Measuring the Digitalisation of Electricity Distribution Systems: towards the Smart Grid

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***Abstract*—This paper proposes a set of digitalisation indicators focused on measuring the different digital capabilities and infrastructure of electricity distribution systems, as opposed to previous indicators which have mainly focused on performance and quality of service aspects.**

The indicators are classified according to the pillars of digitalisation: sensor and actuator, connectivity, data processing, and digital culture. They are use-case-agnostic and do not require a huge amount of information. In addition to this, three possible new applications of these indicators for distribution system operators and regulatory authorities are identified and discussed.

The extensive use of these indicators in Europe could allow the development of fruitful collaborations between distribution system operators, allow the identification of cause-effect relations between grid performance and digital infrastructure, and improve the replicability of innovative smart grid solutions. However, this will only be possible if regulators promote the adoption of the proposed indicators and the dissemination of their results.

***Index Terms*—Smart Grid, Digitalisation, Distribution System Operator, KPIs, indicators,**

I. Introduction

THE Energy Transition is requiring, among other measures, the decarbonisation of the energy sector (generation and demand). This is leading to a massive electrification in the energy system and an increase in the use of renewable sources. In electricity distribution networks, this is translating into an increase in the number of distributed energy resources (DER), Electric Vehicle (EV) charging points, and active participation of demand (e.g., prosumers, demand response), that pose challenges for the operation of the network, which is required to be more dynamic. To cope with those challenges, the development of smart grids is key.

The smart grid can be defined as the application of information and communication technologies (ICT) to the electricity grid (and, therefore, the deployment of monitoring and control devices), so that real time changes in the network (consumption, failures, overload of power lines, etc.) can be remotely detected, processed, and managed. From an infrastructure point of view, a smart grid can be understood as the digitalisation of the electricity grid infrastructure to achieve a better performance.

In Europe, the distribution of electricity is regulated: a National Regulatory Authority (NRA) defines the remuneration scheme for Distribution System Operators (DSOs), including incentives and penalties, based on aspects such as quality of service, CAPEX, OPEX, etc. However, the increasing digitalisation of the distribution grids towards the development of a smarter electricity grid, together with the objectives of higher energy efficiency and penetration of renewables, are requiring the evaluation of how ”smart” the grid is becoming, or needs to become, for the ultimate achievement of these objectives.

In the last decade, there has been an increasing interest in defining key performance indicators (KPIs) to be used in the evaluation of the ”smartness” of the grid [1, 2], its reliability [3], and the performance of smart grid projects [4].

At a European level, this interest is reflected in Directive 2019/944 of the European Parliament [5], which sets in its article 59.1 that the national regulatory authorities (NRAs) shall evaluate how DSOs perform regarding the development of a smart grid that enables higher levels of energy efficiency and renewable energy; this evaluation should be based on a set of indicators, and published in a periodical report with some recommendations.

To address this Directive, European System Operators (SOs) associations proposed a set of eight KPIs groups of up to 58 key indicators that can be calculated to monitor the smartness of grid operation and its evolution [6]. The eight KPIs groups are related to system observability, system controllability, active system management, smart grid planning, transparency in data access, local flexibility markets and customer inclusion, smart asset management, and TSO-DSO coordination capabilities.

Prior to this joint effort from SOs, in [1] a set of KPIs organised in 24 categories were proposed to measure the six main characteristics that a smart grid should present: enable informed participation by customers; accommodate generation and storage options; additional services; power quality; optimisation of assets and efficient operation; and resilient operation.

Reference [4] provides an extensive review on what KPIs are used by smart grid projects and recommends a set of KPIs in six categories: metering, asset management, quality of supply and distributed generation (DG), sustainable communities, flexibility, network balance, and digitalisation.

The Smart Grid Index in [2] tries to benchmark different DSOs regarding how smart is their grid based on publicly available information and according to seven dimensions: monitoring and control, data analytics, supply reliability, DER integration, green energy, security, and customer empowerment and satisfaction.

As presented, the existing literature about smart grid KPIs

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covers almost all the aspects that can be expected in a smart grid. However, most of them focus on the performance of the grid and not on the evaluation of the means and infrastructure implemented that drive that performance. In addition, they do not provide a full view on how digitalised DSOs are nor allow their fair comparison in this aspect. Indicators exclusively focused on the digitalisation of electricity distribution grids have to be developed to be able to draw solid conclusions about the impact of digitalisation in distribution grids, to assess the cause-effect relation between digitalisation investments and grid performance, and to measure and compare the digitalisation efforts of DSOs in a clear and objective way, regardless of their size.

This paper aims at proposing, for the first time, a set of indicators to measure the digitalisation of distribution systems to assess the digital capabilities and infrastructure put in place to achieve the grid performance levels. The digitalisation indicators in this paper have been proposed by a interdisciplinary group of experts (i.e., the authors) with wide experience working with different DSOs and the DSO Observatory of the EU Joint Research Center; from energy regulation experts to ICT and sensors experts, thus including all the areas of expertise required by smart grids.

Instead of using categories related to the operation of smart grids, the indicators in this paper are classified according to the pillars of digitalisation of distribution grids: sensors and actuators, connectivity, and data processing indicators. In addition, this paper contributes with an additional fourth pillar, the DSO's digital culture, which is proposed together with its corresponding indicators. Another contribution of this paper is that the indicators proposed, in contrast to most KPIs in the literature, are aimed at evaluating the digitalisation measures and infrastructures implemented by DSOs, and not the resulting performance of smart grids and demonstrations' success. In addition, this paper discusses three possible applications extremely useful for DSOs and NRAs that will be more difficult to achieve with the solely use of performance indicators.

The rest of the paper is organised as follows. First, the pillars for the digitalisation of power distribution grids are presented in Section II. Section III describes the key indicators proposed for the measurement of digitalisation of power grids. These indicators are classified based on the pillars for digitalisation, including the digital culture of DSOs. Section IV discusses the usefulness and advantages of these indicators for DSOs and NRAs. Finally, conclusions are drawn in Section V.

II. Pillars for the digitalisation of power distribution grids

In the last few years, the digitalisation of the electricity sector has taken a significant step with the massive deployment of smart meters in many countries. Thanks to this deployment, many DSOs have already started using big data techniques and machine learning algorithms to extract valuable information from smart metering data, and consumers can access their consumption data more easily.

In addition to smart metering, many DSOs are currently deploying advanced low voltage supervision sensors in secondary substations, improving the detection of technical and commercial abnormalities, and Phasor Measurement Units (PMUs), which improve system control and monitoring. However, in general, distribution networks are not sufficiently digitalised yet to cope with the massive integration of DER that is expected.

Digitalisation of power distribution grids is mainly based on three pillars [7]: sensors and actuators, which are necessary to monitor and control the grid; connectivity, related to the ICT implemented for the communications of sensors and actuators with other systems; and data processing, related to the exploitation of the data collected. One could think of them as the *muscles* and *senses*, the *nervous systems*, and the *brain*, respectively.

In addition to these, a fourth pillar for the digitalisation of distribution grids is here proposed: the digital culture of the DSO. The development and testing of new digital solutions in the grid, and the adoption of cybersecurity measures in all the DSO's activities, are things that could be facilitated by a DSO that trains its personnel in digital capabilities, provides them with the appropriate digital tools, and that makes it possible to customers to interact through digital means. DSO's digital culture can become a facilitator or a barrier when implementing most technical solutions.

These pillars of digitalisation show a high level of interdependence, as shown by Fig.1; a significant development of one pillar usually requires an equivalent development of one of the others, increasing the number of use cases and applications of digitalisation. For example, the deployment of a great number of sensors may require to adapt the communications infrastructure needed to collect the data, and to increase the computing and storage capacity of the servers in charge of processing and analysing such data. Regarding the digital culture, the DSO should make sure that the personnel involved have the adequate tools and training to fully and properly leverage and maintain the new infrastructure.

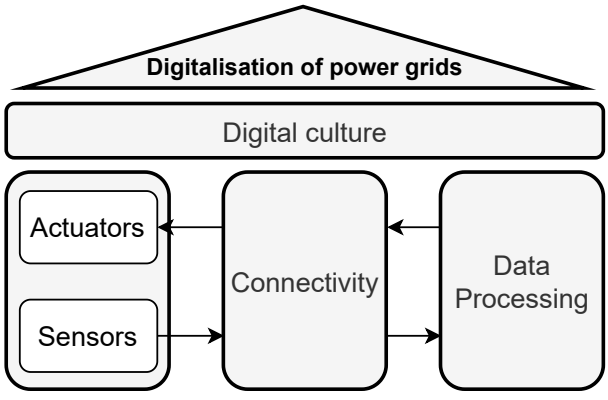


Fig. 1. Pillars of digitalisation of power distribution grids

III. Key Indicators of Digitalisation

Given the four key pillars of digitalisation in section II, the proposed KPIs, which would have to be measured by the DSO,

TABLE I
INDICATORS TO EVALUATE THE DIGITALISATION OF POWER DISTRIBUTION GRIDS

Category	Indicator
A. Sensors and actuators	A1. % of smart meters deployed over the total consumption points A2. % of primary substations with automation and remote control A3. % of distribution transformers with automation and remote control A4. Number of non-buried elements in the network with remote control, per km of netwok A5. % of LV power line outputs monitoried over the total number of feeders or output power lines from a substation or distribution transformer A6. % of equipment remotely monitored for maintenance purposes
B. Connectivity	B1. % of primary substations with broadband communications B2. % of distribution transformers with broadband communications B3. % of non-DSO devices that establish communications with the distribution network
C. Data processing	C1. % of network observable C2. % of network elements with digital twins
D. Digital culture	D1. Existence of a digitalisation plan and responsible person D2. Existence of continuous training in digital technologies and cybersecurity for all employees and field workers D3. % of field workers with access to documentation through connected devices D4. % of the distribution network documentation that is accessible digitally D5. Availability of a digital platform for consulting and carrying out procedures about electricity supply for users D6. % of network users who use their electricity supply applications frequently

are classified based on these:

- Sensor and actuator indicators.
- Connectivity indicators.
- Data processing indicators.
- Indicators of digital culture.

Indicators for each group are presented in Table I and briefly described and discussed in the following section. In order to offer a fair comparison between DSOs of different sizes, most indicators are expressed as a percentage.

A. Sensors and Actuators Indicators

The indicators in this group aim to measure the digitalisation of the distribution system in terms of the deployment of sensors and actuators. These devices allow a faster, more automated, and more sustainable operation of the network.

1) % of smart meters deployed over the total consumption points: The deployment of smart meters allow users to measure their consumption accurately and remotely, and to modify their consumption and contracted power (if applicable) to adapt it to prices and actual use of the network. At the same time, smart meters also protect users against overloads. In addition to this, the DSO can use smart meter data to quickly and easily detect and locate supply interruptions, considerably improving the quality of service.

2) % of primary substations with automation and remote control: The number of operators in charge of a power distribution area is limited and a maintenance crew is not always close to the location of the breakdown. This indicator, together with the following one, measures if, and to what extent, the DSO is able to automatically and remotely reconfigure the network and restore the service, by acting on the devices deployed from the control center.

3) % of distribution transformers with automation and remote control: As mentioned above, this indicator is similar to the previous one.

4) Number of non-buried elements in the network with remote control, per km of network: To operate the network safely, it is necessary to install devices (e.g., switches and voltage control devices) at certain points of the network and not only in the substations and distribution transformers. These devices enable the DSO to carry out actions remotely and reduce supply downtime.

5) % of LV power line outputs monitored over the total number of feeders or output power lines from a substation or distribution transformer: The monitoring of LV distribution power lines can be key to improve network operation and reliability.

6) % of equipment remotely monitored for maintenance purposes: Electrical equipment is usually very expensive and is either in constant operation (e.g., HV/MV and MV/LV transformers) or in standby, ready to act whenever it is necessary (e.g., breakers, switches, and reclosers). Having sensors measuring critical parameters of this equipment (such as oil temperature [8] and vibrations [9] in transformers, or thermal and partial discharge monitoring for switchgears [10] can help to predict and, mainly, to prevent failures before they happen through a proper maintenance. In addition to ensuring the security of the distribution network and the electricity supply, this can also lead to an extension of the useful life of the monitored equipment.

B. Connectivity Indicators

In order to support the deployment of sensors and actuators in the network, the control centers of DSOs must have the necessary communications infrastructure to send control signals and receive monitoring data. The faster and more distributed these communications are, the more secure the electricity supply will be.

1) % of primary substations with broadband communications: Although, currently, it is not necessary to have broadband communications in all the substations and distribution transformers, this is something to consider in the coming years. With a broadband communications infrastructure, the DSOs will be able to manage not only the devices deployed by themselves, but also all the energy management and generation/storage devices installed by users in a near future. Communications closer to real-time between control centers

and substations and distribution transformers (next indicator) will allow the DSO to increase its knowledge about the status of its network and will help to increase the number of possible functionalities and services for user participation and consumption.

2) % of distribution transformers with broadband communications: As mentioned above, this indicator is similar to the previous one.

3) % of non-DSO devices that establish communications with the distribution network: This indicator refers to all devices that, not having been deployed by the DSO, establish communication with it in order to coordinate their actions for the safe and efficient operation of the network. For example, Home Energy Management Systems (HEMS), Battery Management Systems (BMS), communications for Electric Vehicle (EV) charging infrastructure, generators or storage for self-consumption, etc. The existence of this communication provides the users the possibility of having an active role in the electricity system if they wish.

C. Data Processing Indicators

These indicators are related to the processing of the data generated by sensors, which were transmitted using connectivity capabilities, and then translated into specific functionalities.

1) % of network observable: The electrical distribution system is incredibly extensive geographically, so it is not economically or technically feasible to have every point of the system monitored at every voltage level. However, by optimising the arrangement of sensors [11] and applying mathematical techniques with the available data, the state of the parts of the grid that are not being directly monitored can be estimated (i.e., power system state estimation) with a reduced margin of error [12].

2) % of network elements with digital twins: The prediction on the behaviour of equipment or part of the network allows optimising the operation and making better decisions.

Despite some additional indicators related to the amount of data processed (e.g., volume of information processed versus the volume of information collected during a period; number of uses cases based on advanced analytic) could be added, these have eventually been discarded due to the complexity of accurately and fairly measuring them from a practical point of view.

D. Indicators of Digital Culture

A highly digitalised distribution network cannot be properly leveraged if the people who interact with it (e.g., for planning, operation, or maintenance activities) do not have the necessary training and resources. Consequently, we foresee the following indicators regarding Digital Culture.

1) Existence of a digitalisation plan and responsible people: The existence of a plan within the DSO to digitalise the distribution network implies that it has not only studied the weak points and aspects to improve the network, but also that the DSO is aware of the potential functionalities and services that users willing to participate actively could demand.

2) Existence of continuous training in digital technologies and cybersecurity for all employees and field workers: A DSO that cares about the training and continuous learning of its employees means that it values its human resources and that knows that they constitute the basis of an efficient and safe operation of the network.

3) % of field workers with access to documentation through connected devices: If technicians and maintenance crews can access all the information needed through a laptop or tablet, they will be much more agile and efficient in performing tasks than if they instead have to carry up-to-date papers and notebooks with the technical specifications of devices and equipment.

4) % of the distribution network documentation that is accessible digitally: In relation to the previous indicator, it is important that, apart from the operators deploying connected devices, the information needs to be available in digital format.

5) Availability of a digital platform for consulting and carrying out procedures about electricity supply for users: When users have the possibility to interact with the DSOs easily and online, the barriers to their active participation are significantly reduced.

6) % of network users who use their electricity supply applications frequently: The first step towards an active participation of users in the distribution network is that they show interest in their own electricity consumption.

IV. Discussion

The advantages and applications of the proposed indicators are numerous.

First, these indicators do not require a huge amount of input information and complex calculations in contrast with when measuring smart grid performance indicators because they are related to the digital infrastructure of the grid and not its resulting performance. For example, in [6] KPIs' formulas involve calculating different weights for the addends/summands, whereas the digitalisation indicators presented in this paper are mostly percentages, much easier to calculate. Since the remuneration of DSOs is regulated, they carry out the accountability of network investments and maintain an inventory of the assets installed at primary and secondary substations. Indicators such as *"A5. % of LV power line outputs monitored over the total number of feeders"* could be extracted by the DSO from already-available information. Other, such as *"A1. % of smart meters deployed"* and *"A2. % of primary substations with automation and remote control"* are already measured [13, 14]. Therefore, the process of measuring the proposed indicators would not be very time-consuming.

Second, the proposed indicators have been categorised according to the pillars of digitalisation of power distribution grids and they are use-case-agnostic. Any smart grid solution would be related to, at least, one of these indicators. As mentioned in section II, a significant development in one indicators category (i.e., pillar of digitalisation) would typically require a similar improvement in at least another category. Therefore, to completely leverage these indicators, every category should be analysed considering the others.

And last but not least, the digitalisation indicators proposed in this paper are in line with the recommendations of the DSO Observatory, an initiative supported by the European Joint Research Center (JRC) that monitors how DSOs are evolving to foster the energy transition [14]. The DSO Observatory recommends to follow an European-wide approach to collect DSO technical data, and to reflect, at a policy level, on the adequacy of grid digitalisation versus grid expansion. The proposed indicators would provide more information on the digitalisation characteristics of DSOs that could be measured with different objectives that can be of great interest for both NRAs and DSOs: A) to get a *screenshot* of the distribution system, B) to determine the relation between performance and digital infrastructure, C) to obtain more information for the replicability of solutions. These objectives are discussed below.

A. Screenshot of the distribution grid

By measuring the proposed indicators, the current state of the digital infrastructure of the grid could be summarised.

Sensors and actuators indicators provide information about how large the control and monitoring infrastructure on field is. The larger this infrastructure is, the smarter the grid can become. With the increasing deployment of DG, DER, and new energy services, the distribution grid will require a wider range of action and more information to guarantee grid reliability.

Connectivity indicators show the preparedness level of the grid to communicate in a fast and reliable way not only with the already-deployed sensors and actuators, but with new devices that may be installed in the future either by the DSO or third parties.

Data processing indicators provide an idea of how good the DSO processes data and how sensors and actuators' data are leveraged for an efficient and safe operation of the grid. For this category, it is extremely important to consider the two previous categories to obtain relevant good insights. If the scores in sensors and indicators and connectivity are acceptable, but the scores for data processing are low (e.g., low observability of the grid), the DSO should improve its capacity to process grid data, so that the sensors and communication infrastructure can be better leveraged.

Digital culture indicators, despite being related to the corporate level of a DSO, show if the digitalisation of the distribution grid is being accompanied with the development of the digital capabilities of the DSO's personnel and customers. High scores in this category would show that both employees and customers may find less difficulties and resistance to change when implementing new smart grid solutions and services.

B. Relation between performance and digital infrastructure

The full digitalisation of the distribution grid may not be necessary to keep an excellent performance and quality of service. For example, the reliability of MV grids, regardless of the topology, does not significantly increase for automation degrees higher than 20-30% [15]. By measuring the digitalisation of different distribution grids, the relation between grid performance and digitalisation may be observed and leveraged to keep cost-effectiveness, avoiding over-investments. Large DSOs could carry out comparisons between their distribution zones with different digitalisation levels and energy services, and determine to what extent the digital infrastructure influences grid performance so that new investments can be better planned.

NRAs could also benefit from this. By measuring the proposed indicators in addition to performance indicators for all the DSOs, the NRA may get a clear view of which digitalisation indicators have to be enhanced in order to improve performance. With these insights, NRAs could identify clusters of DSOs with similar scores and provide ad hoc recommendations or even design new regulatory schemes to promote specific investments that prove to have a positive influence on grid performance.

C. Information for replicability of solutions

One of the most important parts of a smart grid solution is the assessment of its scalability and replicability potential. The scalability of a solution can be understood as how well it can increase its size, scope, or range [16]. On the other hand, replicability is related to the ability of the solution to be implemented in a different location or time [16].

The functional scalability and replicability analysis (SRA) in smart grid research and demonstration EU projects are usually based on simulations and KPIs assessment for different scenarios [16, 17]. However, once the project is finished, future similar implementations may find some difficulties when extrapolating the insights for a specific distribution grid. The assessment of the proposed indicators could complement the SRA insights and demonstration's KPIs in order to facilitate the replication of the solution in the future.

For example, let's consider a demand response (DR) solution demonstrated within a smart grid project. Together with the SRA and the KPIs that show the performance of the solution, the proposed indicators could be measured for the electricity distribution area where DR is being implemented. Some indicators may show a strong influence on performance: smart metering (indicator A1) is essential to know how and which consumers are responding to the DR scheme; the existence of broadband communications in primary and secondary substations (indicators B1 and B2) may play a key role in the transmission of all the data involved in the solution; and a high share of consumers with energy consumption awareness (indicator D6) could mean that the interest and participation in DR would be higher and, therefore, improve the performance of the DR scheme. Specially in DR demonstrations, as the duration of the pilot is limited, consumer's motivation and participation may be high during the pilot and decrease with time. However, if consumers already presented some energy awareness before, it could be used as a basis for the DR scheme. With this knowledge, future post-project implementations of the DR scheme could evaluate if, based on its digitalisation indicators, the distribution grid area under consideration presents worse, similar or better digitalisation characteristics than the demonstration's area, and take action to maximise the probability of success in the implementation.

V. Conclusion

The existing list of KPIs to evaluate the performance of smart grids covers almost all the aspects that can be expected in a smart grid. However, most of these KPIs do not provide insights on which digitalisation investments and infrastructure have been carried out to deploy smart grids.

So far, existing KPIs have focused on performance and quality of service aspects. However, nowadays, the main approach followed by DSOs to improve their performance indicators is the digitalisation of the grid and its processes. The set of indicators proposed in this paper, which is the first exclusively focused on digitalisation and not on performance, aims to answer the need of measuring the digitalisation level of distribution grids and to become a mean to determine which digital capabilities are driving the performance levels measured.

The proposed indicators are in consonance with the JRC DSO Observatory's recommendations to measure the digitalisation of DSOs and to facilitate the comparison of international experiences and best practices. They are use-case-agnostic, do not require a huge amount of information, and could be leveraged by both NRAs and DSOs to get a complete view of the digitalisation level of distribution grids, to identify cause-effect relations between performance and digital infrastructure, and to foster the replicability of innovative smart grid solutions.

The extensive use of these indicators among DSOs and NRAs could open new synergies. DSOs would be able to take advantage of other DSOs' experiences when considering different digitalisation alternatives and when estimating the success and replicability of innovative smart grid solutions. At the same time, NRAs would be in a better position to promote or discourage certain digitalisation investments. Nevertheless, these benefits would only be experienced if regulators promote the adoption of the digitalisation indicators proposed and disseminate their results, so that different experiences and learnings can be shared. Such collaboration between stakeholders could improve the pace at which the challenges of the Energy Transition are addressed.

There are still many research and implementation open questions. For instance, it should be quantified the specific relevance of each proposed indicator for each KPI considered (e.g., weight assignment); in the same way, this relevance should also be quantified for the different generic smart grid use cases. In addition to this, DSOs would have to be willing to measure the indicators and, to validate the framework, the correlation between clusters of similar DSOs (from the digitalisation perspective) and performance should be analysed.

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