Spatial Effects of Flexibility Activation–Case Study of a Real-Life Hungarian Distribution Network

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ABSTRACT As distributed energy sources, energy storage and electric vehicles are spreading, active consumers have appeared, flexibility is playing an increasingly important role in tackling emerging distribution network congestion problems. Applying flexibility can be a cost-effective way to manage such challenges, and it can help to defer grid developments. The purpose of this paper is to present a modeling framework that can help test the operation of flexibility products that may be applied to a distribution network. The load flow based simulations using representative sample networks from Hungary were aimed at solving two selected network problems by a flexibility service, mapping a potential product providing compensation for voltage drop on medium voltage overhead lines and reducing load on the substation’s transformer. As a result of the simulations, spatial contribution factors according to topological location were determined based on sensitivity, and their variability was studied by time sweep analysis on the two different products. A scenario considered the appearance of distributed generation and showed the effects on contribution factors. The variation of the contribution factors due to different loading and distributed generation differs by an order of magnitude in the two different products, due to the parameters of the overhead medium voltage networks. This means that in some use cases – as this long overhead medium voltage line’s voltage drop issue is a practical example – the variation of spatial effects due to different loading is not negligible, which should be considered in the development of flexibility need and activation calculations.

INDEX TERMS Flexibility, distribution network, congestion management, distributed energy resources, flexibility market.

NOMENCLATURE

BRP Balance Responsible Party.
DER Distributed Energy Resources.
DSO Distribution System Operator.
ENKO ENergie intelligent KOordinieren.
FSP Flexibility Service Provider.
GL Grid Location.
HV High Voltage.
LV Low Voltage.
MV Medium Voltage.
MOL Merit Order List – MOL.
TSO Transmission System Operator.
UK United Kingdom.

I. INTRODUCTION

The growing share of renewable-based generation units and the increased system load on the demand side (including the gradual spread of electric vehicles and the electrification of heating and cooling technologies) have brought integration challenges into the electricity system and will continue to do so [1], [2], [3].

The inclusion of decentralized power generation makes it difficult to keep system operation cost-effective, while maintaining voltage and frequency control. The increasing number of distributed energy resources (DER) like distributed generators, storage systems, residential or commercial smart buildings, microgrids on the distribution network may lead to the more frequent formation of network congestions, such as voltage drop, voltage rise and overload of network elements. DERs considered active as they are operated by different
objective functions of market players, such as aggregators. The conventional distribution planning process does not consider such activities. The loads are usually modeled by coincidence factors and statistical profiles. Regarding generation, the connection calculations usually only consider some specific system states. The emerging network congestions can be addressed by distribution system operators (DSOs) through grid developments, but distributed units such as energy storages or controllable loads (such as electric vehicles and heat pumps) and demand-side response (demand response, DR) as flexibility services/products offer a more cost-effective way to deal with emerging grid problems. The use of flexibility as a solution to the challenges of distribution network operation is also strongly supported by policy makers [3], [4], [5]. However, to address the congestions with flexibility, new network calculation methods must be developed by the DSOs to specify the flexibility needs and ensure the security of supply.

Directive (EU) 2019/944 of the European Parliament and of the Council concerning the internal market in electricity sets new requirements for the application of flexibility in the distribution network and for the process for procuring flexibility services. Until 31 December 2020, Member States had to bring into force the laws, regulations and administrative provisions necessary to comply with Article 32 of the Directive [6], [7]. However, the detailed rules and definitions are still being developed in most of the countries.

In accordance with the provisions of the Clean Energy Package, the law LXXXVI of 2007 on electricity was amended in Hungary in 2020. The provisions of the amendment facilitate the development of a flexibility market, which allows the flexibility service provider (FSP) to apply for distribution flexibility services, introduces redispatch (which was not present at the level of distribution in Hungary before) and creates alternative flexible connection for network licensees in the case of failure of the market-based procedure. The document defines the concept of distribution flexibility service, which is the totality of the services used in the distribution market-based procedures and the generation-load redistribution activity, in order to ensure the continuous and efficient operation and operation of the distribution network and to maintain the quality of electricity supply.

This paper aims to analyze the provision of flexibility services on the Hungarian medium voltage (MV) network through a case study. The two use cases analyzed in example networks are voltage drop compensation and transformer overload relief. Due to the attributes of the network (long, radially operated overhead lines are quite usual), these two could be the mostly appearing application of flexibility on the MV level. These services have spatiality: the effect on the congestion depends on the location of the FSP. Other research and pilot flexibility platforms used contribution factors to model this phenomenon. However, most of the examples, which are introduced in detail below in the review section, used static contribution factors that do not change over time. We analyzed the variation of the contribution factors over time due to the change of the loading, and also with the increasing penetration of distributed generation. The case study contributes to the development of the modelling and simulation methods used in the first flexibility platforms, as it points out attributes that should be considered to remain effective in the need calculation and activation. The results discussed here were used to conceptualize the demonstrations of the Hungarian participants in the OneNet Horizon 2020 project (Grant No. 957739), Easter cluster demonstration. The project aims to create a common framework for flexibility provision, where the demonstration sites have similar use cases, and the grid calculation method also relies on the conclusions of this paper.

The paper is organized as follows. Section 2 reviews the key definitions connected to flexibility and some state-of-the-art developments and pilot projects around Europe. Section 3 describes the modelling methodology used in the case study, covering also the simulation scenarios and results. Finally, Section 4 summarizes the main conclusions.

II. FLEXIBILITY DEFINITION AND REVIEW OF PILOT PROJECTS

This section covers the technical background for flexibility, starting with the attributes of flexibility provision and the most important technologies that can participate in such services. Valarezo et al. [8] covered the ongoing flexibility platform developments in Europe, collecting information about 18 market platforms and 4 aggregator platforms with key feature listings. The OneNet project also carried out a review [9] on the developments, analyzing 15 European projects and circulating a questionnaire within the consortium. Business models were benchmarked and recommendations were composed by Farrukh et al. [10], while Köppl et al. [11] introduced a sensitivity-based calculation method in Germany. Storage as a technical solution was thoroughly analyzed by Se Hoon Baik et al. [12]. In our paper, European research projects such as PicloFlex, Enera, NODES and CoordiNet (ENKO is jointly discussed) are reviewed to provide insights into the use cases and market development approaches. The latter served as a basis for the case study presented in this paper.

A. DEFINITIONS AND PRODUCT SPECIFICATION

According to a study by Eurelectric [13], flexibility means the possibility of changing production and consumption patterns in such a way that they can contribute to providing different services in the electricity system as a result of a signal (price or activation signal).

The parameters used to describe flexibility are generally as follows [2], [14]:

- **Direction**: a downward or upward change in production or consumption;
- **Duration**: the period from the start of the actual activation to the end of the activation;
• **Activation time**: the timespan between the activation signal and the time of the actual activation;
• **Location**: location of the flexibility source on the grid (topology);
• **Performance**:
  - **Active power**: the degree of deviation from a predetermined production or consumption, also referred to as the deviation from a baseline;
  - **Reactive power**: although usually neglected in the literature, reactive power is also an important feature in describing flexibility, as compensation can e.g. help to remove thermal transmission constraints.
• **Load change rate (gradient)**

The following figure shows an example of using flexibility if there is an upward change in performance over a period of time (Figure 1).

In addition, the following are frequently mentioned features of flexibility [15]:
• **Time available**: for example, electric vehicles are only available when connected to the grid;
• **Predictability**: the predictability of weather-dependent producers is uncertain;
• **Controllability**: open loop, closed loop, operating mechanism, etc.;
• **Target**: for what problem flexibility service/product is used.

Network needs may vary by topology or user composition. Different applications require different flexibility services. Based on [14], distributed units with similar modeling characteristics can be systematized according to Table 1. Due to their specific characteristics, some models will fit the technical problems to be solved. While maintaining Maximum Power Point Tracking control for solar systems, for example, only downward controlling may be feasible; on the other side, energy storages can participate in upward and downward control as well if the capacity is there. The reactive power compensating ability of the distributed energy sources is also important, as the supply of reactive power can increase the voltage and reduce the load on the items connected in series [2], [16].

High-voltage, fast-response power electronics and energy storage systems prove to be the most promising devices for voltage control, but industrial-type flexible loads and CHPs also have significant potential, although the latter’s

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**FIGURE 1.** Example of flexibility activation [2].

**TABLE 1. DER systematization [14].**

| General                  | Group                        | Technological features/examples                          |
|--------------------------|------------------------------|--------------------------------------------------------|
| Energy storage           | Mobile storage               | Electric vehicles, battery                             |
|                          | Stationary storage           | Pumped storage hydro power, battery, flywheel, etc.    |
| Distributed generation   | Intermittent renewable energy sources | PV, wind turbines                                      |
|                          | Combined heat and power      | Special limits (rate of heat expenditure)              |
|                          | Conventional generators      | Fossil, biogas generators                              |
| Flexible loads           | Load with heat storage capacity | This category includes all loads that can be controlled by a thermostat, e.g. cooling; heating ventilation and air-conditioning, electric boilers, heat pumps, etc. |
|                          | Load rescheduling            | Loads that can reschedule their consumption over time |
|                          | Load reduction               | Loads that can reduce their consumption                |
flexibility is limited by the amount of heat dissipation. Weather-dependent renewables connected to inverters with the appropriate control functions (\(\cos \varphi (P)\), fixed \(\cos \varphi\), \(Q(U)\), fixed \(Q\)) may also be suitable for voltage control, but the unpredictability of availability might be a limitation [17].

**B. OVERVIEW OF STATE-OF-THE-ART PILOT PROJECT**

The DSO can access flexibility in a number of ways, but the ultimate goal is to obtain flexibility on a market basis. To date, several pilot and demonstration projects aim to create a flexibility market. Most of these projects are still in their infancy, and the purpose of different projects is varied. In this section, three projects addressing the development of local flexibility markets are presented. Then the concept of the Coordinet project is discussed in detail in Section 2.3, which served as the conceptual foundation of the case study presented in this paper.

1) **PICLO FLEX**

Piclo Flex began testing phase in 2018 as the first United Kingdom (UK) local flexibility market. All six UK DSOs joined in the market, and Piclo later contracted 3 DSOs to provide flexibility services. The presence of several DSOs in the market facilitates the participation of flexibility providers in the market, and the platform developed allows for price comparisons. Tenders are tied to congestion areas, which serve as the definition of spatiality, so all sources of flexibility in that area can participate in the tender [18].

Piclo Flex is a stand-alone platform, not integrated into existing markets, which allows for easy clearing and price transparency, but hampers smaller players. Tenders are announced at least 6 months in advance, and contracts can last from a few months to 4 years. These longer time-frames allow DSOs to assess whether it is worthwhile to address congestions with flexibility in the long run as an alternative, or it is more cost-effective to solve problems by grid development. The prequalified FSP shall also publish the availability fee and the activation fee in the tender. The tender will pre-determine the times when the DSO can use the flexibility service (for example, in the evening on weekdays in winter when the load is typically high) [19], [20], [21].

In this model, there is an independent market operator, but the selection of bids is made by the DSO. There are standardized products on the market, which ensure transparent operation. In this case, the basic factors of standardization are location, voltage level, service time frame, and duration. The other parameters are validated during the prequalification process. UK Power Networks can access 3 types of products listed in the table below (Table 2) [21].

Prior to activating the flexibility service, the DSO informs the TSO, which ensures that conflicts are avoided, but in addition, there is no cooperation between the two parties. There are no penalties for non-performance, but in the case of 3 or more defective events, DSO may terminate the contract with the service provider. The flexibility provider is responsible for the imbalances created by the use of flexibility [18], [20], [21].

2) **ENERA**

Enera is a joint project of EPEX SPOT, EWE AG, TenneT DE, Avacon Netz and EWE NETZ. In order to avoid redispatch of wind power production, a pilot project promoting the use of flexibility solutions was held in the windy north-western region of Germany. Grid operators have the opportunity to obtain flexibility within a day (intraday, ID) to alleviate congestions. Given that grid congestions can be tied to a specific location, local order books are used. The first transaction was made on February 4, 2019 at 15:25 for a 2 MW power increase of a power-togas unit. Delivery took place between 17:00 and 18:00 that day [18].

The flexibility market, as with Piclo Flex, is a separate platform, not integrated into existing energy markets. The offers and demands published on the platform by FSPs and network operators are constantly matched. Market participants have the opportunity to participate in different markets with the same product, so there is a chance of double activation, which is the responsibility of the FSP. The market operator (EPEX SPOT) is independent, thus ensuring neutrality between buyers and sellers. It is particularly important to preserve the independence of the market operator if, for example, DSOs can own energy storage facilities [18].

Enera does not have an availability fee yet, but there are plans to introduce it in the future. The standardization of the products is the responsibility of EPEX SPOT with the competet (product purchaser) grid operator. As both DSOs and TSOs obtain flexibility services with Enera, their communication is key to conflict prevention. The future idea is to see filtered bids on the platform, so there is no double activation. The FSP is responsible for the imbalances created by the use of flexibility [18].

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**TABLE 2. Piclo flex flexibility products [21].**

| Target | Secure | Sustain | Dynamic |
|--------|--------|---------|---------|
| Peak load reduction on HV/MV transformers | Peak load reduction on MV/LV transformers | Completion for e.g. Secure products |
| Entry limit | Min. 50 kW | Min. 10 kW | None |
| Price | Availability and activation fee | Fixed fee | Activation fee |
| Activation time | Real time | Pre-scheduled | Real time, but FSP can choose not to activate |
| Obligation to deliver | At least 6 months before activation | One month before activation | None |
3) NODES

NODES is a joint project of Norwegian Adger Energi and Nord Pool, launched in 2018. The model operates at three pilot sites: in Norway, where Adger Energi Nett (DSO) is involved in the project, while Germany has 2 pilot sites. In Norway, Adger Energi Nett needs flexibility due to increasing loads, and in Germany, the goal is to avoid the redispatch of renewable production, which is also typical of the Enera project [18].

In the NODES platform ID time frame, network operators and Balancing Responsible Parties (BRPs) can gain flexibility. Flexibilities that are not used are transmitted locally to other existing markets, such as ID or the balancing energy market. FSPs mark their bids as grid location (GL). One or more GLs form a local pricing zone. Within a given GL, an FSP may aggregate flexibilities into one or more bids. TSOs or DSOs can decide the size of a GL. In theory, a DSO can define a GL as all units under a given substation. The GL defined by the TSO may consist of the aggregation of DSO GLs. In the first Norwegian example, a given GL was formed by measuring points under the 132/22 kV substation [18], [22], [23].

NODES is partially integrated into existing markets, as network operators and BRPs gain flexibility on the same platform, and offers that are not used locally are forwarded to other market platforms. In this case, the market operator is not completely independent, because in addition to Nord Pool, Adger Energi Nett is also involved in the operation [18].

Like the other models, there is no availability fee in this case. Flexibility products are not standardized, but FSPs have the option to supply their offerings with technical, financial or even technological (such as source of production) parameters. This creates a database from which customers can choose the offers that suit their needs. In theory, both DSOs and TSOs can access flexibility on the platform [18].

C. CoordiNet PROJECT

A key consideration in the design of local flexibility markets is the location of flexibility sources. This is pointed out, for example, by the CoordiNet project, which has three main objectives [24]:

- demonstrating a framework for TSO–DSO cooperation to achieve a more economical, reliable and environmentally friendly electricity supply;
- definition and testing of standardized products and testing of processes related to their acquisition, activation and accounting;
- development of a TSO–DSO user platform.

As part of CoordiNet, the demonstration began in 2019 at four Swedish pilot sites. The schematic diagram of the grid area participating in the flexibility scheme is shown below (Figure 2).

DSOs are divided into two levels: local DSOs (up to 50 kV) and regional DSOs (typically between 70 kV and 130 kV). Regional DSOs have a contract at the connection level with the TSO, and local DSOs have a contract with the regional DSO, which determines the amount of power they can consume/produce. If DSOs exceed a pre-determined limit, they must pay a penalty. Previously, DSOs could temporarily request an extension of the limits, but more recently, the TSO has denied the request to do so. During the winter, DSOs use flexibility services to reduce peak demand [24], [25].

On the flexibility platform developed within the project, each FSP must provide the following data in terms of their resources [26]:

- maximum power;
- minimum power;
- power step;
- minimum duration of the offer.

In addition, each source has a contribution factor (or sensitivity factor) for each substation participating in the same market. These values determine the effect of a particular source on a given substation, e.g. [26]:

- 1 – Full effect (changing the power of a given source at the substation creates the same change);
- 0.8 – Source has reduced impact on substation (20% effect reduction);
- 0.37 – The source has a low impact on the substation (63% effect reduction);
- 0 – The source has no effect on the substation at all.

It can be seen at the bottom of Figure 3 that both the original (in square brackets) and the contribution factor-reduced capacity (in green) of the given source are shown on the display. In the example above, the contribution factor for the flexibility source would be a cost of SEK 1000/0.61 = SEK 1639, but the value in square brackets should be taken into account as they represent the FSP offer. The contribution factors thus influence the emerging bid price order, as the selection of the winning offers is determined by the combination of price/MWh and the location of the flexibility source (in the form of a contribution factor).
For the first winter demo, the contribution factors were determined based on the overall grid configuration and typical high-load condition. However, according to the Vattenfall CoordiNet project team, in the long run it may be necessary to determine the contribution factors according to the different expected load conditions, which would require further development of the platform [24], [26].

1) SELECTION OF OFFERS
The optimal selection of offers is aided by an algorithm jointly developed by the project ENKO (ENergie intelligent KOordinieren) and the company E.ON, which makes a proposal for the DSO to acquire the right capacities. The DSO may wish to use a flexibility service only if it is less costly to obtain than the penalty for exceeding the pre-determined power limit mentioned earlier. At this point, the algorithm recommends that no flexibility service be procured [26].

It is also possible to set a safety margin for time and quantity (Figure 4). Using these, the algorithm suggests obtaining additional flexibility in terms of both duration and quantity [26].

The CoordiNet project developed a proper method to quantify the effects of spatiality in flexibility activation. In this paper, we applied the concept on real-life Hungarian network models to assess the replicability of the method.

III. CASE STUDY CIRCUMSTANCES AND FLEXIBILITY MODELLING METHODOLOGY
A. TYPICAL HUNGARIAN GRID CONGESTIONS
In Hungary, the 132 kV main distribution network has a typically looped design. The medium voltage network is a 11 kV cable network in the inner city and a 22 kV overhead network in the suburbs and rural areas. These are usually ring-shaped and operated radially. Individual consumers are supplied from the 0.4 kV overhead or cable radial network. Overload is currently the problem in cable networks, while voltage drops above the limit are common problems in overhead lines. Hungary has ambitious PV production goals in the National Energy and Climate Plan [5]. Until 2030, the built-in PV capacity is expected to be more than the peak load (7.1 GW), from the current 3.5 GW value.

Table 3 gives an overview of the network problems caused by the production units at each voltage level in the distribution network and the possible solutions.

B. SIMULATION STUDIES ON THE SAMPLE NETWORKS OF THE HUNGARIAN DISTRIBUTION GRID
In the course of this research, studies were performed for two selected technical problems, for the mapping of a potential flexibility product that would provide compensation for the voltage drop and reduction of the load of the HV/MV transformer on models selected from the representative sample networks characterizing the Hungarian distribution network. Voltage drop on the MV lines must not be more than 5% even in the highest loading conditions. Meanwhile, the overloading of substation transformers is a quite usual practical case. However, the operation limits could differ country by country. In this case, only the effect of the flexibility activation was considered. These two issues are the most common ones from the practical point of view in the country. The aim of this study was to determine the contribution factors of the FSPs based on sensitivity and their topological location, as well as
to study their variability. In the case of the tests to compensate for the voltage drop, the subject of the analysis was, among other things, whether the tests performed at the HV/MV substation level in the CoordiNet project can be interpreted in the case of MV line problems as well, so this study extends the aforementioned developments. The focus was to check that all the assumptions (e.g. variability of the contribution factors) used in previous research are applicable for the cases which are quite common in countries with different grid characteristics.

In our study, only products of active power were considered. While U-Q control proves to be effective at high voltage, the impedance attributes limit the possibilities at the MV and LV level. While in certain cases it will still be effective, in this research the focus is on the FSP effects. Thus, for the sake of simplicity, only the active power changing capacity was analyzed. From the technological point of view, the two cases are different. In the case of the long MV line and the voltage drop issue, demand response was used to relieve the loading (therefore, limiting voltage drop). In the case of the transformer overload, the FSPs were the PV plants themselves.

The simulations were performed using the DigSILENT PowerFactory software. The computer models of the networks were prepared by the author of [27] on the basis of the study [28], which describes a possible way of grouping the sub-networks of the MV distribution network in Hungary. As a result of the clustering procedure [28], 6 different groups were formed, which cover the majority of typical Hungarian network structures. Then representative sample networks were selected that could be used for the simulations applicable to many usual areas (Figure 5).

Out of these descriptive networks, the Cluster 1 network model was used for the voltage drop compensation; and to reduce the load of the HV/MV transformer, Cluster 4 network model was applied. Thus, characteristic problems were analyzed on characteristic models; the voltage drop on a long overhead line, and the overload in the case of a short cable network.

1) SIMULATIONS FOR COMPENSATION OF VOLTAGE DROP
During the simulations, 1-day, minute-resolution data was used. The consumption of the LV supply areas (aggregated to MV/LV transformers) was adjusted based on real measurement results from different areas. In each simulation, the script assigns a specific profile to a specific LV consumer area and, after parameterization, yields the grid conditions for each minute of the day by running load flow calculations.

To create a voltage drop issue, the initial load condition was increased to reach the 5% limit (5/3 increase was needed with the regular loading profiles). In this increased load condition, the maximum voltage drop during the day at the node of the largest voltage drop is 5.14% (Figure 6), which exceeds the limit set in the distribution regulations, so the application of flexibility even has a practical advantage if the loading increases such way. There are e.g. holiday areas in the country where such load increases seasonally observed in recent years.

To solve the network problem, 20 flexibility service providers (FSPs) (marked in red) were placed at different points in the network heuristically, as illustrated in Figure 7. Note that this topology is the Nr. 5. sample topology from Figure 5, and Figure 7 only describes the topology and the position of the connected FSPs (numbered accordingly). The HV/MV substation is denoted with an external grid element (crosshatched rectangle at the bottom), concentrated loads (MV/LV secondary substations aggregated) are denoted by the usual triangle symbols. The purpose with such figures is to show only the technology and allocation of the FSPs, the detailed technical attributes can be found in [27], [28], and [29]. In case of the topologies concerned in this paper, the HV/MV substation is placed on the bottom of the topology
TABLE 3. Fig. 1. Technical problems and possible solutions for production control.

| Phenomenon | HV | MV | LV |
|------------|----|----|----|
| Feed-in from directly high-voltage connected power plant | Point-to-point supply at the connection point or several power plants with higher built-in power on the line, typically intermittent voltage-increasing effect | Voltage-increasing effect at connection point (due to usually high R/X ratio) |
| Problems caused | • Maintain the busbar voltage limit | • Voltage-increasing effect at the connection point, or voltage drop, violation of the voltage limit value problem outside the production period (usually on overhead power lines) | • Voltage value limit violation |
| | • Reversing power flow directions (protection) | • Limit violation at another point on the affected line | • Cable overload |
| | • Delivery problems, congestions | • Reversing power flow | • Transformer overload |
| | • Limit violations in n-1 states | • Overload (typically on a cable network) | • Reversing power flow by circuit, per transformer area |
| | • HV/MV transformer settings | • Limit violation on built-in power | • Distortion in harmonics |
| | • In the case of HV/MV transformer, the control range may be insufficient | • HV/MV transformer can no longer compensate voltage fluctuations, which appear on LV as well |
| Possible solutions | Restriction of production | Restriction of production | Restriction of production |
| | • With schedule | • With schedule | • By measurement P(U) |
| | • By measurement P(U) | • By measurement P(U) | • Consumer influence |
| | • Based on external control signal (open loop, closed loop) | • Based on external control signal (open loop, closed loop) | • Energy storage |
| Production control | • Involvement in system-level services (busbar voltage control with reactive power) | • cosφ(P) | • Can be interpreted by the function of topology |
| | • cosφ(P) | • Fixed cosφ | |
| | • Q(U) | • Fixed Q | |
| | • With energy storage | | |

As a result of the voltage drop compensating effect of activating FSP1, the maximum voltage drop during the day at the node in question is 4.92%, so activating the flexibility solves the technical problem.

The contribution factors of the other FSPs are calculated relative to the rate of voltage rise generated by activating FSP1 as follows.

The voltage rise \( \Delta u_{\text{corr FSP,1}} \) is generated by activating FSP1:

\[
\Delta u_{\text{FSP,1}} = u_{\text{corr FSP,1}} - u_{\text{base}},
\]

where: \( u_{\text{corr FSP,1}} \) is the voltage on the node if FSP_1 is activated;

\( u_{\text{base}} \) is the voltage originally present (without FSP activation) at the problematic node where the voltage drop issue needs to be solved (still the same node).
Contribution factor $s_{FSP_1}$ for FSP_1 is:

$$s_{FSP_1} = 1$$  \hspace{1cm} (2)

The $x^{th}$ voltage increase during activation of FSP on the node problematic node ($\Delta u_{FSP,X}$):

$$\Delta u_{FSP,x} = u_{corr,FSP,x} - u_{base},$$  \hspace{1cm} (3)

where $u_{corr,FSP,x}$ is the voltage when the $x^{th}$ FSP is activated on the node in question and $u_{base}$ remains the same as in (2). The $x^{th}$ FSP contribution factor ($S_{FSP,X}$) is:

$$S_{FSP,x} = \frac{\Delta u_{corr,FSP,1} - \Delta u_{corr,FSP,x}}{\Delta u_{corr,FSP,1}}$$  \hspace{1cm} (4)

Figure 8 shows the range of contribution factors for each FSP during the day by the simulation. The y-axis shows the contribution factor values (relative to FSP1 which is always 1). Due to variations in the loading conditions, each FSP (listed on the x-axis) have an interval of the varying factors.

Different load conditions have different contribution factors. It can be observed that their ID volatility can be as close as 10%, which can affect market efficiency. Therefore, in the case of products intended for voltage regulation, the effect of contribution factors on the given network part during the preparatory tests must be taken into account. This is an important remark, since previous research pointed out that in the case of their products, the variation of the factors is negligible. Meanwhile in this case, due to the network attributes, the contribution factor variation is around 10%, which is not negligible anymore. This highlights the importance of considering the exact services and products of a flexibility platform when creating the technical calculation method behind the market activity.

Also, it is important to point out that contribution factors clearly make sense, since the difference between activating an FSP close to the HV/MV transformer (contribution factor under 0.3) and activating FSP1 is obvious. The latter is more than 3 times more effective relatively; therefore, it can solve the network issue with less flexibility. This underlines the spatiality of flexibility in voltage control products of long overhead MV line networks.

When maximum voltage drop occurs during the day, 5 different contribution factor groups can be distinguished according to topology location (Figure 9, marked with different colors and a demand response pictogram).
Based on the results, the FSPs which are located on the branch line with the highest voltage drop in the given load condition (marked in purple, zone A) have the highest effect on the network constraint. The contribution factor of the FSPs of the backbone line after the wing line (marked in yellow, zone B). The FSPs located on the wing lines closest to the HV/MV transformer have the lowest contribution factor (zone E), they do not reach 0.3 during the load conditions occurring in the simulation. In general, during the daytime load conditions, the contribution factor of FSPs that are not located on the wing line with the largest voltage drop does not exceed 0.5. Based on these, a possible conceptual bid price order (Merit Order List, MOL) is outlined for a case where a 0.2% voltage increase at a given node is required for a quarter of an hour (so the products here are a quarter-hour baseline power products).

Flexibility sources can participate in this market according to the contribution factor weighted MOL (Table 4, Figure 10). The offered capacity (MW) is multiplied with the contribution factor (effect of spatiality), which results in a MOL representative for the service, in this case the voltage drop compensation. In this conceptual case, FSP1 has a less flexible technology, therefore – even if seems very effective – cannot be chosen since other sources are cheaper for the DSO. Figure 10 shows the MOL graphically, the scattered red line indicates the need of the DSO.

C. IMPACT OF PV PRODUCTION ON CONTRIBUTION FACTORS

The effects of PV production were examined on the variability of contribution factors, for which the variation of contribution factors was examined during the day in the production of orange and then blue PVs, which were added in the same way as in previous research which analyzed the hosting capacity of this network (Figure 11) [27].

A representation of the altered contribution factor ranges is shown below (Figure 12). In both cases, it can be observed that the range of the contribution factor has widened for most
FSPs, but the extent of this depends on the location of the PVs for some FSPs. For FSP9 and FSP10, the range narrowed, but the highest contribution factor in the new ranges was smaller compared to the PV-free scenario. It can also be seen that for FSP4 and FSP7, the range did not change in either case. Thus, the increase in solar production clearly has a significant impact on the efficiency of products when controlling the voltage of overhead lines, which must be taken into account when designing the loads. This is also an important aspect when tailoring a flexibility need calculation in a given network area.

**TABLE 4. Example MOL [30].**

| FSP   | Power [kW] | Contribution factor (%) | Voltage drop compensating effect [%] | Price/q.m. hour [p/kWh] | Sensitivity weighted price [p/kWh] | Winning bid? |
|-------|------------|-------------------------|--------------------------------------|--------------------------|------------------------------------|-------------|
| FSP_1 | 200        | 1                       | 0.220                                | 24                       | 24                                 | No          |
| FSP_17| 200        | 0.500                   | 0.110                                | 6                        | 12                                 | Yes         |
| FSP_12| 200        | 0.455                   | 0.099                                | 5                        | 11                                 | Yes         |
| FSP_5 | 200        | 0.409                   | 0.090                                | 5                        | 12,2                                | No          |
| FSP_7 | 200        | 0.273                   | 0.060                                | 4                        | 14,7                                | No          |

**FIGURE 9.** Topological location of FSPs with different sensitivities – clustering of FSPs by topology.

**FIGURE 10.** Example conceptual MOL.

**D. HV/MV TRANSFORMER LOAD REDUCTION**

The effect of the flexibility sources on the reduction of the load of the HV/MV transformer and the load condition were investigated using the Cluster 4 sample network [23]. The following figure (Figure 13) shows the location of the FSPs on the network (numbered along the lines), this is the second usual use case regarding Hungarian MV networks, which is similar to other research projects.

The contribution factors of each FSP as well as their variability were examined similarly to the principle presented.
IV. CONCLUSION

In this paper, contribution factors were determined on two example MV networks according to the topological location. Further away from the HV/MV transformer on each branch is more variable and has higher effects than that of FSPs closer to the considered overloaded element (transformer) under different load conditions. In general, the effect of each FSP on the reduction of HV/MV transformer load depends on the load condition and the distance of FSPs from the transformer. In the case of the examined sample network, it can be said that their contribution factor is practically 1, and their variability according to the load conditions during the day is minimal. Based on this, the variability of the contribution factor in the case of transformer overloads and shorter cable networks is not critical. The results validate the concept of neglecting sensitivity factor changes during the day in other projects.
Based on the performed simulations, the following conclusions can be made.

In the case of voltage drop compensation studies, the values of the contribution factors show significant variability under different load conditions. This suggests that the development of flexibility platforms for such products would require the determination of contribution factors for all projected load conditions (or at least the variations should be taken into account), as this may affect market efficiency. It should be noted that this type of product is less common in pilot projects at the international level, so the variability of factors over time is neglected by the platforms. In this, the network congestions in Hungary may have a special need, which is also pointed out numerically in the present work. The simulations also showed that contribution factors can be clustered, and the closest FSP has the highest effect on the voltage drop. Meanwhile, in the other use case, namely the HV/MV transformer overload relief in short cable networks, simulations showed that the factors do not vary much in the different loading conditions. The farthest FSP has the largest effect (due to the implicit loss reduction with the activation), but the differences are negligible. This is in line with the international examples reviewed in this paper.

PV production causes the widening of the contribution factor range of FSPs in most cases. In the case of compensating for the voltage drop, its extent is not negligible, which also points to the direction of additional computational need. This paper reviewed important aspects of flexibility platform developments from the concept and definition to the state-of-the-art projects, and introduced the Hungarian context. The two use cases showed important remarks for the nuance in the calculation, which could make flexibility platform development more effective in every technical aspect.

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