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Flexibility management in the low-voltage distribution grid as a tool in the process of decarbonization through electrification☆

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Abstract

This article reviews the concept of flexibility management as a critical and necessary tool for the acceleration of the electrification process that will bring significant benefits in terms of decarbonization of the energy system. In addition to identifying the value created by flexibility and how it can be harnessed as a system operation tool, it reviews the current regulatory and technical barriers to the implementation of efficient flexibility management, taking into account that flexibility is concentrated in the low voltage distribution network and can interact with each and every one of the system's agents.

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Keywords: Flexibility; Decarbonization; Electrification; Low-voltage network

1. Introduction

Electrification of the energy system has proven to be one of the most useful tools in the decarbonization process [1]. Electrification is currently a growing and unstoppable trend whose greatest exponents in the low-voltage distribution system are mobility and climate control. This electrification process combined with distributed generation based on renewable energies and distributed energy storage will undoubtedly bring about a paradigm shift in the electricity system [2]. Furthermore, these new loads, as well as generators provide flexibility to the electricity system, helping to maintain the balance between generation and demand, and providing extremely valuable operative tools [3]. However, there are many simplistic flexibility management models that do not consider fundamental aspects of the electricity system and ignore both technical and regulatory barriers.

Flexibility is the only tool that can guarantee a massive deployment of distributed technologies in the low voltage grid without incurring unbearable investment costs in distribution infrastructure that would otherwise disincentive the end user from the adoption of these technologies [4].

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This article reviews the flexibility value generation models in Section 2, but above all identifies regulatory and technical barriers in Sections 3 and 4 respectively for the real implementation of flexibility management systems, taking into account European legislation and the level of digitalization and technological deployment in most distribution utilities. The adoption of new communication technologies and the advance metering infrastructure based on IoT are critical factors.

2. Values generation from flexible energy resources

Flexible, distributed energy resources (DER) can adjust their electricity consumption or generation during a given period of time at a specific location in the network. The power adjustment provided by electric vehicles (EV), energy storage systems (ESS) including battery energy storage (BES), time-shiftable or curtailable loads (SL/CL), and dispatchable distributed generation (DG) such as photovoltaic (PV) systems can be specified by various attributes as depicted in Fig. 1 [5,6]. Shiftable residential loads include, among others, washing machines or dishwashers, while heat pumps (HP), air conditioners (AC) or water heaters represent curtailable loads, whose consumption can technically be interrupted at any point in time.

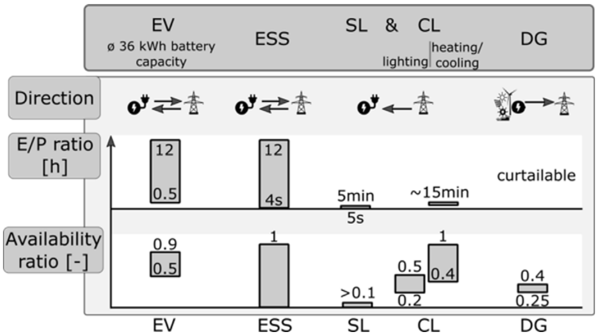

Fig. 1. Attributes of selected flexible DER as suggested by Eid et al. [5] with updated data from [7].

Those DER with a bidirectional electricity flow – as load or source as in the case of EV or ESS – can provide both up- or downwards adjustments in the network. The energy-to-power ratio typically describes how long an ESS provides electricity at its rated output, and is calculated by dividing the energy capacity by the nominal power rating. A common mid-range battery electric vehicle with an energy capacity of 36 kWh [7], (dis)charging at a nominal power of 7.4 kW yields a temporal ratio of nearly five hours. Applying this ratio to various DER as described by Eid et al. [5] gives an indication of their suitability for specific flexibility services. In the case of certain DER, the ratio may relate to physical parameters such as the thermal inertia for water heaters, for instance. A DER with a lower ratio potentially better matches the short-term markets. The comfort levels and preferences of DER asset owners influence the availability of the devices significantly, while DG units are determined by natural factors such as sunlight hours for PV. The typical starting time and duration describe the DER availability in time. The availability ratio and data depicted in Fig. 1 was adapted from [5] and represents the average unit availability in hours, divided by the sum of hours in a week. The DER utilization in local congestion management further relies on the geographical information of the respective assets in the distribution network (DN).

While DER such as EV and ESS provide large flexibility service potentials, their current penetration is still limited compared to the abundance of SL or CL, for instance [5]. Further technical limitations related to the information and communication technologies (ICT) connecting the described DER with the required low latency are further discussed in Section 4.

The flexibility use cases that [6] mention include TSO balancing for frequency control, TSO and DSO congestion management and power quality control such as voltage control in the DN, or BRP portfolio energy balancing. Abbas and Chowdhury [8] identify five distinct services through which customer side resources can serve the power grid in the short- and the long-term:

- Frequency regulation
- Reserve provision

- Voltage management accessing e.g., smart inverters, flexible loads (FL), and BES
- Reliability and resilience improvement
- Capacity expansion or upgrade deferral.

Each DER may form part of various of the above-mentioned services through either price-based or incentive-based demand response (DR), for instance [9,10]. The price-based scheme includes time-of-use (TOU) pricing with on- and off-peak tariffs, critical peak pricing, or real-time (RT) pricing typically based on hourly retail prices according to which the customers can adjust their consumption [11,12]. In incentive-based DR, the energy company pays the customer a compensation for the direct control or curtailment of loads. Niesten and Alkemade [11] stress, however, that DR services from the residential sector are mainly viable through the aggregation of DER.

The aggregator is a new, recognized actor in the energy sector specialized in bundling, managing and trading the flexibility of DER [13]. Balance responsible parties (BRP), utilities or suppliers, and retailers can integrate flexible electric services into their individual portfolios, or request the respective service through a third-party aggregator [14]. Fig. 2 depicts the provision, request, or management of flexibility services between the different stakeholders, and their specific interest in flexibility services. The Council of European Energy Regulators ascribes DSO rather the role of a flexibility user mandating third-parties via connection agreements, network tariffs, a rules-based approach or the classical market-based procurement [15]. Vicente-Pastor et al. [16] mention that potential competition may arise between TSO, DSO and retailers as buyers of flexibility services, varying with the underlying market mechanism.

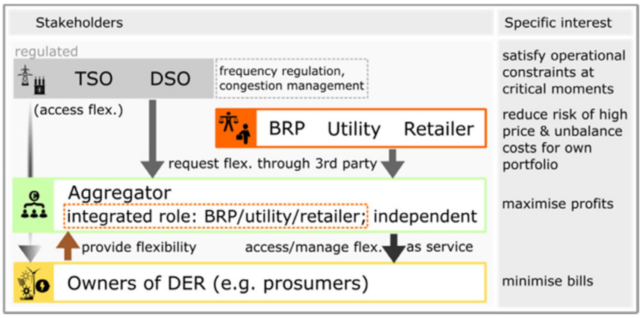

Fig. 2. Stakeholders and their interest in flexibility services.

The market design also fundamentally influences the potential benefits of each participating stakeholder. Niesten and Alkemade [11] qualitatively describe the value of smart grid services for consumers, SO, and aggregators based on a literature review and on pilot projects. Consumers can expect more control over their energy consumption, and reduce their electricity bills, while SO can improve load leveling, reduce congestion costs and energy losses, and defer network upgrades, for instance. Paterakis et al. [12] summarize the benefits of DR in more stable and lower electricity prices, with economic savings for consumers and a control of market power. Obi et al. [9] further state the reduction of peak demand in the system, and the minimization of end-user discomfort.

3. Regulatory barriers in flexibility management

The technical literature presents a broad spectrum of publications on electric flexibility services from DER. These services, however, have only started to develop over the past two decades in consequence to the political reorientation in matters of energy generation and electricity market design as partially depicted in Fig. 3. While the electricity market liberalization has introduced a competitive market for electricity generation and trading, the Paris Agreement and the European Green Deal have marked the turnaround towards a carbon-neutral energy future by 2050. The European Electricity Regulation (EU) 2019/943 and Directive (EU) 2019/944 of the Clean Energy for All Europeans Package in particular define the fundamental principles for integrated electricity markets with non-discriminatory access for aggregated DER from final customers, paving the way for flexibility management services. Kerscher and Arboleya [13] discuss in detail the impact of the recent European legal policies on the aggregator business model, which bases on the management of flexible energy resources. Despite the promotion of flexibility management on the European level, there still exist various barriers for the broad deployment of the

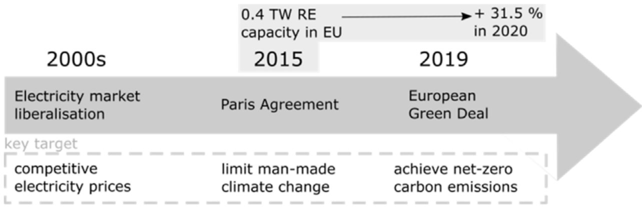

Fig. 3. Key policies to the development of flexibility services.
Source: Data from [19].

respective services. Although we specifically mention developments of the European regulations, similar trends can be observed in the energy systems' transition world-wide.

The implementation of the European provisions into national law will require several years, and will likely take on heterogeneous adjustments to the peculiarities and constraints of each Member State [12]. The Joint Research Centre Science for Policy by the European Commission highlighted the variance in DSO governance and average distribution tariffs, as well as the limited application of DSM in network operation in their reports on the status of DR and DSO in the EU in 2016 and 2018, respectively [17,18].

The three-part classification of Member States according to their advancements in DR engagement lists countries such as France or Belgium as progressive, while Spain or Croatia still marked stringent market restrictions at the time. Numerous states are only starting to adapt new legislation for prosumer market participation, where one key step is to clearly define the roles and responsibilities between the market participants [14]. In Spain, for example, the national commission on markets and competition enacted a law in 2019 defining equal conditions for generation, DR, or ESS in balancing services, including the aggregation of assets to a certain degree [20]. Vallés et al. [21] propose specific regulatory recommendations concerning smart metering, the DSO remuneration, network tariffs which are cost-reflective, the DR provider and consumer protection. These regulatory revisions are fundamental to overcome the initial transitory barriers to a carbon-neutral economy. The former market design, still significantly affecting current energy system operation, bases upon large, centralized energy generation from fossil fuels. The technical barriers to implementing electric flexibility services in this historically developed system are discussed subsequently.

4. Technical barriers in flexibility management

The concept of Internet of Things (IoT) in general involves a whole new sector of services based on the interaction between devices from different nature. Sensors have reduced in size and price, and pose a particular challenge in flexibility management implementation, along with the inclusion of low-power-consumption communication modules.

Palattella et al. [22] make a clear distinction between consumer IoT (cIoT) and industrial IoT (iIoT) applications, where devices related to flexibility management can be classified as part of the latter. Both classifications indeed share some of the principal guidelines regarding IoT device integration, but show clear differences in specific communication requirements. Composed by a plethora of devices and communication protocols, often not compatible with each other, the smart grid is no longer in a mere experimental phase, as specified by Galli et al. [23] in their conclusions. It is now excelling as one of the most feasible solutions to cope with the increasing demand and stress in the low-voltage and medium-voltage distribution networks.

4.1. IoT requirements for smart grid applications

Tightiz and Yang [24] accurately describe the phenomena of monitorization and control of power networks as the true emergence of the smart grid concept, as the traditional, unidirectional power grid system is being progressively replaced by a vast flow of power and information in both ways. Former consumers are increasingly becoming (small-scale) producers through the ownership of RES and DER. In their new role of so-called prosumers they have the ability of exchanging energy, which relies on the coordination of various devices embedded in a reliable and secure communication infrastructure. Applications in the electric market for iIoT impose a breakthrough where devices can cope with DR strategies, such as peak shaving and direct load control by means of economics incentives and RT tariffs. Moreover, the development of adequate advanced metering infrastructures, such as smart meters, represents a key element for providing ancillary services (AS) like load profiling intelligence, power quality control and fraud detection, which not only benefits the end-consumers, but also provides advantages for the distribution companies.

Nevertheless, there are still some technical barriers that the non-mature technology has yet to overcome. Smart grids implementation require low latency communication channels, a suitable bandwidth, and appropriate data rates. A secure infrastructure is particularly critical given the sensibility of data transmitted, robustness in case of failure and self-healing uplinks and downlinks. Reliability must be ensured, together with interoperability among the plethora of devices and manufacturers. For a protocol to be considered suitable, it must show ubiquity in essence and scalability as desire characteristics, as Tightiz and Yang [24] indicate. Fig. 4 presents some of the ancillary services that can be provided by the development of smart grids following the mentioned communication requirements.

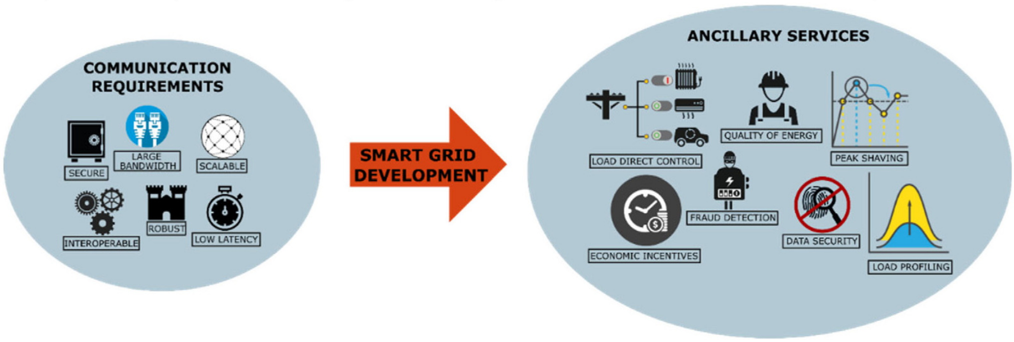

Fig. 4. Communication requirements for a successful integration of ancillary services (AS) in a smart grid.

4.2. Wired connections: The impact of power line communication

One of the premises for IoT devices, especially the ones inherent with industrial deployments, relies on the use of low-cost devices. Therefore, the associated communication infrastructure should also cope with budget limitations, thus extending the ease of adoption of new devices and protocols in the industry. One of the proposed strategies to ensure the high penetration is the use of already existing infrastructures, such as the electrical grid. As Galli et al. [23] correctly pointed out, PLC stands as a unique technological solution with costs comparable to new wireless networks designs. Nowadays, there are three main classes of PLC technologies with the ability to be combined with Automatic Meter Reading (AMR) solutions and further Advanced Metering Infrastructures (AMI) deployments:

- **Ultra-Narrow Band PLC (UNBPLC):** Comprehending an extremely limited data rate capability, around 100 bits-per-second (bps) in the ultra low frequency spectrum between 0.3 and 3 kHz and the upper band of the super low frequency spectrum between 30 to 300 Hz.
- **Narrowband PLC (NBPLC):** Considering the very-low frequency, low frequency, and medium frequency bands, this also includes the CENELEC-A band between 3 and 148.5 kHz as indicated by the Comité Européen de Normalization Électrotechnique (CENELEC). For smart meters data acquisition and AMI infrastructure, the Powerline Related Intelligent Metering Evolution (PRIME) solution works in this spectrum, with measured data rates in the physical layer up to 125 kb/s.
- **Broad-band PLC (BBPLC):** Comprehends solutions working on the high-frequency and very-high frequency spectrum, ranging from 1.8 to 250 MHz.

The lack of interoperability between the presented technologies are one of the main drawbacks behind the deployment of PLC solutions in the industry spectra. According to Galli et al. [23], the CENELEC-A band is the only communication band capable of being used worldwide, as other frequencies suffer from local regulations according to the territory where they are being implemented. Given the CENELEC-A band constrained data rate, alongside with the fact that the PLC channel is an extremely noisy environment, there are fundamental reasons not to consider NBPLC technologies as a feasible solution for RT flexibility management deployments.

4.3. Wireless approach: from small areas to large regions

Deployment of new, wired infrastructures like Ethernet/IP, PROFINET or MODBUS/RTU not only interferes with the principle of ease of scalability, but also could represent a considerable increment in deployment costs and capital expenditure (CAPEX), which limits the scope of smart grid application. Moreover, it imposes a bottleneck in the system, since each device that forms the network should offer at least one physical connection port. Aside from scalability or capital costs for deployment, undoubtedly Ethernet/IP could offer a perfect solution for the integration of AMI, given the abundance of information and documentation available.

Nevertheless, public Internet as an already deployed infrastructure, together with new low-power wireless protocols could be used as a suitable solution for data acquisition and control communication. As pointed by Tightiz and Yang [24], communication in the bi-directional smart grid infrastructure is depicted in three well-defined areas: Home Area Network (HAN), Field Area Network (FAN) and Wide Area Network (WAN). Fig. 5 shows this approach in a graphical way, depicting the distance scale and area of application of each one of them. This shows that focusing on a single communication protocol for solving the communication requirements is not the appropriate solution. A vast spectrum of protocols should be used instead, as Tabaa et al. [25] define, focusing on the suitable application for each one of them and considering interoperability as a central requirement to ensure communication between the plethora of devices belonging to the IoT network. Given that AMI infrastructures are often used in the FAN area, wireless protocols falling in this category are the ones described, focusing on advantages and disadvantages rather than in-depth technical analysis of each one of them. Nevertheless, it is worth mentioning that clustered applications in the HAN area, such as EV charging stations and buildings energy management systems (BEMS) may benefit from shorter range protocols, considering power constraints and offering low latency for RT flexibility management implementation. Table 1 provides a short overview of the analyzed protocols.

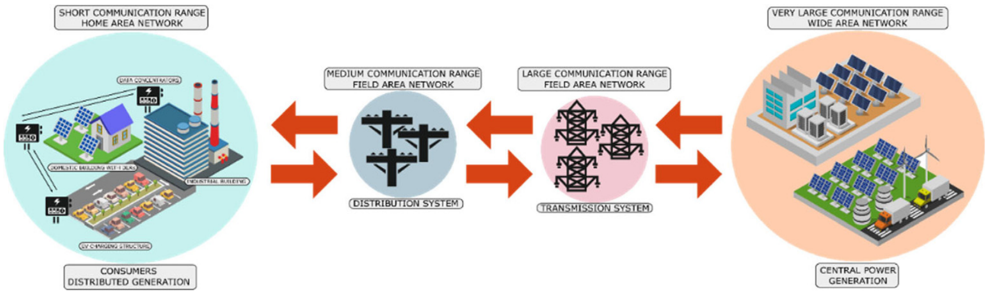

Fig. 5. Analyzing communication areas according to application in the electric market.

Table 1. Comparison between different analyzed wireless protocols/standards.

Wireless protocol/Standard	Area of application	Multi-point/Mesh	Supported frequency band	IPv6 support	Roaming support	Data rate bandwidth	CAPEX/OPEX
ZigBee/Bluetooth (LP)	Small (HAN)	Yes	2.4 GHz	No	No	250 kbps	Low
LoRa and LoRaWAN®	Medium (FAN)	No	863–870 MHz	No	No	50 kbps	Medium
6LoWPAN	Medium (FAN)	Yes	869 MHz	Yes	No	150 kbps	Low
3GPP/4G/5G	Large (WAN)	No	3–300 GHz	–	Yes	100 Mbps	High

4.4. LPWAN protocols: LoRa - LoRaWAN®

Deployment of new, wired infrastructures like Ethernet/IP, PROFINET or MODBUS/RTU not only interferes with the principle of ease of scalability, but also could represent. LoRaWAN® presents a revolutionary approach in their physical layer by using Chirp Spread Spectrum (CSS) modulation in a spread waveform solution. As depicted by Rizzi et al. [26], a deeper analysis on the use of LoRa for IoT applications in metering infrastructures and flexibility management provides several advantages, considering support for large number of nodes in a scattered area of operation, a suitable payload frame and low energy consumption.

Nevertheless, the lack of support for IPv6 integration, combined with a star-network topology imposes a risky bottleneck, increasing the probabilities of failure in a wide operational area, thus requiring a safety redundant infrastructure, and increasing deployment costs. Being a proprietary protocol from Semtech Corporation means an unnecessarily increase in operational costs (OPEX) for large deployments, also considering the risk of depending on a specific manufacturer. Moreover, congestion and access to media for large deployments is an increasing risk, since working in an unlicensed spectrum presents several limitations in the Quality of Service (QoS).

4.5. LPWAN protocols with IPv6 support: 6LoWPAN

6LoWPAN is based on the IEEE802.15.4 standard, it is an open protocol and it is specifically suited for low power consumption in constrained devices, together with the advantages in the integration of an IPv6 adaptation layer, thus addressing a vast amount of IoT devices and guaranteeing interoperability with unconstrained devices running Ethernet/IP protocols, as depicted by Zanella et al. [27].

To reduce the size of packets transmitted, and thus coping with constrained requirements, transport layer is implemented using UDP instead of TCP protocol. Advantages in reduced packet size also face disadvantages such as the lack of acknowledgment in data reception, which leads to uncertainty. Issues like the latter can be solved by implementing Constrained Application Protocol (CoAP) solutions in the application layer, with their own packet acknowledgment mechanisms. Another core aspect comes with IEEE802.15.4 supporting mesh-network topologies, adding a desired capability of self-healing to the overall deployment. The ability of each node to communicate with another node in a neighbor structure comes with an increased cost in transmission round-trip time, given the latency added by each hop in the network. The number of allowed hops and maximum neighbor nodes per device should further be limited to avoid overflowing the data concentrator capacity, which constitutes the backbone infrastructure for uploading data to the cloud for further processing. The area of coverage can either be extended by means of the mesh-network infrastructure, or by using sub-1GhZ frequencies, which are suitable for lossy environments like the open-air communication channel. Working on unlicensed spectra lacks QoS support. Nevertheless, as pointed by Verma and Ranga [28], the use of an adequate routing protocol for low power networks like RPL does not only provide a low-power and self-healing infrastructure, but also the support for QoS, and thus covering many of the requirements for a suitable IoT deployment for flexibility management.

4.6. Cellular networks: The boom around 5G connectivity

Cellular networks, which have a different infrastructure from the star-network, or the mesh-network topologies presented in LPWAN protocols, benefit from the inherent roaming compatibility feature that has been around since the foundations of mobile networks like GSM and GPRS. They also offer another advantage: the licensed spectrum is suitable for ensuring excellent availability and QoS, which cannot be offered in unlicensed spectrum solutions, as depicted by Palattella et al. [22].

As addressed by Agiwal et al. [29], given the vast number of devices in future IoT deployments, and given that cellular network cells are at the boundaries of Shannon capacity, new technological features should be analyzed for a proper deployment of 5G technology.

Massive Multiple-Input Multiple-Output (MIMO) antennas deployment can be combined with mm-wave ranging from 3 to 300 GHz spectrum. The inclusion of Heterogeneous Nets (HetNets), where small cells with low-power consumption are combined with more powerful, legacy cellular towers, could provide a solution for improving long-range capability in IoT device communications. Nevertheless, the deployment of HetNets implies elevated CAPEX and OPEX, which can only be justified by combining the use of this communication channel with a vast variety of applications. This also implies an increase in congestion and the risk of data collision, which can be avoided by the introduction of proper channel access methods such as Wideband Code Division Multiple Access (WCDMA), as it has been done in former 4G deployments.

5. Conclusions

The value of flexibility can only be obtained when it is managed in an appropriate manner, in real or near-real time, and when market mechanisms are established that are accessible directly by end users or through aggregators. This article shows that although progress is being made at the regulatory level defining management mechanisms, in many cases they are insufficient and in others there are still technical barriers that prevent their real implementation in the current distribution network. These barriers have to do above all with the installation of measurement and operation systems that allow data to be obtained with a higher sampling frequency, and this paper has reviewed the existing alternatives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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