The impact of local electricity markets on the operation and development of the distribution networks

Matej Pečjak
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
Matej.Pecjak@fe.uni-lj.si

Jernej Zupančič
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
Jernej.Zupancic@fe.uni-lj.si

Chloé Fournely
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
Chloe.Fournely@fe.uni-lj.si

Jan Jeriha
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
Jan.Jeriha@fe.uni-lj.si

Assoc. Prof. Andrej Gubina, PhD
Laboratory of Energy Policy,
Faculty of Electrical Engineering,
University of Ljubljana, Slovenia
Andrej.Gubina@fe.uni-lj.si

Prof. Boštjan Blažič, PhD
Laboratory of Electricity Networks and Devices, Faculty of Electrical Engineering, University of Ljubljana, Slovenia
Bostjan.Blazic@fe.uni-lj.si

***Abstract*—This paper discusses local electricity markets in relation to the operation of distribution networks. Distribution networks face several challenges, mainly related to the increasing number of generation sources and loads, such as heat pumps and electric vehicles that have been connected recently. The evolving local electricity market, where the traded commodity is not necessarily the energy itself, can have a major impact on the distribution network. Coupled with the smart grid solutions, the local electricity market can provide an alternative to costly network upgrades. An important aspect of local electricity markets is the interaction between the market and the network operator. To exchange information related to the network conditions Traffic Light System can be use. The impact of flexible devices that can participate in the local electricity market are illustrated for the case of Luče, Slovenia, where the establishment of local flexibility market, aiming to enable fair distribution of limited network capacities is under development as part of the X-FLEX project.**

Keywords*—*local electricity market, flexibility, traffic light system, distribution network, voltage deviations

I. Introduction

Evolving electricity networks face several challenges related to maintaining a secure and efficient supply of electricity to the end consumers. These challenges are mainly related to the increasing amount of decentralised renewable energy sources (RES) and increasing consumption of new loads, such as electric vehicles (EVs) and heat pumps (HPs). The transition to smart grids and changing requirements call for new control strategies. In the past few years a large amount of small, dispersed RES generation units has been connected to the distribution network and the trend is still increasing. Most low voltage (LV) networks are still designed only for conventional radial operation and the Distribution system operators (DSOs) need to address all the key challenges that arise in managing the network in order to ensure security of supply, power quality and the rapid resolution of potential disturbances. High RES generation can increase voltage profiles, cause system overloads, reverse power flows and power injection into the high voltage (HV) part of the network [1]. On the other hand, many EVs and/or HPs can cause undervoltage in case of inadequate control or simultaneous operation of most of the units [2]. However, the potential for providing flexibility by these loads is relatively high, which can mitigate the above-mentioned issues. Energy management systems can provide an advanced way of controlling flexible units to limit their impact on the network and to ensure energy supply during periods of high demand [3], [4]. To set up an effective system for the management and control of flexibility units, it is essential to have a detailed knowledge of the energy demand and the network conditions. One option to make the most of flexible devices and the existing network infrastructure is to create a local electricity market. Additionally, ancillary services for the DSO can be provided on the local electricity market, which can significantly impact the operation of the distribution network. However, it should be stressed that market-based ancillary services for the DSOs are a new concept that is still evolving [5].

The following section first describes the concept of local electricity markets, followed by a section on the Traffic light system (TLS), a key system of interaction between the network operator and the market operator. The design of local flexibility market and some tests of flexibility activation and their impacts on the distribution network model are presented for the case of Luče, one of the pilot sites in H2020 Compile [6] and X-FLEX [7] projects. To conclude, a discussion and the summary of the key findings are provided.

II. Local Electricity Markets

Several solutions for optimal usage of distributed energy resources exist. In general, these solutions can be classified into two groups: market-based and control-based methods [8]. Market-based methods include Local energy market (LEM), Local flexibility market (LFM) and Transactive energy (TE) systems [9]. LEM, to which also Local electricity market belongs, empower participants to trade with each other at the local level (neighbourhood, district, or community), mainly with the aim of reducing their costs of energy [8]. Local consumers and prosumers can trade among each other (peer-to-peer trading) or through an aggregator. For example, local peer-to-peer electricity trading can increase self-sufficiency ratio of the feeder to nearly 100% (by the increase of local supply-demand balance, it can increase self-consumption rates and decrease imports from the upstream network) [10].

Apart from the financial benefits for the market participants and increased self-sufficiency, local electricity markets can also contribute to better utilization of existing network infrastructure, RES and energy storage systems. With the use of decentralized trading, the electricity network can be fully or partially relived from congestions, voltage deviations and line losses. Consequentially, the network reliability and efficiency are enhanced [11], [12], [13], [14]. LFM is a subsection of LEMs, where the commodity is not the energy itself but flexibility [15]. Flexibility is any modification of generation or consumption schedules as a response to an external signal e.g. price signal or activation signal, to provide a service to the energy system [16]. LFM can support the operation of smart grids, whereby the cooperation between the market and the network operator is particularly important. Trading on a market platform rather than peer-to-peer enables the market operator to have a complete overview of the network status and define the best solution to benefit all contracting parties [17]. The important advantage of a trading platform over a simple technical management of the flexibility sources (e.g. Virtual power plant - VPP or Active network management - ANM) is the guarantee for end consumers to be empowered and protected in the market, as recommended by the EU [9].

Flexibility could have an impact not only on the short-term operation, but also on the long-term development of the network. Exploiting flexibility can defer some investment decisions while maintaining the quality and continuity of power supply. However, historic network planning and operation do not integrate local flexibility [5]. Market based procurement is not the only way the DSO can take advantage of flexibility, other ways include rules-based approach, bilateral agreements, or network tariffs [8]. Regardless of the flexibility procurement type, traditional DSO practices in the development and management of the distribution networks are competing solution, considering flexibility as a way to fix short-term problems rather than as long-term solutions for the network reliability [8]. The reason for this can be sought in the remuneration schemes of the DSOs, which is out of the scope of this paper. More recently, the focus has shifted towards systems with output-based mechanisms [18], which are more supportive of the use of flexibility.

Irrespective of the purpose of establishing a local electricity market, the interaction between the market operator and the DSO is crucial. The Traffic light system presented in the next section can serve the latter purpose.

III. Traffic Light System (TLS)

The information on the network conditions is important not only for system operator, but also for market participants. This is of much greater importance for the case of local markets, than for the case of wholesale markets due to the topology and branching of the network. To share the information on the network conditions the TLS following the traffic light logic can be used [19]. TLS serves as an interaction between the network operator and the market operator, ensuring that the market operator has all the information related to the network conditions and can adjust the market operation to support the operation of the network. Network conditions can be determined by power flow simulations (based on measured or forecasted inputs) and presented by one of the three stages: green, yellow (sometimes also amber) and red.

The **green stage** refers to network conditions where no critical situations exist. Trading on the market is done exclusively between non-regulated market participants and the benefits of the market come first, without regard to the network operation. In case the market is established for the purpose of allocating network capacities (for consumption and generation) among participants controlling flexible devices, green stage refers to conditions where network capacity limits cannot be exceeded and no market clearing is needed (everything is within the limits and excepted). If the market design does not foresee any feed-in tariff, the price for capacity use in this case is zero.

The **yellow stage** represents the level with a shortage (actual or a potential) in a particular part of the network. In the above-mentioned case of network capacities allocation, this means that the network operation is close to its limit and therefore not all requests for capacity activation can be accepted. In this case, market clearing is done in accordance with the market design, considering available capacities in the network as determined by the network operator.

In the **red stage,** the stability of the system and the security of supply are jeopardised. This means that the network conditions are violated and must be returned within the predefined limits. This can be achieved either by activating services offered on the market or by activating non-market capacities and other actions taken by the network operator. For example, if there is not enough generation to power all the loads (non-controllable and flexible), only offers to reduce power consumption are considered. On the other hand, if the generation from RES is higher than the total demand, only offers to increase power consumption are considered. Market operation in the red stage can be limited only to the provision of ancillary services to the network operator, which requires the latter to play an active role in the market. The aim should be to provide most of the services through the market and only if this is not possible should the network operator take non-market measures to solve the issues in the network.

A concept of the LFM, which aims to enable the distribution of limited network capacities and to provide ancillary services to the DSO is presented in the following section.

IV. Case Study

Within the X-FLEX project the implementation of LFM is under development for the case of Luče. Luče is a small village in Slovenia, whose inhabitants are very engaged in energy-related topics (first energy community in Slovenia set up under the Compile project [20]). Electricity network in Luče is characterized by a weak medium voltage (MV) line resulting in frequently limited RES production and frequent power outages due to congestions and weather events. Therefore, flexibility from different distributed resources, such as a community battery, home batteries, PV units and EVs will be used to allow for further RES penetration in the local LV network, to solve the congestions and to increase network reliability.

The purpose of the LFM in Luče is to demonstrate market-based distribution of limited network capacities for consumption and generation among the participants controlling flexible devices and to enable market-based procurement of ancillary services for the DSO. Implementation of local market in Luče will cover day-ahead, intraday and ancillary services market operations. The granularity of market products will be 15 minutes. Trading will be available via market platform, which will also include TLS. TLS stage of the network will be defined based on the power flow simulation results performed by the network operator. Day-ahead and intraday market will run in the green and yellow stage, while the ancillary service market will run in the red stage.

To demonstrate the potential of flexibility market and its effect on the network in question some test scenarios covering the change of demand and production power were prepared. The whole distribution network in Luče, connected to one MV/LV transformer, is comprised of more than 150 users. However, the implementation of local flexibility market will cover only nine of them, as they are the only ones that own flexible devices (PVs, EV chargers, and five of them also house battery), that allow external control so that practical testing is also feasible and foreseen. The users involved are connected to three feeders as presented in Fig. 1.

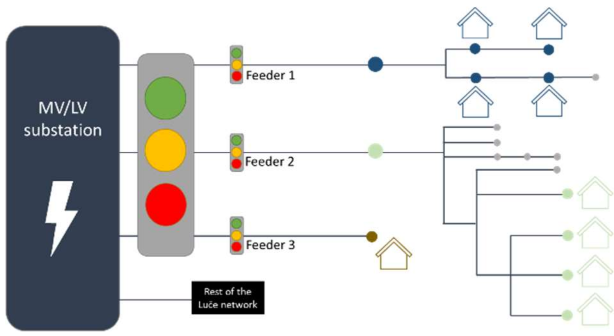

Fig. 1. Presentation of the tested network

The figure also presents the level of TLS, which will be implemented on both, the feeder and on the transformer level. Each feeder will present a trading zone for participants having control over flexible devices connected to that feeder. In the case of transformer overloading will also be considered.

Scenarios to test the impact of the use of flexibility on network conditions were defined on the basis of the first cycle of simulations, where each feeder entire demand was adjusted for 20% compared to the typical demand defined based on the measurements from the real network. In this case, network response indicated no significant deviation. The main reason behind this is the small deviation from the profile that is imposed upon the grid. Further testing was done for much higher deviations from the initial stage, but still considering real operating power of flexible devices owned by participating users. The scenarios tested included the activation of additional generation or consumption first at single location and later at all locations simultaneously, where the participating users are connected. Tested scenarios for Feeder 1 are presented in Table 1 and scenarios for Feeder 2 are presented in Table 2. Feeder 3 with only one individual user and the community battery connected was out of the scope of this analysis. For both feeders, scenarios from 1 to 8 cover only additional activation of consumption (+) or generation (-) per user and the last two scenarios in each table cover the whole feeder activation.

TABLE I. Scenarios for Feeder 1

Scenario	*Feeder 1*			
	User 1	*User 4*	*User 2*	*User 3*
1	+25.5			
2	-14.3			
3		+27.0		
4		-17.9		
5			+22.0	
6			-11.0	
7				+32.0
8				-20.8
9	+25.5	+27.0	+22.0	+32.0
10	-14.3	-17.9	-11.0	-20.8

TABLE II. SCENARIOS FOR FEEDER 2

Scenario	Feeder 2			
	User 8	User 7	User 5	User 6
1	+22.0			
2	-12.9			
3		+27.0		
4		-15.8		
5			+22.0	
6			-10.8	
7				+22.0
8				-11.2
9	+22.0	+27.0	+22.0	+22.0
10	-12.9	-15.8	-10.8	-11.2

All the scenarios were defined considering the rated power of installed devices (EV charger 22kW, PV 10.8–12.0kW and house battery rated power 3.5–10kW) owned by participating users. The proposed scenarios were tested trough power flow simulations on the detailed model of the network in OpenDSS. Same model of the network will also be used later during the real test of the market to defined available capacities in the network and to define TLS stage. The results of analysis are presented in the following section.

V. RESULTS AND DICUSSION

The additional activation of generation or consumption was performed only for the locations of participating users and the network conditions were analysed for all users connected to the same feeder. The main results of the power flow simulations were the voltages at each node of the tested network. Voltages for the first part of scenarios for Feeder 1 are presented in Table 3 and for the second part in Table 4.

TABLE III. VOLTAGES FOR THE FIRST PART OF SCENARIOS FOR FEEDER 1 [P.U.]

Scenarios / Users	0	1	2	3	4	5
User 1	1.03	1.00	1.05	1.00	1.05	1.00
User 2	1.03	1.00	1.05	1.00	1.04	0.99
User 3	1.02	1.00	1.03	0.98	1.05	1.00
User 4	1.01	0.99	1.02	0.95	1.05	0.99
User 10	1.01	0.98	1.02	0.95	1.05	0.99

TABLE IV. VOLTAGES FOR THE SECOND PART OF SCENARIOS FOR FEEDER 1 [P.U.]

Scenarios / Users	6	7	8	9	10
User 1	1.04	1.00	1.05	0.91	1.10
User 2	1.05	1.00	1.05	0.89	1.10
User 3	1.03	0.97	1.05	0.88	1.11
User 4	1.02	0.96	1.04	0.85	1.11
User 10	1.02	0.96	1.04	0.84	1.11

Blue colour indicates the activated nodes for each scenario. Activation of the entire feeder assets yields most voltage drop or increase, that is even out of the predefined boundaries of 0.9 and 1.1 p.u. In addition to the absolute values of the voltage at each node, deviations from the initial conditions were also calculated. These deviations for Feeder 1 are presented in Fig. 2.

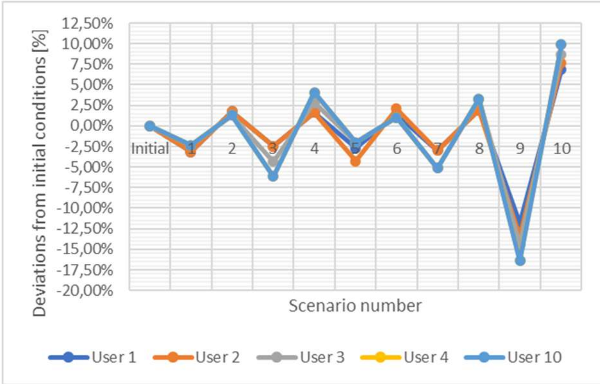

Fig. 2. Deviations from the initial conditions, Feeder 1 all scenarios

In the case of scenario 9, voltage drop at the node where User 1 and User 10 are connected, was more than 16%.

First part of results for Feder 2 is presented in Table 5 and the second part in Table 6.

TABLE V. VOLTAGES FOR THE FIRST PART OF SCENARIOS FOR FEEDER 2 [P.U.]

Scenarios / Users	0	1	2	3	4	5
User 11	1.03	1.01	1.03	1.01	1.04	1.01
User 12	1.03	1.01	1.03	1.01	1.04	1.01
User 13	1.03	1.01	1.03	1.01	1.04	1.01
User 14	1.03	1.01	1.03	1.01	1.04	1.01
User 15	1.03	1.01	1.03	1.01	1.04	1.01
User 16	1.02	1.00	1.03	0.99	1.03	1.00
User 5	1.01	0.99	1.02	0.99	1.03	0.98
User 6	1.01	0.98	1.03	0.97	1.03	0.99
User 7	0.98	0.95	1.00	0.87	1.04	0.96
User 8	1.01	0.97	1.03	0.97	1.03	0.99

TABLE VI. VOLTAGES FOR THE SECOND PART OF SCENARIOS FOR FEEDER 2 [P.U.]

Scenarios / Users	6	7	8	9	10
User 11	1.03	1.01	1.03	0.96	1.06
User 12	1.03	1.01	1.03	0.96	1.06
User 13	1.03	1.01	1.03	0.96	1.06
User 14	1.03	1.01	1.03	0.96	1.06
User 15	1.03	1.01	1.03	0.96	1.06
User 16	1.03	1.00	1.03	0.93	1.06
User 5	1.03	0.99	1.02	0.92	1.06
User 6	1.02	0.98	1.03	0.89	1.07
User 7	0.99	0.95	1.00	0.81	1.08
User 8	1.02	0.98	1.02	0.88	1.08

Also in this case deviations from the initial conditions were defined. The results are presented in Figure 3.

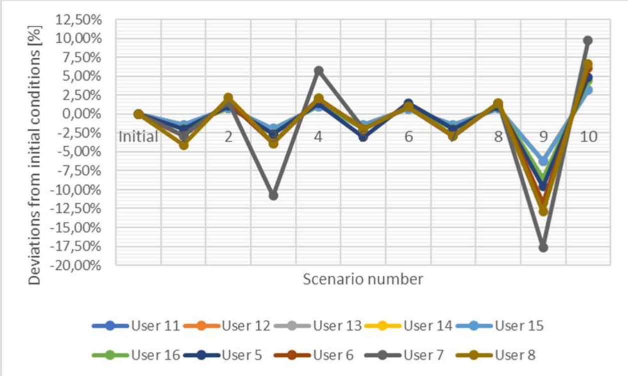

Fig. 3. Deviations from the initial conditions, Feeder 2 all scenarios.

In the case of Feeder 2, the location of User 7 presents the feeder critical location. With the whole feeder activation (Scenario 9), the voltage drops down for more than 17% which is, same as in the case of Feeder 1, a very severe network situation.

The results of power flow simulations show that simultaneous activation of units can lead to critical network conditions, which can be avoided by scheduling of flexible devices, considering limited network capacities. This is the aim of establishing a local flexibility market in Luče, which is also to be tested in practice with physical activation of the units. Final results are expected to be available at the end of the X-FLEX project in autumn 2023.

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