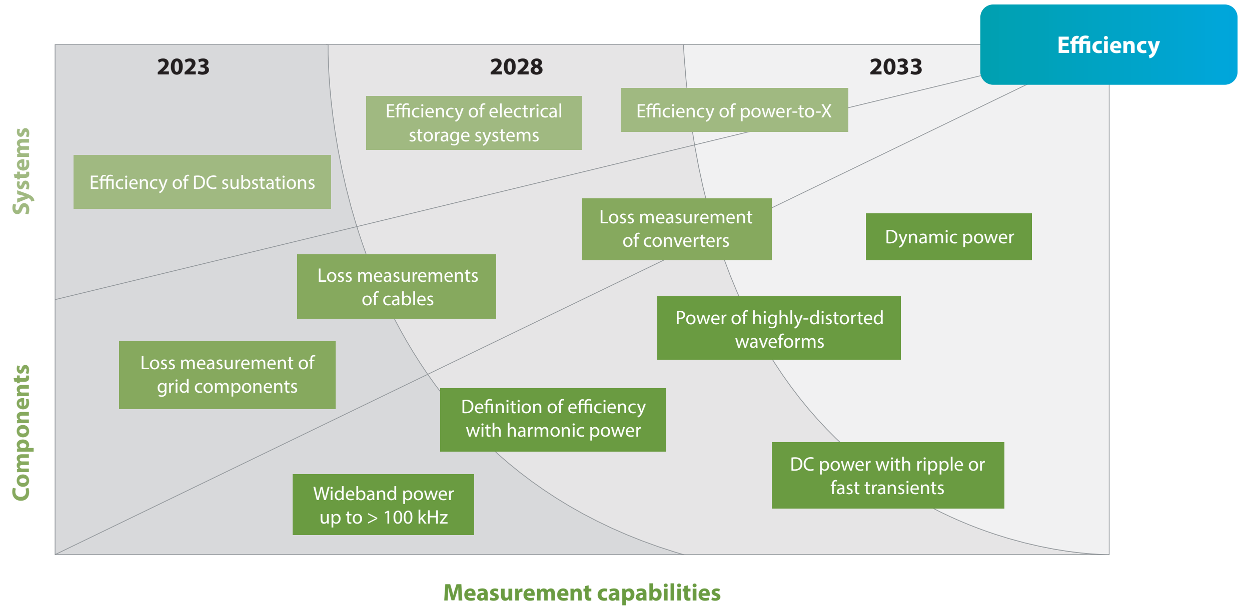
Evaluation of converter efficiency requires accurate measurement of power in a wide frequency range in presence of highly distorted voltage and current waveforms. These characterisation methods must account for the specific final application and actual working conditions, including non-stationary situations. The complexity of the required measurements, combined with the lack of comprehensive standards or metrological traceability offered by the NMIs, result in declared efficiency values that are neither traceable nor obtained by standardised procedures for accuracy evaluation.

Storage systems have been the preferred approach for mitigating demand vs. supply with increasing shares of renewable energy in the distribution network. Electric vehicle fleets can potentially serve the electrical grid as an independent distributed energy source, by delivering the energy stored in their batteries according to the concept of vehicle to grid (V2G). In both cases, evaluating the efficiency of the storage system involves measurement of DC and AC power under highly dynamic and distorted conditions.

4.6.1 Measurement challenges - Efficiency

- Wideband power references up to above 100 kHz
- Traceable power of highly distorted waveforms
- Wideband power under dynamic grid conditions
- Measurement of DC power in the presence of high frequency ripple and/or fast transient events
- Measurement systems for loss measurement in transformers, reactors, capacitors as HV grid components
- Loss measurement of converters and inverters and their components
- Loss measurement of cables
- Efficiency of DC substations and converters
- Efficiency of electrical storage systems
- Efficiency of power-to-X
- Efficiency definition in presence of harmonic power

4.6.2 Implementation roadmap - Efficiency



4.7 High-voltage testing

4.7.1 Ultra-HV systems

In the production of equipment for high-voltage grids, dielectric testing is performed to verify that the equipment can withstand the operational environment, including high voltage and high current impulses. Methods and schemes for traceable calibration are defined in IEC 60060-2 for high voltage and in IEC 62475 for high current. However, system voltages are currently increasing to levels higher than those covered by this standard, and there is a need to extend the traceability of the test methods into the ultra-high voltage range above 800 kV.

The expansion of UHV grids, now operating at 1100 kV system voltage for DC and 1200 kV for AC, requires testing with voltages up to 2000 kV and traceability of DC and AC signals are now established up to 1600 kV. For switching and lightning impulse measurements, the impact on measurements due to proximity effects, corona, front oscillations, divider topology and measuring cables has been studied and will be collected in a good practice guide. The highest test voltages surpass 2500 kV for lightning impulse testing, 4000 kV for extreme cases, and the traceability is typically available up to 800 kV on site and up to 2000 kV at NMI laboratories. New methods need to be developed to linearly extend traceability to the highest voltage in testing facilities. Large measurement systems are strongly affected by corona and proximity effects, and generally methods to handle wave shape distortions, like front oscillations and losses in measurement cables, need a revision. Providing traceability for these measurements is especially challenging in the case of impulse voltages above megavolt level. Traceability is also required for voltage dividers and measuring systems for composite and combined voltage tests. During these tests, a high impulse voltage is applied to the test object in addition to continuous high AC or DC voltage.

For verification of high-voltage DC systems, there is an increased need for traceable partial discharge (PD) measurements. Whilst PD measurements for AC grids is a well-developed area, the reliable measurement and categorisation of PD for high-voltage DC grids is a relatively new area that requires further metrological research and development of traceable reference instrumentation and measurement methods.

4.7.2 HV transformers and reactors

Loss measurements on large transformers and reactors are performed using complex measuring systems that rely on extremely precise voltage and current transducers connected to advanced power meters. For large power transformers it is necessary for manufacturers to measure the active power with an uncertainty of better than 3 % at a power factor that may be 0.01, which leads to an accuracy requirement of 0.03 % of the apparent power. Therefore, the calibration of such measuring systems at the manufacturer's site should be done with a level of accuracy that is improved by at least a factor of 3. Individual component calibration is only partly suitable for the calibration of such systems and so new calibration facilities are required that provide a system calibration service for this purpose with sufficient accuracy (i.e., uncertainty smaller than 0.01 % in ratio or 100 µrad in phase).

Transformer and reactor loss calibrations are presently performed under sinusoidal conditions, but the actual grid conditions suffer from an increasing number of harmonics (see § 4.2). New metrology is needed to traceably quantify the impact of these harmonics on the losses of transformers, reactors and other grid components.

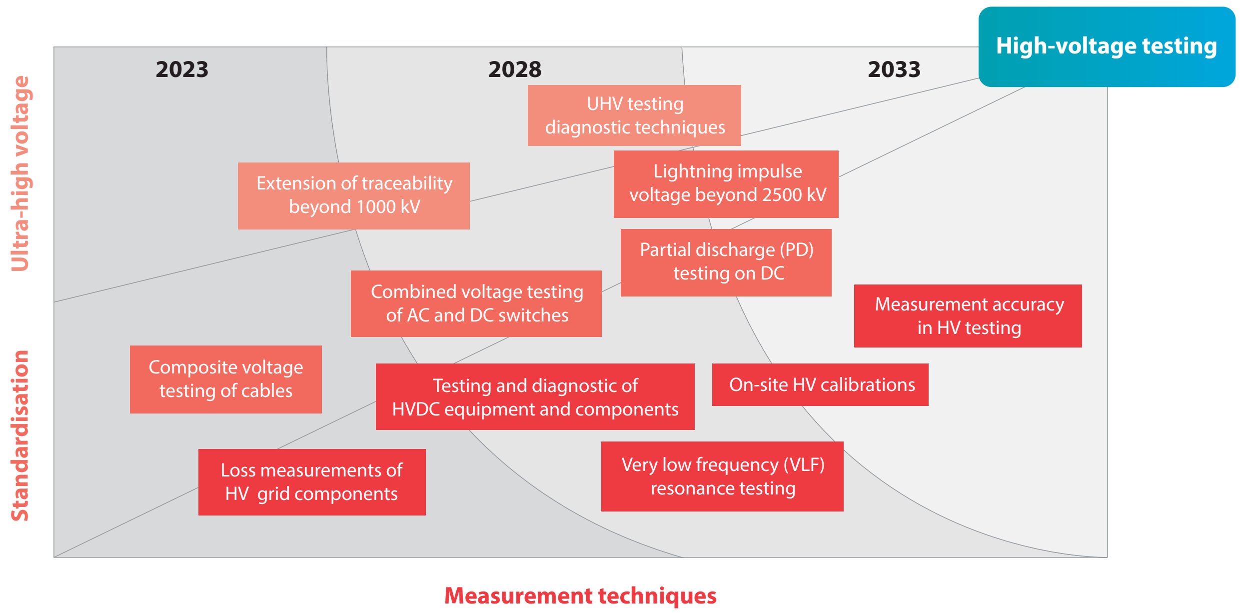
4.7.3 HV components

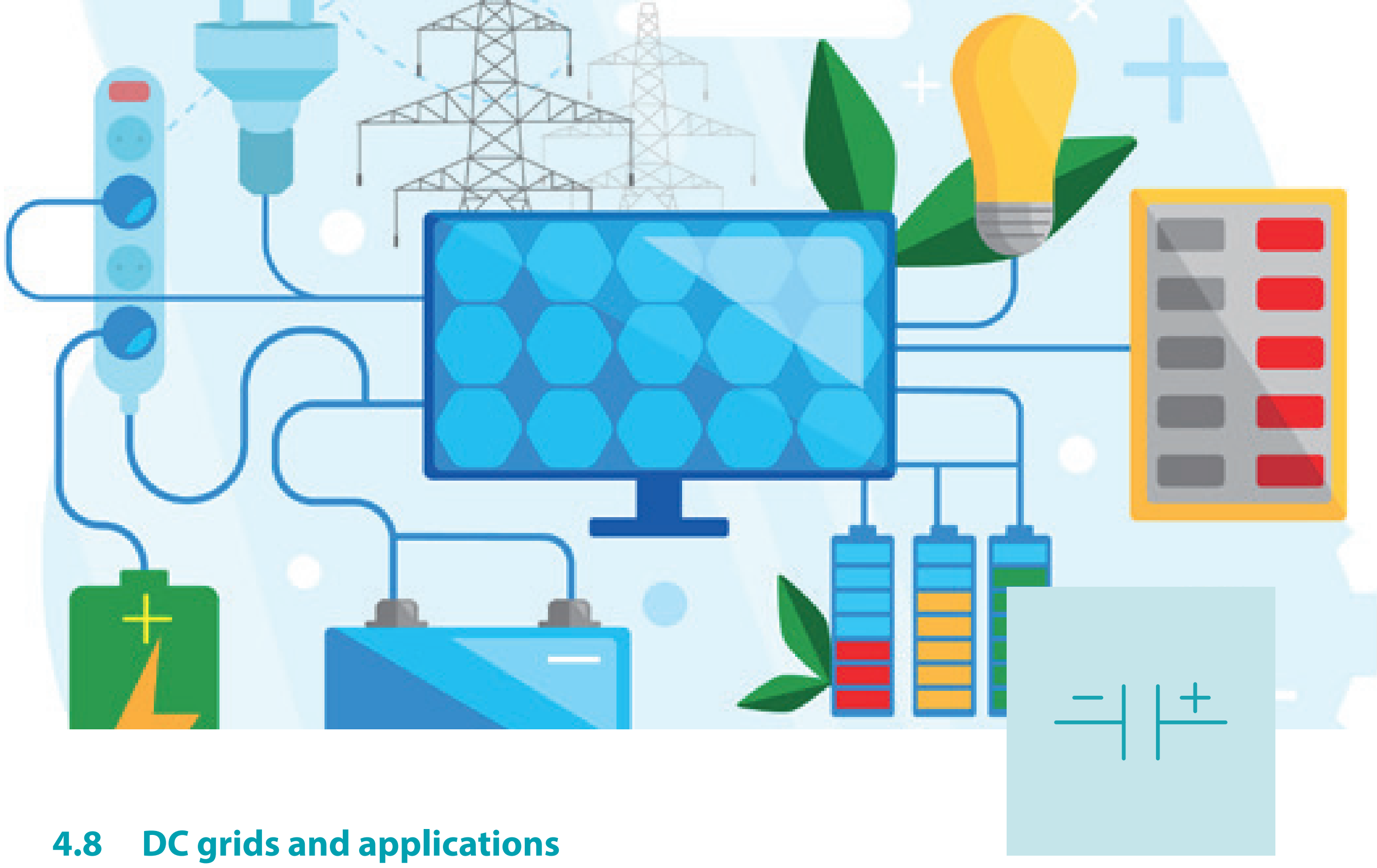
High-voltage components such as cables, insulators, instrument transformers, capacitors, surge arresters or switchgears require thorough testing, which typically includes, in addition to measurement of withstand voltage, the measurement of loss factor, insulation resistance, partial discharge, and life-time assessment of power electronics. Non-destructive testing methods are also required for commissioning or preventive maintenance of large equipment used in installations such as power transformers, overhead lines and cables (e.g., new wave shapes for DC cable testing), high-voltage substations or HVDC converter stations. This can involve superimposition of DC signals, high-frequency harmonics, switching patterns in power electronics, new wave shapes for DC cable testing. On-site testing brings about significant logistical and technical challenges with complex interconnection schemes. For instance, high-capacitive test objects such as power cables, generators or capacitors can be tested after their installation on-site using very low frequency technique (VLF) down to 0.1 Hz.

4.7.4 Measurement challenges - High-voltage testing

- Traceability of very low frequency resonance testing methods including loss measurements
- Loss measurements of power transformers, and HV capacitors and reactors
- On-site measurement of HV calibrations
- General improvement of measurement accuracy in HV testing
- Linear extension of lightning impulse voltage beyond 2500 kV level
- Testing and diagnostic of specific HVDC equipment and components
- Traceability for UHV component testing up do 2000 kV
- UHV testing diagnostic techniques
- Composite voltage testing of cables
- Combined voltage testing of AC and DC switches
- Partial discharge testing of DC

4.7.5 Implementation roadmap - High-voltage testing





4.8 DC grids and applications

Over the last two decades, a paradigm shift in our way of dealing with energy generation and consumption has increased the attractiveness of local DC grids as an extension to traditional AC distribution networks. Renewable energy sources (RES) such as wind and solar energy are becoming more reasonably priced, and consequently, distributed generation is growing. Simultaneously, LED lighting has shown to be a much more efficient way of illumination compared with the old-fashioned incandescent lamps and have taken over the market very rapidly. Many of these sustainable technologies are fundamentally DC, requiring power inversion to connect to the AC grid. Furthermore, storage systems such as batteries and supercapacitors are intrinsically DC, and electric vehicles (EV) and all electronic devices operate on DC power. Therefore, there is a realisation amongst grid operators that utilising local low voltage DC (LVDC) grids will lead to less energy wasted in the conversion process. Investigations are needed to determine to what extent many promises of DC grids can be fulfilled, for examples, whether losses can be reduced by means of localisation, voltage drops can be improved, the number of substations can be reduced, the management of reactive power and PQ can be improved, implementation of renewable energy sources can be made more simple, or if distribution losses can be reduced.

For DC grids, PQ issues such as ripple, inrush currents, voltage fluctuations and short circuit events, are different in nature from those in AC grids in terms of dynamics, duration, and magnitude. Therefore, for DC power systems there is a need for metrological support to obtain proper PQ definitions, a practical measurement guide, and realistic and well-defined PQ limits. Since the nature of PQ in DC grids is currently unclear, on-site measurements must be performed in real LVDC trial grids to determine which disturbances have the highest influence in terms of losses, inconvenience to customers, or potential to damage grid equipment and other connected loads. Such grid measurements should preferably cover a variety of representative consumer and producer connection types, such as solar panels, wind turbines, EV charging stations, battery storage systems, industrial and household applications, and different grid topologies, with voltage and current levels up to at least 1 kV and several hundreds of amperes respectively. The measurements should be performed with target uncertainties below 0.1 % considering the presence of AC ripple and other disturbances. Special measurement equipment and methodologies are necessary to conduct the required surveys for setting compatibility levels. This same equipment will be the basis of future ‚planning level' surveys carried out by utilities to manage the PQ levels in future DC networks.

A second important issue regarding DC grids is the accurate measurement of power and energy for billing purposes. In most countries, electricity meters are type tested with respect to standards issued for AC grids only. Therefore, there is a need to investigate additional specific metrological aspects of DC meters, which should be included in a future revision of this standard. Examples of such aspects are magnitudes of ripple currents and voltages existing in range up to tens of kilohertz, the immunity of DC energy measurement against such ripples, how to measure the energy contained in such ripples, the losses due to cables, etc.

The concept of DC grids finds natural applications at LV microgrids, where users connect fundamentally DC appliances and renewable energy sources. Furthermore, HV DC point-to-point connections are well established as a link between different larger regions in Europe and elsewhere. However, the concept of MV DC distribution grids is not very well established yet.

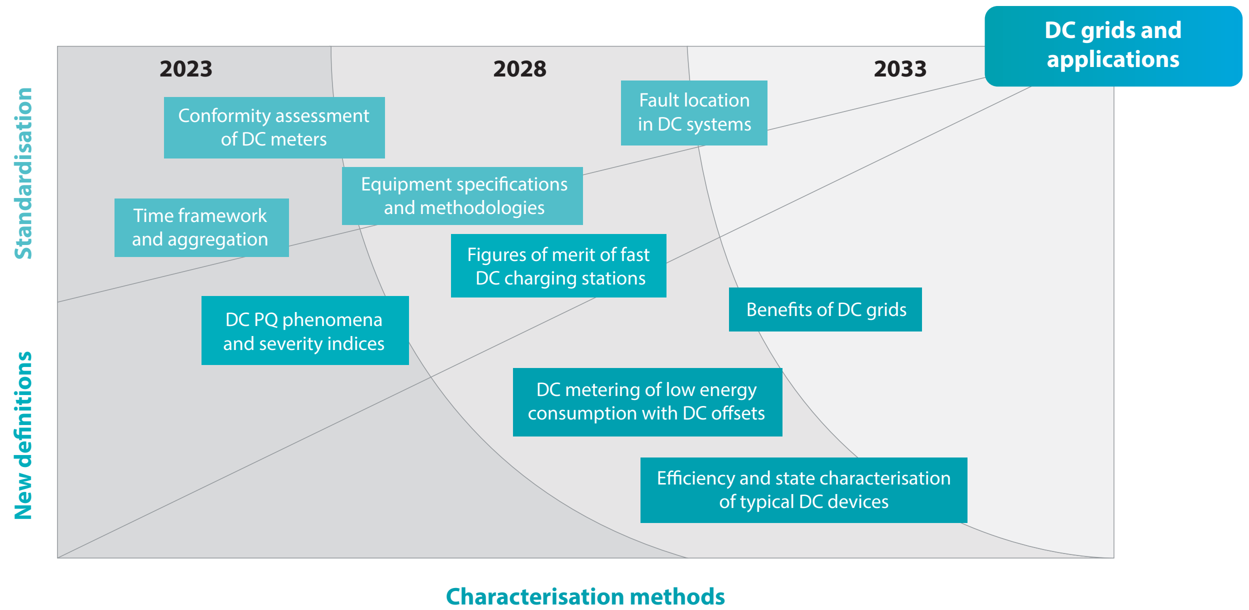
One of the major hurdles is protection by circuit breakers, which experience severe challenges when switching due to the lack of zero-crossings at DC (whereas the time-dependent voltage changes polarity 100 times per second in AC grids, facilitating switch openings without significant arching). The related fast transients need to be monitored for grid control purposes. If the concept of LVDC grids is extended to MV distribution grids, new measurement challenges will definitely appear.

Traceability is an essential part of ensuring customer confidence for emerging DC grids, but is presently non-existent for DC power and DC PQ and not defined yet as a classified service category in the context of the CIPM MRA.

4.8.1 Measurements challenges - DC grids and applications

- Equipment specifications and methodologies for PQ monitoring in LVDC grids and for high-accuracy laboratory measurements
- Measurements for the proposition of DC PQ phenomena and severity indices definitions as technical input for standardisation institutes (IEC, IEEE) to put into force standards of DC PQ
- New definitions of measurement time framework and aggregation intervals (in the absence of ‚half-cycles' as for AC)
- Quantify the overall practical benefits of DC grids
- Electrical figures of merit, i.e., efficiency as well as PQ emission and immunity, of fast (DC) EV charging stations
- Fault location at DC systems
- Test waveforms and methods for conformity assessment of DC electricity meters
- DC metering of low energy consumption in the presence of DC offsets
- Characterisation methods regarding efficiency and state of devices for typical DC applications: railway systems, battery charging storage processes, etc.

4.8.2 Implementation roadmap - DC grids and applications



4.9 Grid integration

Seamless grid integration of traditional generation, renewables and storing technologies is a key element in addressing challenges posed by decarbonisation, decentralisation and digital transformation. The key objective is maintaining grid stability while taking into account new supply and demand concepts, new power surplus and shortage patterns, new business models affecting consumption habits. In order to underpin grid stability and reliability requirements, sector coupling becomes a necessity, as do new storage and conversion schemes. Also to be considered are stronger interactions with other grids such as gas grids and the coexistence of DC and AC grids, such as railway and electric vehicle grids, emerging battery grids composed of domestic & distribution solutions, and novel storage concepts like power-to-X (P2X).

4.9.1 Measurements challenges - Grid integration

- Measurement concepts for power-to-X processes
- Measurement concepts for storage processes
- Measurement concepts for charging processes, e.g., EV
- Measurement concepts of coexisting DC and AC grids, for instance related to bidirectional DC-AC substations

Even though grid integration is very likely to experience increasing relevance in the coming years, measurement challenges have not been clearly identified. Therefore no implementation roadmap is presented for this theme at this stage.

5. Conclusion

Electricity grids are the key backbone infrastructure to meet the energy needs of our society. Smart grids are a proposed solution to changing patterns of supply and demand induced by the energy transition, designed to be more flexible and responsive, and ensure reliable connectivity.

Metrology has high relevance for the secure and trustworthy operation of smart grids, as measurements are crucial for monitoring and control of the grid now that production and consumption patterns become very dynamic owing to the increased share of renewable energy. This Strategic Research Agenda focusses on nine themes identified as bearing particular relevance to the metrology of smart grids. Addressing the identified measurement challenges with dedicated implementation roadmaps requires attention and cooperation beyond the metrological community, namely of all stakeholders of the electric energy value chain involved in the energy transition. We hope that it will be a valuable resource and reference point for metrological research and application for the wider community - metrologists and stakeholders) - that will underpin the successful deployment of smart electricity grids.

6. Glossary

CIPM MRA	Mutual Recognition Agreement of the International Committee for Weights and Measures
DSO	Distribution System Operator
DSR	Demand Side Response
EDSO	European Distribution System Operators for Smart Grids
EMN	European Metrology Network
ENTSO-E	European Network of Transmission System Operators for Electricity
ESMIG	European Smart Meter Industry Group
EURAMET	European Association of National Metrology Institutes
EURELECTRIC	Union of the Electricity Industry
LED	Light Emitting Diode
NMI	National Metrology Institute
EV	Electric Vehicle
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
HV	High Voltage
HVDC	High-Voltage Direct-Current
IT	Instrument Transformer (can also be Information Technology)
LPIT	Low-Power Instrument Transformer
LV	Low Voltage
LVDC	Low-Voltage Direct-Current
MV	Medium Voltage
P2X	Power-to-X
PMU	Phasor Measurement Unit
PLC	Power Line Communication
PPS	Pulse Per Second
PQ	Power Quality
PTP	Precision Time Protocol
RES	Renewable Energy Source
ROCOF	Rate Of Change Of Frequency
SAMU	Stand Alone Merging Unit
SCADA	Supervisory Control And Data Acquisition
SEG	Smart Electricity Grid
SRA	Strategic Research Agenda
TSO	Transmission System Operator
VLF	Very Low Frequency
UHV	Ultra-High Voltage
UTC	Universal Time Coordinated
WAM	Wide Area Monitoring

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