INCREASE

INCREASING THE PENETRATION OF RENEWABLE ENERGY SOURCES IN THE DISTRIBUTION GRID BY DEVELOPING CONTROL STRATEGIES AND USING ANCILLARY SERVICES

D3.2 – Integrated simulation platform which models the key components and control strategies

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Comments

This deliverable report corresponds to Task 3.2 – 'Integration of the MAS based control system in the network simulation platform'.

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List of symbols and abbreviations

Symbol	Description	Symbol	Description
P_{nom}	Nominal (rated) power of inverter	g_1	Fundamental input conductance
υ_g	Voltage at the connection point	w	Coefficient vector
P_{inj}	Injected active power	g_d	damping conductance
P_{ref}	Reference power of the control inverter	V_g	Voltage at the PCC
P_{MPP}	Maximum power point active power	ΔP, ΔQ	Change in active and reactive power
P_{curt}	Curtailed active power	J_1, J_2, J_3, J_4,	Sub-matrices of the Jacobian matrix
S	Sensitivity matrix	$\Delta\|V\|$, $\Delta\delta$	Change in voltage magnitude and angle
x_{ij}	Elements of the sensitivity matrix	$\underline{\upsilon}_0$, $\underline{\upsilon}_1$, $\underline{\upsilon}_2$	zero-, positive- and the negative-sequence components of the grid voltage
ΔV_g	Change in the voltage magnitude	υ_{cpb}	Constant power band voltage
υ_{max}	Maximum allowable voltage in the grid as defined by the corresponding Standards	υ_{min}	Minimum allowable voltage in the grid as defined by the corresponding Standards
AG	Agent	JADE	JAVA Agent Development Framework
D	Deliverable	LV	Low-Voltage
DG	Distributed Generation	MAS	Multi-Agent System
DRES	Distributed Renewable Energy Source	MV	Medium-Voltage
DSO	Distribution System Operator	MPP	Maximum Power Point
EPRI	Electric Power Research Institute	PCC	Point of Common Coupling
FIPA	Foundation for Intelligent Physical Agents	pu	per unit
FPS	Fair Power Sharing algorithm	TSO	Transmission System Operator
GUI	Graphical User Interface	VUF	Voltage Unbalance Factor
HV	High-Voltage	WP	Work Package

1. Introduction

1.1. Context

The INCREASE project focuses on intelligent ways to manage distributed renewable energy sources (DRES) in low- (LV) and medium-voltage (MV) networks. This is achieved by providing ancillary services, namely voltage control and provision of reserve, towards distribution (DSOs) and transmission system operators (TSOs). The cornerstone of the project activities is the introduction of inverter-interfaced DRES that enables high flexibility and advanced features, further supported by an intelligent multi-agent-based control system with enhanced structure and algorithms. INCREASE aims at providing solutions for operational problems in power systems, allowing increased penetration of DRES as well as providing advanced technological solutions and intelligent control strategies for the prosumers.

Under the INCREASE framework, and especially in Work Package (WP) 3, a supporting simulation platform will be developed, allowing for the design, analysis, and optimization of the developed solutions. This simulation platform will be a valuable tool for DSOs in order to investigate the influence of DRES in their distribution grids, implementing either the INCREASE proposed solutions or any other similar control scheme. The simulation platform will be developed on existing open-source software and will include the following major features:

- Simulation of the distribution system (both LV and MV networks) with the presence of unbalanced loads and generation.
- Integration of the locally controlled, inverter-interfaced, distributed generation (DG) units, i.e. of the Local Control scheme for overvoltage and voltage unbalance mitigation.
- Incorporation of a Multi-Agent System (MAS) taking into account the multi-objective Overlay and Scheduling Control algorithms.
- Implementation of a communication network simulator for the evaluation of the existing infrastructure and the communication requirements for the MAS control system.

The software platform architecture will also allow the integration of other external and independent software modules, such as forecasting algorithms, demand side management and demand response simulation modules, as well as constraint optimization tools.

1.2. Goals

In this report, the incorporation of the MAS-based Overlaying Control algorithm developed in D2.5 and the INCREASE simulation platform is thoroughly presented. This agent-based approach is mainly developed to cope with overvoltages, which are a significant technical issue arising when integrating multiple DRES units in the distribution grid.

First, the algorithm flowchart of the Overlaying Control is presented, focusing on the achievement of certain criteria, like fairness in the process to mitigate overvoltages caused by inverter interfaced DRES of same or different nominal power. Next, the combination of Local and Overlaying Controls is discussed, presenting the consecutive activation of both control schemes and the update of the various control parameters in each simulation time interval. Finally, the actual implementation of MAS in JADE environment is analyzed, highlighting the bi-directional communication between the Core platform and JADE component of the INCREASE simulation platform.

The performance of the Overlaying Control is demonstrated on a selected pilot installation and is compared to the case of no DRES power curtailment as well as to the Local Control scheme. Results show the efficiency of the proposed algorithm in mitigating overvoltage by a fair contribution of curtailed power among the installed PV inverters, while maintaining low levels of power losses in the distribution network.

1.3. Report outline

This introductory chapter is followed by:

Chapter 2: Overview of the INCREASE simulation platform. The overall structure and the individual components of the INCREASE simulation platform are summarized. The report mainly focuses on the development of the agents GUI and on an overview of Local Control, originally presented in Deliverable D3.1.

Chapter 3: Implementation of Overlaying Control. The Overlaying Control, described in D2.5, is incorporated in the INCREASE simulation platform for the fair power sharing (FPS) among the connected DRES. The integrated model is generalized including proper weighting factors in order to be also applicable to PV inverters with different rated power.

Chapter 4: Simulation results. Simulation results from a pilot installation are presented revealing the effectiveness of the proposed Overlaying Control. Results are compared with the corresponding from other control methods, whereas a detailed investigation is also performed on the resulting active power injection and losses levels along the distribution network.

Chapter 5: Conclusion. General conclusions are summarized and a plan for the next research steps is proposed.

2. Overview of the INCREASE simulation platform

The main goal of the INCREASE simulation platform is to simulate and analyze MV/LV electrical power grids, including various inverter-interfaced DRES, different types of loads and control strategies of the DRESs. Due to the required analysis over extended observation times, a quasi-dynamic solution has been selected instead of detailed dynamic simulations, since it can offer a better insight of the system steady-state conditions and is also numerically efficient, needing significantly smaller execution times [1]. A detailed description and validation of the INCREASE simulation platform can be found in D3.1.

In the framework of the INCREASE project, three distinct control strategies are developed, which are fully integrated in the INCREASE simulation platform. More specifically:

- The first level control, named as *Local Control*, is associated with the controllable inverters for overvoltage and voltage unbalance mitigation [2]-[5]. It works continuously, adjusting the total amount of the inverter active power output and its distribution among the three phases according to the voltage at the Point of Common Coupling (PCC).
- The second level control, known as *Overlaying Control*, is related to the MAS coordination algorithms for the application of specific control strategies focused on voltage control and line congestion management [7], [8]. It is an event-driven control, able to change various aspects of the Local Control system, such as the slopes of the inverter droop curves and the corresponding set-points. Generally, the Overlaying Control is addressed to all controlled DRES in the examined network.
- The third level control, known as *Scheduling Control*, addresses problems on a longer time scale, incorporating forecasting of load and generation, demand response, as well as possible energy market inputs [9]. Scheduling Control is also implemented through a MAS.

Finally, the INCREASE simulation platform employs a discrete event simulator of communication networks in order to evaluate the communication performance of the MAS control system. This simulator is mainly used to analyze possible contingencies of the communication infrastructure on the operation of the MAS control system. However, it can also be used to investigate alternative options on the design of the necessary infrastructure and to examine the communication system vulnerability and its impact on the control system performance.

2.1. General architecture

The overview of the simulation platform is presented in Fig. 2.1. The INCREASE simulation platform consists of different open-source tool components and of their mutual interconnections. Specifically, the developed software includes:

- The Core platform, which is the base of the simulation software and interconnects the different tool components.
- The Draw tool, a graphical pre-processor with design capabilities to allow the user-friendly input and configuration of the distribution or transmission network under investigation.
- The OpenDSS environment [10], which is a phasor-domain grid simulator, capable of handling unbalanced power flow problems.
- The JADE environment [11], which is the environment integrating the MAS and the corresponding communication in the INCREASE platform for the implementation of both the Overlaying and Scheduling Control algorithms.
- The OMNeT++ simulator [12], which is a dedicated tool for the evaluation of the communication infrastructure performance of the system under study.

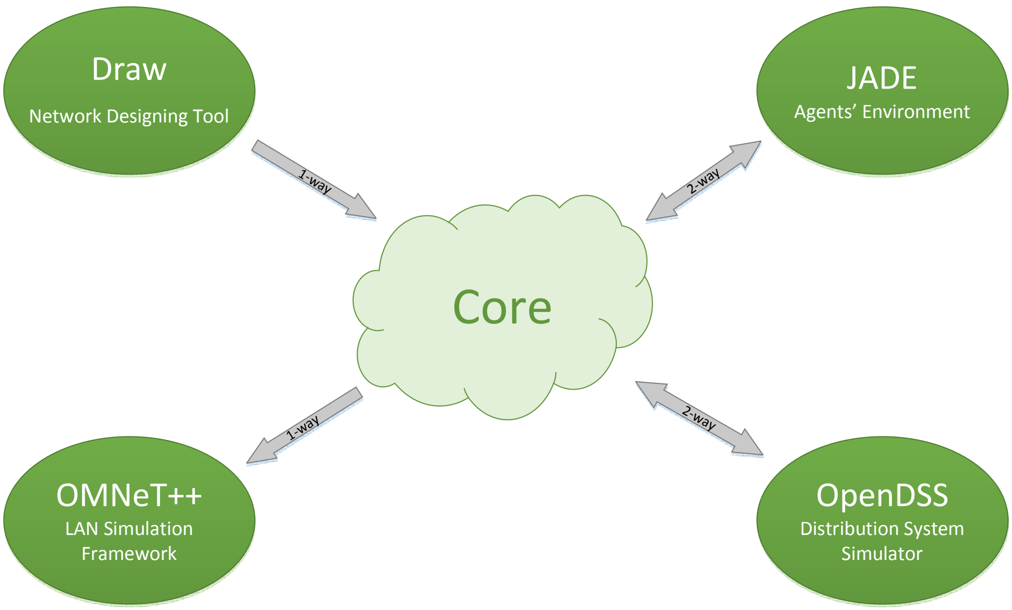

Fig. 2.1: Overview of the INCREASE simulation platform.

2.2. Tool components

In this section a brief description of the required tool components contained in INCREASE simulation platform is presented. A more detailed analysis can be found in D3.1.

2.2.1. Core platform

The Core platform is developed in MATLAB, which is a high-level language and interactive environment, suitable for numerical computations, visualization, and programming [13]. The Core is responsible for the implementation of the interconnections between the different components of the INCREASE simulation platform. As shown in Fig. 2.1, there are four interconnections among the key elements of the platform.

2.2.2. Draw tool

The graphic library for the input of all individual network components is based on SIMULINK models [14] and contains the components defined in the toolbox of Fig. 2.2. This collection includes all basic power system components, such as loads and generation units, as well as the more advanced models of controllable inverters and agents. All elements work in a drag and drop environment by simply putting them in the design area, configuring their required data, and making the appropriate connections. Furthermore, all elements are accompanied by brief help descriptions, when pressing the corresponding button.

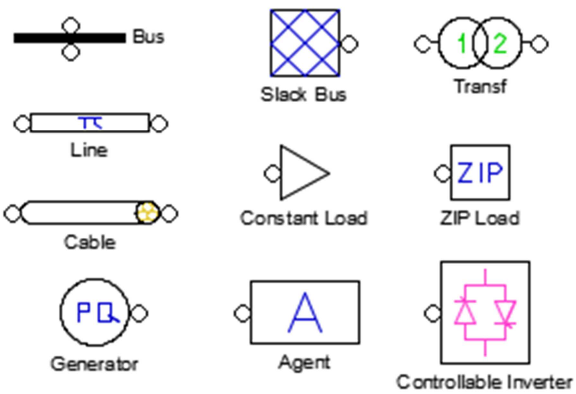

Fig. 2.2: Main window of draw library

Specifically, the GUI for the agent component is shown in Fig. 2.3. By selecting the corresponding checkboxes, measurement reports regarding voltages, currents, active and reactive power can be obtained.

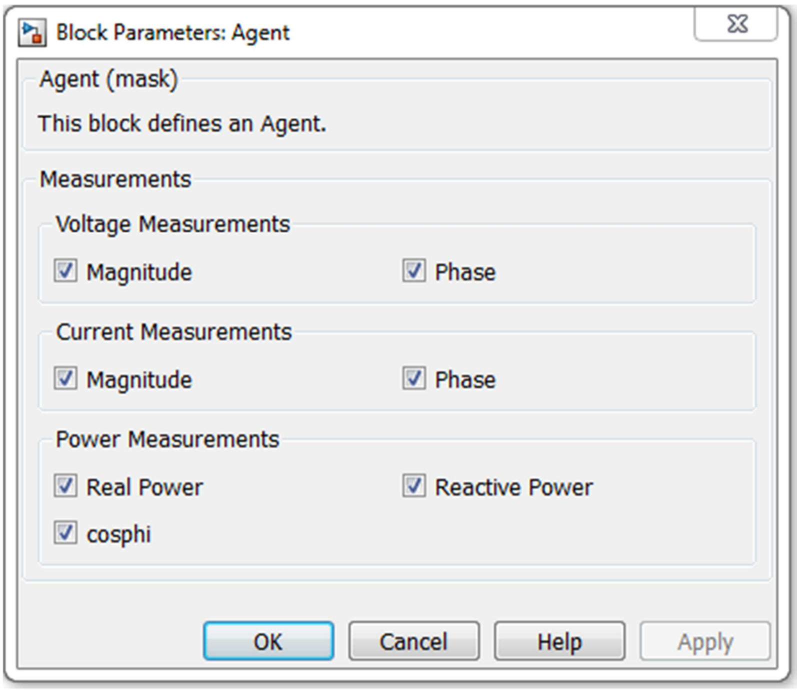

Fig. 2.3: Indicative GUI of agent

2.2.3. OpenDSS simulator

The OpenDSS simulation tool [10] has been chosen as the power flow solver within the INCREASE simulation platform. OpenDSS is a comprehensive, open-source simulation tool for electric utility distribution systems, developed and distributed by the Electric Power Research Institute (EPRI). It offers the most common power system analysis algorithms for both steady-state and dynamic analysis. It also includes various quasi-dynamic solution modes, such as snapshot-daily-yearly power flows and harmonic analysis, making it ideal for sequential time simulations. The time period can be arbitrary selected, whereas users may also implement external macros to drive the load models in any arbitrary user-defined manner. The results of a power flow generally include bus voltages, branch currents, grid losses and other information available for the total system, for each component, and for certain defined areas.

2.2.4. JADE environment

A thorough presentation of the JADE environment is conducted in the next Section [11], since it is the main scope of this Deliverable.

2.2.5. OMNeT++ simulator

A detailed description of OMNeT++ simulator will be included in D3.3 [12].

2.3. Local Control scheme

The Local Control scheme is a low-level control applied to controllable DG units via grid-interfaced inverters. Its main objective is to perform voltage control in low voltage networks, ensuring the safe operation of the distribution grid. The major advantage of the Local Control is the exclusive use of local parameters, measured at each inverter PCC, such as the grid voltage and the available power, offering the ability to immediately react on grid disturbances.

In the INCREASE simulation platform the implementation of Local Control is based on the interaction of each controlled DRES with the grid, neglecting the detailed power electronics analysis of the inverters [1]. This approach allows the use of quasi-dynamic analysis for the network, ignoring the quick responses of power electronic switching elements like IGBTs. The proposed Local Control scheme incorporates two basic control features, namely the droop control of the injected active power as a function of the grid voltage and the voltage unbalance mitigation.

In LV grids, where distribution lines have mainly resistive characteristics, efficient voltage control can be accomplished only by controlling the active power output of the DGs connected to the LV grid feeders. Therefore, the principal objective of this control is the active power curtailment of DG units, in order to avoid unacceptable overvoltages along the distribution lines where these units are connected. This avoids the switching on and off of the DG units, due to overvoltages, while the voltage profile of the distribution feeder is actively controlled. The droop control is based on the voltage at the point of common coupling (PCC) υ_g, while a typical droop curve is depicted in Fig. 2.4.

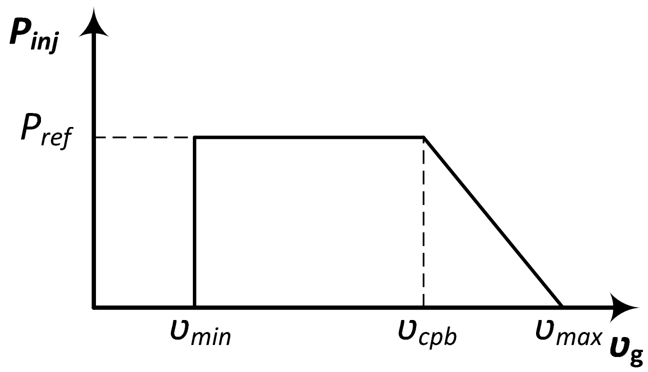

Fig. 2.4: Typical droop curve of controllable DG units

Voltages υ_{cpb} and υ_{max} are the thresholds for the activation of active power curtailment and for the complete cut-off of power injection, respectively. Additionally, υ_{min} is the inverter minimum operating voltage, whereas P_{ref} is the maximum active power the inverter can deliver at a specific time instant, defined from the available power of the primary source.

In the second integrated control scheme of the Local Control, inverters mitigate voltage unbalance by injecting zero- and negative-sequence currents proportionally to the zero- and negative-sequence voltages at the PCC, respectively. A proportionality term is introduced, called damping conductance g_d, which results in a resistive behaviour of the inverter towards the zero- and negative-sequence components of the grid voltage. The injected currents in symmetrical components are calculated according to the following equation [2]-[5],

$$\begin{bmatrix} \overline{i}_0 \\ \overline{i}_1 \\ \overline{i}_2 \end{bmatrix} = \begin{bmatrix} g_d & 0 & 0 \\ 0 & g_1 & 0 \\ 0 & 0 & g_d \end{bmatrix} \cdot \begin{bmatrix} \overline{\upsilon}_0 \\ \overline{\upsilon}_1 \\ \overline{\upsilon}_2 \end{bmatrix} \tag{2.1}$$

where $\overline{\upsilon}_0$, $\overline{\upsilon}_1$, $\overline{\upsilon}_2$ are the zero-, positive- and negative-sequence components of the voltage at the PCC, and g_1 refers to the injected active power and is the fundamental conductance of the inverter having an opposite sign of g_d in case of generation.

An extensive presentation of the Local Control is available on D2.4. Further results considering the performance and the effectiveness of the proposed Local Control scheme are included in D3.1.

3. Implementation of Overlaying Control

A significant drawback of the Local Control is the unfair power curtailment that is mainly observed for the DRES which are connected to the end of the radial LV feeders. The Overlaying Control acts complementary to the Local Control, redistributing the curtailed power in a fair way among the DRES.

3.1. Problem formulation

The radial LV feeder of Fig. 3.1 is assumed, consisting of various DRES and/or constant PQ loads connected to the *n* LV buses. In principle, each of the *m* inverters is characterized by its maximum power point (MPP) P_{MPP}^{j}, droop-control reference power P_{ref}^{j} and actual active power injection P_{inj}^{j}, depending on the voltage at the corresponding PCC V_{g}^{j} according to Fig. 2.4.

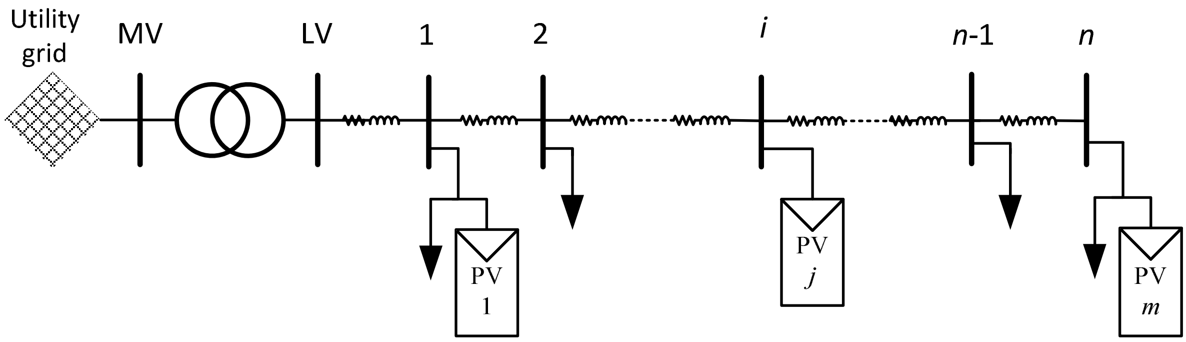

Fig. 3.1: Radial LV feeder

Since each voltage V_{g}^{j} is dependent on the grid impedance between the MV/LV transformer and the respective PCC, the corresponding power injection P_{inj}^{j} of Fig. 2.4 will be also different for each inverter, leading to an unfair power flow exchange condition. This unfairness is expressed in the following equation [8]:

$$P_{curt}^{1} \neq \ldots \neq P_{curt}^{j} \neq \ldots \neq P_{curt}^{m} \leftrightarrow V_{g}^{1} \neq \ldots \neq V_{g}^{j} \neq \ldots \neq V_{g}^{m} \quad (3.1)$$

where the absolute curtailed active power P_{curt}^{j} of inverter *j* is given by:

$$P_{curt}^{j} = P_{MPP}^{j} - P_{inj}^{j}, \forall P_{MPP}^{j} > P_{inj}^{j} \quad (3.2)$$

3.2. FPS using sensitivity matrix

One of the objectives of the Overlaying Control is to obtain a fair power curtailment among the inverters, while mitigating the overvoltage in the radial LV feeder. The fair power curtailment is based on a sensitivity matrix methodology, by curtailing the active power of each inverter [8].

In principle, the effect of active power change at bus *k* on the voltage at bus *l* can be observed using the concept of the sensitivity matrix, which is an inverse matrix form of the Jacobian matrix. The Jacobian matrix provides a linearized relation between the change in active and reactive power ΔP, ΔQ with the change in voltage magnitude $\Delta|V|$ and angle $\Delta\delta$ as expressed in the following equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{3.3}$$

Assuming that the change in reactive power is zero during the control period, (3.3) can be simplified to:

$$[\Delta P] = \left[J_2 - J_1 J_3^{-1} J_4\right]\left[\Delta|V|\right] \tag{3.4}$$

Equation (3.4) is modified to (3.5), in which the inverse of the Jacobian matrix is denoted as the sensitivity matrix $[S]$.

$$[S] = \frac{\left[\Delta|V|\right]}{[\Delta P]} = \left[J_2 - J_1 J_3^{-1} J_4\right]^{-1} \tag{3.5}$$

After the elimination of the elements that do not correspond to buses with connected DRES, the complex relation between voltage magnitude and active power for different buses is linearized by the elements of the sensitivity matrix, which are shown below:

$$[S] = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \tag{3.6}$$

where $i = 1,\ldots,n$ and $j = 1,\ldots,m$.

Changes in the power of DRES $[\Delta P]$ lead to the change in the voltage magnitude $\Delta\left|V_g^j\right|$ of *i*-th bus, as shown below:

$$\Delta\left|V_g^j\right| = \begin{bmatrix} x_{i1} & \cdots & x_{im} \end{bmatrix}\left[\Delta P\right] \tag{3.7}$$

Assuming, first, that the LV feeder consists of a number of same size droop-based PV inverters, the changes in active power of all DRES are assumed to be equal in real values, thus $\Delta P_1 = \Delta P_2 = \ldots = \Delta P_m = \Delta \mathrm{P}$. Considering that the *i*-th bus exhibits the worst overvoltage, (3.7) is deduced to (3.8). Using (3.8), the required change in active power of all DRES connected to the specific LV feeder can be computed, in order to mitigate overvoltage on bus *i*. As a result, the fairness or equal power curtailment in real values of power to reach the desired voltage can be calculated as follows:

$$\Delta \mathrm{P} = \frac{\Delta\left|V_g^j\right|}{\sum_{j=1}^{m} x_{ij}} \tag{3.8}$$

Then, for the case of different-sized droop-based inverters, (3.7) and (3.8) have to be generalized to perform the fair power curtailment in a non-absolute way, relative to the MPP of each inverter. For this purpose, the coefficient vector $\left[w\right]$ is introduced below,

$$\left[w\right] = \frac{\left[P_{MPP}\right]}{\min\left(\left[P_{MPP}\right]\right)} \tag{3.9}$$

where $\left[P_{MPP}\right]$ is a vector containing the MPPs of all inverters at a given time instant and $\min\left(\left[P_{MPP}\right]\right)$ is the minimum element of $\left[P_{MPP}\right]$. Then, the curtailed active power $\Delta \mathrm{P}$ of the inverter with the minimum P_{MPP}^j is given by (3.10), while the active power curtailments $\left[P_{curt}\right]$ of all the other inverters are given by (3.11).

$$\Delta \mathrm{P} = \frac{\Delta\left|V_g^j\right|}{\sum_{j=1}^{m} w_j \cdot x_{ij}} \tag{3.10}$$

$$\left[P_{curt}\right] = \Delta \mathrm{P} \cdot \left[w\right] \tag{3.11}$$

3.3. Extension to multiple feeders

The extension of the presented FPS from one LV feeder to a LV network is performed in a straightforward way. After the calculation of the sensitivity matrix in (3.5) and (3.6), it can be observed that matrix $\left[S\right]$ in (3.12) has a structure close to a block diagonal one, since the main diagonal block matrices generally yield much higher values than the corresponding off-diagonal blocks. This is attributed to the higher sensitivity between the nodes of the same than of different LV feeders.

$$[S]=\begin{bmatrix}[x]_{11} & \cdots & [x]_{1k}\\ \vdots & \ddots & \vdots\\ [x]_{k1} & \cdots & [x]_{kk}\end{bmatrix},\ [x]_{ii}>>[x]_{ij} \tag{3.12}$$

Due to this particular structure, (3.12) can be simplified to the block diagonal matrix of (3.13), where the off-diagonal blocks are set to zero. This implies that the FPS algorithm of the Overlaying Control can be applied individually to each feeder of the LV network without significant loss of accuracy.

$$[S]\cong\begin{bmatrix}[x]_{11} & \cdots & [0]\\ \vdots & \ddots & \vdots\\ [0] & \cdots & [x]_{kk}\end{bmatrix} \tag{3.13}$$

3.4. Resetting of inverter droop curves

After the application of the Overlaying Control, leading to new power injections for all inverters, a new power flow is solved to calculate the corresponding voltages at inverter PCCs. From the acquired set-points, the droop characteristics of all inverters are reconfigured as shown in Fig. 3.2. In the first two cases, the initial droop curves are simply reconfigured to the dash lines, which satisfy the fair power curtailment among the inverters. In the last case, the reconfiguration of droop curve is performed in such a way that does not violate the MPP value of the inverter at the given time instant.

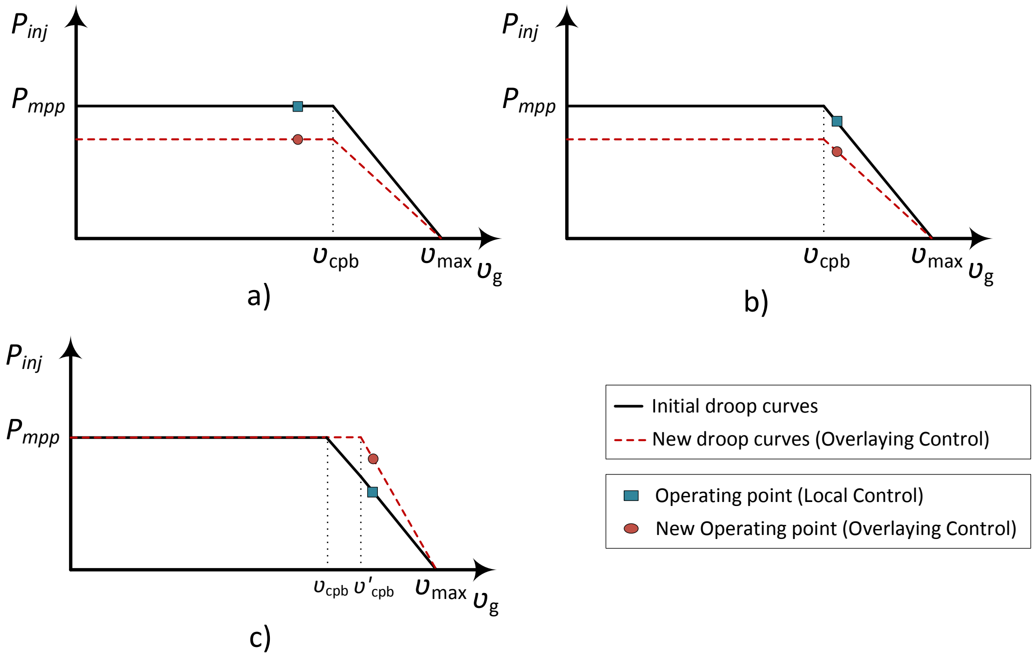

Fig. 3.2: Reconfiguration of inverter droop curves

3.5. Integration with Local Control

The integration concept of the Local and Overlaying Control is presented in Fig. 3.3, where a detail of a 15-min timeslot is also depicted. Since the Local Control is designed to be embedded at the hardware level of the inverter, it is continuously active during the 15-min timeslot. After the first 5 min all the data considering the voltages at PCC, the inverter power injections and the net power flow are monitored and communicated to the MAS platform layer. In case of detecting any unfairness in curtailing the inverter power injections, the FPS algorithm is activated and the new reference control signals are sent to each inverter. Then, the droop curves are reconfigured and this state retains until the end of the 15-min timeslot, where the droop curves reset and the loads as well as the MPP inverter values are updated to new values. The length of the specific time slot can be flexible and depends mainly on the sampling rates of the actual monitoring system implemented in each specific grid.

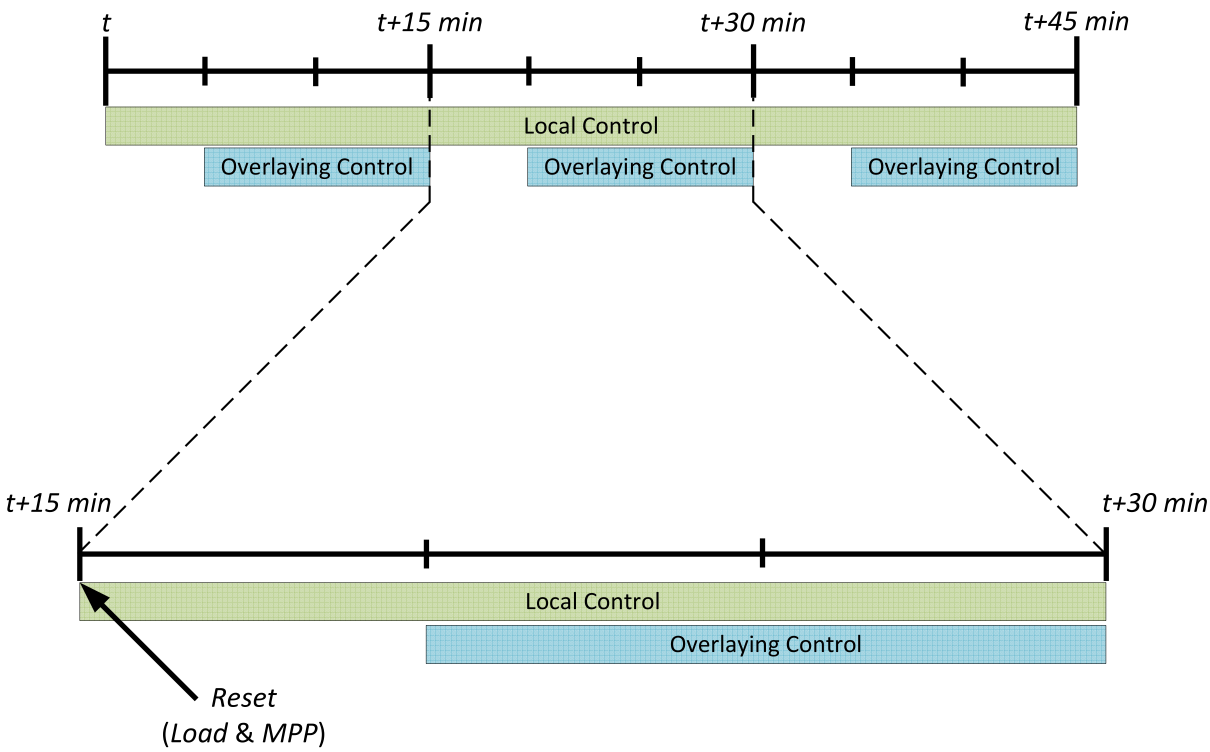

Fig. 3.3: The 15-min timeslot concept

3.6. Actual implementation

3.6.1. Introduction to JADE

JADE is a software development framework aimed to develop MAS and applications conforming to FIPA standards for intelligent agents. It includes two main components, namely a FIPA-compliant agent platform and a package to develop Java agents [11].

JADE is written in an object-oriented programming language, namely JAVA, due to the many attractive features it provides, such as Object Serialization, Reflection API and Remote Method Invocation (RMI). Furthermore, it comprises of various Java packages, giving agent developers both ready-made pieces of functionality and abstract interfaces for custom, application dependent tasks. The main features of JADE are listed in the following:

- Library of FIPA interaction protocols ready to be used.
- In-process interface to allow external applications to launch autonomous agents.
- Distributed agent platform, which can be split among several hosts. Only one Java application, and therefore only one Java Virtual Machine, is executed on each host.
- Agents are implemented as Java threads and live within Agent Containers that provide the runtime support to the agent execution.

- Intra-platform agent mobility, including transfer of both the state and the code (when necessary) of the agent.
- Support to the execution of multiple, parallel and concurrent agent activities via the behaviour model.

3.6.2. Integration in the INCREASE simulation platform

In the frame of INCREASE simulation platform, JADE is employed as the MAS developing environment where the Overlaying Control is implemented. More specifically, the code referring to the FPS algorithm of the Overlaying Control is actually written in JADE, making it an essential component of the simulation platform. The combined operation of Core, which is implemented in MATLAB, with JADE is achieved through TCP/IP communication. Considering a specific time instant, the Overlaying Control procedure is depicted in Fig. 3.4 comprising of 6 steps which are analyzed as follows:

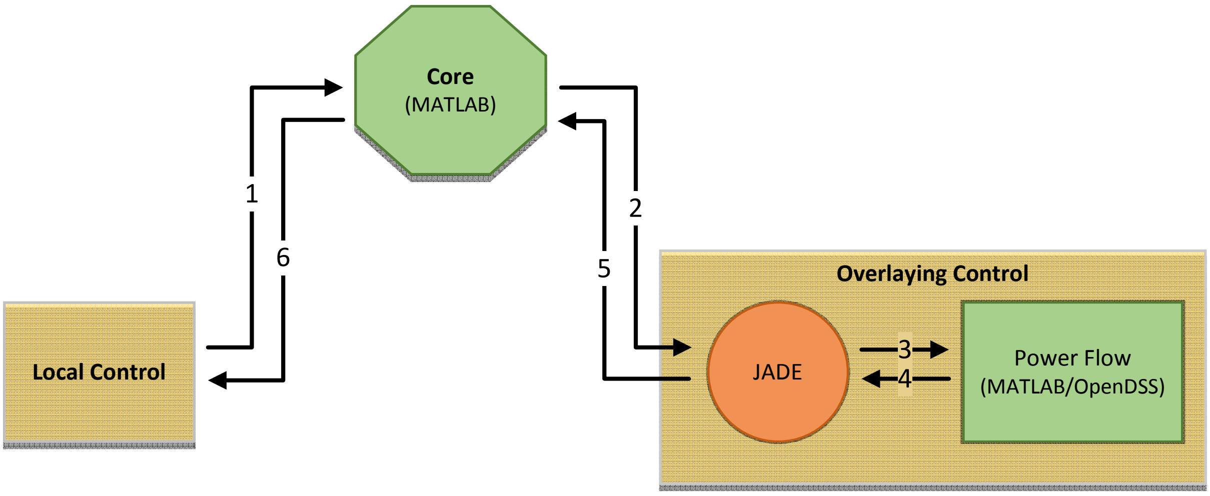

Fig. 3.4: Conceptual implementation of Overlaying Control

Step 1: The results of the Local Control regarding voltages, injected active power of DG units, etc., are forwarded to the Core of the INCREASE simulation platform. Then, the Core checks whether an active power curtailment has occurred. In the case of DG units with curtailed active power, the Overlaying Control is activated. Otherwise, the procedure moves to Step 6 and Overlaying Control remains deactivated.

Step 2: This step is implemented via a TCP/IP communication channel, established between Core and JADE. The data passed to JADE refer to the network configuration and the results obtained from Local Control, i.e. voltages, loads, injected active power of DG units, etc. In the event of an unfair active power curtailment among DG units, the MAS activates the fair power curtailment algorithm. Otherwise, the procedure moves to Step 5.

Step 3: According to the aforementioned fair power curtailment algorithm, two power flow calculations are necessary. In the first power flow each DG unit is considered to inject its maximum available power, i.e. in MPP operation, whereas in the second one it injects the active power defined by the fair power curtailment algorithm. These power flow calculations are implemented in MATLAB and OpenDSS, but are initiated by the MAS established in JADE.

Step 4: The results obtained from the power flow calculations are passed to JADE. Then, the sensitivity matrix and the new droop curves are calculated based on the first and the second power flow, respectively.

Step 5: Considering the unfair power curtailment, the new droop curves of DG units are forwarded back to the Core via another TCP/IP communication channel.

Step 6: Finally, the droop curves of DG units are passed to the Local Control and a new iteration is initiated.

4. Simulation results

The Overlaying Control implemented in the INCREASE simulation platform is demonstrated in the pilot installation of Elektro Gorenjska. The examined LV network is shown in Fig. 4.1 and consists of 79 nodes, where 70 inductive unbalanced loads are connected, and a typical MV/LV distribution transformer. The green nodes denote the location of the existing controllable PV units. This network configuration does not allow the implementation of Overlaying Control, since there is no feeder with at least two PV units. As a result, 24 additional PV units are considered in this installation depicted by the red nodes in Fig. 4.1. The rated power of the PV units as well as the transformer data are shown in Table 4-1 and Table 4-2, respectively. The MV/LV transformer is equipped with an OLTC and the LV side voltage has been considered 1.05 pu. Finally, the 4-wire distribution lines have cross sections ranging from 4x16 mm^2 to 4x150 mm^2 with their lengths vary from 10 m up to 176 m.

In the following simulations, 5 different control schemes are assumed and investigated:

1. *No Control*, where no control is assumed and PV units inject their nominal active power.
2. *Local Control*, where the droop control of the injected active power of PV units is implemented.
3. *Overlaying Control*, which includes the implementation of the FPS algorithm.
4. *Offset 1 Control*, which is an enhanced *Overlaying Control* scheme by adding an arbitrary offset value in the calculation of (3.10), as shown in (4.1). In this case, the offset is equal to 0.1 % of the nominal voltage on the examined network.

$$\Delta P = \frac{\Delta\left|V_g^j\right| - Offset}{\sum_{j=1}^{m} w_j \cdot x_{ij}} \tag{4.1}$$

5. *Offset 2 Control*, which is similar to Offset *1*, but the arbitrary offset value in (4.1) is now equal to 0.2 % of the nominal voltage on the examined network.

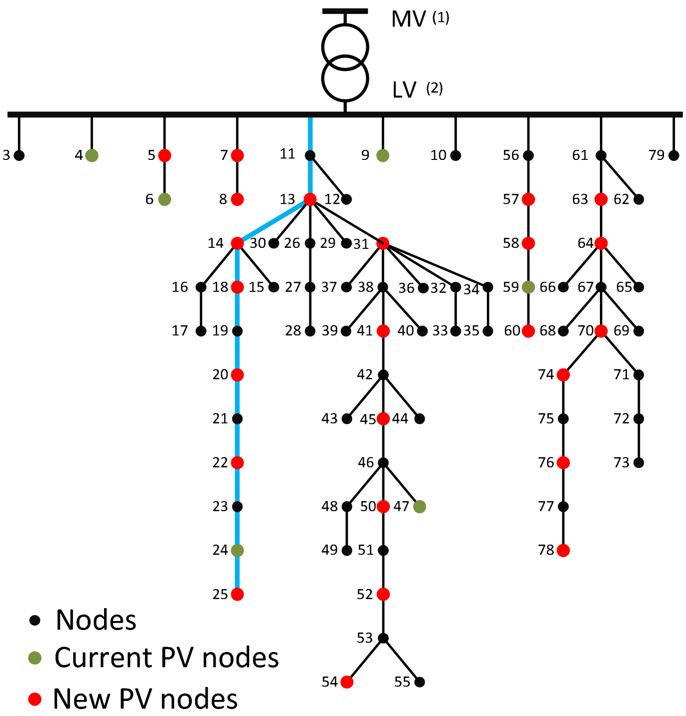

Fig. 4.1: Elektro Gorenjska network topology

Table 4-1: PV units rated power

Name	Node	Rated Power (kW)	Name	Node	Rated Power (kW)
PV 4	4	4	**PV 45**	45	7
PV 5	5	7	**PV 47**	47	7
PV 6	6	3	**PV 50**	50	7
PV 7	7	7	**PV 52**	52	7
PV 8	8	7	**PV 54**	54	4
PV 9	9	4	**PV 57**	57	7
PV 13	13	7	**PV 58**	58	7
PV 14	14	8	**PV 59**	59	7
PV 18	18	8	**PV 60**	60	7
PV 20	20	4	**PV 63**	63	7
PV 22	22	7	**PV 64**	64	8
PV 24	24	7	**PV 70**	70	3
PV 25	25	7	**PV 74**	74	7
PV 31	31	7	**PV 76**	76	7
PV 41	41	7	**PV 78**	78	4

Table 4-2: Distribution transformer characteristics

S_n (kVA)	U_n (kV)	Vector group	u_k (%)	No-load losses (W)	On-load losses (W)
250	20 / 0.4	Dyn5	4	425	3250

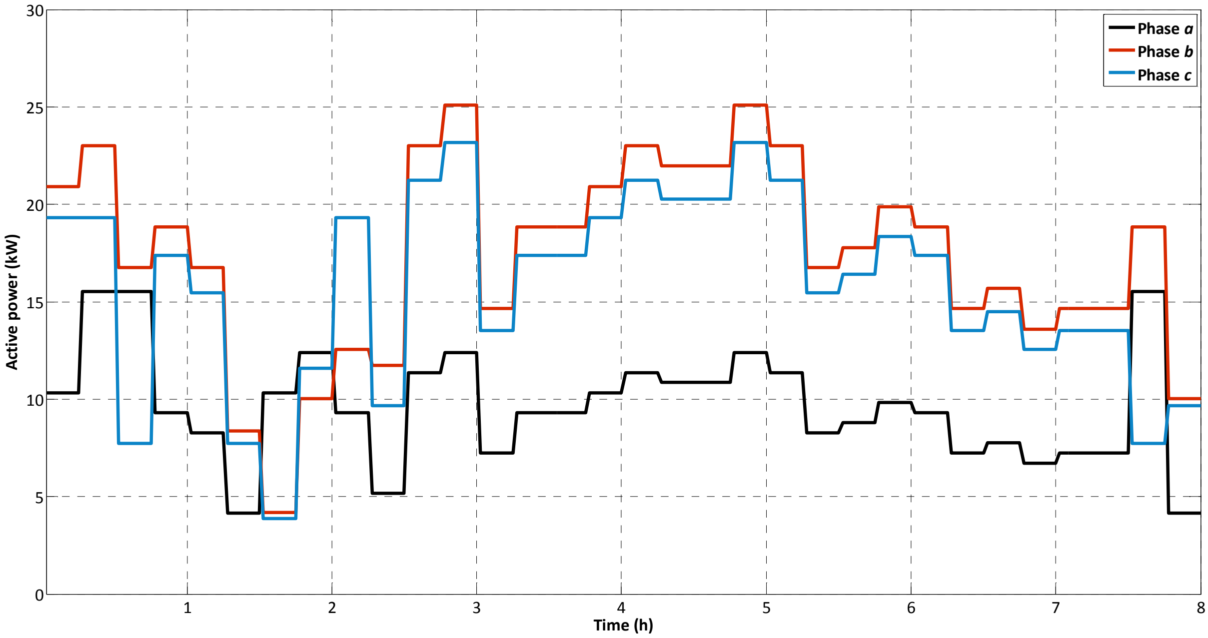

Fig. 4.2: Active power profile of the aggregated load vs. time

This chapter is divided into two sections. In the first one, the different implementations of Overlaying Control are presented and compared with *Local* and *No Control* schemes. These comparisons are made for one time instant, corresponding to instantaneous values, where power consumption, generation and all network characteristics remain constant. The second section presents a time-series simulation, where the combination of Local with Overlaying Control is evaluated for different implementations of Overlaying Control. Each timeslot is considered equal to 15 min and the simulation covers a period of 8 hours. All loads are considered with constant power factor 0.9 lagging, whereas the active power profile of the aggregated load is depicted in Fig. 4.2.

4.1. Comparison of different implementations of Overlaying Control

In this section, it is assumed that the PV units are capable of injecting their rated power and that the active power of the aggregated load is equal to the value of the first 15-min timeslot, as shown in Fig. 4.2. The injected active power of all the PV units in the same feeder as indicated by the blue line shown in Fig. 4.1 after the implementation of the different control schemes and the corresponding positive-sequence voltage profiles are presented in Fig. 4.3 and Fig. 4.4, respectively. All data are shown at a pu scale based on the rated voltage and power of each DRES unit.

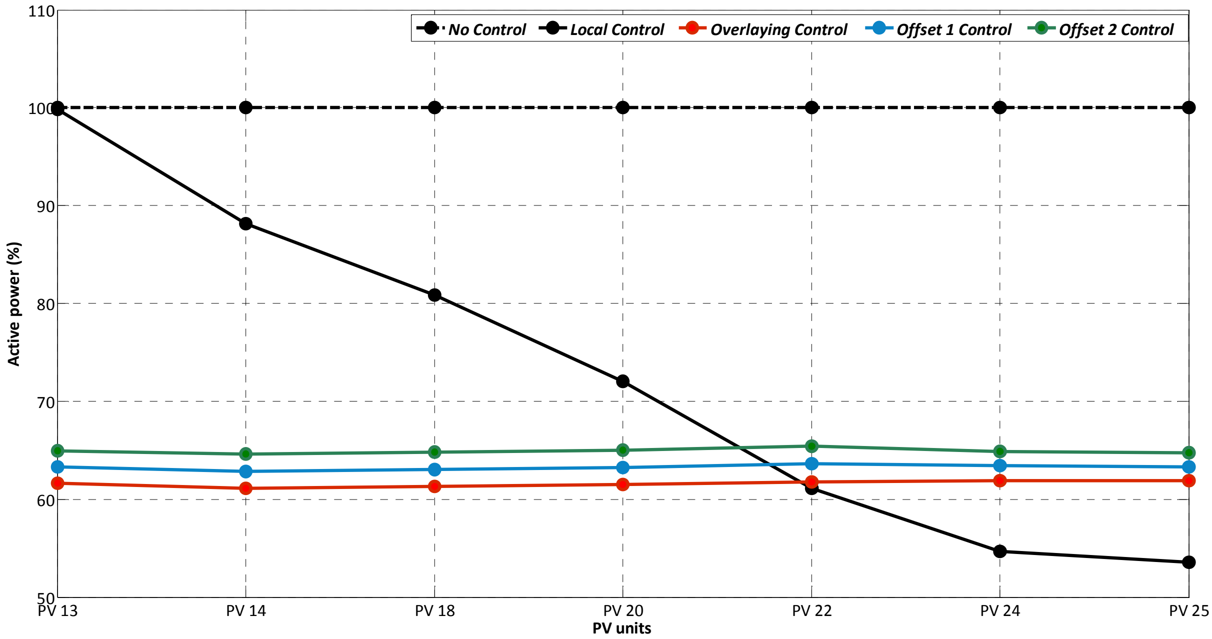

Fig. 4.3: Injected active power of PV units along a single feeder

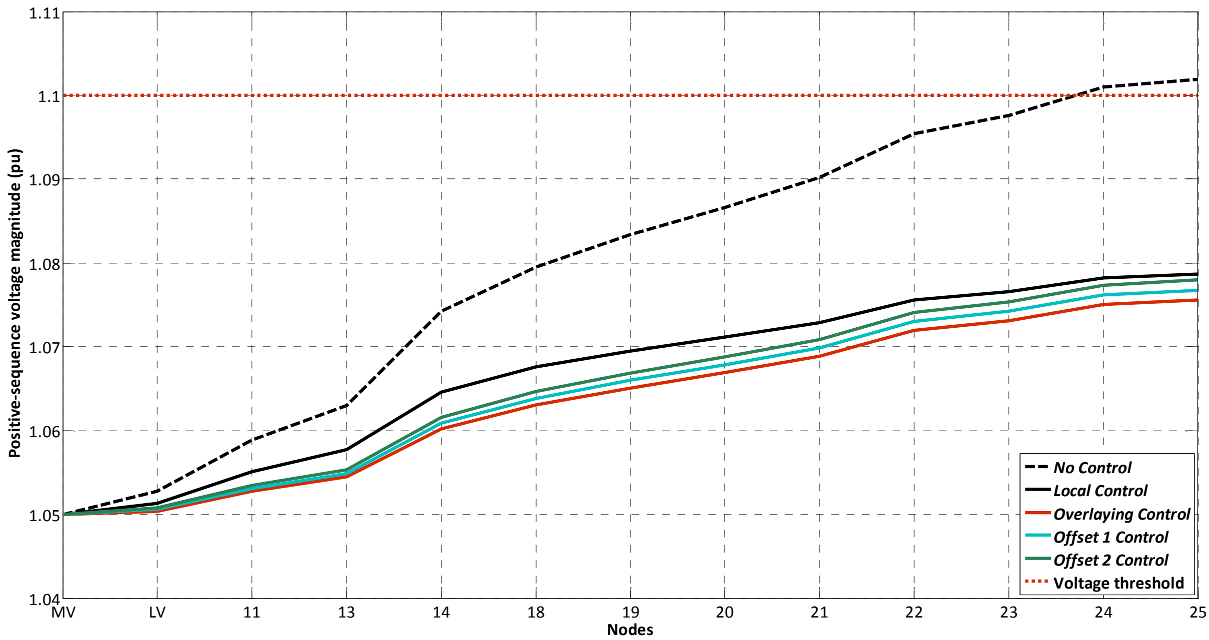

Fig. 4.4: Positive-sequence voltage profile along a single feeder

Considering Fig. 4.3, *No Control* corresponds to the points on the 100% line, where each PV unit injects its nominal active power. Since no active power curtailment is occurred, the voltage at the last nodes of the feeder exceeds 1.1 pu which is the maximum permissible voltage, as defined by the EN 50160 standard. This is clearly shown in the voltage profile along the feeder, shown by the dashed line of Fig. 4.4. This overvoltage is mitigated by applying the *Local Control* scheme. However, in this case the PV units located at the end of the feeder suffer from a severe active power curtailment compared to the corresponding located at the beginning, as shown from the points on the continuous black line of Fig. 4.3. To overcome this problem, the *Overlaying Control* scheme is applied, resulting in a uniform active power curtailment among the PV units of the same feeder, as shown in points along the red line of Fig. 4.3. According to the results of the Overlaying Control, the injected active power of PV units located at the end of the feeder is increased, where the PV units at the beginning of the feeder have now an increased active power curtailment, compared to the previous *Local Control* case.

The total injected active power of PV units for the examined feeder is shown in Fig. 4.5. Despite the fact that *Overlaying Control* scheme reduces the active power curtailment of the last PV units, the overall injected active power is decreased compared to the *Local Control* scheme. The introduction of the *Offset* control scheme seems to partially mitigate this issue. As the offset control value increases, the injected active power of PV units is also increased, while maintaining almost uniform active power curtailment among PV units. Moreover, the voltage profile is also improved as shown in Fig. 4.4. Thus, the *Offset 1* and *Offset 2* control schemes present an improved performance compared to the *Overlaying Control* scheme. Finally, in Fig. 4.6 the voltages of all network nodes is shown and similar conclusions can be drawn.

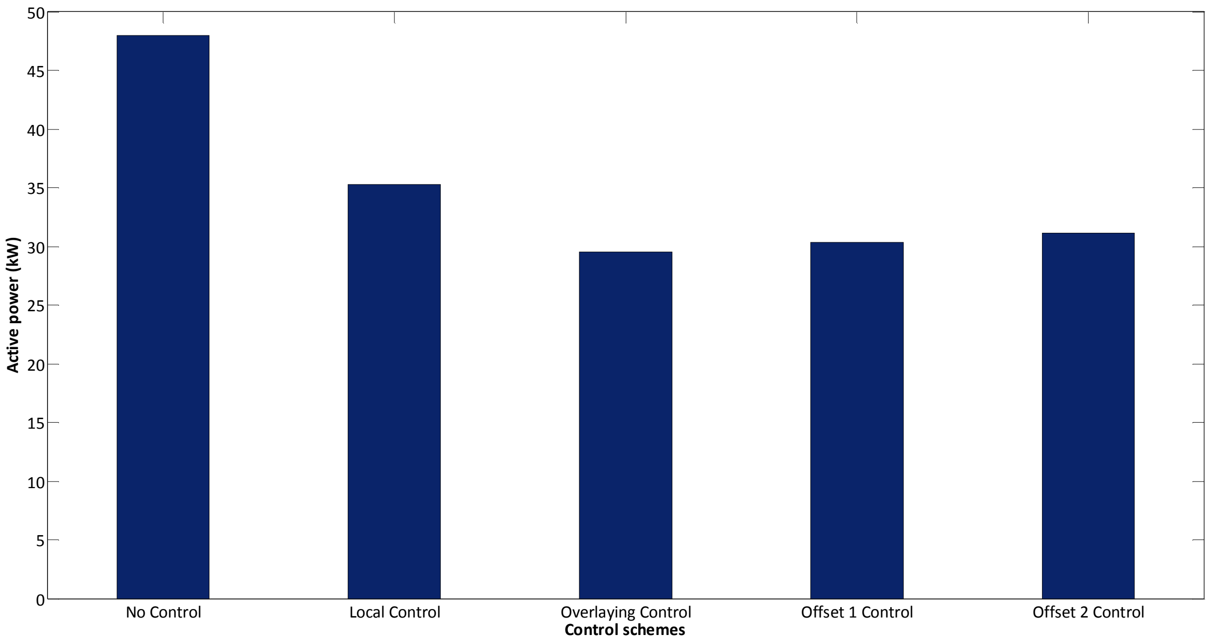

Fig. 4.5: Total injected active power along a single feeder

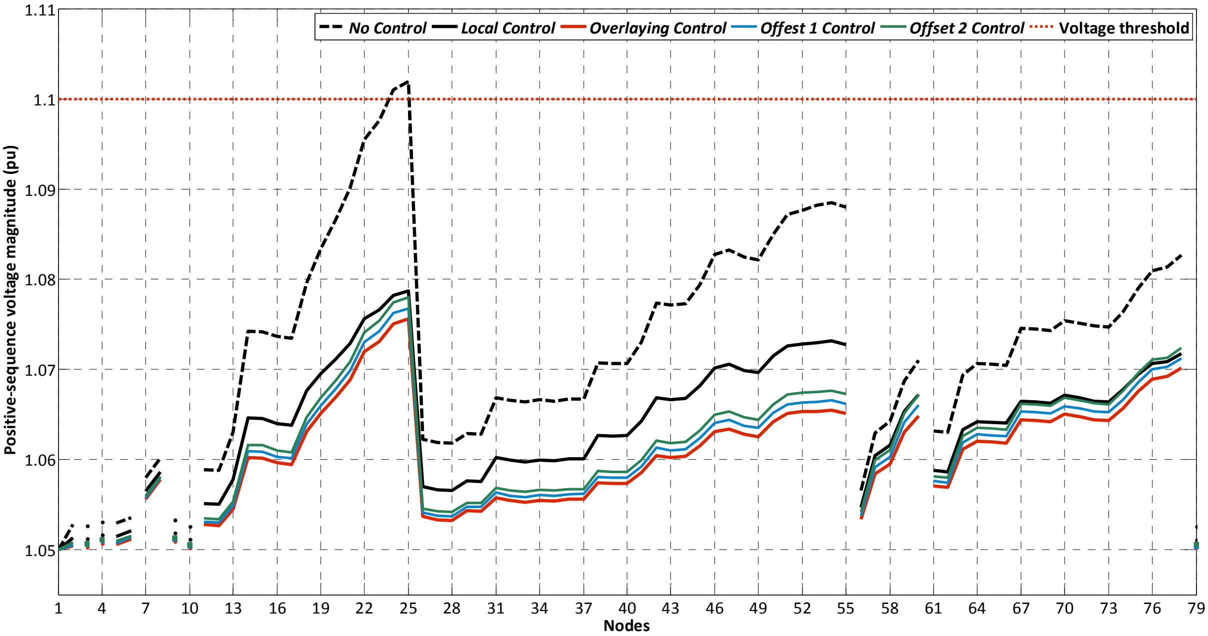

Fig. 4.6: Positive-sequence voltage profile along the network

4.2. Time-series simulation

In this section, the maximum available power of all PV units in the system is considered constant and equal to their rated power, whereas the load varies according to Fig. 4.2. The total injected active power of all PV units with respect to time is presented in Fig. 4.7 and Fig. 4.8, the latter zooming over a specific time instant to show the sequential implementation of the different control schemes. In these figures, the Local Control is combined with the different implementations of the Overlaying Control. The corresponding active power network losses are depicted in Fig. 4.9. Finally, in Fig. 4.10 and Fig. 4.11 the voltage profile of the node with the most severe overvoltage is shown, over the whole simulation period and zoomed over a specific time instant, respectively.

As it is already mentioned, the *No Control* scheme results in zero active power curtailment, but also in severe overvoltages. The use of the *Local* control scheme mitigates overvoltages and the voltage is actively controlled as shown in. Fig. 4.10 and Fig. 4.11. Considering constant available power of PV units, the variation of the injected active power depends on the current situation of the network and more specifically, on the loading conditions. High consumer loads allow increased active power injection by the DRESs, as shown in Fig. 4.7.

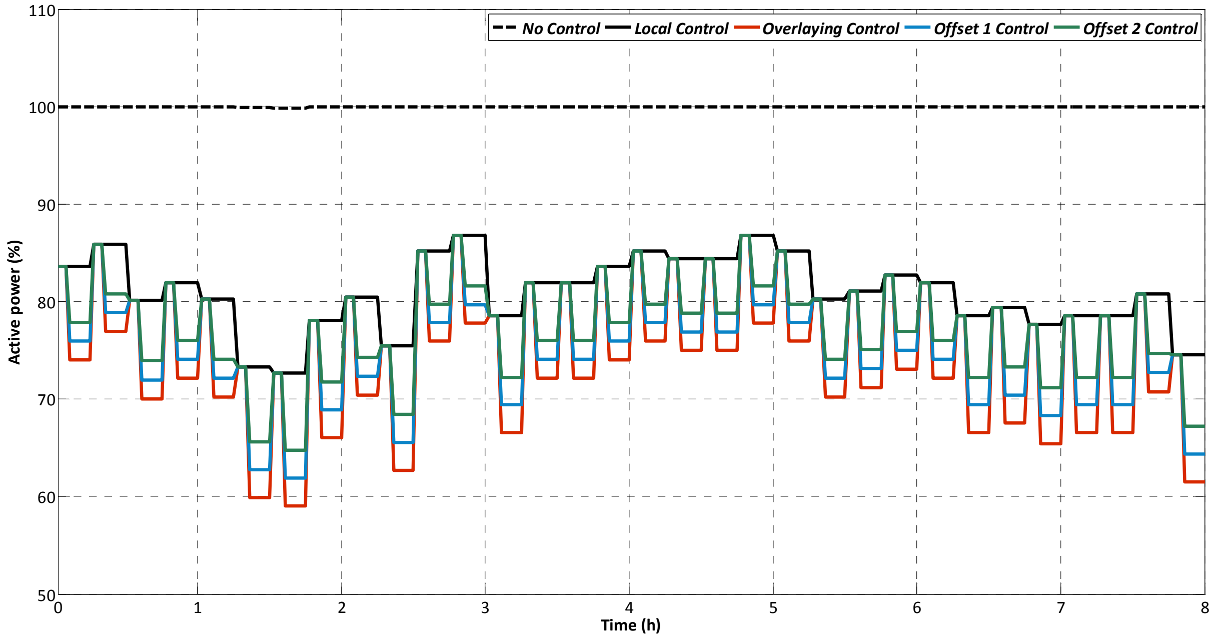

Fig. 4.7: Injected active power of PV units vs. time

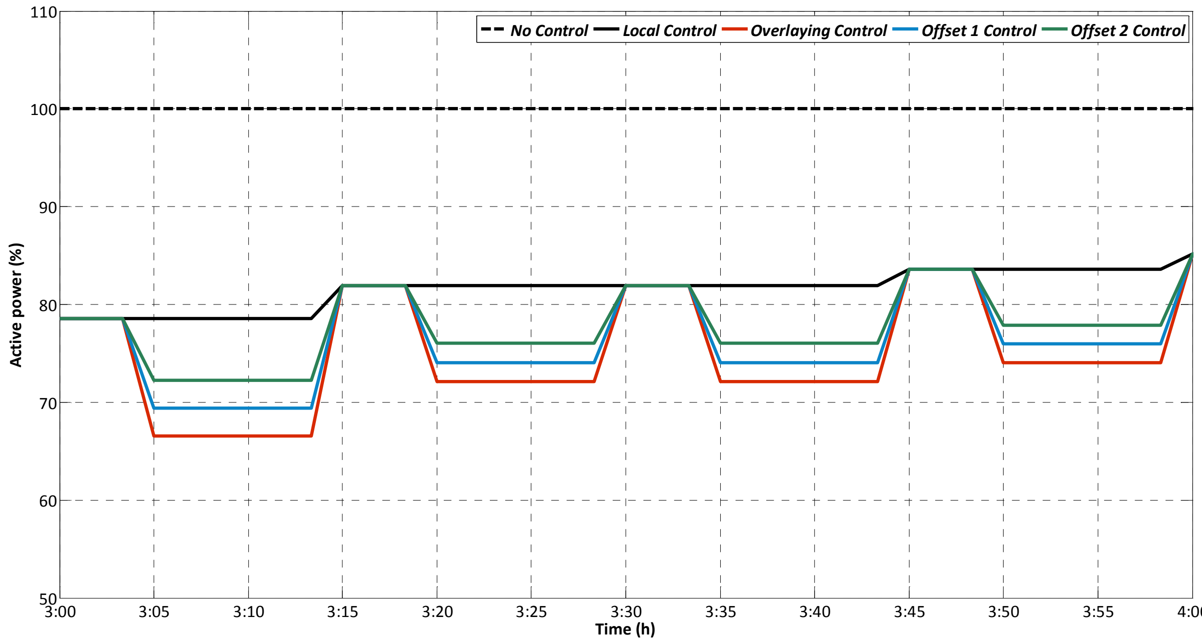

Fig. 4.8: Injected active power of PV units from 3:00 to 4:00

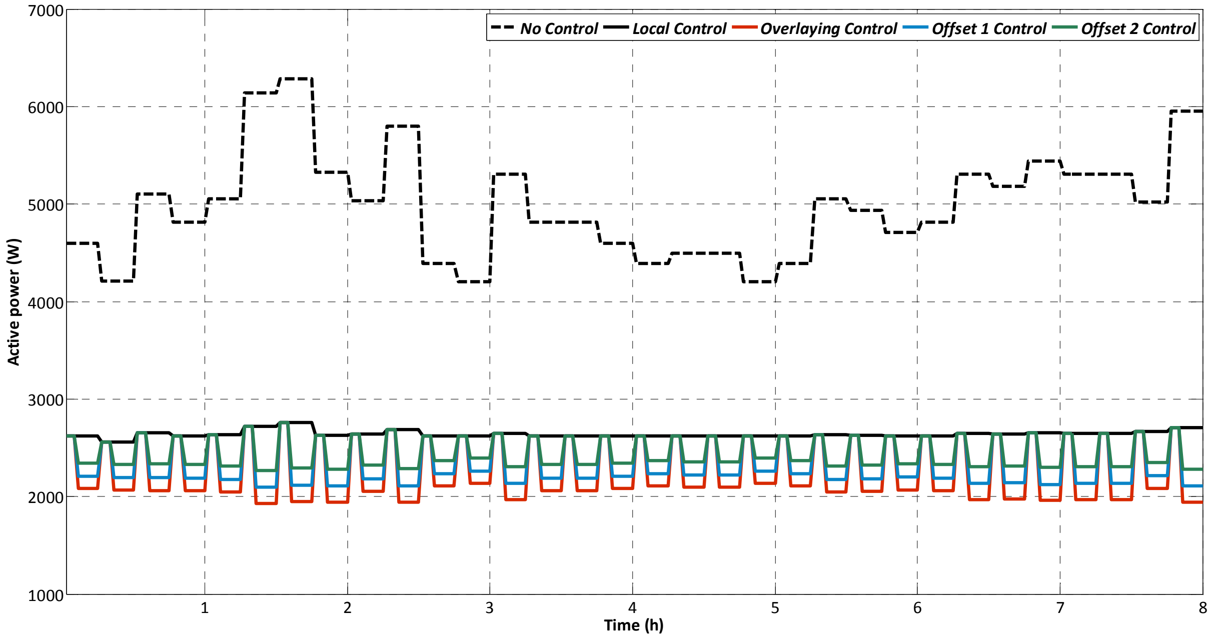

Fig. 4.9: Network losses vs. time

The *Overlaying Control* scheme, according to the 15-min timeslot concept, results in a more uniform active power curtailment among PV units. The main drawback of this method is the further reduction of the total injected active power, compared to the *Local Control* scheme. Nevertheless, this is partially compensated by employing the *Offset Control* schemes, as shown in. Fig. 4.7 and Fig. 4.8. Considering the power losses, since a reverse power flow is observed, the reduction in the injected active power results in the reduction of the network losses as well. Finally, from Fig. 4.10 and Fig. 4.11 it can be concluded that the voltage profile is also considerably improved after the application of the *Offset Control* schemes, making them the most suitable and preferable option for the implementation of the Overlaying Control.

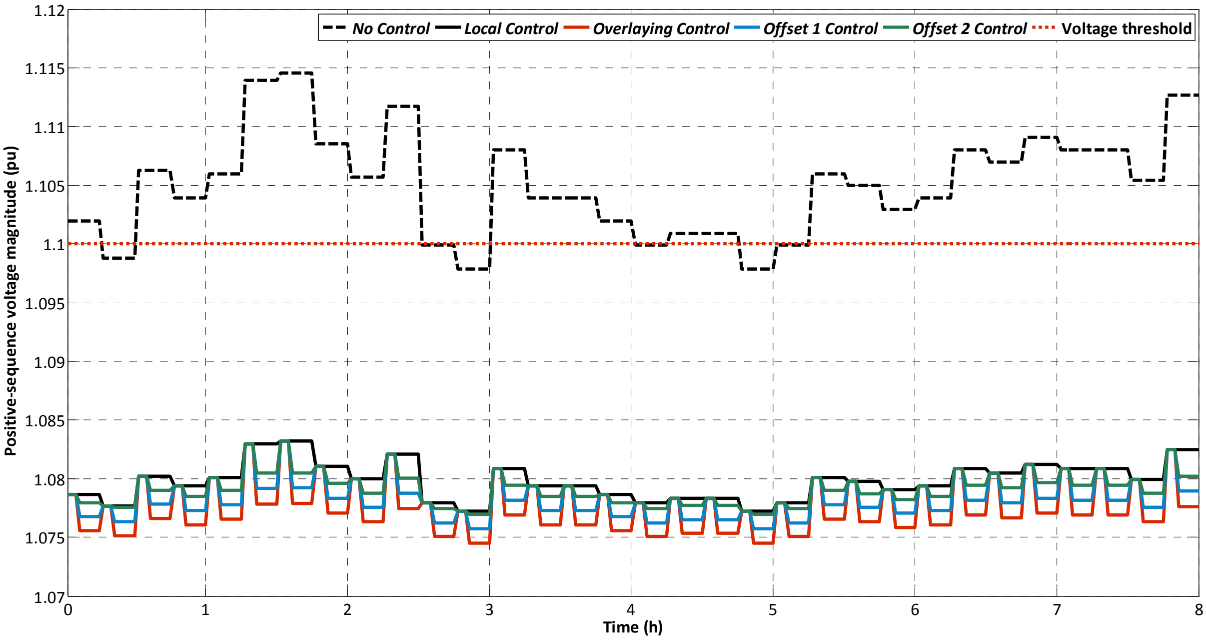

Fig. 4.10: Profile of the maximum voltage in the network vs. time

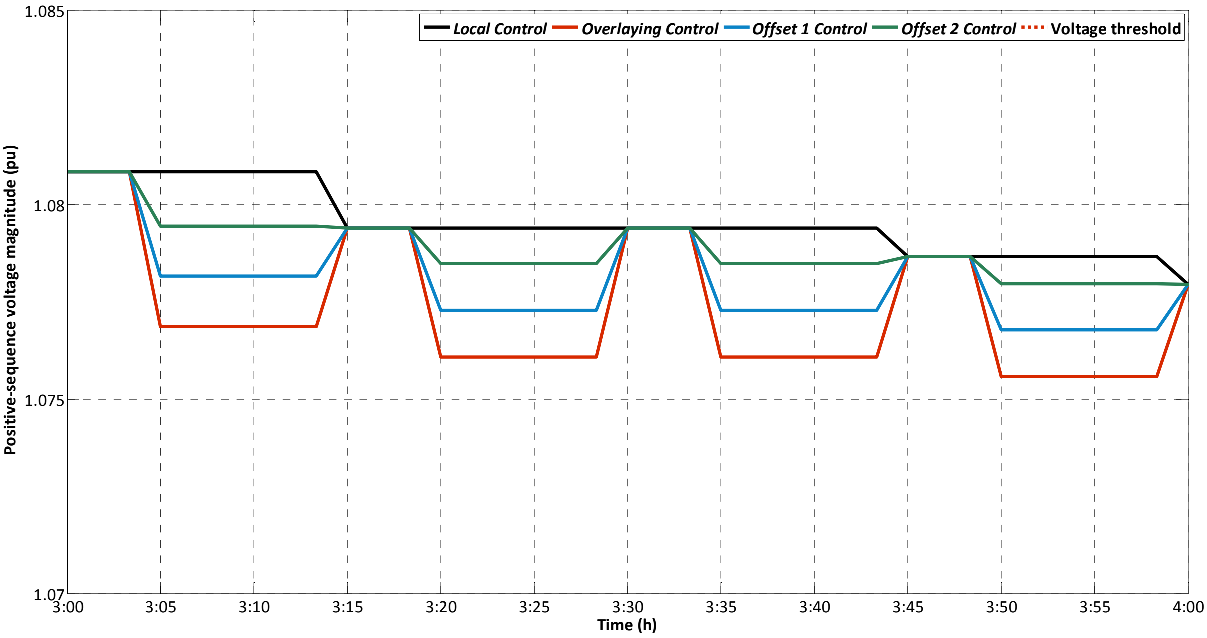

Fig. 4.11: Profile of the maximum voltage in the network from 3:00 to 4:00

5. Conclusions

This report presents a detailed description of the Overlaying Control and its implementation in the INCREASE simulation platform. The analysis starts with a brief presentation of the overall structure and the individual components of the INCREASE simulation platform, including the development of agent GUI and an overview of Local Control, as presented in D2.4 and D3.1.

Then, the successful implementation of the FPS algorithm of the Overlaying Control in the INCREASE simulation platform, as described in D2.5, is presented. The Overlaying Control aims to the uniform active power curtailment among the connected DRES, introducing a 'fairness' criterion. The implemented control method is applicable to PV inverters with either equal or different nominal powers, by including proper weighting factors. The reconfiguration of the inverter droop curves and the incorporation with the Local Control within the 15-min timeslot are also presented, together with the actual implementation in an agent-aggregator concept in the MAS layer of the INCREASE simulation platform.

Simulation results from a pilot installation reveal the effectiveness of the proposed Overlaying Control. Results, compared to the advanced Local Control of D3.1, show the uniform active power curtailment that is succeeded among PV units of the same feeder, together with the successful overvoltage mitigation. It is also observed that this control method results in decreased total active power injection to the distribution network. To overcome this drawback, an arbitrary offset voltage value is introduced to the Overlaying Control, resulting in higher DRES active power injection compared to the simple Overlaying Control scheme, while at the same time mitigating efficiently the feeder overvoltages.

The selected criterion of 'fairness', as implemented using the weighting factor concept of the Overlaying Control, is just a control option. The overall structure of the Overlaying Control layout, together with the weighting factors, allow the implementation of different control strategies, based on alternative criteria set by the DSOs or the corresponding Grid Codes, apart from the presented fair power curtailment.

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