MARKET ENABLING INTERFACE TO UNLOCK FLEXIBILITY SOLUTIONS FOR COST-EFFECTIVE MANAGEMENT OF SMARTER DISTRIBUTION GRIDS

Deliverable: D9.4

Polish Demonstrator - Data collection, analysis and conclusions

Demonstration results assessment and data collection report

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D9.4	Demonstration results assessment and data collection report

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Abbreviations

AMI	Advanced Metering Infrastructure
AMS	Active Management System
BUC	Business Use Case
SLR	Static Line Rating
D	Deliverable
DER	Distributed Energy Resources
DLR	Dynamic Line Rating
DSO	Distributed System Operator
FMO	Flexibility Market Operator
FS	FlexStation
FSP	Flexibility Service Provider
LV	Low Voltage
MV	Medium Voltage
OLTC	Onload Tap Changer
PLC	Power Line Communication
POC	Point Of Connection
PV	Photovoltaic
RES	Renewable energy source
SS	Secondary Substation
SUC	System Use Case
UMEI	Universal Market Enabling Interface
ICUF	Installed Capacity Utilization Factor
WP	Work Package

Executive Summary

This deliverable has been formulated within the scope of the EUniversal project, which seeks to address existing limitations in the utilization of flexibility by DSOs for congestion and grid management. With a focus on aligning with the European approach, fostering harmonization, and establishing standards, one of EUniversal's objectives is to create and integrate a Universal Market Enabling Interface (UMEI). This interface aims to ensure system interoperability, enabling easy access to multiple flexibility market platforms and, consequently, to distributed flexibility.

Throughout the project, the UMEI undergoes testing in three European locations: Portugal, Germany, and Poland. The assessment involves examining its effectiveness in market-based flexibility procurement across various use cases.

This specific report pertains to the Polish Demonstrator and serves as a follow-up to deliverable D9.2 for the demonstration titled " Demonstration of grid observability and future networks supporting flexibility management via the UMEI", where the test framework and test scenarios were described. Deliverable D9.4 evaluates the project results, drawing conclusions based on the outcomes of the Polish EUniversal Demonstration. Additionally, this final report from WP9 outlines the lessons learned during the demonstration.

Demonstration results concern three basic issues:

- congestion management & voltage control with market-based active/reactive power flexibility,
- Congestion management using permissible line capacity based on the Dynamic Line Rating (DLR) system,
- Voltage Control with the use of FlexStation solution.

Each of these issues has been tested in real field conditions, however, where necessary, some parts of the test were done in a simulated environment. The results of the tests have been used for the Key Performance Indicators (KPIs) calculation. KPIs evaluation methodology has been outlined and in necessary cases, also validated according to the updated recommendations.

1. Introduction

1.1 Scope and objectives of this document

The purpose of this task is to validate the results, align the main findings with the previous background and describe the conditions for the use of flexibility in LV, MV and HV making use of the UMEI concept. This task is to ensure that all relevant data from the demonstration were appropriately collected, ensuring data availability and quality, and taking measures to mitigate possible problems during the demonstration operation regarding missing or flawed data.

The data obtained in this task, collected from the demo sites, and required for assessment versus KPIs defined in WPs 2, 3, 4 and 5 are also pre-evaluated in WP6, and aggregated and subject to further analysis in WP10.

1.2 Report structure

Chapter 2 provides an overview of Polish Demo activities, detailing the setup and objectives of various test scenarios.

The demo test results are thoroughly examined and quantified in Chapter 3. The demonstration phase involved testing a set of System Use Cases, each addressing specific functional elements within the broader flexibility value chain. This chapter presents the demonstration results aligned with the predefined system use cases and their associated KPIs from WP2 and WP6 of the project.

In the final Chapter 4, the key conclusions drawn from the Polish demo test results are presented. Additionally, there is a reflective analysis of the overall flexibility value chain. The insights gained from this demonstration will play a crucial role in supporting WP10 by contributing to the development of business models for leveraging EUniversal's outcomes. Furthermore, the findings will be used to provide recommendations for policymakers and regulatory authorities in establishing a framework for flexibility markets.

2 Demonstration activities

Field tests constitute an indispensable facet of the EUniversal project, serving as a pivotal mechanism for ascertaining the feasibility of elaborated tools and market solutions and substantiating the achievement of predefined objectives defined by KPIs.

The objectives of the Polish EUniversal demonstrator were as follows:

1) Facilitating the delivery of flexibility services utilizing the MV network infrastructure.
2) To ascertain the extent of flexibility in transmission capacity for HV lines using the Dynamic Line Rating (DLR) method.
3) To validate the concept of improving the observability and preparedness of the LV substation for its role in providing flexibility services.

The scope of the tests and the method of conducting them result from the previously defined SUC (System Use Case) and the control algorithms described in the project (D2.2). In particular, the following BUCs (Business Use Case) defined in Demo PL Table 2-1 were used.

Table 2-1 Business use cases covered by the testing scope

No.	Process/Activity	Business function
1	BUC PL AP/RP	Congestion Management & Voltage Control with market-based active/reactive power flexibility
2	BUC PL DLR	Congestion management using permissible line capacity based on Dynamic Line Rating (DLR) system
3	BUC PL FS	Voltage Control with the use of FlexStation solutions

To conduct the tests, procedures defined in Deliverable D2.3 as SUC (System Use Case) were used:

1) SUC 9 HV and MV network state forecasting based on load and weather forecasts.
2) SUC 10 HV and MV congestion detection and flexibility need identification.
3) SUC 11 Congestion management using permissible line capacity based on Dynamic Line Rating (DLR).
4) SUC 13 – Short-term flexibility procurement.

The tests resulting from SUC/BUC are specified in Table 2-2 and called the process tests. Other tests called performance tests were used to collect the necessary data for analysis and KPI determination.

Table 2-2 List of test scenarios

Scenario ID	Name	Test purpose and scope
Process tests		
Flexibility service tests		
ST_001	Obtaining active/reactive power flexibility	Management of constraints and voltage regulation to obtain active/reactive power flexibility
ST_002	Flexibility of transmission capacity of 110 kV lines	Management of transmission constraints using the permissible line load capacity based on the Dynamic Line Rating (DLR) system
Tests to increase flexibility services		
ST_003	Voltage control	Voltage control using FlexStation solutions
Performance tests		
ST_011	Correctness of DLR calculations	Determining the accuracy of line space location based on the weather forecast and predicted line load
ST_012	Reading data from AMI	Measurement of the quality of reading data from AMI meters
ST_013	Collision of reading with the AMI system	Identification of the impact of meter reading by SCADA on reading by CBP (Central Metering Database) AMI

All the tests specified in

Table 2-2 were performed in the test environment of the AMS system, and covered the following location specified in D9.2:

1) MV network
2) HV 110 kV network
3) LV FlexStation

The tests were carried out using the technical components listed in Table 2-3 and test applications according to

Table 2-4.

Table 2-3 List of technical components of the test environment

No.	Name	Type	Description
1	Switch server	Server	Auxiliary server for reading ZKB concentrators and writing data to controllers
2	Secondary server for data collection	Workstation	In the IEN office for data collection
3	ZKB concentrators in FlexStations	Device	ZKB concentrators device that reads and provides measurement data from meters
4	Controllers in Flex stations	IED device	Installation locations of the voltage control algorithm
5	SCADA servers' production	Server	SCADA servers - production in the Płock and Kalisz Branches
6	Demo system SN area Telemechanic server in RDM Gdańsk	Telemechanic server	User terminal for functional tests
7	Demo system Area 110 kV	Server	Project CDM Gdańsk Projekt CDM Gdańsk
8	Demo system DLR system (DOL)	Server	DLR system

Table 2-4 List of application components used in tests

No.	Name	Type	Description
1	Reading/writing voltage measurements	Application	Application for reading ZKB and writing to controllers
2	Voltage control	Module in the controller	Software that performs voltage regulation functions in the MV/LV station
3	DLR Application Modules	Application Set i	Software modules installed on the DLR server Data import from KK (*meas_import*), Import of current and forecast weather data (*wd_import* and *wd_forecast_import*), DLR calculations (*DLR-calc*)

According to the document "D6.2 Definition KPI for DEMOs", the common and demo-specific KPIs related to PL DEMO have been in this report evaluated, based on the performed tests.

2.1 PL specific KPIs

Item	Name	KPI Description	KPI Formula	Comments	Target
1	PL_KPI_1 – RES energy enlargement	RES generated energy above the connection agreement value.	$\text{PL KP1} = \frac{\Delta A_Y}{A_T - \Delta A_Y}$	ΔA_Y = Total yearly production above connection agreement	120%
2	PL_KPI_2 – Monitoring Information Categories	indication of the increase of data amount for newly monitored currents, powers, or voltages in primary substations, secondary substations, or customer-level	$MIC(\%) = \frac{MD_{Flex} - MD_{BAU}}{MD_{BAU}}$	MD_{BAU} - Total monitored data according to the count criterion in the BAU scenario	200%
3	PL_KPI_3 – Increased local PV hosting capacity	Flexible substations will allow for increased RES and DER hosting capacity	$\frac{P_{max}}{P_0}$	P_{max} = Maximum technically allowable PV installation capacity calculated with the presence of the flexible substation	130%
4	PL_KPI_4 – Fulfilment of voltage limits	to evaluate the power quality and quality of supply of distribution networks. The 95% percentage voltage value during the monitoring period in a selected critical point in the LV network will be measured after flexible substation installation with automatic control disabled	$V(\%) = \frac{V_{BAU} - V_{Flex}}{V_{BAU}}$	The 95% percentage voltage value during the monitoring period in a selected critical point in the LV network for the BAU/Flex scenario	2,5%

2.1.1 Common KPIs for the Polish demo

No	KPI ID	KPI name	BUC
1	CM_KPI_1	Flexible capacity vs. flexible volume offered ratio	PT1, PT2, PT3, PT4 PL AP, PL RP DE AP, DE RP
2	CM_KPI_2	Flex volume offered by FSP vs. Flex request by DSO	PT1, PT2, PT3, PT4 PL AP, PL RP DE AP, DE RP

3 Demonstration results

In the following sections, a description of the results obtained during the Polish Demo tests for each of the relevant System Use Cases is given. Where applicable, the results are quantified according to the Key Performance Indicators (KPIs) associated with each System Use Case. These KPIs are identified and described in deliverable D6.2.

3.1 BUC PL AP/RP Congestion Management & Voltage Control with market-based active/reactive power flexibility

3.1.1 Test description

The demonstration area and detailed test scenario, described in D9.2 chapter 2.1.1, covered two wind Farms, Biogas Power Plant, a few industrial customers, and the Flexibility Service Provider. The testing of the functionality of this BUC was split into the following tests:

- Network state forecasting based on load and weather forecasts,
- Congestion detection and flexibility needs identification,
- Market-based flexibility procurement on the NODES market platform via the UMEI.

Full monitoring of the area indicated above has been carried out since January 2023. All data were registered in the RDM Gdańsk SCADA system. No network restrictions were recorded during the entire period. Therefore, the tests had to be performed in simulation mode.

Based on recorded real data, the limitations were artificially induced by changing the parameters of the transmission line and cable sections and the topology of the MV network.

3.1.2 Test results

3.1.2.1 Network state forecasting based on load and weather forecasts

Estimating the future state of the network based on historical data and weather forecasts was the first step for subsequent calculations.

To calculate the future state of the network, static data describing the network model, such as parameters of wires, transformers, and topology, are needed. Additionally, historical data on flows and loads at individual points of the network are needed. The third essential element is weather forecasts.

The verification of the network state forecasting based on load and weather forecasts was done by checking on the graph the obtained results for selected measurement points. The forecasted values were within technically reasonable limits.

Forecasting the generation of wind farms may require an individual approach to each wind farm. In the tested case, the degree of correlation between the wind farms generated power and wind speed measured at ground level (7 meters above ground level) and the height of 100 m was calculated.

The heatmap in Figure 3-1 presents the correlation between wind farm power and various weather parameters, such as:

- ambient temperature [℃]

- wind speed at the ground [m/s] (Wind)
- wind speed at the ground squared $[m/s]^2$ (Wind ^{2})
- wind speed at ground level to the third power $[m/s]^3$ (Wind ^{3})
- wind speed at the 100m [m/s] - (Wind@100m)
- wind speed at the ground squared $[m/s]^2$ (Wind@100m ^{2})
- wind speed at ground level to the third power $[m/s]^3$ (Wind@100m ^{3})

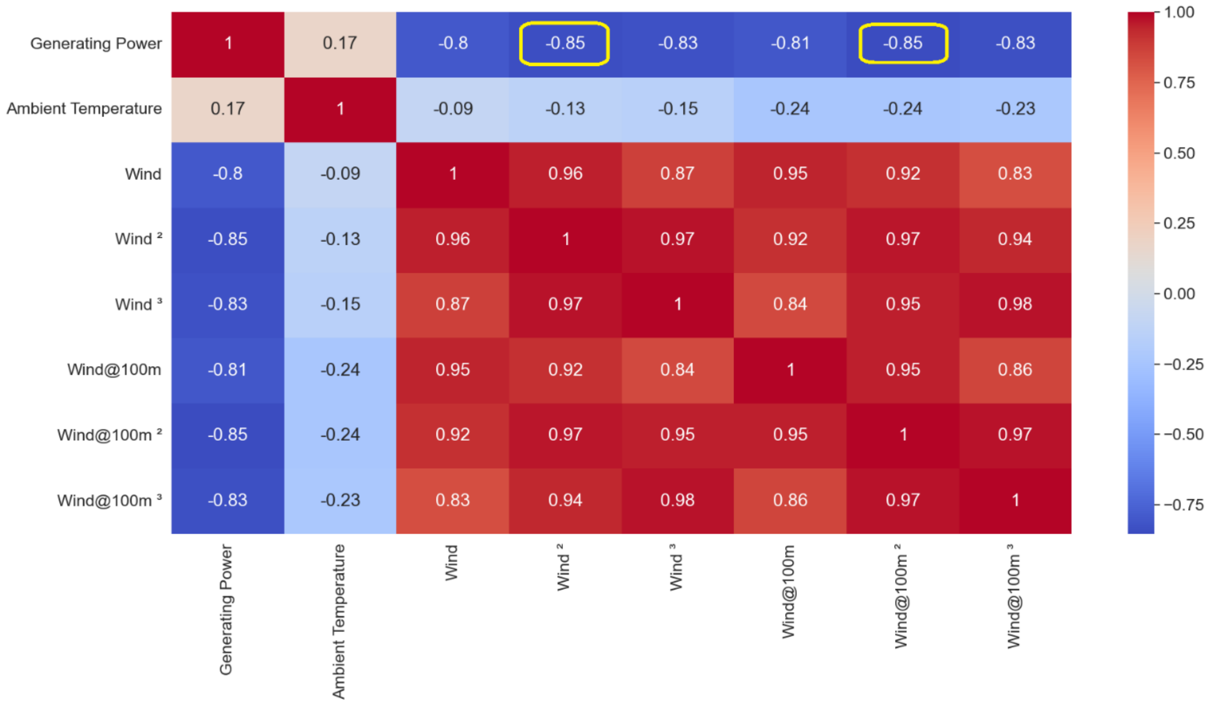


Figure 3-1 Heatmap – correlation between generated power and various weather conditions

A heatmap chart shows the correlation of all parameters, including the correlation of individual parameters with each other. From the point of view of selecting the most appropriate parameter for accurate estimation of wind power generation, the correlation between that parameter and different transformations of the wind speed is important. The different values of the correlation are placed on the first row of the presented graph.

The best correlation (absolute value closest to 1) occurs for the attributes "Wind^2" and "Wind@100m^2".

The negative values of the correlation coefficient linked to the ambient temperature resulted from the agreed convention of the direction of power flow: the negative sign means that power is generated, and the positive sign means that power is consumed.

Despite general knowledge indicating that the generated power is related to the wind speed in the 3rd power, in this case, the best degree of correlation was demonstrated by the wind speed at ground level in the 2nd power.

A detailed comparison between real wind farm generated power and wind speed at the ground level squared is depicted in Figure 3-2. The scale of the wind speed squared was so fitted to show the coincidence of both characteristics.

Figure 3-3 shows the comparison between recorded wind farm-generated power and the power forecasted. The differences between these values are negligible.

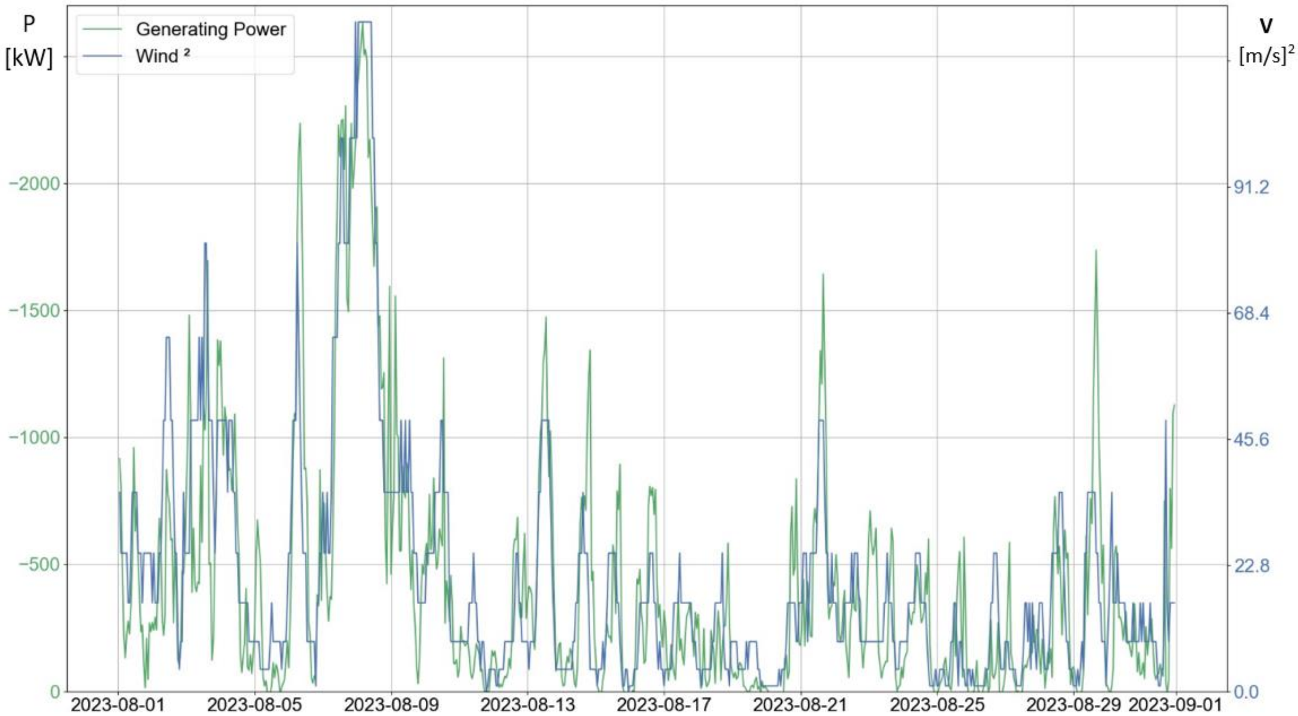


Figure 3-2 Comparison between real wind farm generated power and wind speed at the ground level squared

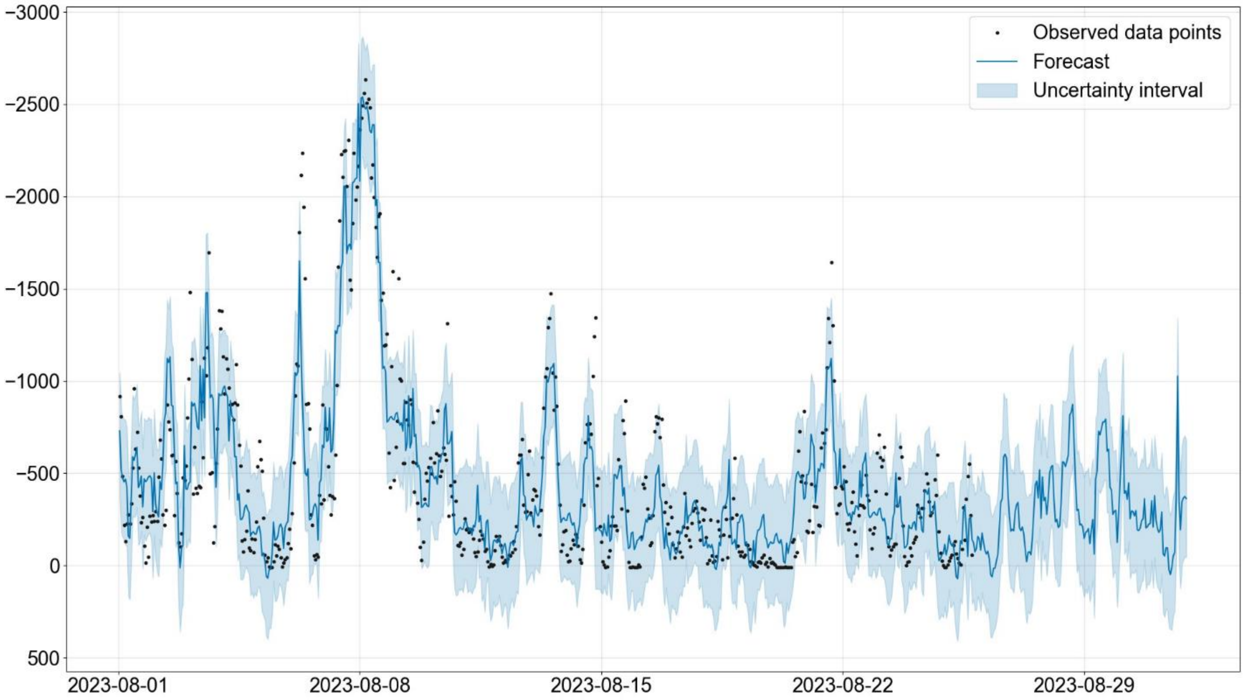


Figure 3-3 Comparison between recorded wind farm-generated power and the power forecasted

3.1.2.2 Congestion detection and flexibility needs identification

Congestion detection and the demand for flexibility services are based on the forecasted generation and load values in the power network, determined by the previously described methods.

The power flow (PF) module was used to detect the overloads. Calculated (forecasted) power flows are compared with the rated data of individual elements of the network, such as cable/overhead lines, and transformers. Congestion detection and the demand for flexibility services are based on the forecasted generation and load values in the power network, determined by the previously described methods.

For the test case in the simulation mode, the following modifications in the power flow model were introduced:

- the current carrying capacity of the cables was reduced,
- the value of generation from wind farms was increased (in some cases several times) while maintaining the rated generation values.

The modification aims to examine how the cable allowable current can limit the wind farm generation thus procuring the need for flexibility services from the DSO side.

The detailed testing procedure was as follows:

1) The current carrying capacity of the cable was reduced from its nominal permissible current of 320A to 120A.
2) The generation values of selected wind farms were modified. In the examples below, the measurement values have been multiplied by 4 and truncated to the nominal powers.
3) An estimation of loads and generation was carried out for a given period, and the power flow calculation was activated. As a result, the places where overload occurred were pointed out.
4) The next step was to launch the network optimization process with the objective function of releasing the overload of the cable using the generation of wind farms as the decision variable. Such restriction caused the reduction of the possible generated power from 3 MW to 2 MW and from 1,5 MW to 0,4 MW in the case of another wind farm.

Figure 3-4 and Figure 3-5 show how the cables' allowable current limits influence the wind farm generation of the two wind farms for 1 week and 1 month respectively.

The upper parts of the charts present wind farm generation of the two selected wind farms: WF Łebcz (red colour) and WF Połczyno (green) in case of no restriction on cable allowable current and case of the restriction. In each case, the value marked in a darker colour is the value before optimization, while the lighter colour is the suggested value after optimization, eliminating exceedances in the network.

The middle part of the chart, called overload [%], presents the current in two selected cables in % to its nominal rating. Nominal rating values were reduced for the test purposes from real 320A to 120A and 120A was taken as the reference 100% value.

For such a test case the cable current capacity limits the wind farm generation which has to be decreased to a value that does not produce the cable overload.

The current values before optimization are marked in a darker colour, while after optimization, in a lighter colour.

The lower part of the chart is named the FSP Act. [MW], shows the generation reduction values of the previously mentioned wind farms, caused by cable load limit. These values were sent to the NODES platform and then successfully matched with the offers of individual FSPs, which consequently led to the creation of a transaction.

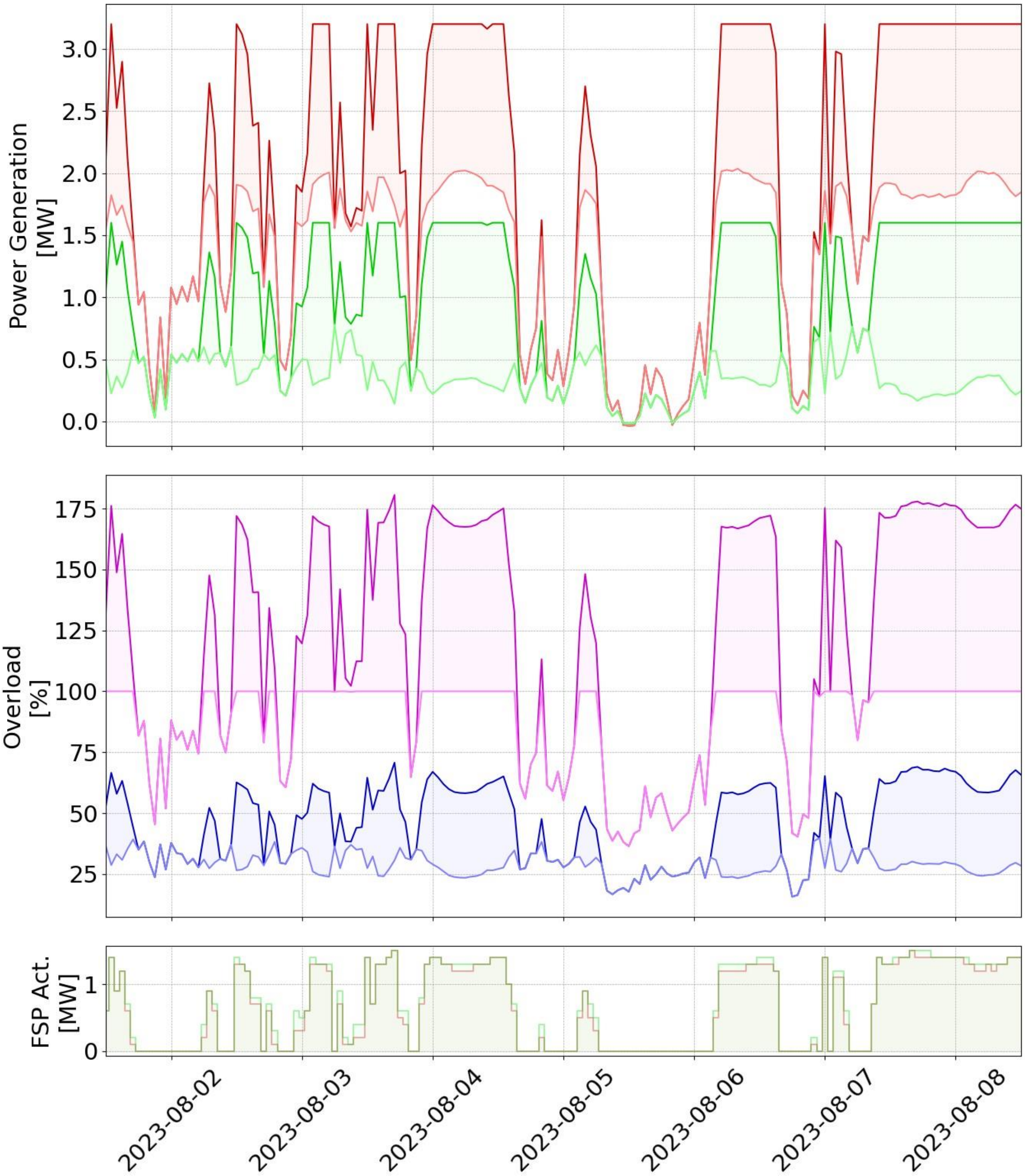


Figure 3-4 Wind farms' generation and cables' currents (in % of rated value) before and after rated cable current reduction (1-week record)

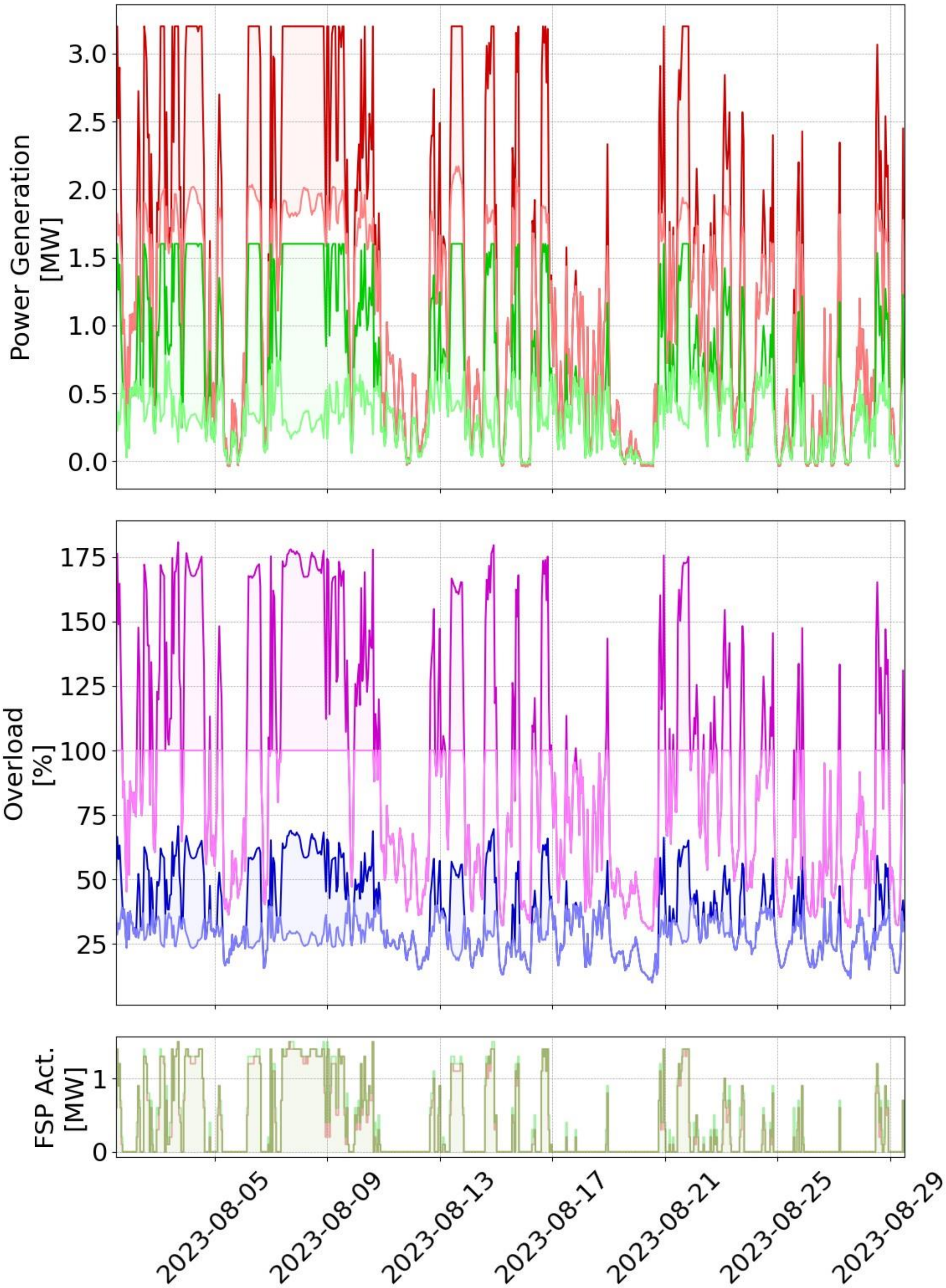


Figure 3-5 Wind farms' generation and cables' currents (in % of rated value) before and after rated cable current reduction (1-month record)

3.1.2.3 Market-based flexibility procurement on the NODES platform via the UMEI

NODES as an independent market operator provides the central environment for market-based procurement of flexibility in this Demonstrator ensuring correct and transparent transactions between buyers and sellers (without consideration of the post-trading activities, i.e., validation and settlement, as these functionalities are not yet implemented in the UMEI V01).

Market-based flexibility procurement on the NODES market platform via the UMEI used in the Polish Demonstrator ensured correct and transparent transactions between buyers and sellers. Using NODES integrated market design, shown in Figure 3-6, flexibility in the test condition was offered, allowing for efficient use of available flexibility resources across all grid levels.

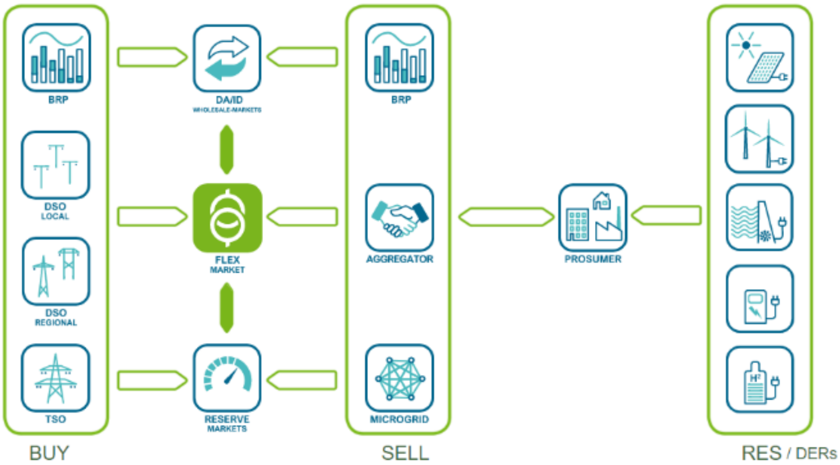
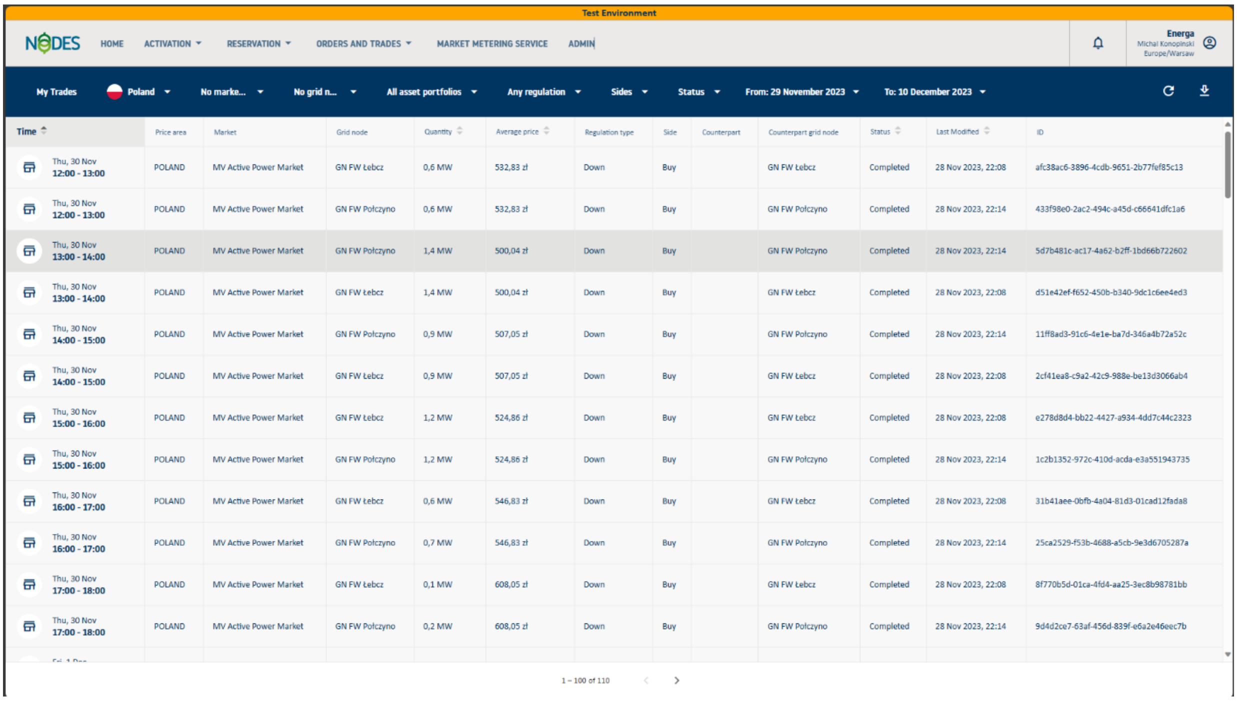


Figure 3-6 NODES integrated market design (www.nodesmarket.com)

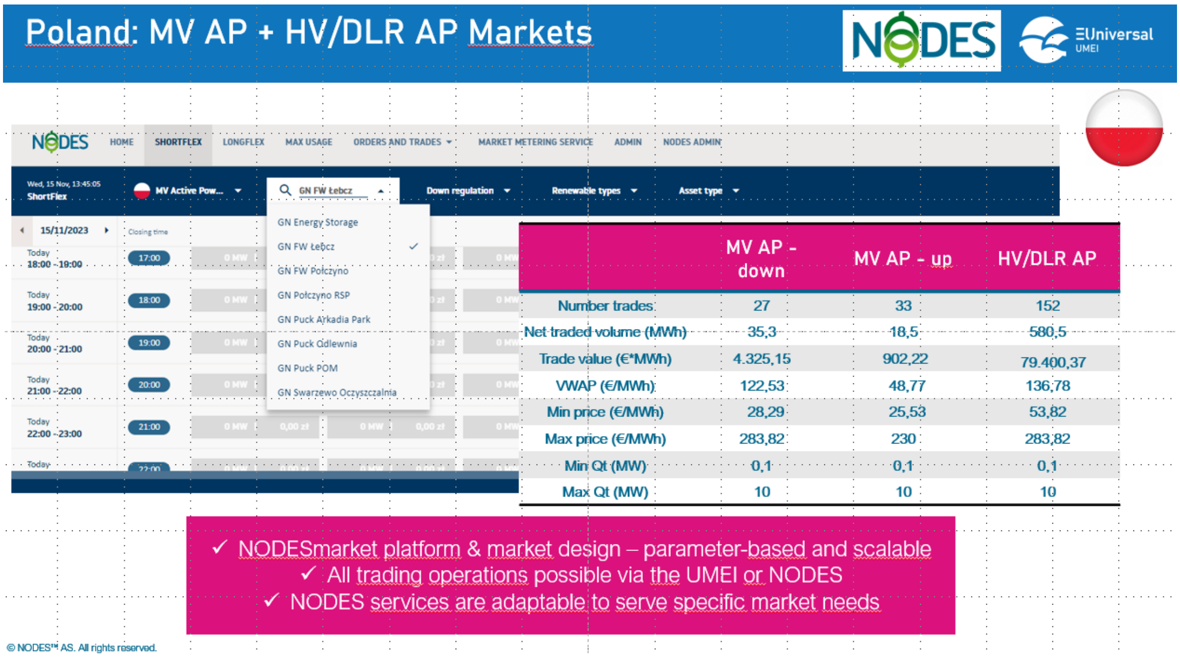
The screenshot Figure 3-7 shows an excerpt of the transaction record of the NODES platform corresponding to the flexibility related to the generation reduction values by two wind farms as shown in Figure 3-4.

The screenshot Figure 3-8 shows summarised transactions on MV and HV markets with the number of trades, net trade volume and values. Transactions on the HV market (HV/DLR AP) are explained in Chapter **Błąd! Nie można odnaleźć źródła odwołania.**.



Time	Price area	Market	Grid node	Quantity	Average price	Regulation type	Side	Counterpart	Counterpart grid node	Status	Last Modified	ID
Thu, 30 Nov 12:00 - 13:00	POLAND	MV Active Power Market	GN FW Łebcz	0,6 MW	532,83 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	afc38ac6-3896-4cdb-9651-2b77fef85c13
Thu, 30 Nov 12:00 - 13:00	POLAND	MV Active Power Market	GN FW Połczyno	0,6 MW	532,83 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	433f98e0-2ac2-494c-a45d-c66641dfc1a6
Thu, 30 Nov 13:00 - 14:00	POLAND	MV Active Power Market	GN FW Połczyno	1,4 MW	500,04 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	5d7b481c-ac17-4a62-b2ff-1bd66b722602
Thu, 30 Nov 13:00 - 14:00	POLAND	MV Active Power Market	GN FW Łebcz	1,4 MW	500,04 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	d51e42ef-f652-450b-b340-9dc1c6ee4ed3
Thu, 30 Nov 14:00 - 15:00	POLAND	MV Active Power Market	GN FW Połczyno	0,9 MW	507,05 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	11ff8ad3-91c6-4e1e-ba7d-346a4b72a52c
Thu, 30 Nov 14:00 - 15:00	POLAND	MV Active Power Market	GN FW Łebcz	0,9 MW	507,05 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	2cf41ea8-c9a2-42c9-988e-be13d3066ab4
Thu, 30 Nov 15:00 - 16:00	POLAND	MV Active Power Market	GN FW Łebcz	1,2 MW	524,86 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	e278d8d4-bb22-4427-a934-4dd7c44c2323
Thu, 30 Nov 15:00 - 16:00	POLAND	MV Active Power Market	GN FW Połczyno	1,2 MW	524,86 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	1c2b1352-972c-410d-acda-e3a551943735
Thu, 30 Nov 16:00 - 17:00	POLAND	MV Active Power Market	GN FW Łebcz	0,6 MW	546,83 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	31b41aee-0bfb-4a04-81d3-01cad12fada8
Thu, 30 Nov 16:00 - 17:00	POLAND	MV Active Power Market	GN FW Połczyno	0,7 MW	546,83 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	25ca2529-f53b-4688-a5cb-9e3d6705287a
Thu, 30 Nov 17:00 - 18:00	POLAND	MV Active Power Market	GN FW Łebcz	0,1 MW	608,05 zł	Down	Buy		GN FW Łebcz	Completed	28 Nov 2023, 22:08	8f770b5d-01ca-4fd4-aa25-3ec8b98781bb
Thu, 30 Nov 17:00 - 18:00	POLAND	MV Active Power Market	GN FW Połczyno	0,2 MW	608,05 zł	Down	Buy		GN FW Połczyno	Completed	28 Nov 2023, 22:14	9d4d2ce7-63af-456d-839f-e6a2e46eec7b

Figure 3-7 Screenshot with the transaction record related to the generation reduction



	MV AP - down	MV AP - up	HV/DLR AP
Number trades	27	33	152
Net traded volume (MWh)	35,3	18,5	580,5
Trade value (€*MWh)	4.325,15	902,22	79.400,37
VWAP (€/MWh)	122,53	48,77	136,78
Min price (€/MWh)	28,29	25,53	53,82
Max price (€/MWh)	283,82	230	283,82
Min Qt (MW)	0,1	0,1	0,1
Max Qt (MW)	10	10	10

Figure 3-8 Screenshot with summarised transactions on the MV and HV markets

3.1.3 KPIs calculation - CM_KPI_1 & CM_KPI_2

3.1.3.1 CM_KPI_1 Flexible capacity vs. flexible volume offered ratio

In the Polish demonstrator, CM_KPI_1 was calculated as it was originally planned i.e., as the ratio of the amount of flexibility offered by the FSP to the overall amount of flexibility registered.

The existing MV test area infrastructure including lines, network topology and nominal RES power, is quite sufficient for the generation and transfer of the power to the customers. Thus, it was assumed that the whole flexibility capacity registered would be offered on the marketplace. In that case CM_KPI_1 = 100%

In the simulation mode, by changing the network topology and limiting the current carrying capacity of the selected cables, a potential for offering the flexibility of the generation sources (wind farm) was created. Flexibility service related to decreasing the generated power by the wind farm has been registered and offered on the flexibility market via UMEI.

3.1.3.2 CM_KPI_2 Flex volume mobilized

CM_KPI_2 is used to assess to which extent the market has been able to mobilize flexibility from the network area. It measures the quantity of flexibility available in the market and is calculated as the overall sum of flexibility available.

The definition and calculation of this KPI have changed concerning the CM_KPI_2 as defined in D6.2. An extended explanation of this KPI is given in the final version of D6.3.

Taking into consideration the existing MV test area infrastructure in the Polish demo it is imaginable that a kind of downward flexibility could be needed. It means that in some network conditions, the decreasing of the generated power from flexible assets might be necessary due to MV network elements' (lines and cables) allowable current capacity. All tests were performed in simulation mode. The restrictions were caused by artificially changing network parameters. Then, the possibility of their liquidation was simulated by using the potential of flexibility services. These calculations were based on actual historical data. Since the NODES platform operates in real-time, it was not possible to link the removal of restrictions with offers introduced to the NODES platform. Therefore, it was not possible to link the amount of flexibility requested by the DSO with the amount of flexibility offered by the FSP. Therefore, it is not possible to determine CM_KPI_2.

3.2 BUC PL DLR Congestion management using permissible line capacity based on Dynamic Line Rating (DLR) system

3.2.1 Test description

The basic assumption for the test:

Grid selection according to D9.2 chapter 2.1.2 with the following 110 kV network elements

- the interconnection of the lines starting from the substation 400/220/110 kV Dunowo-> Ustronie Morskie → Kołobrzeg Koszalińska → Kołobrzeg VI D.P -> Trzebiatów,
- two wind farms: WF Kukinia and WF Karścino taking part in the test and are entitled to issue the buy order on the Nodes platform in case of forecasted generation above the power greater than the connection agreement power,
- another 3 WF deliver the power to the a/m interconnection: (Biesiekierz) 15 MW, Słupia- 23,4 MW and Tymień 48MW.

The date for the test was selected when the expected wind velocity was above 10m/s which allows for the wind farm generation close to their nominal installed power value i.e., WF Kukinia = 52,9 MW and WF Karścino = 51 MW.

Two test scenarios are assumed, differing in 110 kV network configurations which results in the directions of power flow from the WF:

1) Interconnection of the lines are linked only with the substation Dunowo – one-way direction power flow to Dunowo,
2) Interconnection of the lines are connected on both sides to the 110 kV network i.e., Dunowo and GPZ Trzebiatów (ENEA DSO) which also receives power from the wind farm. Two directional power flows i.e., towards Dunowo and GPZ Trzebiatów.

The projected permissible hourly load profile was calculated for all 110 kV lines managed by Energa-Operator (DSO) and used in the congestion management calculation program. The calculation process starts with a resolution adapted to the weather forecast update cycle (6 hours), and the time range of the hourly limit load profile is 72 hours. The main stages of the calculation process are:

1) Reading input data such as mechanical data of critical spans: span, the height of cable attachment points on both sides of the span, cable characteristics (diameter, cable type, cooling/heating factors) and cable pre-tension.

2) Selection of the weather forecast appropriate for the location of the critical span of the line.

3) Calculation of the permissible load in the forecast weather conditions using the thermal model of the line by CIGRE recommendations.[2].

4) Preview of the power flow results showing the forecasted power profiles for the line, considering the generation reported by the Kukinia WF, e.g., at the level of 52 MW
    - Dunowo-Ustronie Morskie
    - Ustronie Morskie - Kołobrzeg Koszalinska
    - Kołobrzeg Koszalińska -Kołobrzeg VI D.P.
    - Kołobrzeg VI D.P. –Trzebiatów

5) Initial adjustment of the constraints calculated in DLR and AMS to the line load profiles calculated in point 2 and transferring these new calculations to AMS.
6) Transfer of the calculation results to the Syndis AMS SCADA system for use by the program to calculate the flow in the 110 kV network, considering the determined permissible line loads.
7) Finally, the acceptable generation of the Wind Farm is calculated.

The process of handling the wind farm producer's notification of the intention to produce energy on contractual terms was supported by the NODES service platform used as part of the EUniversal project. The Universal Market Enabling Interface (UMEI) was used to test its applicability regarding information exchange and flexibility trading in various markets and market settings.

3.2.2 Test results

Tests were conducted from 07.08.2023 to 08.08.2023. The selected parties involved in the trial were ENERGA, the seller of the flexibility services, WF Kukinia and WF Karścino, acting as the buyer. During the test run the duties of the buyer were simulated, but real needs and the testing environment were arranged including real weather condition forecasts and expected (calculated) power flow.

Two use cases were considered: the first use case happened on Day 07.08.2023 when the power flow from Wind Farms was in the one-way direction i.e., toward 220/110 kV substation Dunowo and the second use case on Day 08.08.2023 when power flow from Wind Farms was in the two directions i.e., toward 220/110kV Substation Dunowo and GPZ Trzebiatów substation.

3.2.2.1 Use case 1: 110 kV lines with one-way direction power flow

The weather conditions along the line on Day 07.08.2023 when the power flow from Wind Farms was in the one-way direction i.e. toward 220/110 kV Substation Dunowo are presented in Table 3-1 and Figure 3-9.

Table 3-1 Weather conditions on 07.08.2023 along the lines

Time	Wind speed (7 m a.g.l)	Wind direction	Ambient temperature
	[m/s]	deg	deg
19:00	4,0	15	18
20:00	4,5	16	17
21:00	4,6	16	16
22:00	4,8	17	15
23:00	4,9	17	14
0:00	5,0	17	14
1:00	4,9	16	14
2:00	4,5	16	14
3:00	4,1	15	13
4:00	4,0	15	12

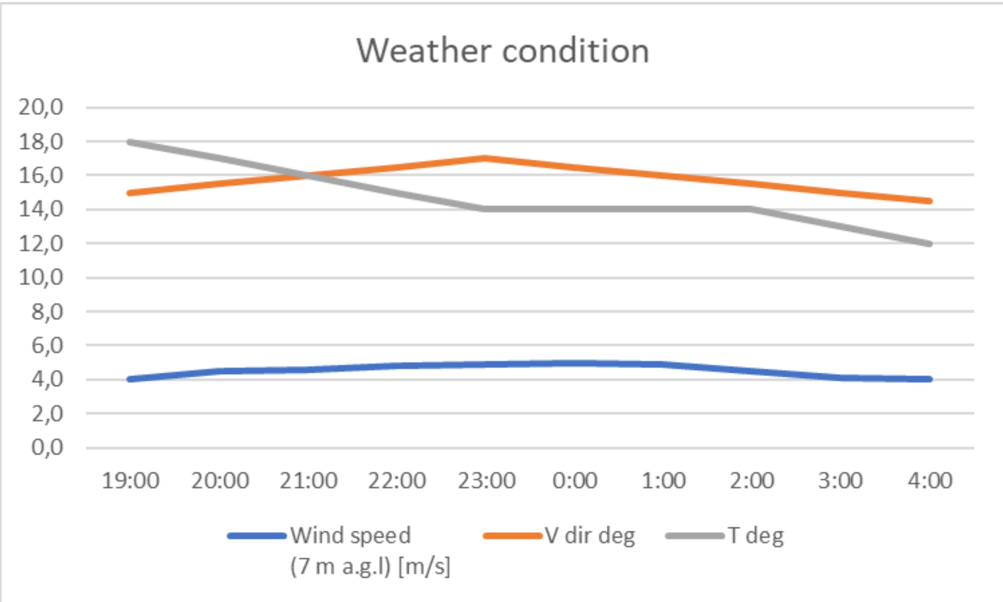


Figure 3-9 Weather conditions on 07.08.2023 along the lines

Dynamic line ratings for the specified lines resulting from the weather forecast are presented in Table 3-2 and Figure 3-10.

Table 3-2 Forecasted DLR and estimated power flow

Time	L7		L6		L5		L4		L3			L2		L1	
	TBT-KCO		KLG-KCO		KOK-KLG		KKA-KOK		USM-KKA			PNO-USM		DUN-PNO	
	DLR forecast	PF estimated	DLR forecast	PF estimated	DLR forecast	PF estimated	DLR forecast	PF estimated	DLR forecast	PF estimated	PF allowed	DLR forecast	PF estimated	DLR forecast	PF estimated
19:00	132	0	133	47,8	132	47,8	133	47,8	98,6	95,4	95,4	150	95,4	129	95,4
20:00	140	0	141	48,2	140	48,2	135	48,2	103,4	97,0	97,0	156	97,0	142	97,0
21:00	150	0	152	48,5	150	48,5	135	48,5	111,0	98,4	98,4	168	98,4	165	98,4
22:00	152	0	153	49,9	152	49,9	137	49,9	110,7	100,3	100,3	168	100,3	166	100,3
23:00	144	0	145	51,2	145	51,2	137	51,2	106,9	102,8	102,8	159	102,8	145	102,8
00:00	140	0	141	51,8	141	51,8	138	51,8	104,1	102,7	102,7	154	102,7	139	102,7
01:00	139	0	139	48,8	139	48,8	137	48,8	97,6	102,2	97,6	152	102,2	136	102,2
02:00	138	0	140	47,7	138	47,7	134	47,7	95,5	99,1	95,5	155	99,1	140	99,1
03:00	137	0	138	46,4	137	46,4	132	46,4	92,8	97,6	92,8	156	97,6	138	97,6
04:00	140	0	141	45,7	139	45,7	129	45,7	92,8	91,3	91,3	161	91,3	144	91,3

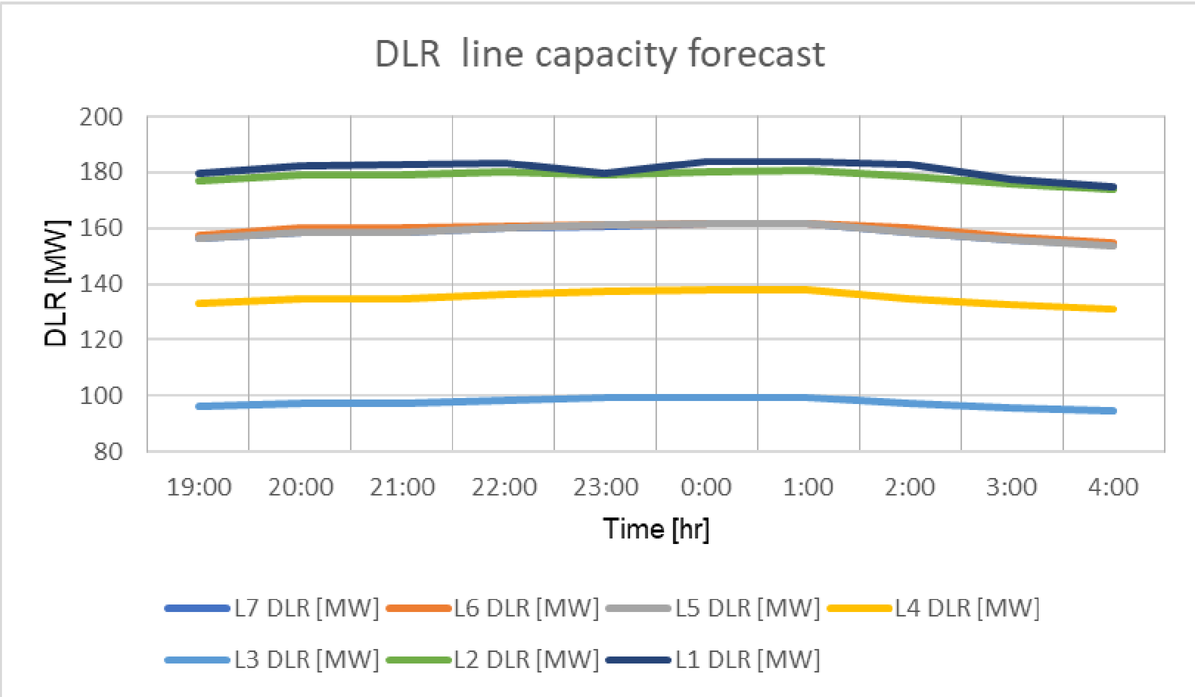


Figure 3-10. Forecasted DLR (07.08.2023)

The estimated power flow calculated by Power flow software in line 3 USM-KKA indicated that between 01:00 and 03:00 the estimated power flow exceeded the allowable power – DLR forecast. (marked with orange in the table) and in Figure 3-11.

The power flow calculation was conducted based on the anticipated wind farm power generation as outlined in Table 3-3. In the case where the estimated power flow on line 3 exceeds the permissible limit set by DLR, it becomes necessary to decrease the power generation at wind farm Kukinia to a level that adheres to these constraints. This adjustment is detailed in Table 3-3.

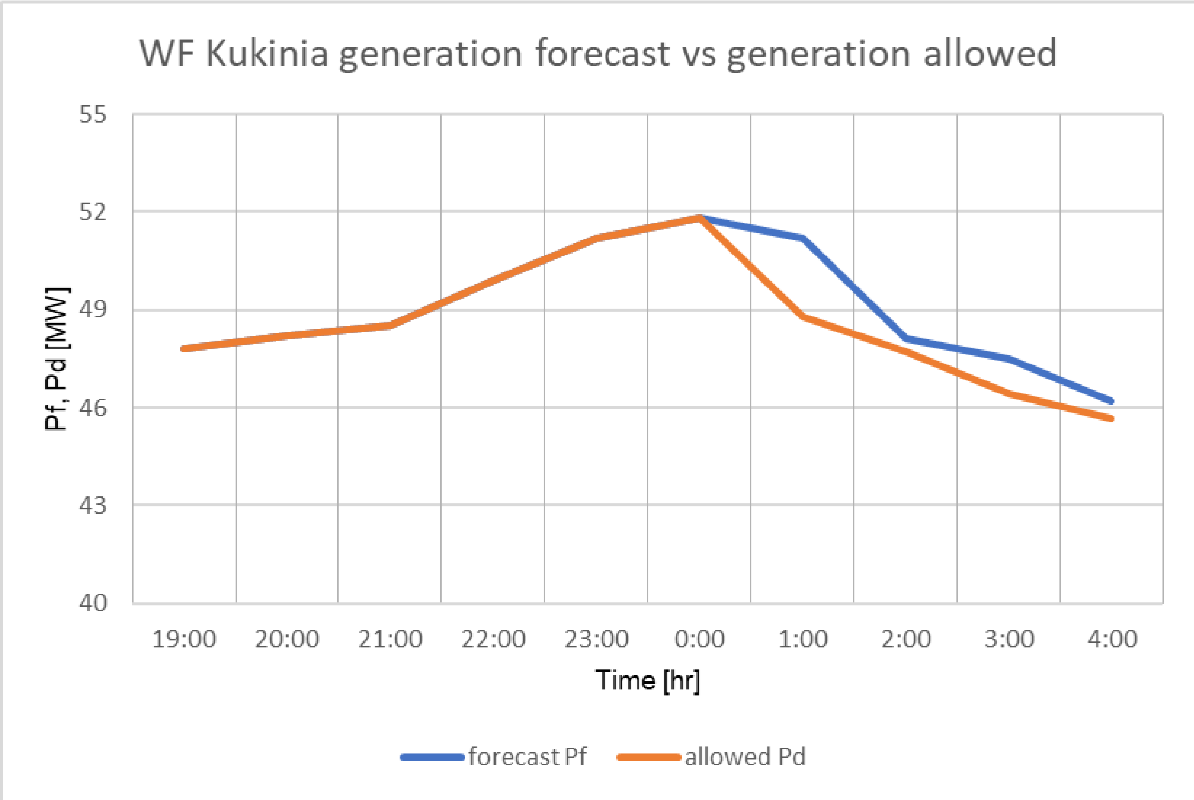


Figure 3-11. Wind farm Kukinia power generation reduction

Table 3-3 WF generation: forecasted vs. allowed

time	Wind speed	Wind Farm generation - one way direction power flow							
		KKA Kukinia (Pca=46MW/Pn=52MW)				KCO Karścino (Pca=47MW/Pn=51MW			
	[m/s]	forecast	allowed	Contract agreement	P_d-P_{ca}	forecast	allowed	Contract agreement	P_d-P_{ca}
	V	P_f	P_d	Pca	Surplus	P_f	P_d	Pca	Surplus
19:00	13	47,8	47,8	46,5	1,3	47,6	47,6	47,0	0,6
20:00	13,7	48,2	48,2	46,5	1,7	48,8	48,8	47,0	1,8
21:00	13,8	48,5	48,5	46,5	2,0	49,9	49,9	47,0	2,9
22:00	14,5	49,9	49,9	46,5	3,4	50,4	50,4	47,0	3,4
23:00	14,8	51,2	51,2	46,5	4,7	51,6	51,6	47,0	4,6
0:00	15,2	51,8	51,8	46,5	5,3	50,9	50,9	47,0	3,9
1:00	14,9	51,2	48,8	46,5	2,3	51,0	48,8	47,0	1,8
2:00	13,5	48,1	47,7	46,5	1,2	51,0	47,7	47,0	0,7
3:00	12,5	47,5	46,4	46,5	0,0	50,1	46,4	47,0	0,0
4:00	11,9	46,2	45,7	46,5	0,0	45,1	45,7	47,0	0,0
				Total	**21,9**			**Total**	**19,7**

3.2.2.2 Use case 2: 110 kV lines with two-direction power flow

The weather conditions along the lines on Day 08.08.2023 when the power flow from Wind Farms was two-way i.e., toward 220/110 kV Substation Dunowo and GPZ Trzebiatów are presented in Table 3-4 and Figure 3-12.

Table 3-4 Weather conditions on 08.08.2023 along the lines

Time	v7	V dir	T
[h]	[m/s]	deg	deg
19:00	5,2	15	18
20:00	5,5	15,5	17
21:00	5,5	16	16
22:00	6	16,5	15
23:00	6	17	14
00:00	6	16,5	14
01:00	6	16	14
02:00	5,5	15,5	14
03:00	5	15	13
04:00	4,6	14,5	12

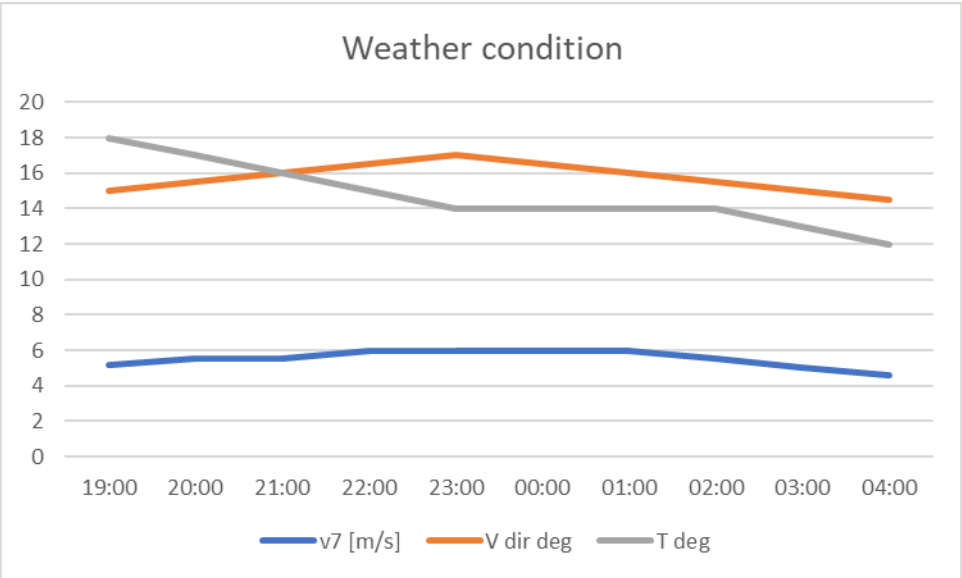


Figure 3-12 Weather conditions on 08.08.2023 along the lines

Dynamic line ratings for the specified lines resulting from the weather forecast are presented in Table 3-5 and Figure 3-13.

Table 3-5 Forecasted DLR and estimated power flow

Time	L7		L6		L5		L4		L3		L2		L1	
	TBT-KCO		KLG-KCO		KOK-KLG		KKA-KOK		USM-KKA		PNO-USM		DUN-PNO	
	DLR forecast	PF forecast	DLR forecast	PF forecast	DLR forecast	PF forecast	DLR forecast	PF forecast	DLR forecast	PF forecast	DLR forecast	PF forecast	DLR forecast	PF forecast
19:00	157	47,8	158	47,8	157	47,8	133	47,8	96	47,7	177	47,7	180	47,7
20:00	158	48,4	160	48,4	158	48,4	135	48,4	97	48,7	179	48,7	182	48,7
21:00	158	49,6	160	49,6	158	49,6	135	49,6	97	49,8	179	49,8	183	49,8
22:00	160	50,0	161	50,0	160	50,0	136	50,0	99	50,3	180	50,3	183	50,3
23:00	161	51,3	161	51,3	161	51,3	137	51,3	99	51,5	179	51,5	180	51,5
00:00	162	50,8	162	50,8	162	50,8	138	50,8	100	50,9	180	50,9	184	50,9
01:00	162	51,2	162	51,2	162	51,2	138	51,2	100	51,1	180	51,1	184	51,1
02:00	158	51,6	160	51,6	158	51,6	135	51,6	97	51,2	179	51,2	183	51,2
03:00	156	50,3	157	50,3	156	50,3	133	50,3	96	50,2	176	50,2	178	50,2
04:00	154	45,9	155	45,9	154	45,9	131	45,9	95	45,4	174	45,4	175	45,4

The estimated in the power flow calculation power in all the lines is smaller than DLR allowable power flow, so no limitation in the power generation forecast is needed.

The power generation forecast/allowed for the FW Kukinia and FW Karscino are shown in Table 3-6.

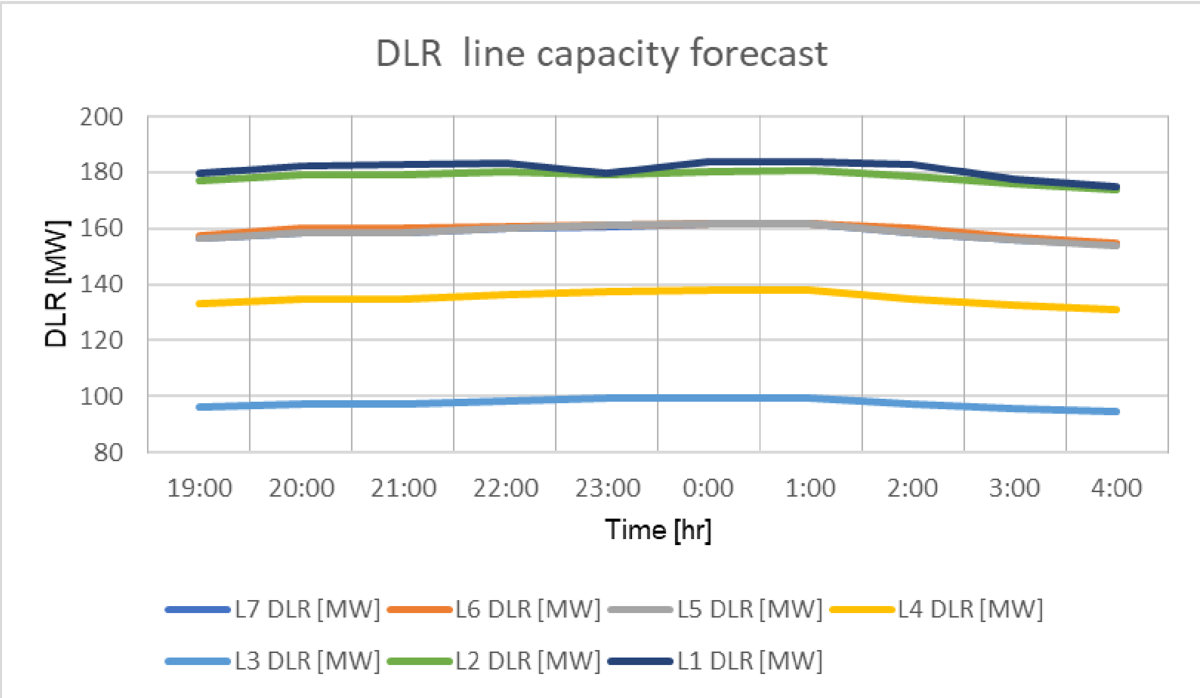


Figure 3-13. Forecasted DLR (08.08.2023)

Table 3-6 WF generation: forecasted vs. allowed

time	Wind speed	Wind Farm generation - two way direction power flow							
		KKA Kukinia (Pca=46MW/Pn=52MW)				KCO Karścino (Pca=47MW/Pn=51MW			
	[m/s]	forecast	allowed	Contract agreement	P_d-P_{ca}	forecast	allowed	Contract agreement	P_d-P_{ca}
	V	P_f	P_d	Pca	Surplus	P_f	P_d	Pca	Surplus
19:00	13	47,8	47,8	46,5	1,3	47,6	47,6	47	0,6
20:00	13,7	48,2	48,2	46,5	1,7	48,8	48,8	47	1,8
21:00	13,8	49,5	49,5	46,5	3,0	49,9	49,9	47	2,9
22:00	14,5	49,9	49,9	46,5	3,4	50,4	50,4	47	3,4
23:00	14,8	51,2	51,2	46,5	4,7	51,6	51,6	47	4,6
0:00	15,2	50,8	50,8	46,5	4,3	50,9	50,9	47	3,9
1:00	14,9	51,2	51,2	46,5	4,7	51	51	47	4,0
2:00	13,5	51,8	51,8	46,5	5,3	51	51	47	4,0
3:00	12,5	50,4	50,4	46,5	3,9	50,1	50,1	47	3,1
4:00	11,9	46,2	46,2	46,5	0,0	45,1	45,1	47	0,0
Total					**32,3**				**28,3**

3.2.2.3 List of the transactions

Figure 3-14 contains the list of the transactions on the NODES platform related to the flexibility services buy/sell order.

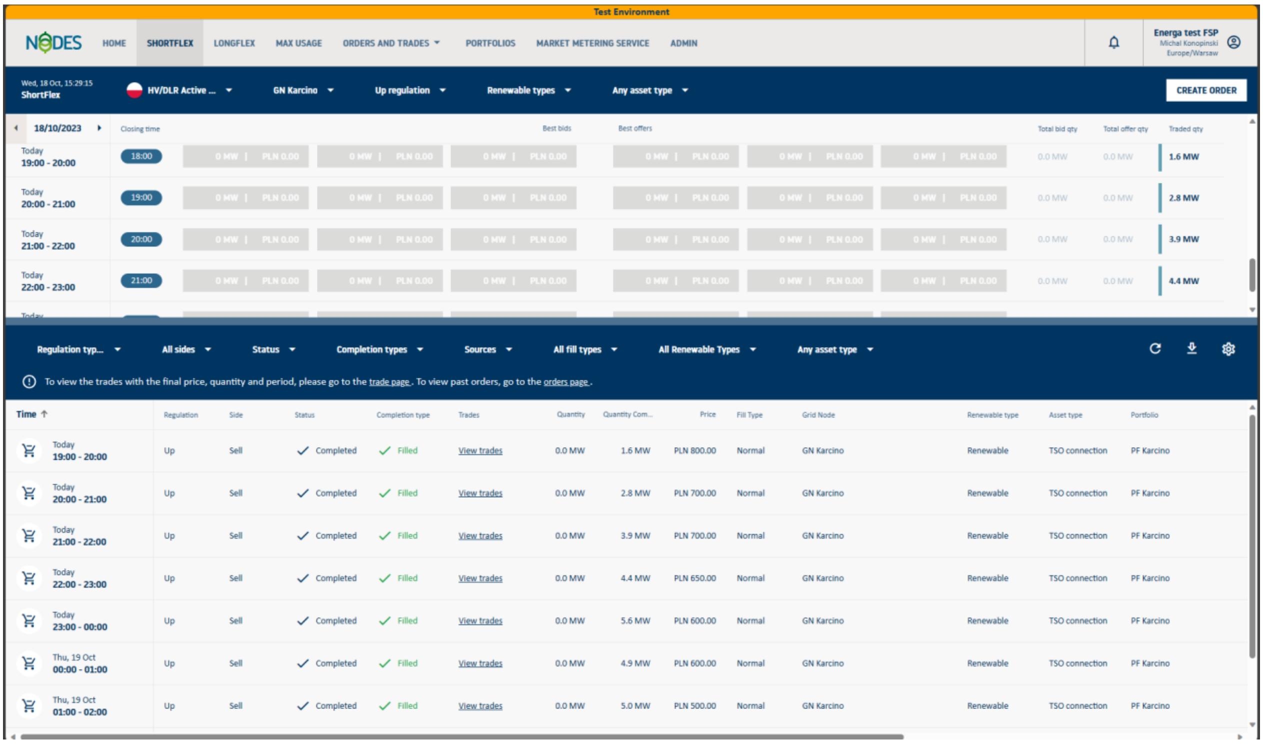


Figure 3-14 Tested transactions in the HV/DLR market on the NODES market platform

3.2.3 DLR performance test

The test is intended to verify the correctness of the calculations of the permissible load capacity of the line in the forecast weather conditions.

One of the basic conditions for the safe operation of a power line is maintaining a safe distance from the ground and objects located under the high-voltage (HV) line. This distance depends on the objects specified in the applicable standard [7] and for lines with a rated voltage of 110 kV, this distance from the ground surface should be 5,85 meters.

The technical implementation of this requirement consists in determining the maximum current which, when flowing through the line in the atmospheric conditions adopted for the calculations, will not result in an unacceptable approach to objects located under the line. The current determined in this way is called dynamic linear current to emphasize that its value changes with changing atmospheric conditions.

To determine the load capacity of a line, the type and size of the phase conductor must be considered, as well as topographic data of the line such as its location, critical spans and height above ground level. One of the methods of determining the permissible load capacity is to use weather forecasts to calculate the spatial position of the cable in the span. This approach differs from others that are based on measurements of conductor parameters such as temperature, voltage, angle of inclination, or vibration frequency. The use of dynamic line load capacity in distribution networks can help in more efficient use of line transmission capacity. For example, for a wind speed of 6 m/s blowing perpendicular to the line, the load capacity of the line increases by 50% compared to a wind speed of 0.5 m/s.

Calculations of the permissible line load are made using the line thermal model recommended by CIGRE based on the heat balance between the cooling and heating of the line in static conditions.

$$P_J + P_S = P_C + P_r$$

where:

Heating: P_J = due to current flow (Joule heat), P_S = solar heating
Cooling: P_c = by convection; P_r = by radiation

For the selected line span, weather conditions near the line were measured and the value of the current flowing in the line was obtained.

The measuring equipment used was a measurement set for determining the position and height above sea level, type Reach RS2 (Figure 3-15) consisting of a multi-band RTK GNSS receiver with centimetre accuracy for measurements, type Emlid Reach RS (L1). The set ensures positioning accuracy of up to several millimetres and accuracy of measuring height above sea level of up to 1 cm. Measurements of the distance from the ground to the wire were performed using a Leica DISTO laser distance meter.

Figure 3-15 View of the RTK GNSS receiver and the Leica DISTO distance meter

Based on these data, the distance to the ground was determined and compared with the measured value of the distance of the conductor to the ground.

The measurement results and DLR calculation for the selected line are presented in Table 3-7. The compliance of the calculations with the measurement within ±10 cm was assumed as the correctness of the calculations and the operation of the thermal model of the line.

The correctness of the thermal model allows us to determine the permissible load on the line in given weather conditions, i.e., the load at which the permissible normative distance to the ground will be maintained.

Table 3-7 The DLR calculated distances to the ground vs measured in the field

HV line name	Span #	Measurement #	Ambient temp	Wire temp	Distance to ground		Difference measured - computed
					measured	DLR computed	
KKA - KOK	48 - 49	1	19,6	25,2	6,20	6,20	0,00
		2	28,9	37,1	6,05	6,00	0,05
		3	25,5	32,7	6,12	6,10	0,02

3.2.4 PL_KPI_01 calculation

According to the test procedure, one WF was selected (here Kukinia WF) which submitted an offer to supply energy (purchase of transmission capacity from EOP) above the contracted capacity (e.g., 3 MW for 5 hours a day). After considering the possibilities, this offer was accepted and implemented. The KPI estimation was based on the results of the test conducted on August 7 and 8, 2023 in the simulated process of purchasing energy production capacity above the contract value by the Kukinia wind farm.

The PL_KPI_01 calculation methodology was updated by inserting into its formula base value =1, which allows the achievement of KPI_01 value interpreted as the increasing of the RES production above base value 100%The KPI "*PL_KPI_1 – RES energy enlargement*" assesses the RES generated energy above the connection agreement value. Computing details are described in deliverable D6.3.

The results obtained from the conducted test were taken as the representative for the calculation of the total amount of the yearly energy production above the connection agreement value.

For the calculation, the following assumptions were made:

1. According to the meteorological annual for the year 2022, during 2022 meteo station Łeba (north Poland) registered 94 days when the wind velocity exceeded 10 m/s and 17 days when wind velocity exceeded 15 m/s. For the KPI calculation, the value of the 100 days was taken, when wind velocity enables the power generation of nominal, (installed) value. A wind farm reaches its nominal power when the wind speed is in the range of 11-16 m/s. A threshold of 12 m/s was taken.
2. The average hourly production above the connection agreement for the tested wind farm is 4 MWh (based on the test simulation results)
3. Installed Capacity Utilization Factor (ICUF) for the WFs localized in the north of Poland 30%. The Installed Capacity Utilization Factor (ICUF) for a wind farm is a measure of how efficiently the wind farm is generating electricity compared to its installed or rated capacity. It provides insight into how well the wind turbines at the farm are performing in actual operation. To calculate the ICUF for a wind farm the following formula is used:

$$\text{ICUF (\%)} = \frac{\text{Total Actual Energy Generated}}{\text{Installed Capacity} \times \text{Number of Hours in the Period}}\ 100\%$$

Based on the a/m data, it is justified to assume that within the year the number of hours when the wind farm can generate the nominal power is:

- Number of hours with production above connection agreement: 100 days x 24 hours/day = 2400 hours
- Average hourly production above connection agreement: ΔA_{hi} = 4 MW
- Total yearly production above connection agreement:

$$\Delta A_Y = 2400\text{h x } 4 \text{ MW} = 9\,600 \text{ MWh}$$

- Hourly nominal production of the tested wind farm: A_n = 52 MWh
- The total yearly production of the tested wind farm for ICUF = 30%

$$A_T = 30\ \%\ 52\ \text{MW x } 8760\text{h} = 136\ 656\text{MWh}$$

$$\mathrm{PL}_{\mathrm{KPI}_{01}} = 1 + \frac{\Delta A_Y}{A_T - \Delta A_Y}$$

ΔA_Y = Total yearly production above connection agreement

A_T = Total yearly production

$$\mathrm{PL}_{\mathrm{KPI}_{01}} = 1 + \frac{9\,600}{136\,656 - 9\,600} = 108\%$$

3.2.5 Conclusions

Determining the dynamic load capacity of lines to manage transmission constraints and provide flexibility services will allow for achieving benefits such as preventing network overloads, especially lines, improving the quality of energy supply or limiting or postponing network investments.

Managing constraints and offering renewable energy producers flexibility of the distribution network using forecasts of the dynamic load capacity of the 110 kV line is already possible in most DSOs in Poland (Energa, ENEA, Tauron, PGE - some branches) that have systems for monitoring the permissible load capacity of the lines (DOL systems) using measurement of weather conditions. To achieve this objective, the mechanical data of existing lines within the system and the identical algorithm for assessing the dynamic load capacity of the line were employed. In this process, the weather conditions data measurements were substituted with forecasted values.

The use of DLR to manage the generation of wind farms is particularly effective when the wind farms, taking advantage of good wind conditions, operate at a power close to the rated power, and at the same time the transmission line conductors are cooled more intensively than in calm weather.

The implementation of congestion management using dynamic line load capacity makes it possible to ensure the safe operation of the distribution system technically and cost-effectively both in current operating conditions and in expected (forecast) conditions. The use of dynamic line load capacity in the operation of the distribution network leads to better and more effective use of the line's transmission capacity.

The performance test described in the chapter proved that the accuracy of the conductor space location (distance to the ground) is calculated with the accuracy of ±0,1m.

The PL_KPI_01 value of 108% was calculated based on the relatively small difference between connection agreement power Pca and nominal power Pn, which was the case of wind farm Kukinia. Previously set for PL_KPI_01 target value of 20% is difficult to reach because for most of the wind farms difference between Pca and Pn is very small, if any.

However, using DLR for mitigation of the network curtailment allowing for bigger RES utlisation is very effective, and a redefinition of PL_KPI_01 can result in its higher value.

The current practice of calculating allowable power flow is based on static line rating (SLR), i.e. allowable line power flow depending on the season or average temperature during the day. This usually leads to a greater reduction in energy production from wind farms. Adopting DLR allows for more efficient use of the energy from the wind farms. If the SLR threshold value was taken, the estimated PL_KPI_01 would be significantly greater.

3.3 BUC PL FS – Voltage Control with the use of FlexStation solutions

3.3.1 Test purpose

The increasing prevalence of PV micro-installations in Low Voltage (LV) electrical grids has resulted in voltage issues due to the inadequacy of current grid infrastructure. Specifically, PV energy production is suspended as voltage levels exceed permissible limits. To address this issue, efforts are being made to enhance the flexibility of LV grids to accommodate a greater number of PV micro-installations.

The main goal of the test is to evaluate how LV at the client premises can be controlled with the use of an MV/LV transformer with an OLTC to mitigate voltage issues and maximize PV generation by preventing the switch-off of the PV installation caused by inverters' overvoltage protection.

The distinctive aspect of this method is the use of online voltage measurements at the Point of Connection (POC) PV systems, measured by smart meters and read by the data concentrator in the secondary substation, utilizing the existing PLC data transmission.

The test operation of the voltage control took four months starting from the 1st of June up to the end of September.

The detailed specification of the test network is described in Deliverables D9.2 and covers 3 FlexStations located on the territory of three Branches: Płock, Kalisz and Gdańsk.

All the substations were equipped with OLTC transformers. The necessary data from each substation were collected using two separate communication channels: one for the daily network local control centre operation and other for the demonstration purposes under the EUniversal project.

The scope of the measurements in each substation includes the data from the selected meters (accessed via AMI infrastructure) and from the substation. The detailed meter list is in the D9.2 document.

3.3.2 Scope of the tests

To obtain data for the determination of KPIs, the following tests were performed related to various aspects of voltage control:

a) Voltage control using OLTC in conditions of huge PV generation,

b) Comparative recording of voltage changes in comparable conditions without voltage control.

Obtained results can be the base for possible future implementation of control algorithms other than voltage control using OLC.

3.3.3 Test results

Voltage control using OLTC was deployed in three installations of secondary substations implemented as part of the EUniversal project. Since the very beginning, the algorithm was in the mode “live”.

Energy meter measurements were continuously collected in the test database by communication software installed on a central dedicated server in the DMZ of the Distribution System Operator (DSO) technological network via a data concentrator located at the substation. The following data were acquired and stored for further elaboration with a time resolution of 1 minute:

- Voltages measured by the client meters at selected points,
- Voltages and current in the outgoing feeders from the FS,
- OLTC position and the time of change of the tap (recorded as the event).

The recorded data were analysed in terms of:

- LV voltage variation at the substations and end-of-circuit customers (prosumers),
- Latency in acquiring data under different network conditions for different locations,
- The range of voltage changes at the customers corresponding to the change of the OLTC transformer tap position under different loading conditions,
- The number of switches the transformer tap changer OLTC during the day.

The voltage control algorithm implemented in the new RTU in secondary substations is to ensure continuous power generation PV installations at all points in the grid, which could be disrupted if the inverters are turned off due to overvoltage protection as required by EN 50549-1 [3].

This protection is activated when the upper permissible voltage value U_{10UL} = 1.1 Un is exceeded by the voltage value U_{10}, which is calculated as the square root of the arithmetic mean of the squares of the voltages measured at least every 3 seconds for 10 minutes using a moving window approach. The phase with the highest voltage is selected for the U_{10} calculations. The inverters can be switched on again once the calculated U10 value falls below 2% of the permissible value (U_{10} < 1.078 Un) after a minimum observation time of 60 seconds (default inverter setting).

The one-minute voltage recordings in the selected customers in the LV network supplied from Mława FS in the two subsequent weeks are shown in the following figures:

a) Figure 3-16: voltage record from July 24 to 30, 2023 - without the voltage control.

b) Figure 3-17: voltage record from July 17 to 23, 2023 - with the active voltage control.

Both graphs show the lowest and the highest voltage measurements at two different customers, observed at a given moment, i.e., one minute.

When the voltage control was "on" the algorithm kept the average voltage within ±3%Un (red waveform between green lines). There were practically no exceedances of the upper limit (+10%Un, thick grey line). It was counted that during this period (one week) there were 43 one-minute periods where voltage values exceeded 253 V. The voltage control algorithm intentionally has a proper time delay, to prevent too frequent tap changes, therefore a very speedy voltage rise may last up to 3 minutes.

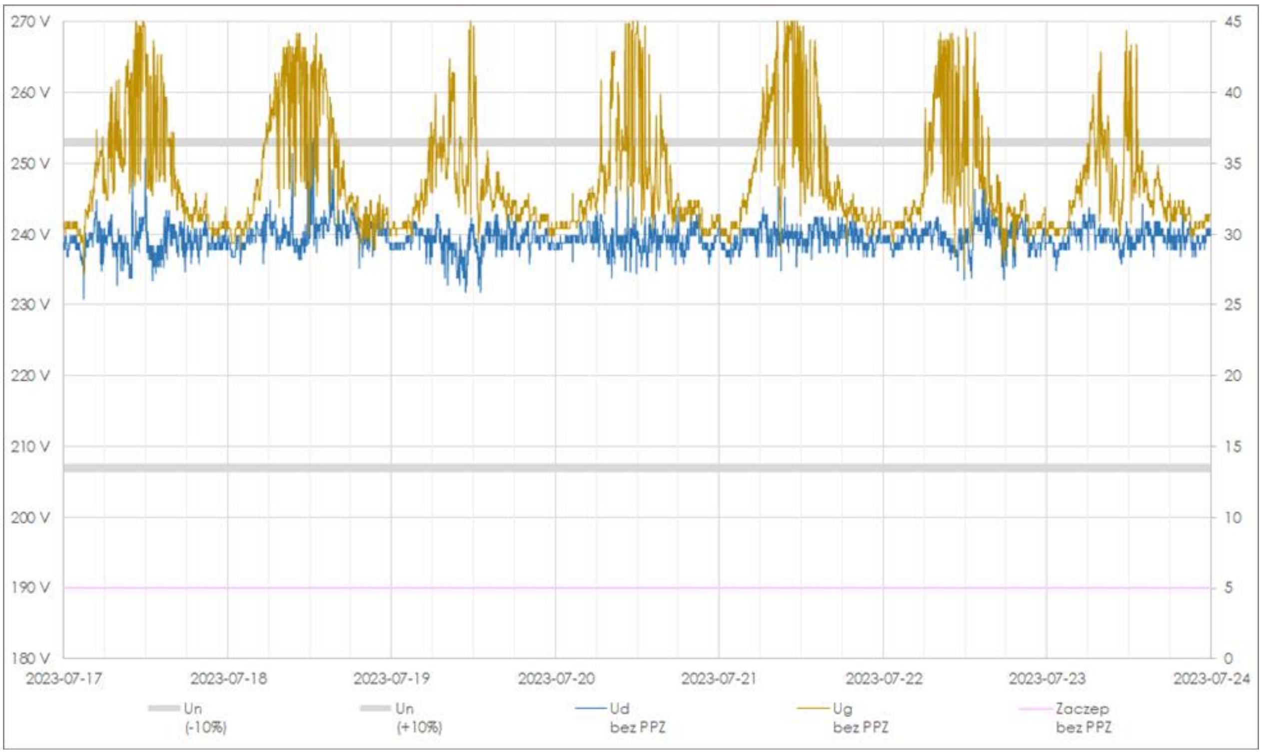


Figure 3-16 Voltage waveforms FS Mława – voltage control OFF

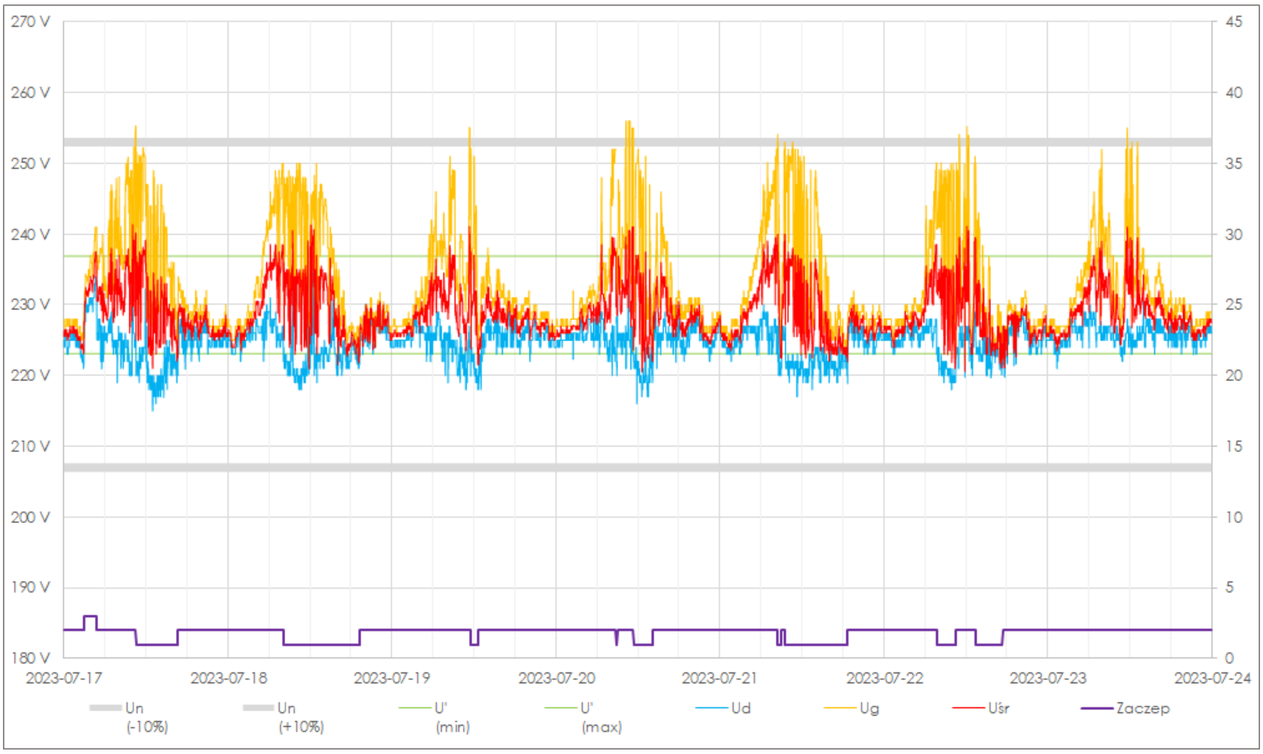


Figure 3-17 Voltage waveforms FS Mława – voltage control ON

When the voltage control was off, and the transformer tap changer was set to the neutral (middle) position (for given OLTC this corresponds to position 5) the total number of exceedances during the observation time was 2116. The number of these events results from the random switch on-off inverters working close to a threshold value (253V), caused by overvoltage protection. During the trial, it was not possible to record the inverters' status (on/off).

The colours used in Figure 3-16 and Figure 3-17 show:

- orange and blue – measured voltages Ug and Ud, and simulation of these voltages for the rated ratio (bold and darkened)
- red – average voltage Us (calculated from Ug and Ud),
- green – dead band ±3% Un,
- grey – permissible voltage zone ±10% Un,
- purple – tap position.

The obtained result was used for the PL_KPI_4 calculation (see chapter 3.3.4.3).

The test results at FS Czajków refer to the situation before the implementation of voltage control (Figure 3-18) and the period after the implementation of the control (Figure 3-19) i.e., at the end of summer 2023. Both days had similar solar conditions.

At this substation, regular voltage drops below the threshold of 207 V were observed, caused by switching on energy-consuming machines in nearby companies (including pallet production). An example of voltage recording from one day is shown in Figure 3-21. The orange waveform reflects the highest measurement (U_g), and the blue waveform reflects the lowest measurement (U_d) in each minute.

Measurements are with minute resolution. In periods when the meters were not read (visible in Figure 3-18) maintaining the voltage from the previous minute is simulated.

Figure 3-19 shows the voltage waveform and the tap changer position with voltage regulation in operation, the algorithm of which had the following control settings:

- dead bandwidth: ±3% Un (slow adjustment),
- slow regulation delay time: 10 minutes,
- thresholds for eliminating exceedances: ±10% Un (fast regulation),
- quick adjustment delay time: 6 minutes.

Delay times are counted from the moment a given threshold is exceeded. If the voltage returns to the permissible range before the set time has elapsed, the timer is reset (the overflow must occur for the entire set time).

The course of U_g and U_d voltages when the voltage control is on is shown with orange and blue lines (as before). The red line shows the average voltage *Us*. The dead zone around Un is marked with green lines, and the rapid regulation thresholds are marked with orange and blue lines (bold).

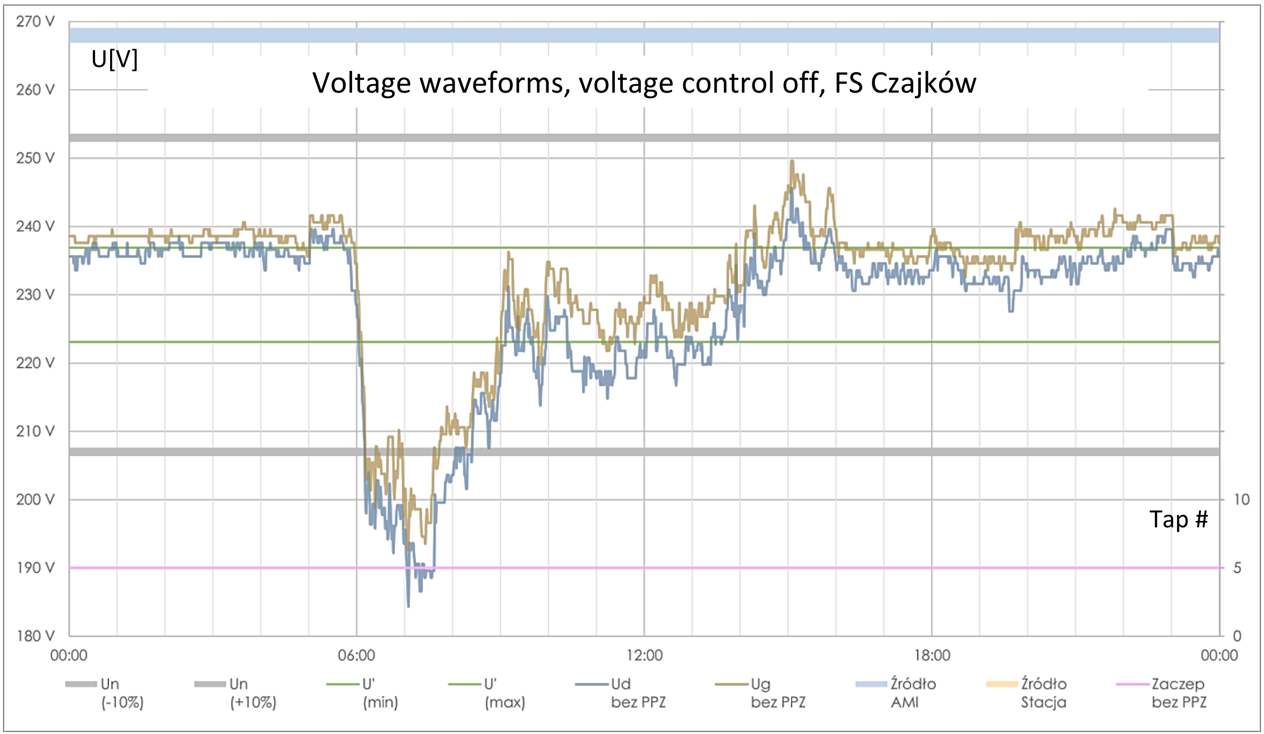


Figure 3-18 Voltage waveforms FS Czajków – voltage control off

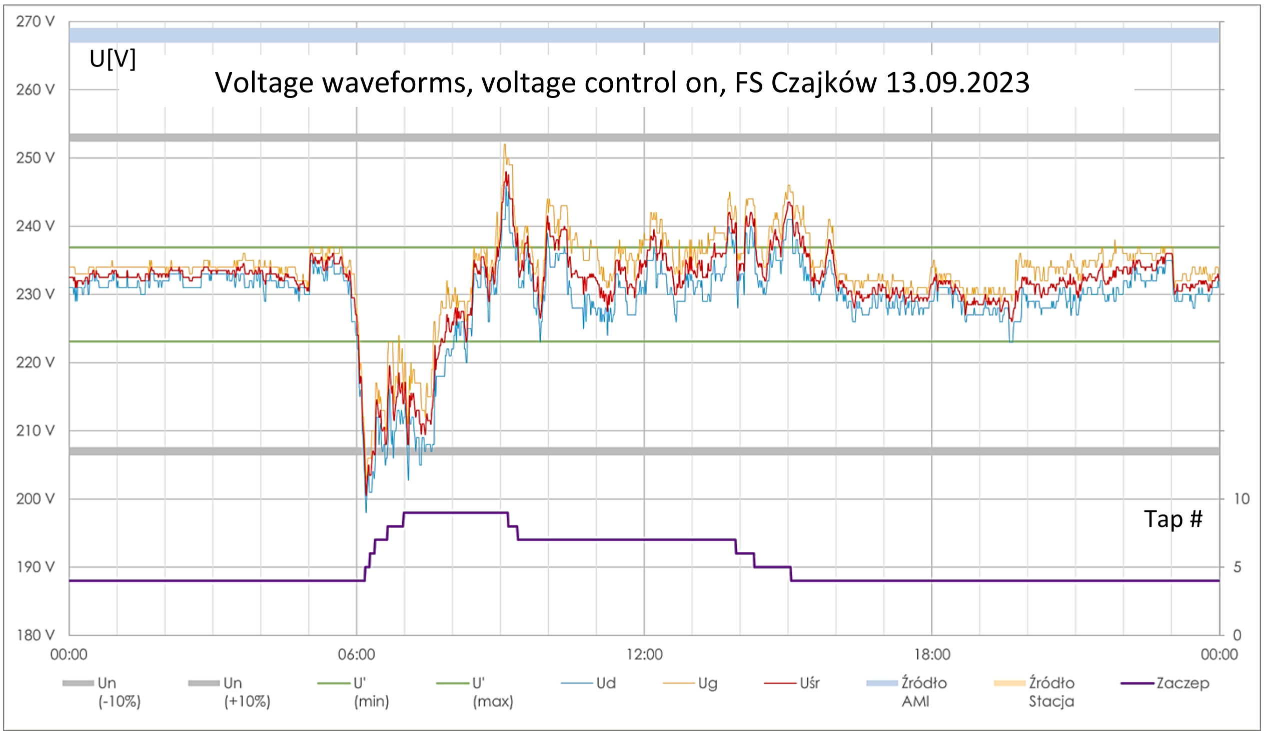


Figure 3-19 Voltage waveforms FS Czajków – voltage control on

The purple line maps the position of the tap changer that was used for the voltage control. The tap changer has 9 taps and changes the secondary voltage linearly, with a constant step, in the range of ±8% Un. The difference between successive taps is 4.6 V. The neutral tap, corresponding to the rated ratio of 15.75 kV / 420 V, is number 5.

The significant voltage reduction (190 V) a few minutes after 6:00 a.m. was eliminated with the delay resulting from the quick regulation setting. During the rest of the day, the voltage is kept in the dead zone.

Voltage controllers in three FSs were installed and launched at the turn of spring and summer 2023 with settings determined during model tests. In the first weeks of operation, the problem of too long a delay in response to exceeding the upper voltage threshold in quick regulation (+10% Un) became apparent. Based on the voltage waveforms, it was estimated that the prosumer inverters are turned off before the OLTC regulation algorithm switches the tap to a lower one. This behaviour was the result of the difference between the OLTC algorithm (permanently exceeding the set time) and the method of operation of the overvoltage protection in the inverter.

During the research, it was decided to change the method of operation of the quick regulation and the '2 of 3' algorithm was used. Switching occurs if within three minutes there are two voltage exceedances beyond the ±10% Un zone, with a one-minute time resolution of measurements. This means that switching will occur within 2 or 3 minutes of exceeding the threshold. The principle of operation and settings of slow regulation have remained unchanged.

Figure 3-20 shows the operation of the voltage regulation system at the Linia Flex Station on September 17 (Sunday). The regulation is correct (red line), and the voltage is within the dead zone (green lines). The tap changer operates in the range from tap 1 to tap 4, i.e., in the area of lowering the voltage by 4-14 V. Lack of OLTC regulation (or permanently setting it on tap 5 - pink line) would result in voltage exceedances in the hours from 10 a.m. to 3 p.m. by about 10 V, resulting in prosumer inverters being turned off.

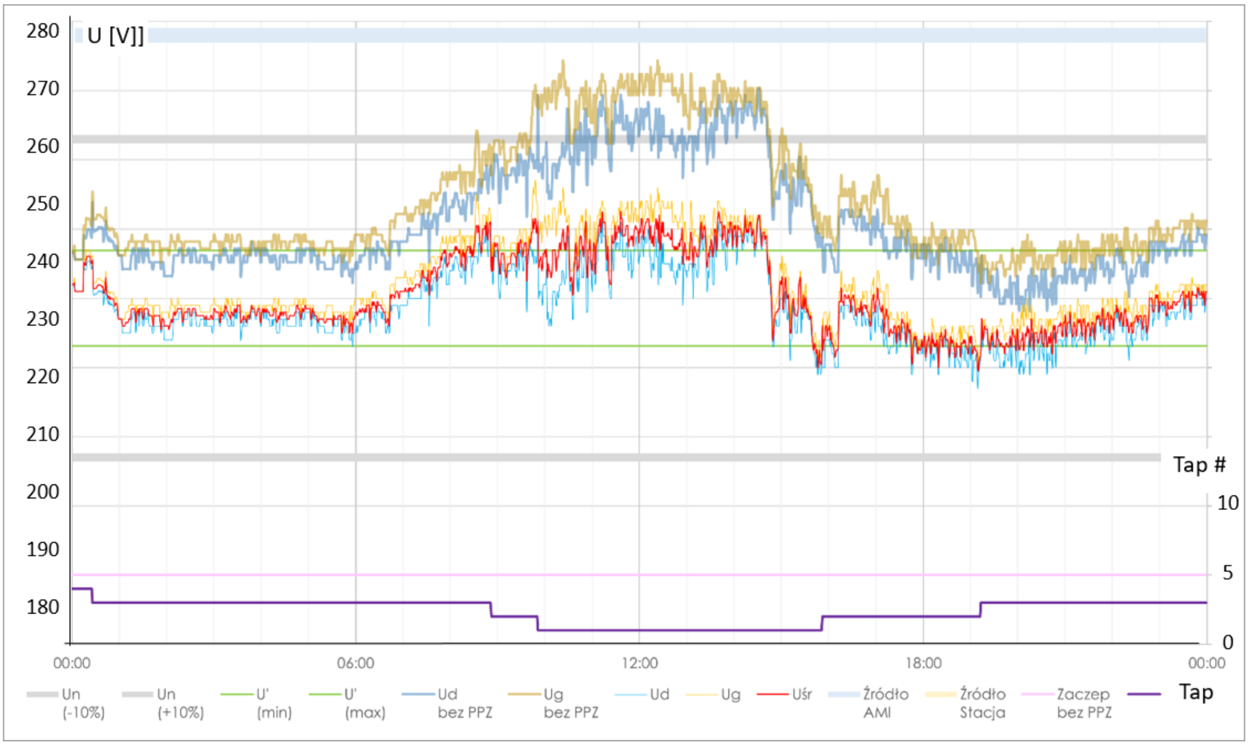


Figure 3-20 Voltage waveforms FS Linia

3.3.4 KPIs calculation

3.3.4.1 PL_KPI_2 – Monitoring Information Categories

Monitoring data volume is an indication of the increase of data amount for newly monitored currents, powers, or voltages in primary substations, secondary substations, or customer levels. One of the main objectives of the EUniversal project is the integration of measurement data for low voltage network control tools, for supporting state estimation and power flow algorithms, or for congestion management.

The PL_KPI_2 indicator concerns the quantification of the increase in data collected at the substation

$$MIC(\%) = \frac{MD_{Flex} - MD_{BAU}}{MD_{BAU}}$$

MD_{BAU} - Total monitored data according to the criterion in the BAU scenario

MD_{Flex} - Total monitored data according to the criterion in the flexibility scenario

For the pole station and indoor station, the following were counted:

- the number of MD_{BAU} data that would be transferred to the SCADA system in the case of the previously used method of station monitoring (BAU scenario - Business as usual)
- the number of MD_{Flex} data transferred to the FlexStation, i.e., a station with increased observability.

The calculations were made based on the data exchanged between FlexStation and Control Center (DSO) defined in the data exchange protocol (DNP 3.0 - Distributed Network Protocol v. 3.0), and data collected from AMI meters. The calculations do not consider the frequency of data collection, assuming that the reading frequency is similar in both cases. The calculation results are presented in Table 3-8, divided into pole and indoor substations.

The sum of monitored MD_{BAU} data for a typical MV/LV station for a pole station and an indoor station, respectively, is:

- MD_{BAU} pole substation = 40
- MD_{BAU} indoor substation = 159

The sum of monitored data for the flexible station is:

- MD_{Flex} pole substation = 112
- MD_{Flex} indoor substation = 310

For the pole substation:

$$MIC(\%) = \frac{112 - 40}{40} = 298\%$$

For the indoor substation:

$$MIC(\%) = \frac{310 - 159}{159} = 177\%$$

Table 3-8 Number of signals from traditional substation vs. from FlexStation

Signal category	Location	Signal type		OSD (BAU) Pole	OSD (BAU) Indoor	Flex station Pole	Flex station Indoor
BI Binary Inputs	MV switchgear	General		6	8	5	6
		Line feeder 1	switch	8	7		8
			SC signal.	7	7		7
		Line feeder 1	switch		7		8
			SC signal.		7		7
		Line feeder 1	switch		7		8
			SC signal.		7		7
		Transformer bay			6		7
	OLTC controller	OLTC status				16	16
	LV switchgear	feeders	Pole: Σ 7 feeders Indoor:Σ10feeders			21	30
BO Binary Outputs	MV switchgear	General		2	2		2
		Line feeder 1	switch	2	2		2
			SC signal.	4	4		4
		Line feeder 1	switch		2		2
			SC signal.		4		4
		Line feeder 1	switch		2		2
			SC signal.		4		4
		Transformer bay			3		3
	OLTC controller	OLTC control				6	6
AI Analog Inputs	MV switchgear	Line feeder 1	SC signal	11	11		13
		Line feeder 2	SC signal		11		13
		Line feeder 3	SC signal		11		13
		Transformer bay e					
	LV switchgear	Buses				4	4
		feeders	Pole: Σ 7 feeders Indoor:Σ10feeders			63	90
	AMI Data Concentrator	Meters	Σ 10 meters			40	40
AO Analog Outputs	OLTC controller	OLTC control algorithm settings				4	4
	Total			**40**	**112**	**159**	**310**

3.3.4.2 PL_KPI_3 – Increased local PV hosting capacity

The PL_KPI_3 indicator concerns the quantification of the increase in the permissible level of the PV installation in the low-voltage network powered by FlexStation, and this increase results mainly from the devices installed at the substation to control (reduce) the voltage level so that the voltage at the end of the circuit does not exceed the permissible level of 253V.

$$PL_{KPI_3} = \frac{P_{max}}{P_0}$$

P_{max} = Maximum technically allowable PV installation capacity calculated with the presence of the flexible substation

P_0= Total PV capacity installed before flexible substation.

The power flow calculation of the maximum allowable PV capacity in the presence of the control feature of the flexible substation was performed for each of the FlexStations. In every substation, the worst-case scenario was selected. The line (feeder) with the highest PV generation was simulated for the voltage drop calculation between the most distanced PV location and the LV substation bus.

Calculation covered a few degrees of the increase in total PV generation, placed in the accessible location. Simultaneously the cable current resulting from the assumed power was calculated. This allowed the elimination of such cases in which the current exceeds the existing allowable current carrying capacity for a given cable type (diameter).

To calculate the influence of the use of the OLTC in the FlexStation the voltage level at the tap changer position below nominal positions was calculated at the assumption that the maximum voltage level in the most distant PV location cannot exceed 253 V and the lowest voltage at the LV buses shouldn't be lower than 207 V.

The results of the estimation of the increase in the permissible level of the PV installation in the FlexStation in Mława are shown in Table 3-9 and the FlexStation Czajków in Table 3-10.

Simulation calculations for Mława FlexStation were performed for feeder No. 6, direction KRSN which supplies the housing estate of 57 single-family terraced houses by YAKXS 4x240 cable, each of which is equipped with a PV roof installation with a power of 5.5 kW to 6 kW and a heat pump. The total installed PV capacity is 340 kW.

Various variants of the power generated by PV installation were assumed and the voltage drops corresponding to these powers were calculated between the PV plant with the highest voltage and the station. Customers' self-consumption was assumed zero.

Table 3-9 Power flow calculation result for the Mława FlexStation

Power increase		Voltage drop	The voltage on the LV bus at the tap changer position					Phase current
%	kW	V	0	-1	-2	-3	-4	A
100	340	23	230	225,4	220,8	216,2	211,6	493
130	440	29	224	219,4	214,8	210,2	205,6	637
150	506	34	219	214,4	209,8	205,2	200,6	734
1,88	622	41	212	207,4	202,8	198,2	193,6	902

The increase in the permissible level of the PV installation is 130% at which it is possible to maintain the bus station voltage above 207 V and not violate the allowable current carrying capacity for the cable type YAKXS 4 x 240 i.e., 674 A

$$PL_{KPI_3} = \frac{P_{max}}{P_0} = \frac{440}{340} = 130\%$$

For the FlexStation Czajków calculations were carried out for feeder no. 4, where the PV generation with a total power of 34 kW connected to various nodes of the low-voltage network is installed.

The main feeder is an overhead cable type of AsXsn 4 x 95, the resistance of one conductor is 0.32 ohm/km and the allowable current carrying capacity at an ambient temperature of 30°C is 258A.

Assuming the PV generated power is equal to the installed power, the maximum voltage increase at the end of the circuit at the PV connection point will be 3.3 V. Therefore, there is quite a lot of space for connecting the "extra PV generation" to use out the 23 V margin.

In the considered circuit, an additional maximum power PV generation of 125 kW could be installed on the end of the circuit, while maintaining 230V voltage in the substation, at the neutral tap changer position of 5 and current at the value of 181 A (below allowable value). For the above-described condition, the P_{max}/P_o ratio is 368%.

$$PL_{KPI_3} = \frac{P_{max}}{P_0} = \frac{125}{34} = 368\%$$

Using OLTC for lowering the voltage at the substation it would be possible to connect "extra PV power" of 178 kW which corresponds to the cable allowable current carrying capacity (258A) and tap changer position (minus 2). In this case, the P_{max}/P_o ratio is 524%.

Table 3-10 Calculations of voltage drop caused by PV generation, FlexStation Czajków

Branch of the feeder 4	Distance to the substation	1phase resistance cumulative	PV power	Voltage drop cumulative	Voltages at nodes
#	m	ohm	kW	V	V
1	10	0,003			230
2	50	0,016			230,0
3	90	0,029	9,92	0,41	230,4
4	140	0,045	6,32	0,41	230,8
5	180	0,058			230,8
6	220	0,070	3,24	0,33	231,2
7	260	0,083	2,16	0,26	231,4
8	300	0,096	3,72	0,52	231,9
9	340	0,109	8,64	1,36	233,3
Total			**34**	**3,30**	
Extra PV	**340**	**0,109**	**125**	**19,71**	**253**

3.3.4.3 PL_KPI_4 – Fulfilment of voltage limits

PL_KPI_4 – Fulfilment of voltage limits is to evaluate the power quality and quality of supply of distribution networks. The 95% percentage voltage value during the monitoring period in a selected critical point in the LV network will be measured after flexible substation installation with disabled automatic control:

$$V(\%) = \frac{V_{BAU} - V_{Flex}}{V_{BAU}}$$

V_{BAU} - the 95% percentage voltage value during the monitoring period in a selected critical point in the LV network for the BAU scenario.

V_{Flex} - the 95% percentage voltage value during the monitoring period in a selected critical point in the LV network for flexibility scenario.

The EN 50160:2023 [6] [indicates that the range of variation of the r.m.s. magnitude of the supply voltage, whether line to neutral or line to line to phase, is Un ± 10 % or Uc ± 10 % for 95 % of a week. In practice the r.m.s. value could be determined over a fixed interval of 20 milliseconds and the basic measurement could be made by determining the average of these values for 10 minutes. The assessment of compliance over an observation period of one week, including Saturday and Sunday, could be then performed by checking that 95 % of the ten-minute values fall within the specified range.

The use of this criterion leads to an expected improvement in the indicator only when it was less than 100%, i.e., when the voltage exceeded 253 V. However, in networks with high saturation of PV generation, the permissible voltage values are not exceeded because after reaching this threshold value, the PV is turned off earlier through 10-minute overvoltage protection and we will not observe any effect of the voltage control. The purpose of voltage control using OLTC is to prevent power electronic-based inverters from turning off.

The method of calculating PL_KPI_4 was adjusted accordingly as the ratio of voltage quality indicators was calculated according to [6] before and after the introduction of voltage control:

$$V(\%) = \frac{I_{Flex}}{I_{BAU}}$$

I_{Flex} - voltage quality index after the introduction of voltage control

I_{BAU} - voltage quality index without voltage control

I(%) - Voltage quality index is calculated as:

$$I(\%) = \frac{N_{Total} - N_{th}}{N_{total}}$$

N_{Total} – number of voltage measurements in the analysed period (e.g., one week)

N_{th} - number of voltage measurements outside the thresholds

Due to the existing problems, the Mława demonstration area was selected for analysis and KPI calculation. At Mława FlexStation, long-term voltage values were measured both on the station buses and on selected customers (prosumers).

Two periods were selected for analysis:

- the period from 17/07/2023 to 23/07/2023 in which the voltage regulation was operated as described in chapter 3.3,
- and 24/07/2023 to 30/07/2023 - in which voltage regulation was intentionally turned off.

V(%) was calculated as the measure of the reduction in the overvoltage duration when the voltage control was on. The calculation for the FS Mława was based on the data from testing the performance of the control algorithm shown in Chapter 3.3.
Count of one-minute voltage measurements surpassing the threshold value U_{th} = 1.1 Un
a) with voltage regulation turned off, U_{1min} = 2116 Index I(%) = 79%
b) with voltage regulation switched on U_{1min} = 43 Index I(%) = 99,6%
Total count of one-minute measurements within a week: 10 080

$$V(\%) = \frac{I_{Flex}}{I_{BAU}}$$

$$V(\%) = \frac{99{,}6\%}{79.0\%} = 126\%$$

Such a result proved a significant improvement in the voltage quality in cases when the OLTC voltage control was based on measurements from customers' premises.
Using OLTC makes it possible to significantly improve the quality of the voltage. Another benefit factor is to reduce the number of the necessary cut-offs of the inverter to avoid overvoltage.
An alteration to the above-described calculation method of PL-KPI_4 can be done by setting the thresholds lower than 1.1 *Un*. The threshold can be selected up to ±9% Un, ±7% Un and±5% *Un* correspondingly, which would allow us to estimate the improvement in the quality of voltage control in networks with high PV saturation.

Based on the same voltages measurement as in Chapter 3.3., but taking other thresholds the results of the PL_KPI_4 calculations are presented in Table 3-11

Table 3-11 PL_KPI_4 calculation

U_{10} threshold upper limit	VC off		VC on		PL_KPI_4 [V%]
	U_{10} Number	I [%]	U_{10} Number	I [%]	
U10>1.05Un	814	19,2%	136	86,5%	449,5%
U10>1.07Un	438	56,5%	55	94,5%	167,2%
U10>1,09Un	290	71,2%	7	99,3%	139,4%

The markings in the table refer to:

U_{10} threshold– limit values of 10-minute average voltages

U_{10} number – number of measurements above the threshold value

I [%] - voltage quality index according to [6]

Total count of ten-minute voltage average within a week: 1008

In the presence of voltage control, the numbers of measurements above the threshold values are significantly lower in comparison to the situation with the voltage control off.

3.3.5 Performance tests

3.3.5.1 The possibility of collisions between the readings

This test is intended to check for the possibility of a collision between the readings used for voltage regulation and the AMI system readings.

Selected meters are read both by the AMI system several times a day and by a dedicated server that collects voltage measurements for voltage control in power stations.

It should be examined whether this method of reading meters does not threaten the deterioration of KPI in the AMI system and, on the other hand, whether the reading of the AMI system does not affect the availability of readings from meters selected for voltage control. Moreover, reading data by the AMI system may result in the cyclical extension of the data collection interval, especially at selected times of the day, i.e. when all meters are read for AMI purposes.

The test consisted of comparing KPIs calculated in the AMI system in two situations:

a) during concurrent operation of readings for AMI and voltage regulation

b) with the meter reading function disabled for voltage regulation lasting 3 days.

Test results

No significant difference was observed in the KPI values in the AMI system between the values calculated over a long period and the values when the data reading function for voltage regulation was turned off.

Analysis of the delay times in response to the command to read selected readings in specific periods of the day when all meters in each station were read did not show any significant differences compared to other periods of the day.

Therefore, there is no collision between the readings for the AMI system and the readings for voltage regulation.

3.3.5.2 Time delay in the meter reading

The efficacy of the voltage regulation algorithm, utilizing voltage measurements deep within the network obtained through the AMI system, is heavily reliant on the accessibility of these measurements. Specifically, the time delay in acquiring information, measured from the initiation of the query command, holds significance, with an expectation that it does not surpass 1 minute.

The objective of the assessment was to quantitatively evaluate the delay in readings for several designated meters. For each location, a set of 5-7 meters was chosen where obtaining current readings was feasible, implying that responses to queries were received in less than 1 minute.

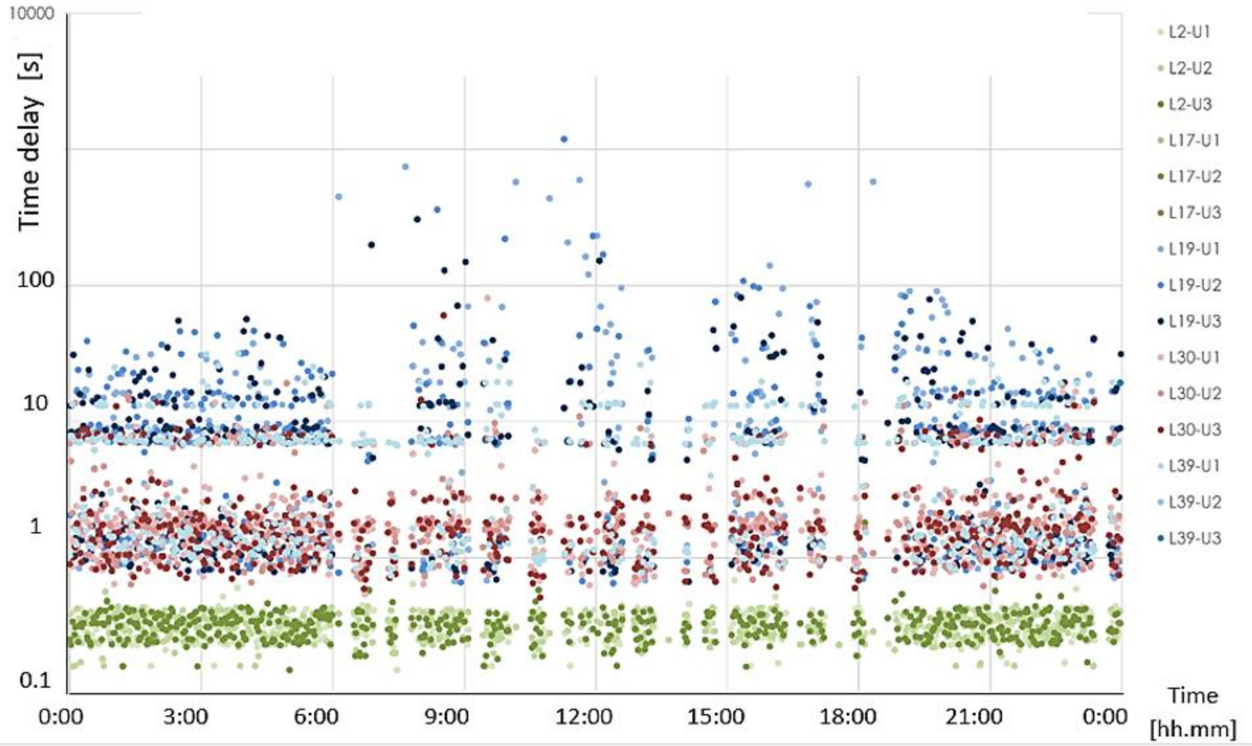


Figure 3-21 Time delay of the meter reading

In Figure 3-21 an illustrative depiction is presented, showcasing the statistical distribution of response times to voltage queries from 5 meters in the town of Czajków on November 29, 2022. Except for the L17 meter, which exhibited infrequent responses, most measurements were accessible to the controller within approximately 10 seconds of the query. However, noticeable periodic interruptions in readings from other meters are evident.

3.4 The conclusion from voltage control

Voltage control using OLTC of the MV/LV transformer correctly regulates the voltage in the network, responding to changes in generation and loads. The operation of the algorithm based on voltage measurements deep in the network plays a key role here.

Measurements from AMI meters are an effective source of voltage for the control algorithm with a one-minute resolution, despite observed interruptions in PLC communication. In the event of loss of data from AMI meters or another source deep in the network, the regulator must switch to voltage measurements in the station. This measurement does not show local voltage increases and decreases, so the regulation must consider larger safety margins.

The presented test results and KPIs calculated indicate that power control using OLTC based on the voltage measurement in the depth of the LV network, mostly at the POC of the PV, protects against power limit violation and thus provides the possibility of uninterrupted operation of the PV installation with no power limitations and without the need to manage reactive power.

The frequency of OLTC tap-changes operation is lower than it results from the number of tap-changes over the lifetime of the OLTC.

In case of an insufficient range of voltage control using OLTC in the MV/LV substation coordinated voltage control in HV/MV substations should be considered. Special attention should be paid to the appropriate selection of the nominal ratio of the MV/LV transformer in such a way that the range of the OLTC operation covers the expected voltage variation in the LV network.

4 Conclusion

Key lessons from the Polish implementation include:

The most promising network voltage level in which flexibility services can and should be implemented is the area of low and high voltage. This requires solving the following issues:

It is necessary to develop and improve the network infrastructure of LV networks, mainly in terms of the capacity to accommodate renewable energy sources, especially those that are difficult to predict, such as PV.

The primary focus should be on managing the voltage levels within the network and guaranteeing sufficient cable capacity. Using the transformer with OLTC controlled based on the voltage from the prosumer maters is undoubtedly the proper solution.

A highly efficient approach to optimize the utilization of the current HV network infrastructure involves implementing the operational control of HV lines through the utilization of dynamic line rating (DLR). This entails adjusting allowable line capacity based on rapidly changing weather conditions. This applies to both forecasting network power flow and providing flexibility services, as well as real-time monitoring of line loads to ensure safe operation.

Table 4-1 Overview table of the KPIs target vs. achieved

Item	Name	**Target**	**Achieved**
1	PL_KPI_1 – RES energy enlargement	120%	108%
2	PL_KPI_2 – Monitoring Information Categories	200%	Pole FS – 298%
			Indoor FS – 177%
3	PL_KPI_3 – Increased local PV hosting capacity	130%	FS Mława 130%
			FS Czajków – 368%
4	PL_KPI_4 – Fulfilment of voltage limits	2,5%	26%

5 References

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[4] Babs A., Samotyjak T, Tarasiuk M., Noske S.: DLR as the tool for providing flexibility services in the distribution network. Paper n°10478. 27th International Conference on Electricity Distribution, Rome, 12-15 June 2023

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[6] EN 50160:2023 Voltage characteristics of electricity supplied by public electricity networks

[7] [EN 50341-1:2012 Overhead electrical lines exceeding AC 1 kV - Part 1: General requirements - Common specifications