INCREASE

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

Final publishable summary report: part 3

13/02/2017

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in the distribution grid by developing control strategies and using ancillary services
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INCREASE – *Increasing the penetration of renewable energy sources in the distribution grid by developing control strategies and using ancillary services*
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1 Description of the main S&T results/foregrounds

1.1 Introduction

To meet the European 20-20-20 targets, the share of renewable energy needs to be 20% of the electric energy demand in 2020. This ambitious objective can only be met if the number of distributed renewable energy sources (DRES) at the low voltage distribution grid will significantly increase and large wind or solar plant farms will be installed at the medium voltage (MV) level.

The significant rise in distributed renewable energy sources is placing an enormous burden on the secure operation of the electrical grid, impacting as well the transmission (TSOs) as the distribution system operators (DSOs). Five scientific and eight industrial partners participated in the ambitious research project INCREASE ("Increasing the penetration of renewable energy sources in the distribution grid by developing control strategies and using ancillary services") which aimed to solve these problems with innovative three-phase grid-connected inverters and new operational and control strategies in order to maintain the ability of the system to provide the consumers with reliable supply of electricity at an acceptable power quality level.

INCREASE investigated the regulatory framework, grid code structure and ancillary market mechanisms, and proposed adjustments to facilitate successful provisioning of Ancillary Services (AS) necessary for the electricity grid operation, including flexible market products. It aimed to enable DRES and loads to go beyond just exchanging power with the grid which enables the DSO to evolve from congestion to capacity manager. This facilitates higher DRES penetration at reduced cost. The simulation platform developed in the scope of INCREASE enables the validation of the proposed solutions and provides a tool for the DSOs to investigate the DRES influence in their network. Not only by lab test at TU/e and at Lemcko (UGent), but also real field trials in Austria, Slovenia and the Netherlands validated the INCREASE solutions.

1.2 The INCREASE solution

1.2.1 Introduction

To increase the penetration of renewables in the low and medium voltage network, INCREASE proposes a three level approach. The first level (physical layer) only uses local parameters (voltage at the point of connection, exchanged power) for the control. This is a fast control that mitigates the voltage unbalance (at the LV network) and uses P-V droops to achieve soft curtailment to solve the overvoltage problem (at the LV and MV network). The first level control ensures the reliability and stability of the system. The second level (middleware layer) control results in an optimal system and aims to minimise the loss of renewable energy and ensures fair sharing of the curtailed energy. This second level control is achieved by a multi-agent aggregator concept and consists of fair power sharing, the coordination of OLTC control and PV inverters to solve (current and voltage) congestion. In order for the DSO to evolve from congestion manager to capacity manager, a service layer is required. This service layer is the third level in the INCREASE approach. It solves a multi-objective optimisation problem by combining and extending optimisation strategies and results in flexible energy products to provide Ancillary Services with them. The DSO always needs to have control over the grid in order to prevent that the DR and DRES schedules worsen the supply security. For this purpose, a Traffic Light System

(TLS) is used that gives the DSOs the ultimate control over the DR unit schedules. The complete INCREASE solution is depicted in Figure 1.

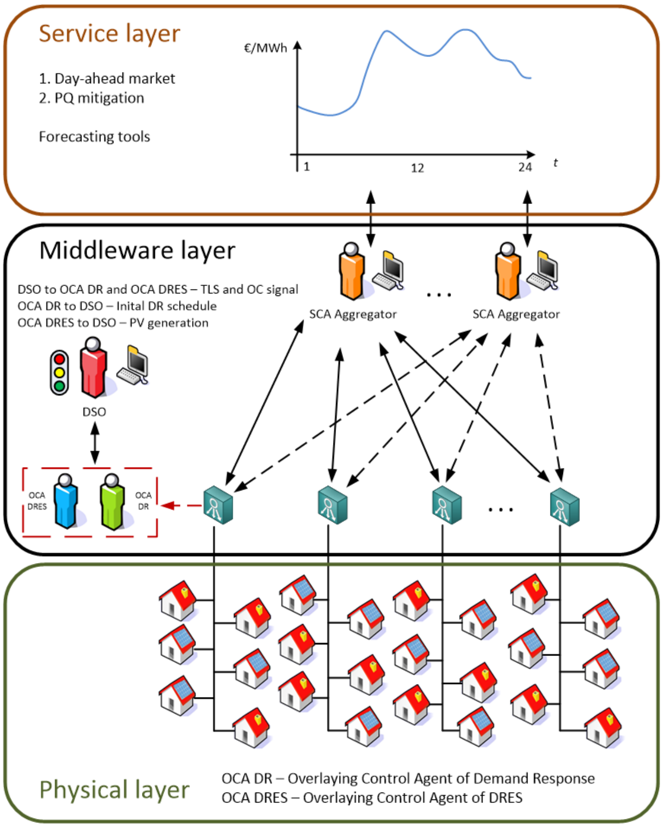


Figure 1: General overview of the INCREASE solutions

The developed INCREASE simulation platform enables the validation of the proposed solutions and provides the DSOs with a tool they can use to investigate the influence of DRES on their distribution network. The INCREASE solutions have also been validated (i) by lab tests, as well as (ii) in four field trials in the real-life operational distribution network of Energienetze Steiermark in Austria, of Eandis in Belgium, of Elektro Gorenjska in Slovenia, and of Liander in the Netherlands.

INCREASE also looked into how the regulatory framework and business modelling aspects influence the INCREASE solutions.

1.2.2 The local control strategy

The main objective of the INCREASE local control strategy is the continuous mitigation of overvoltages and voltage unbalance in low voltage distribution networks. The INCREASE local control strategy thus improves the power quality of the distribution grid.
We need this because the increased penetration of renewables can lead to voltage problems in the low voltage distribution grids which in severe cases results in a disconnection of the solar inverters from the

grid. Mitigating overvoltages and voltage unbalance thus leads to an increased production of solar energy. Overvoltages are the main cause of your solar inverter disconnecting from the grid and as a result, a loss of energy production.

The local control strategy is implemented in the inverter that connects the solar panels to the grid. The inverter measures the voltage and power at his terminals and based on this decides what needs to be done. There is no need for communication with external parties, the inverter works independently.

The INCREASE Local control strategy consists of two strategies:

1. **The voltage-based droop control**:

   This strategy lowers the produced PV power in case the grid voltage rises so that disconnection of the solar inverter is avoided.

2. **The voltage unbalance mitigation control**:

   The voltage unbalance mitigation control distributes the produced PV power in the different phases so that less loaded phases receive more power than the higher loaded phases and vice versa. This strategy can only be applied in three-phase inverters. One of the extra advantages of this control strategy is that the grid is also supported during voltage dips caused by grid faults.

The voltage-based droop control

In INCREASE, we propose an active power (P/V) control, namely the voltage-based droop control. The basic principle behind this control strategy is depicted in Figure 2. The inverter injects the available power into the grid until a certain voltage threshold is reached (eg $v_{g,up}$ = 248V). Then, the injected power is decreased compared to the available power. This is achieved by forcing the inverter to deviate from his optimal working point.

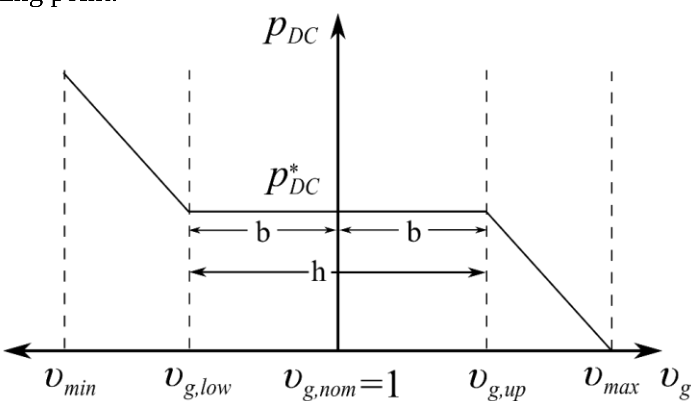


Figure 2: Voltage-based droop control

The voltage unbalance mitigation control

The voltage unbalance mitigation strategy is implemented in three-phase inverters. This control distributes the solar power between the three phases such that lower loaded phases receive more power compared to the higher loaded phases. Figure 3 depicts the voltages and Figure 4 depicts the currents that the inverter injects if those voltages are present at the inverter terminals.

The voltage unbalance mitigation strategy is achieved by giving the inverter a resistive behavior towards the zero-sequence and negative-sequence voltage component. This results in the inverter injecting more current in the phase with lower voltage and higher current in the phase with a higher voltage.

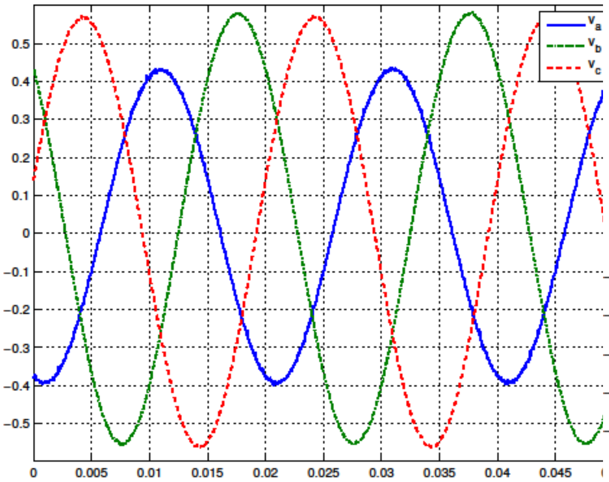


Figure 3: Unbalanced three-phase grid voltage

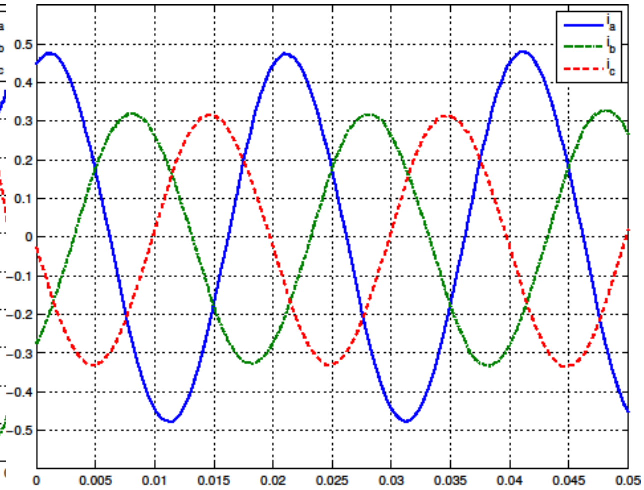


Figure 4: Three phase current corresponding with the voltage unbalance mitigation control

Some results

Figure 5[1] depicts the probability of having a certain voltage at a node in a low voltage network in four different cases:

- Classical on/off control – inverter switches off when 1.1pu is reached
- 3ph-DPC: INCREASE local control strategy
- 3ph-Sym: 3-phase connection of renewables with voltage-based droop control
- Q-control: voltage control by means of reactive power control.

It can be seen from Figure 5 that the INCREASE local control always results in the lowest grid voltage which means that there is more room to integrate more renewables in the low-voltage distribution grid. The proposed solution does not use communication which is very beneficial for the implementation of the solution.

[1] Klonari, V., Meersman, B., Bozalakov, D., Vandoorn, T., Vandevelde, L., Lobry, J., & Vallée, F. (2016). A probabilistic framework for evaluating voltage unbalance mitigation by photovoltaic inverters. *SUSTAINABLE ENERGY, GRIDS AND NETWORKS*, *8*, 1–11.

1.2.3 The overlaying control strategy

The overlaying control (OC) of INCREASE aims to mitigate over-voltage and over-loading problems in LV networks while providing an equal opportunity for power injection for all the customers. It has been developed as a complementary control mechanism to the local control for the provision of coordination means with other network controllers like Photovoltaic (PV) inverters and the On-Load Tap Changer (OLTC).

The INCREASE OC consists of three main control modules with their dedicated control tasks:

i. Fair Power Sharing (FPS) module aims to mitigate over-voltage problem by curtailing active power equally among PV inverters;
ii. Congestion Management (CM) module aims to relieve the congestion occurring at the Medium-Voltage/Low-Voltage (MV/LV) transformer;
iii. Coordination control module for OLTC and PV inverters to maximize renewable energy production.

Fair power sharing (FPS)

The local control mitigates the overvoltage problem however it leads to an unequal/unfair power curtailment among the inverters. Therefore, the overlaying control complements the local control. The FPS algorithm of OC redistributes the curtailed power uniformly/fairly among the inverters. The control algorithm is implemented using the DRES inverters. An example network where the OC can be implemented is depicted in Figure 6. The network consists of a MV/LV transformer and a LV feeder and five PV inverters are connected to the LV feeder.

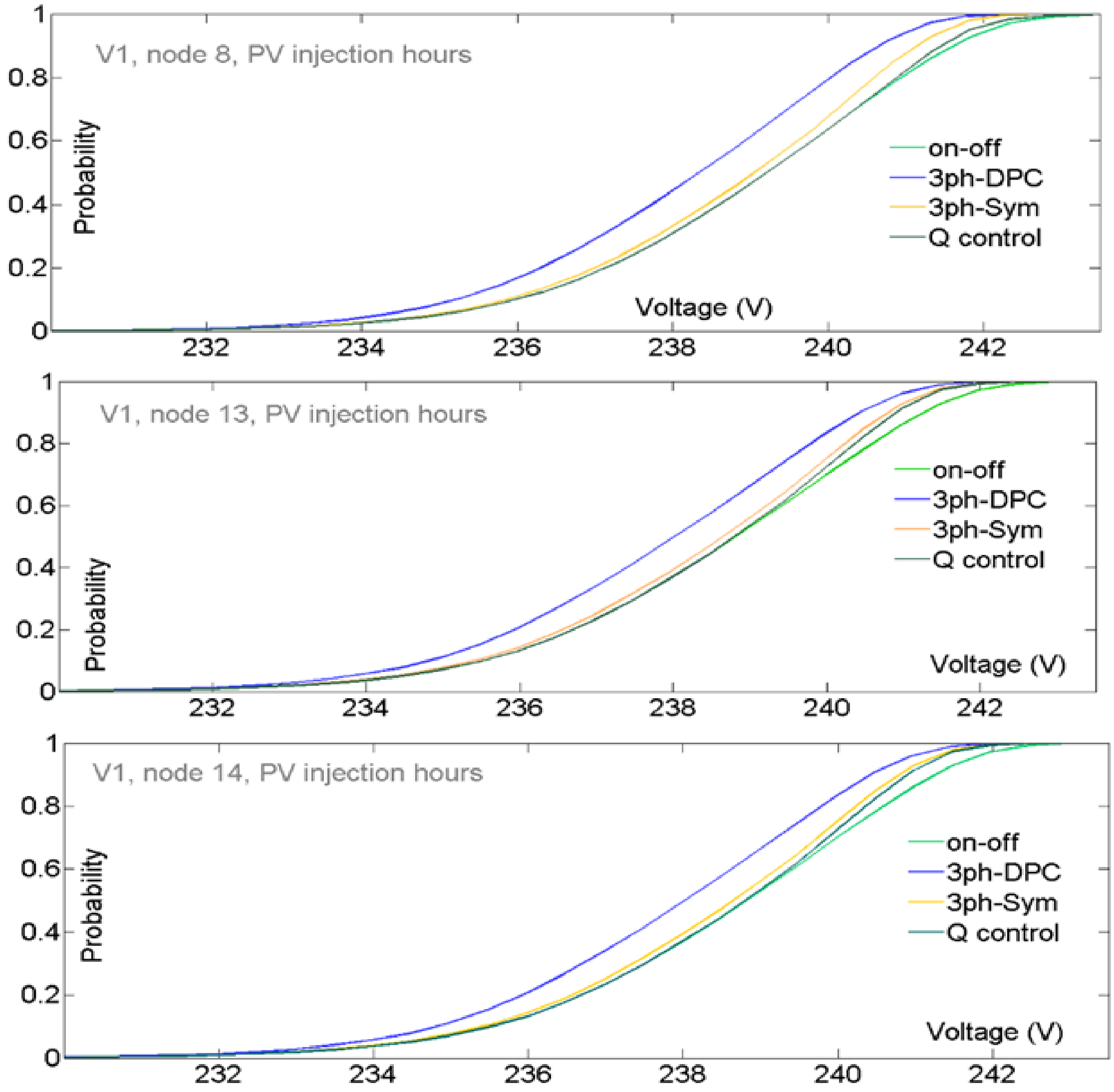


Figure 5: Probability of a voltage at a node in a low voltage network

Congestion management

Congestion generally refers to a situation when the demand or generation at a certain point in the distribution network exceeds the transmission capabilities. The developed congestion management (CM) solution of INCREASE is based on the similar principle of fair power curtailment dealing with an excessive reversed flow due to PV production.

- Distribution transformers are more prone to congestion than the cables. In the Netherlands, 87% of the MV/LV transformers will be overloaded in 2040 compared to 34% of cables.
- The amount of required curtailment depends on the local loads at any given time.
- Higher local loads reduce the reverse power flow across the transformer thus the congestion does not occur.

Coordination for OLTC and PV inverters

The development of the agent-aggregator platform enables the possibility for INCREASE's OC to coordinate OLTC with DRES inverters in real-time. Based on the remote measurements at critical locations in the downstream area of the LV grid, the coordination control algorithm determines the tap position of the OLTC such that the voltages in the LV network remains within the predefined voltage limits.

The coordinated control is verified using a numerical simulation

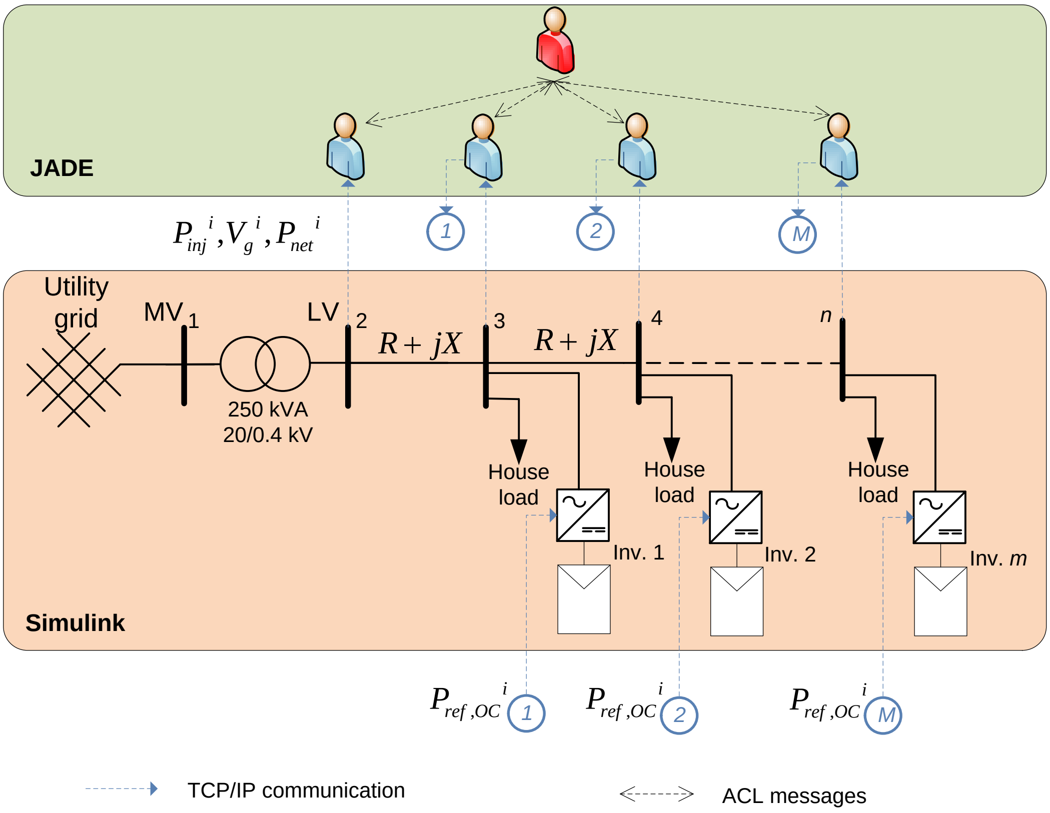


Figure 6: Low voltage test feeder and ICT infrastructure (n=7,m=5)

1.2.4 The scheduling control strategy

In addition to the technical solutions focusing on the integration and intelligent control of distributed renewable energy sources (DRES), the INCREASE project also developed accompanying control strategies with the objective to maximize the created value for the various stakeholders. For this purpose, the scheduling control strategy has been developed.

As the top hierarchical layer of the INCREASE control structure, the scheduling control plans the operation of demand response (DR) units according to various optimization criteria. The whole process of scheduling and grid operation integrates inputs like market price, advanced forecasting of demand, DRES generation, network topology and power quality (PQ) boundaries. This way, DRES units are able to generate maximum energy within the boundaries set by the objectives of the local control and overlaying control while the scheduling control agent (SCA) schedules the DR unit based on the energy or economic optimization according to their optimizations criteria, e.g. maximum green energy infeed or maximum profit.

In INCREASE, the following parameters were used to describe the DR units:

- Time of use
- Energy constraints
- Power
- Internal DR unit price

The DR units used for simulation were based on heat pump parameters and had three operation modes: normal level of operation ($P_{DR/2}$), where the heat pump is running on its medium installed power, full power mode ($P_{DR\ MAX}$) and full stop ($P_{DR\ 0}$). In simulation, this load is added on top of the various household load profiles generated from real measurements of the Suha demo site in Slovenia. This load profile creation together with heat pump operation modes is presented in **Fout! Verwijzingsbron niet gevonden.**7.

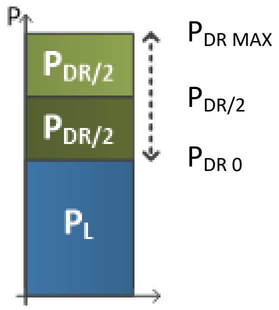


Figure 7: Load profile with added operation modes of DR (heat pump)

Economic optimization of DR units

The economic optimization schedule is based on the input data of wholesale electricity market prices and internal costs of DR units. Deployment schedules for each DR unit are made considering the limits of individual DR unit parameter values. The objective function J_E (1) maximizes the profit of DR schedule through maximizing the income of DR unit's flexibility on wholesale day-ahead market and minimizing the DR unit's adjustment cost. By increasing the consumption of DR units to $P_{DR\ MAX}$ in the hours with lower energy prices and reducing it to $P_{DR\ 0}$ during the high price periods, the SCA realizes profit/savings with its flexible energy portfolio (FEP).

$$J_E = \sum_{k=1}^{N}\sum_{i=1}^{N_D} a_{ik}\left[\left(W_{ik}^{+} + W_{ik}^{-}\right)S_{Mk} - \left(W_{ik}^{+} + W_{ik}^{-}\right)S_{Di}\right] \quad \max \tag{1}$$

where:

- N_D number of DR units
- N number of time steps
- W_{ik}^{+} upward energy adjustment of i-th DR unit in hour k
- W_{ik}^{-} downward energy adjustment of i-th DR unit in hour k
- S_{Mk} wholesale market price in hour k (energy price)
- S_{Di} internal output adjustment price of i-th DR unit

In the INCREASE project it was assumed that DR unit's flexibility price is zero due to the fact that *full energy payback* is taken into account for each DR unit, where the energy sum of all energy adjustments at the end of the day is equal to zero for each DR unit (2).

$$\sum_{k=1}^{N}\left(W_{Dik}^{+}-W_{Dik}^{-}\right)=0 \tag{2}$$

This way, any increases or decreases in consumption must be fully compensated by the end of the day. By including the full energy payback with the energy consumption, no comfort loss can be assumed and therefore no additional money compensation is needed.

Energy optimization of DR units

The goal of energy based optimization is to fully support DRES production in the network and enable maximum injection of DRES produced green energy. DR schedule is designed to minimize the difference between local consumption and production in the LV grid. With decreasing energy difference in the network, power flows are minimized and voltage fluctuations are lowered. Due to a lower voltage level in the network, the DRES inverter control curtails less active power and greater DRES energy injection is achieved. By energy optimization a profit loss for the aggregator is expected. The objective function J_W can be written as in (3).

$$J_W=\sum_{k=1}^{N}\left(\left(W_{loadk}-W_{PVk}\right)+\sum_{i=1}^{N_D}a_{ik}\left(W_{ik}^{+}-W_{ik}^{-}\right)\right) \quad \min \tag{3}$$

Variables used are:

- N_D number of DR units
- N number of time steps
- W_{ik} energy of i-th DR unit in hour k
- $W_{load,k}$ total network load in hour k
- $W_{PV,k}$ total network PV production in hour k

The energy difference between the values $W_{load,k}$ and $W_{PV,k}$ is reduced by the activation of the DR units to increase or decrease their consumption in order to achieve energy balance.

Traffic light system

The Scheduling Control solution as well as the entire MAS control concept in INCREASE have been designed in such a way that they enable DSOs to always have control over the grid. For this purpose, a Traffic Light System (TLS) concept has been introduced that gives DSOs the ultimate control over DR unit schedules. The main purpose of TLS is to assure that the schedules of DR units, generated by the aggregator, do not have negative impact on the network situation. It is applied to the schedules on day-ahead and shorter time-frames (i.e. intraday and balancing) due to very low accuracy of week-ahead forecasts on the distribution network.

For the implementation of the TLS, the DSO are equipped with an additional TLS module to check for the possible effects of the initial DR schedule on the network, in order to detect any Power Quality (PQ) violations in the system. In INCREASE, the PQ violations typically include over/under voltages and current congestions in the feeder under consideration. The TLS module's main task is to determine whether the SC-supplied schedule of each individual DR unit causes any PQ violations. The TLS is fed with information from the power flow based on the joint load schedule of DR units and inflexible load. The different TLS function logic is shown in Table 1 below and the whole concept of information exchange between actors is described next.

Table 1: Types of Traffic Light Systems

Action taken	**Does the joint load schedule causes PQ violations?**		**Direction: Does DR schedule help reduce PQ violations?**	
TLS Type	**No**	**Yes**	**No**	**Yes**
Simple	Accept DR schedule	Reject DR schedule	/	/
Advanced	Accept DR schedule	Check direction	Reject DR schedule	Accept DR schedule
Intelligent	Use 15-min forecasting to optimally schedule DR units.			

INCREASE Scheduling process with Traffic Light System

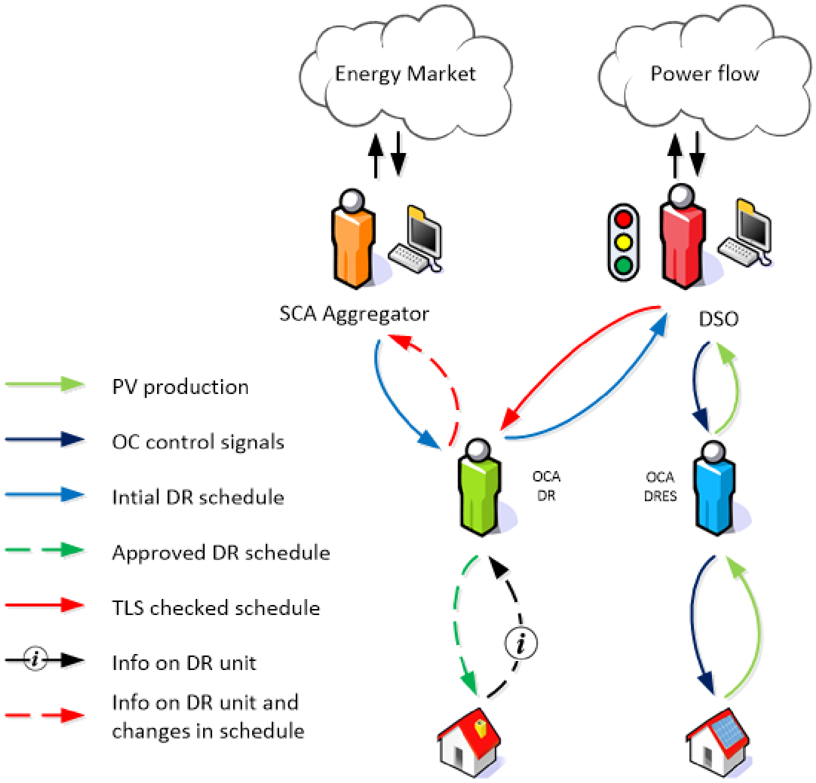


Figure 8: Overview of the communications between main actors

The responsibilities of the actors shown in **Fout! Verwijzingsbron niet gevonden.** 8 are divided among the scheduling agent (SCA) aggregator, DSO, the overlaying control agent (OCA) DRES and the overlaying control agent (OCA) DR**Fout! Verwijzingsbron niet gevonden.**:

- **Scheduling agent aggregator**
  - makes the schedules for each DR unit based on the chosen optimization goal and transmits this information to the DR units corresponding OCA DR
- **DSO**
  - As it has all the necessary information and the ICT equipment, the DSO runs power flow calculations needed for the PQ violations check and PQ violations forecast processes.
  - The DSO transmits the results of the PQ analysis and new control signals back to the local agents at each feeder, the OCA DRES and the OCA DR. These control signals comprise: 1) fair curtailment PV generation values as a result of OC (transmitted to the OCA DRES) and 2) new DR unit schedules due to the TLS activation (transmitted to the OCA DR)
- **The OCA DRES**
  - Transmits the PV generation information to the DSO; and
  - Receives the return information on fair PV curtailment from the DSO.

- **The OCA DR**
  - Collects the local information about DR unit parameters and transmits them to the relevant SCAs.
  - Receives the schedule for each DR unit in the feeder from the SCAs.
  - Forwards the DR unit schedule to the DSO which performs the PQ violations check using TLS. Further, if there is a change due to the TLS activation, it returns the new DR unit schedule from the DSO to the relevant SCAs.
  - Forwards all the changes in the DR units' schedule from the SCA to the DSO.

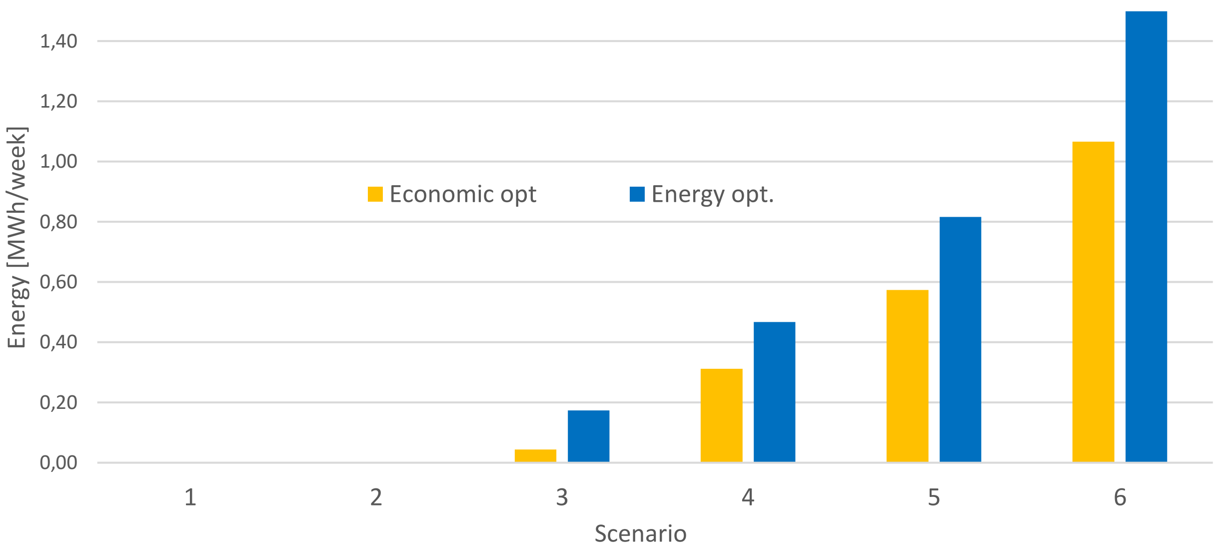
Results of the simulations and conclusion

The simulations were performed using information of Elektro Gorenjska demo site Suha grid model with the use of OpenDSS and Matlab for calculating power flow and technical analysis for different PV penetration scenarios which are presented in Table 2.

Table 2: DR development scenarios

Scenario	Number of PV installed	Number of DR units	Installed DR units power [kW]	DR integration [%]
1	6	5	44	7.14
2	9	10	95	14.29
3	15	15	139	21.43
4	21	20	183	28.57
5	24	25	224	35.71
6	30	30	264	42.86

In



10 the results of the main project parameter, the PV energy infeed, are shown for different penetration levels and both, economic and energy, scheduling optimizations.

The main findings extracted from the simulation results for different optimizations and TLS logic are listed below:

Economic optimization

- maximizes the aggregators profit,
- causes more PQ violations,
- there is a risk for penalties for unsuccessful activation of DR for the aggregator,
- reduces the green energy infeed from PV

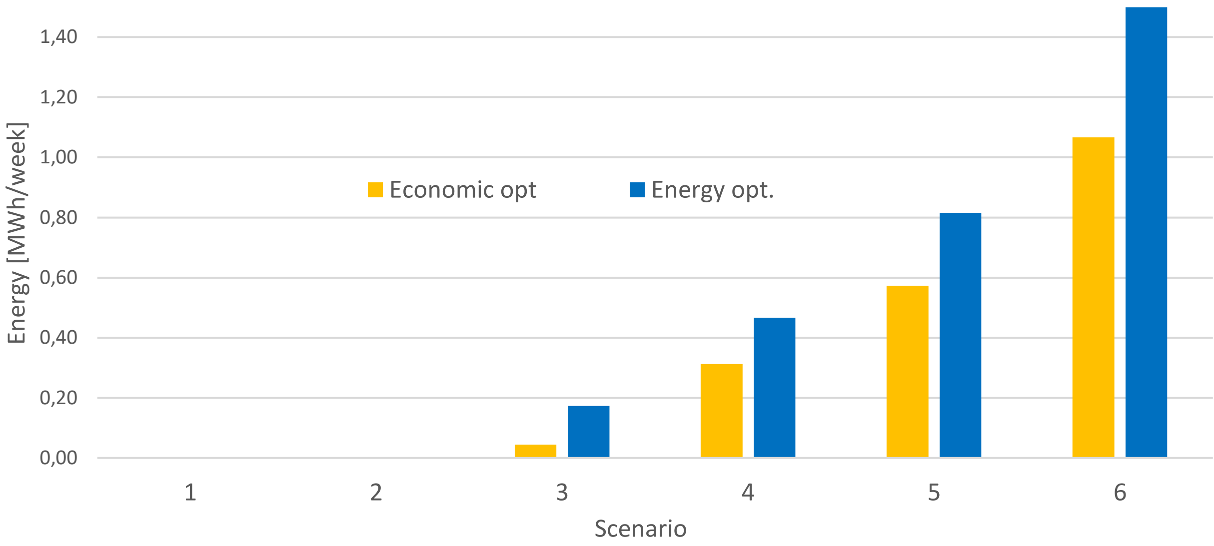


Figure 9: Energy infeed for different penetration levels and economic and energy optimization schedule

Energy optimization

- maximizes the aggregators profit,
- causes more PQ violations,
- enhances the green energy infeed form PV

TLS

- more advanced TLS logic enhances the green energy infeed

Through results of the scheduling controls simulations INCREASE confirmed the hypothesis of the optimization process and provided a basis for new business models of sharing the profit of increased PV production to cover the losses of the aggregator because of the energy optimization.

1.3 The INCREASE simulation platform

New challenges in the distribution network

Over the past decades, research has focused on developing software tools to analyze, plan, optimize and simulate electrical networks. The advent of distributed generation (DG) has gradually changed power flow in the power distribution network from downstream unidirectional to a bidirectional scheme, introducing challenging technical issues, such as unacceptable overvoltages, voltage unbalances, line congestions, and protection issues. Although novel control schemes have been proposed for interfacing DGs to the grid and mitigating these issues, such controlled inverters need to be also efficiently incorporated in the simulation software packages.

Limitations of current software platforms

Most of the commercially available software platforms for power system analysis allow the use of customizable configurations covering almost all electrical aspects in generation, transmission and distribution, including steady-state calculations, power quality optimization and protection coordination. However, a major drawback is that they usually have a closed form architecture, not allowing the easy and efficient integration of user developed models, especially regarding control systems.

Considering the simulation of power system networks, the existing open source and commercial software products can be divided into two main categories as shown in Figure 11.

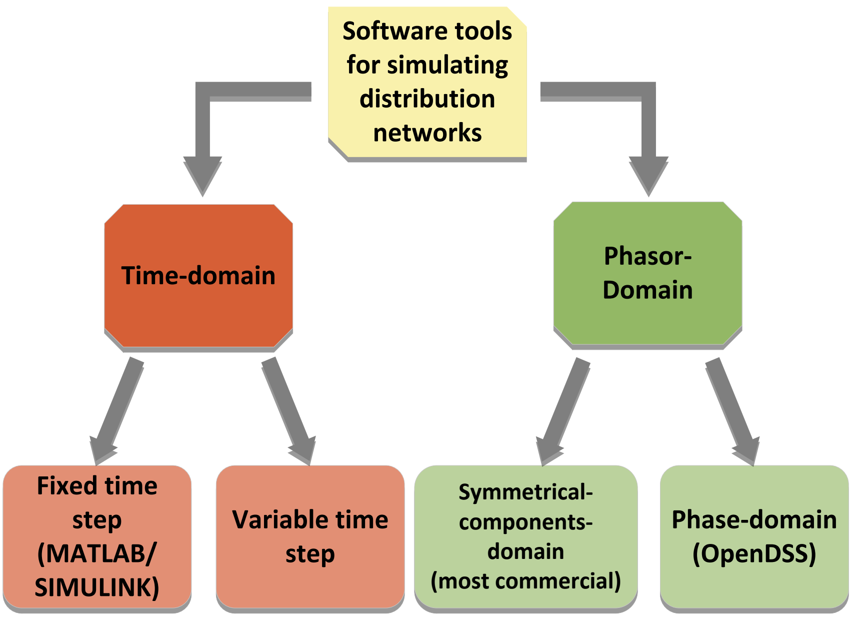


Figure 10: Categories of software tools for simulating distribution networks

Software tools based on time-domain solutions simulate the power system network by solving differential equations that describe all power system components. Although these simulation tools provide the ability to integrate DG control schemes in a very straightforward manner, they cannot be used for the simulation of extended networks, due to the prohibitive execution times.

Software platforms based on phasor solutions use algebraic equations for the simulation of power systems operating in steady-state condition. As a result, power flow and harmonic analysis calculations can be readily performed with small execution times, even in cases of extended networks. The major drawback of such models is that their core calculation routines may become cumbersome with the incorporation of DG droop controls or of other additional control schemes.

The INCREASE approach

To overcome these issues, **INCREASE has developed a new simulation platform,** comprising the benefits of both software categories and allowing the efficient integration of several distributed renewable energy sources (DRES) control strategies. The new simulation tool has the following basic characteristics:

- Employs **phasor-domain** solutions, resulting in short execution times even in cases of extended distribution networks.
- Offers a **graphical user interface** (GUI) for the convenient input and configuration of the system under study.
- Can allow the efficient incorporation of any DG control scheme.
- Can be **interlinked** with other software platforms and tools to form a generic **co-simulation** platform, capable to simulate modern power system networks from both power, control and communication point of view.

Architecture

The INCREASE simulation platform is presented in Figure 12. The developed software comprises **different open-source** tool components and their mutual interconnections.

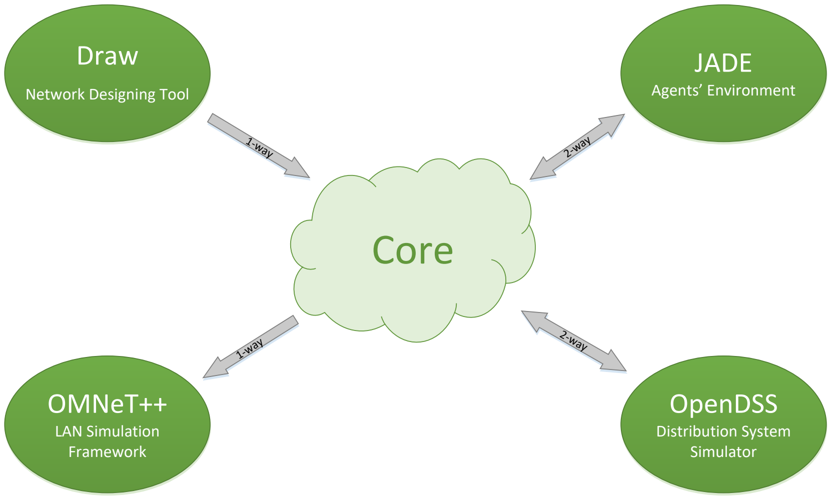
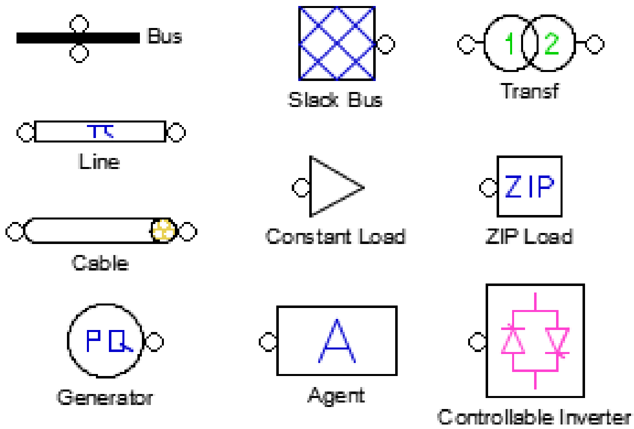


Figure 11: The internal structure of the INCREASE simulation platform

More specifically, the INCREASE simulation platform includes:

- The **Core** engine, which is the base of the simulation platform. The core is developed in MATLAB and implements the interconnections between the different components of the INCREASE simulation platform.
- The **Draw tool**, which is a **graphical pre-processor** with design capabilities to allow the user-friendly input and configuration of the distribution or transmission network under investigation. 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.



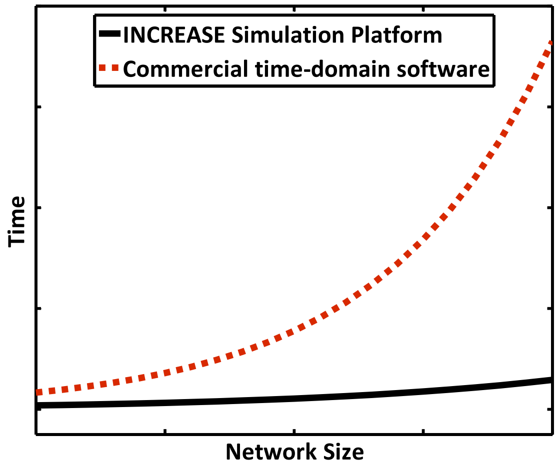
- The **OpenDSS** software, which is a phasor-domain grid simulator, capable of performing unbalanced power flow calculations. OpenDSS provides all the advantages of an open-source software, while it also offers highly accurate results, remarkable numerical performance, and vast communication abilities with external software tools.

- The **JADE software**, which is the tool integrating any intelligent multi-agent based control system (MAS) and the corresponding communication in the INCREASE platform for the implementation of high level control strategies.
- The **OMNeT++ simulator**, which is an open source LAN simulator, used for the analysis and the evaluation of the communication infrastructure of the examined smart grid.

Features

The INCREASE simulation platform provides the user with a **co-simulation tool** that can be used to investigate the influence of DRESs on their distribution system. In general, the simulation platform offers the following major features:

- **Detailed analysis** of MV/LV electrical power grids, including all potential DRESs, DGs, loads and control systems. Due to the required analysis, a **quasi-dynamic** solution is adopted.
- Incorporation of an adaptive **Multi-Agent System** (MAS) taking into account multi-objective control algorithms as well as the communication among the individual agents.
- Implementation of a **multi-layer** control strategy for the secure and optimal operation of active distribution grids. The distinct control strategies are coordinated by employing a user defined **timeslot concept**.
- Ability to simulate **balanced** as well as **unbalanced** distribution networks with **high accuracy** .
- A **near-zero** mismatch between the results obtained from the INCREASE simulation platform and most of the available commercial time-domain software platforms.
- Provides **reduced order equivalent models** for both passive and active parts of extended distribution grids.
- Can incorporate of the most **high-end** control schemes in DRESs for the effective overvoltage and voltage unbalance mitigation.
- Offers the ability to perform time-series simulation with **reduced** execution times.



- Allows the integration of load and generation forecasting algorithms for short- and medium-term provision of reserve, focusing on the power loss reduction, maximizing active power injection and the optimal performance of DRES.
- Offers the ability to simulate several control schemes for the locally controlled inverter-interfaced DRESs. The P(V) droop control is considered as the default control strategy. Other control schemes such as the Q(V) and the cosφ(P) control strategy can be readily incorporated into the simulation platform.
- Employs a discrete LAN simulator of communication networks to evaluate the communication performance and the vulnerability of the MAS control system.
- The LAN 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.
- **Simple** GUI for the power system design with **user-friendly** post-processing tools for reporting and plotting results as depicted in Figure 13.

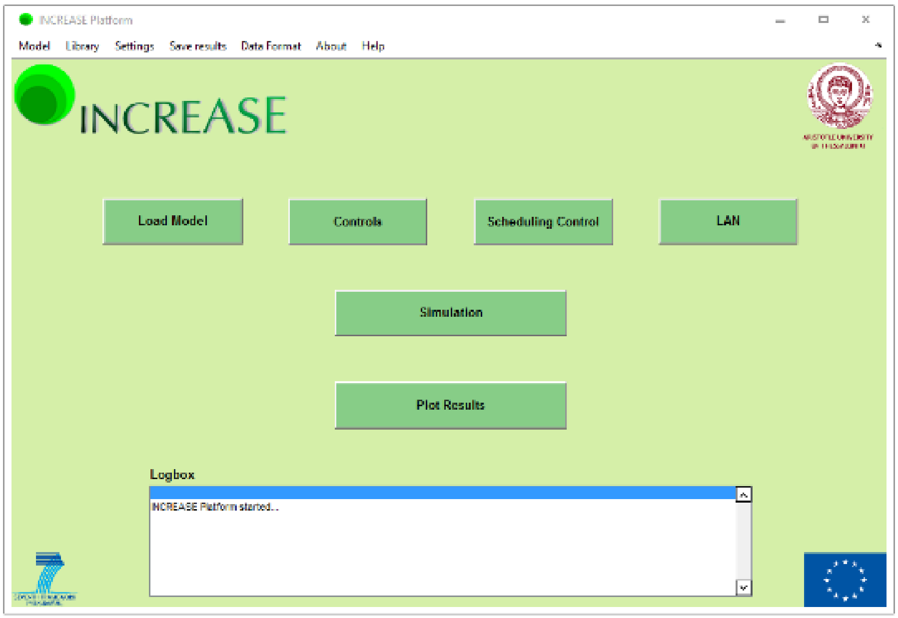
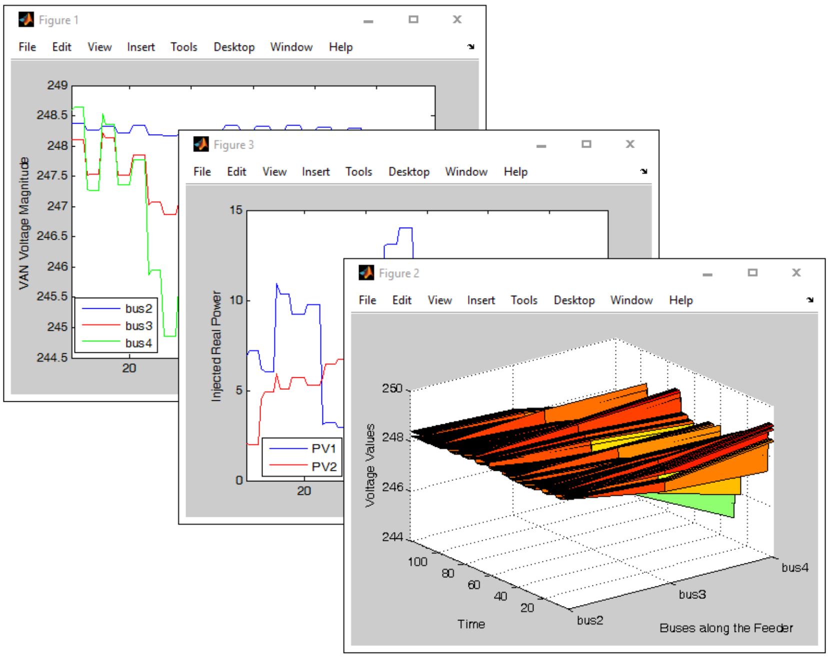


Figure 12: The GUI of the INCREASE simulation platform



- **Built-in** import and export features for most common data and calculation formats.
- **Flexible** platform based on **open-source** software with **modular** architecture structure to readily integrate future packages, features and functions.

The above features and advantages, make the INCREASE simulation platform a **competitive** simulation program among other commercial and open-source software packages.

Key stakeholders

The key stakeholders that can make use of the INCREASE simulation platform include:

- **Distribution system operators** (DSOs). They can perform **long-term analysis** of the distribution grids to assess different control techniques of DRESs and their impacts.
- **Transmission system operators** (TSOs). The INCREASE simulation platform can be a valuable tool for developing and/or evaluating the provision of **ancillary services** for the TSOs.
- **Aggregators**. It can be used as a **powerful tool** for the aggregators to ensure the safe and reliable network operation, following certain interventions.
- **Power retailers.** The developed platform can be used to investigate **different pricing policies** for the prosumers, taking also into consideration the network operation from a power systems point of view.
- **Other regulatory authorities.** They can exploit the INCREASE simulation platform to develop new and/or assess existing **regulatory frameworks**.
- **Energy companies.** It can be used to investigate the **long-term performance** of the network from the grid side as well as from the economic point of view.
- **Universities or research institutes.** They can perform simulation studies to evaluate existing control techniques and/or to develop new control strategies.

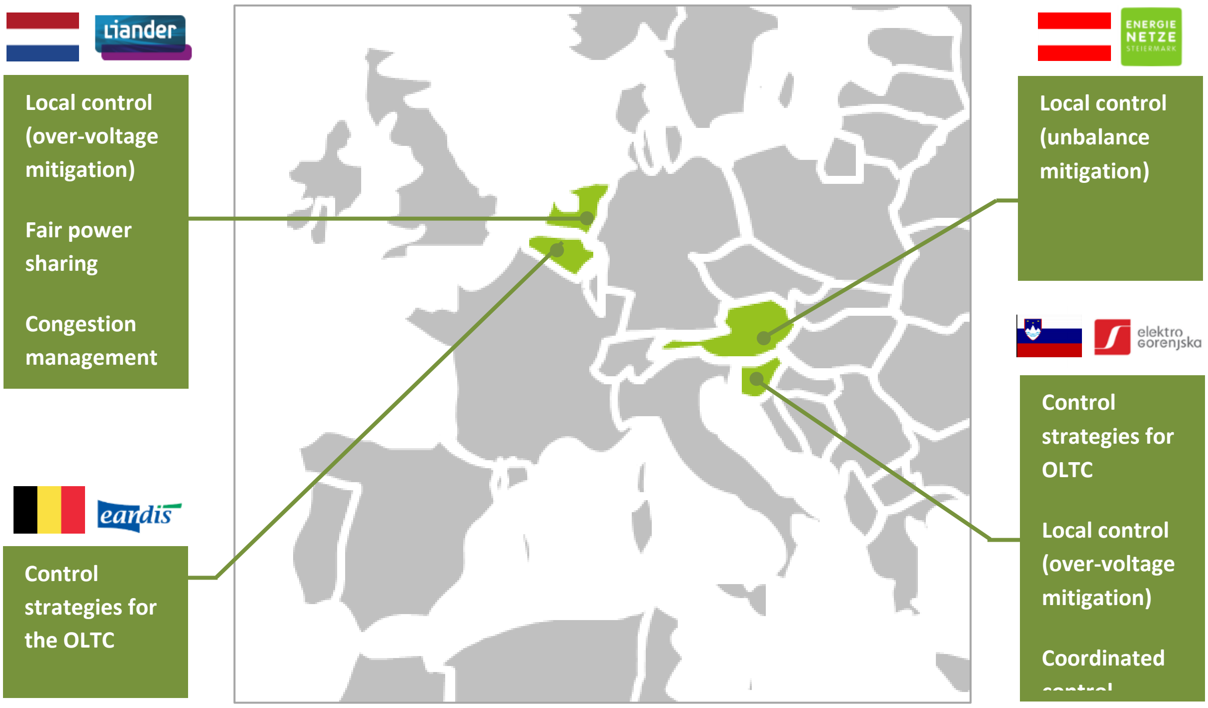
INCREASE – *Increasing the penetration of renewable energy sources in the distribution grid by developing control strategies and using ancillary services*

Final publishable summary report part 3

13/02/2017

1.4 Validation of the INCREASE solution: field trials

1.4.1 General overview and key facts



Dutch field trial

- **Responsible DSO:** LIANDER
- **Location:** Holiday park Bronsbergen
- **Pilot network:** LV network of the first micro-grid in the Netherlands with a high share of PV (installed on approx. 50% out of 210 cottages).

Austrian field trial

- **Responsible DSO:** ENERGIENETZE STEIERMARK (ENS)
- **Location:** Main administration building of ENS in Graz
- **Pilot network:** Roof-mounted part of a PV installation, which consists of several single-phase PV inverters with a total installed capacity of 47 kWp.

Belgian field trial

- **Responsible DSO:** EANDIS
- **Location:** Koningshooikt, a rural region near Mechelen
- **Pilot network:** Cable type LV network with a significant share of DRES on the LV level as well as on MV level. Main types of DRES are PV and combined heat and power (CHP).

Slovenian field trial

- **Responsible DSO:** ELEKTRO GORENJSKA (EG)
- **Location:** Village Suha near Kranj
- **Pilot network:** Rural cable type LV network with a high penetration of PV. The total installed capacity of the PV is 210 kW.

1.4.2 Belgian field trial

The pilot network selected for the Belgian field trial contains a large number of PV and heat loads, connected to the LV level. Consequently, there are high voltage variations, which are in some cases close to the limits, specified by the power quality standard EN 50160. A large PV and CHP unit on MV level additionally contributes to high voltage variations in the LV network. To cope with these variations, EANDIS decided to investigate the possibilities of voltage control using OLTC, and to examine whether OLTC is a suitable techno-economic measure for increasing the load and DRES penetration in LV networks.

To set-up the field trial, EANDIS replaced a conventional distribution transformer with a 400 kVA unit, equipped with OLTC (Figure 14). To monitor the impact of OLTC, monitoring devices were deployed at the transformer station and at four key points, located at the end-points of LV cables. The communication infrastructure was also deployed, to provide real-time acquisition of the measurements and remote control of OLTC, using a centralised algorithm. Measurements were transmitted to the distribution management system (DMS) of EANDIS via a mobile network.

Figure 13: Substation with OLTC (left) and cable cabinets with measurements and communications (right)

EANDIS conducted extensive tests of OLTC performance for more than 1 year. Different OLTC control algorithms have been evaluated:

- A basic OLTC control, where there is a fixed voltage set-point at the LV side of the transformer and the tap position is adjusted in order to obtain the given voltage set-point.
- A basic control algorithm with line drop compensation (commonly known as LDC with ABC points), which operates in a similar way as the basic control algorithm, but here the voltage set-point depends on a power flow through the transformer.
- A central OLTC algorithm (remote control from the control centre), which takes into account the measurements from critical points of the network (e.g. end-points of the long feeders) and selects the optimal tap position accordingly

First two algorithms operate locally based on local parameters (voltage at LV bus of transformer), while the third operates on a central location (DMS in control center), based on measurements from multiple points of the network. Therefore adequate communication and measurement infrastructure is required.

As can be concluded from the results for different demonstration cases (**Fout! Verwijzingsbron niet gevonden.**15) , basic local OLTC control improves the voltage only locally at the LV bus of transformer and shortest LV feeder. High voltage variations remain in range of the longest LV feeder, since basic local OLTC control does not consider voltage conditions of other points of the network. In case of LDC and centralised OLTC control, an overall improvement of voltage can be observed, since the voltage variations are significantly reduced, thus also at the end of the longest LV feeder.

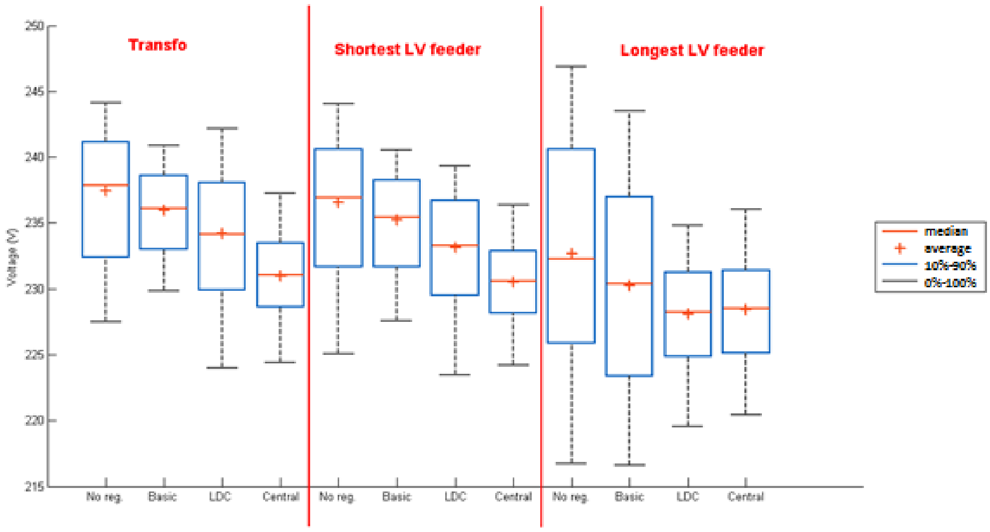


Figure 14: Comparison of results for different demonstration cases

A very similar performance of LDC and centralised algorithm can be observed, especially in considering the most critical point at the end of the longest LV feeder. Based on these conclusions, EANDIS decided that the most suitable control algorithm for future implementation would be the LDC control, since there is no need to invest into additional communication and measurement infrastructure, as in the case of centralised algorithm. There is also a reduced risk in the case of communication failure and need for back-up of the local OLTC control algorithm in case of communication failure is avoided.

The most valuable outcome of the Belgian field trial is that the OLTC can be a suitable techno-economic option for the integration of additional loads and DRES into the LV network. To identify an optimal OLTC control algorithm, specifics of the LV network must be considered, not only voltage variations, but also available communication and measurement infrastructure. If there is a need to invest into new measurements and communications, classical local OLTC control algorithms might be a better option than centralised algorithms.

1.4.3 Slovenian field trial

The pilot network selected for the Slovenian field trial consists of many PV units causing voltage rises on one hand, and several long feeders without PV units, causing voltage drops on the other hand. Specifics of the pilot network provided a nice testing environment for the evaluation of different INCREASE and alternative solutions for improvement of the voltage conditions in LV networks. Besides classical OLTC control algorithms, the Slovenian field trial focused on the evaluation of local control for mitigation of over-voltages and coordinated control of OLTC and local control.

To set-up the trial, Elektro Gorenjska (EG) implemented network analysers for monitoring of the key nodes in the pilot network (substation, PV units, end-node of the longest feeder without PV units). Measurements were acquired within a 1-minute period and transmitted to the control centre of EG (PQ database) via their private WiMAX communication network.

To enable voltage control, a 400 kVA transformer, equipped with OLTC was deployed. A dedicated remote control algorithm for OLTC was developed by TU/e and deployed on a separate computer. This algorithm uses measurements from multiple points of the network to determine new tap settings of OLTC.

To demonstrate functionalities of the INCREASE local control, a 22 kW PV unit, where the highest voltages appear, was selected. A controllable load was installed in parallel with the PV unit, as an introduction of a new controllable 3-phase inverter would lead to significant interactions with private installations of PV owners (large space requirements, reconnection of the PV panels, potential risks of new equipment. That way the same effect as in the case of a controllable inverter was achieved, however without interfering with private owned PV installations.

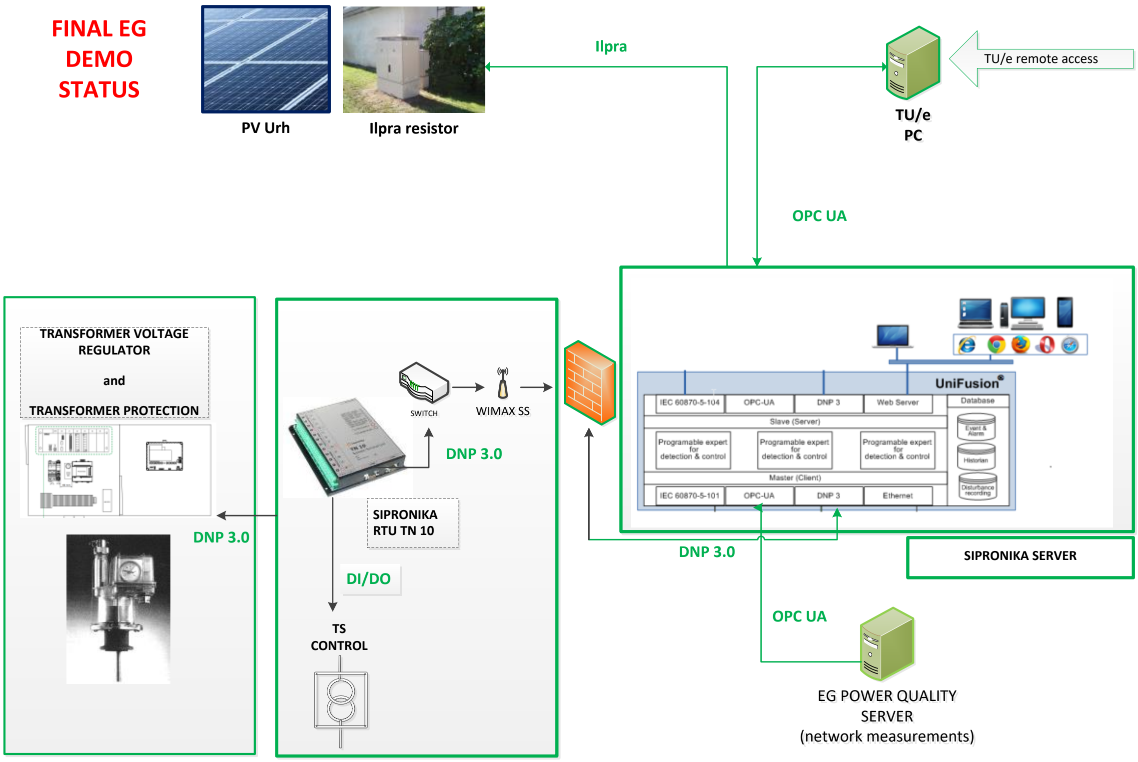


Figure 15: Basic set-up of the Slovenian field trial

To connect all devices used in the Slovenian field trial, a dedicated state of the art SCADA system (SIPRONIKA Unifusion server) was deployed, to enable communication between the systems in a standardised way (standard communication protocols such as OPC UA, DNP3.0). Furthermore, the SCADA system served for a basic visualisation of the network measurements. The complete set-up is shown **Fout! Verwijzingsbron niet gevonden.**16.

Following demonstration scenarios were evaluated in scope of the Slovenian field trial:

- SC1 Business as usual, no control measures applied
- SC2 Basic local OLTC control, with fixed voltage set-point
- SC3 INCREASE centralised OLTC control, using average phase voltages
- SC4 INCREASE centralised OLTC control, using phase voltages
- SC5 INCREASE local control (using controllable load) only
- SC6 Coordinated control: basic local OLTC control and INCREASE local control
- SC7 Coordinated control: INCREASE centralised OLTC control (phase voltages) and INCREASE local control

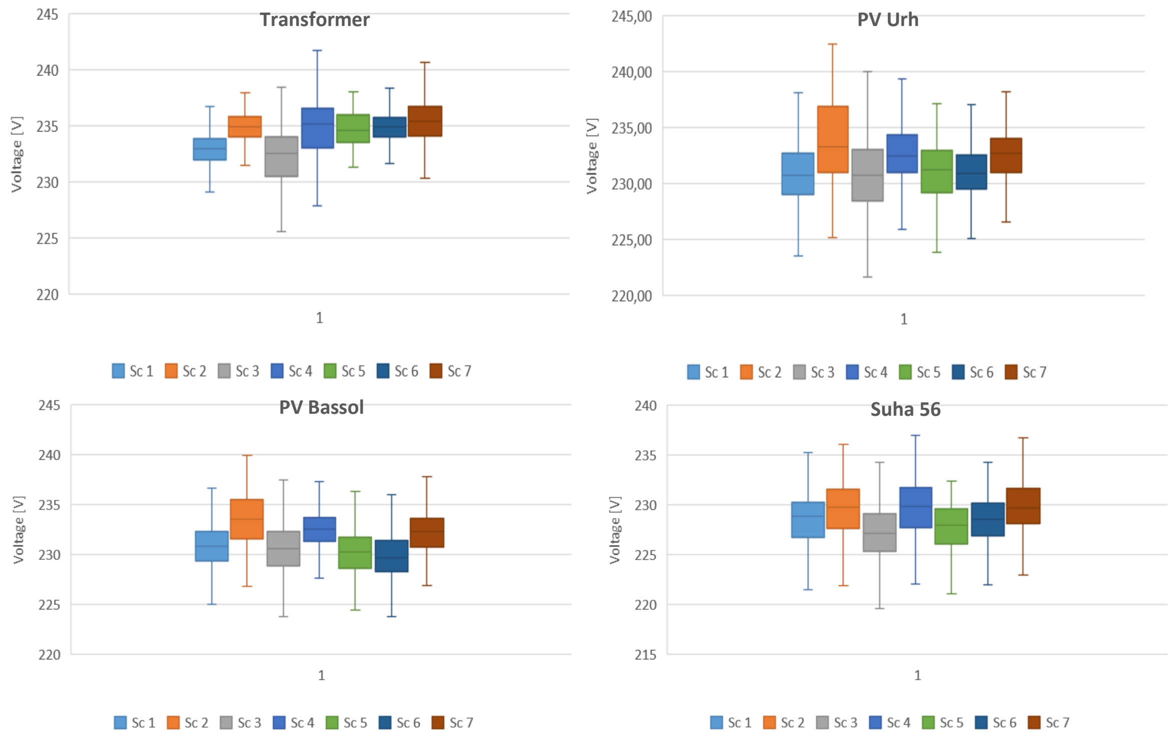


Figure 16: Statistical analysis of average phase voltages

The results shown in **Fout! Verwijzingsbron niet gevonden.**17 were evaluated for the four key nodes:

- LV bus of transformer
- PV Urh, 22 kW PV unit, where the highest voltages occur and controllable load is deployed
- PV Bassol, 22 kW PV unit
- Suha 56, node where the lowest voltages are experienced

Scenario 1 reveals significant voltage variations in the pilot network. There are voltage rises at PV units and voltage drops at the end of the longest feeder without a PV unit. Similar as in the case of the Belgian field trial, the basic local OLTC control (scenario 2) improves the voltage only locally, at the LV bus of transformer, where voltages are concentrated around a given set-point of 235 V. High voltage variations remain unchanged, especially in case of PV Urh.

Centralised OLTC control algorithms, developed within INCREASE (scenario 3 and 4) result in more variations at the LV bus of transformer, but improve the voltage at other critical nodes. Better results are obtained in the case of scenario 4, where the algorithm considers minimal and maximal phase voltages - voltage at the node with the lowest voltage drops is slightly increased, while significant voltage variations at PV Urh and PV Bassol are reduced.

Scenario 5 was meant to evaluate the performance of the INCREASE local control for mitigating over-voltages, without the support of the OLTC. Due to local characteristics of such control, there is no significant impact on other nodes than PV Urh, where the controllable load was deployed. The load started to consume PV generation (imitation of PV curtailment), when the voltage of PV Urh exceeded a value of 236 V. The controllable load (INCREASE local control) contributed to less significant voltage rises at PV Urh.

In scenario 6, there was a coordinated control of a basic local OLTC control and INCREASE local control for mitigation of over-voltages. Similar as in the case of scenario 2 (basic local OLTC control), most significant voltage improvement is achieved on the LV bus of transformer. In addition, the voltage rises were reduced at PV Urh, due to PV curtailment using controllable load.

Compared to scenario 6, overall improvement of voltage was achieved in scenario 7, since both, the lowest and highest voltages, were considered. Lowest voltages are mainly tackled by the centralised INCREASE OLTC control (using phase voltages), which has a priority to solve lowest voltages in the network by increasing the tap position. Highest voltages on the other hand are reduced with INCREASE local control, installed at PV Urh, with most significant voltage rises.

In the scope of the Slovenian field trial, all solutions were successfully validated, however a more significant impact of control strategies, especially of coordinated control, was expected before the trial. The deviation of achieved from expected impacts is a consequence of several challenges, faced during the implementation and operation phase:

- Due to network configuration (high PV generation and long feeders without PV units), there were low and high voltages in different nodes at the same time, which hindered the operation of the OLTC (tap adjustment would improve voltage in some parts of the network, while voltage in the other parts of the network would be deteriorated)
- Coordinated control of INCREASE centralised OLTC control using phase voltages and INCREASE local control (PV curtailment) is a possible solution for previous challenges, but extensive tests over a longer period with different parameters (settings) would be required
- High voltage unbalances also hinder operation of OLTC control algorithms, especially in the case of algorithms based on average phase voltages (Scenario 3)
- Bad weather conditions and practical implementation challenges, associated with integration of new equipment (controllable load) resulted in a limited amount of reliable results for last three scenarios

In conclusion, to obtain an optimal OLTC control algorithm and parameters, extensive tests of different algorithms and control settings of OLTC over a longer period (e.g. one year) are required. The same thing applies to INCREASE local control, where tests over different seasons are required to obtain optimal settings, i.e. voltage thresholds, where PV curtailment is initiated and voltage thresholds, where PV generation must be switched off.

In case that the LV network is experiencing low and high voltages at the same time, one solution (only OLTC) might not be enough to cope with these issues. Combinations of several measures (e.g. coordinated control) would be a better option in such cases.

1.4.4 Dutch field trial

The main objective of the Dutch field trial was to validate the fair power sharing algorithm and the congestion management algorithm. This was done by replacing some of the existing PV inverters with inverters, provided by Mastervolt. These inverters have the capability to remotely adjust the active power limiting set-point. However, since the Mastervolt inverters were not able to droop the power based on the grid voltage, a solution using communication was developed. This solution is called emulated droop control (EDC) to distinguish between the physical integrated droop control and the droop control implemented via Intelliweb. The cloud platform IntelliWeb enabled owners of the Mastervolt inverters to monitor the performance of their PV installation on a near real-time basis using a Wi-Fi network.

Three basic scenarios were conducted: operation of EDC, FPS and congestion management.

Figure 17: Operation of EDC and FPS

Congestion management of a distribution transformer was validated on August 28th 2016. Since there was no actual congestion of transformers in the pilot network, the algorithm was provided with such settings, that it reduced the reverse power flow, caused by PV. Congestion management was activated after there was a continuous reverse power flow for more than 9 minutes.

18 shows some results of EDC and FPS operation on October 25th 2016. The measurements were acquired from inverters at 2 locations, Bronsbergen 49 and 172. The upper graph represents voltage measurements, while the lower graph represents active power measurements and active power limiting set-points.

Active power measurements shown in

Figure 17: Operation of EDC and FPS

Congestion management of a distribution transformer was validated on August 28th 2016. Since there was no actual congestion of transformers in the pilot network, the algorithm was provided with such settings, that it reduced the reverse power flow, caused by PV. Congestion management was activated after there was a continuous reverse power flow for more than 9 minutes.

18 indicate that after EDC was activated, the PV generation (curtailment) is not equally redistributed among the observed inverters. Around 15:39 h, FPS took over and provided new active power limiting set-points for both inverters in such a way that their PV output was equalised.

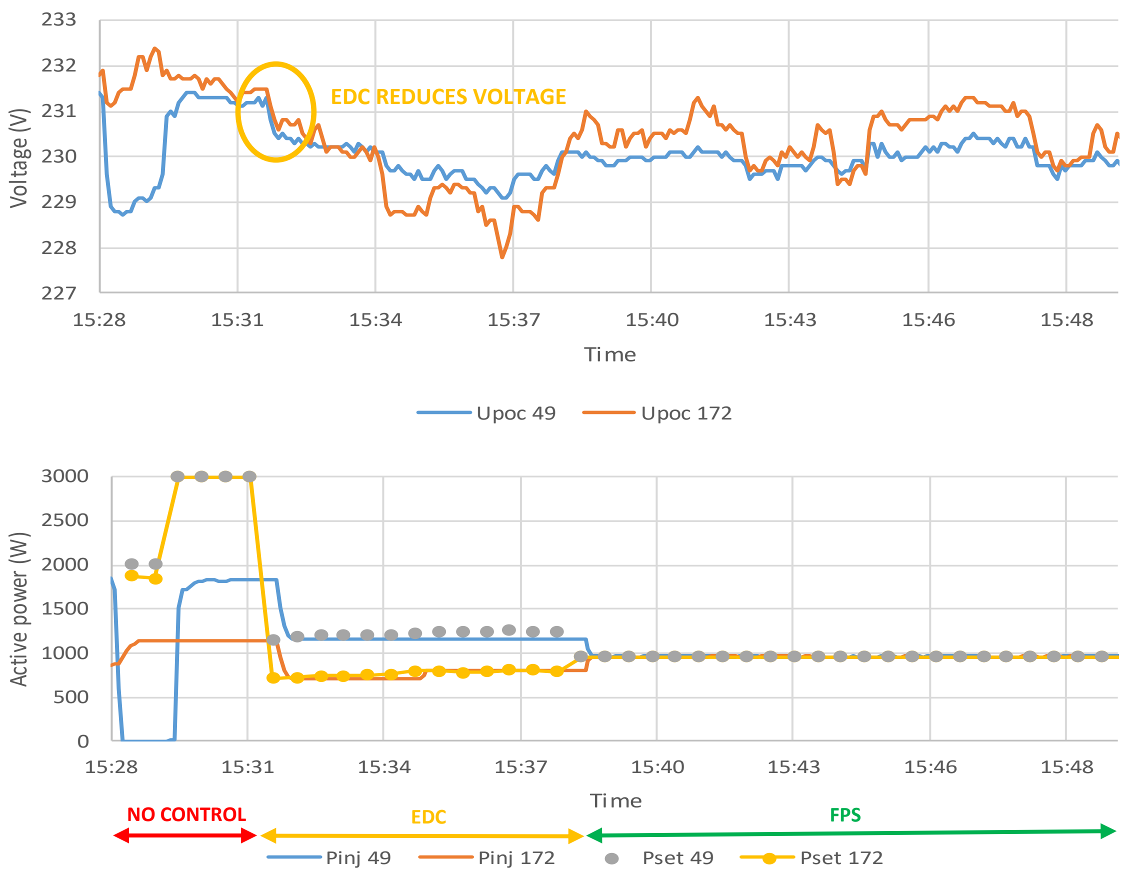


Figure 17: Operation of EDC and FPS

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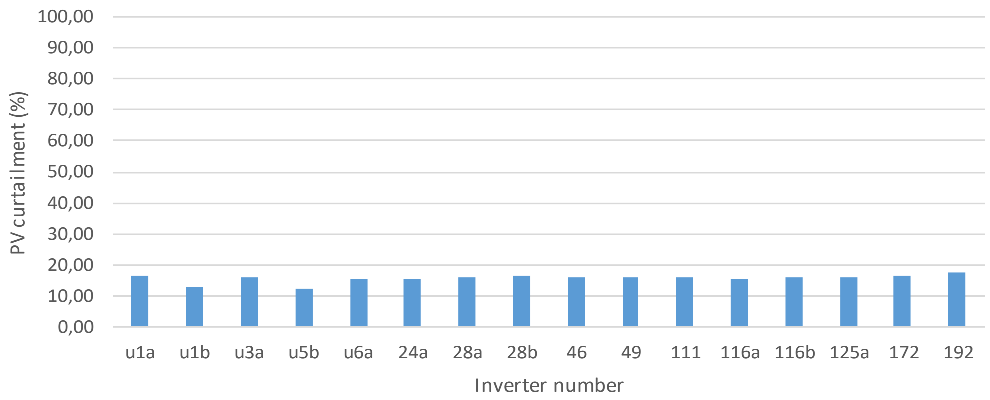

Figure 18: Congestion management – relative curtailment per inverter

Figure 18: Congestion management – relative curtailment per inverter

19 shows relative values of the PV curtailment, thus in reference to PV generation before activation of congestion management. Results showed that PV curtailment is done in such a way that each inverter curtails an equal share of available PV generation.

Also in case of congestion management, a principle of fairness is considered, although a bit different as in the case of FPS, since the same relative value of PV injection must be achieved instead of the same absolute value.

Within the Dutch field trial, all proposed control concepts were successfully validated, despite several unpredicted technical challenges, related with real-life implementation.

1.4.5 Austrian field trial

The pilot network of the Austrian field trial, consisting of different single-phase PV inverters, was chosen to validate and evaluate the concept of the INCREASE local control for mitigating voltage unbalances (unbalance mitigation control in the following).

The basic idea of the Austrian field trial was to replace 2 existing single-phase 8 kVA PV inverters with 2 controllable three-phase 15 kVA inverters. The remaining 4 single-phase inverters are then reconnected to the same phase L1, to create voltage unbalances, which are then tackled by controllable inverters (unbalance mitigation control).

To set-up the trial, 2 controllable PV inverters were deployed, each with a corresponding controller, which was also used to acquire measurements at connection points of the controllable inverters. In addition, a network analyser was deployed at the main bus of the 10th floor, to monitor the three-phase voltages and the total phase currents and the neutral current of the main line, supplying the 10th floor of the ENS building.

Figure 19 Initial (left) and final (right) site configuration

Two simple demonstration cases were conducted. First is the basic scenario, where the single-phase inverters create the unbalances, by injecting PV generation into the same phase L1, while the unbalance mitigation control of controllable inverters is switched OFF. The INCREASE scenario was the same, but here the unbalance mitigation control was switched ON, to tackle the unbalances, created by single-phase inverters.

Performance of the unbalance mitigation control was validated and evaluated using voltage and current measurements, acquired from the main bus and main line supplying the 10th floor of the ENS building. **Fout! Verwijzingsbron niet gevonden.**21 indicates high current unbalances, generated by unsymmetrical PV generation. The highest current was obtained in phase L1, since all single-phase PV inverters inject the power into phase L1. There was also a high neutral current, which further revealed high current and voltage unbalances. After the unbalance mitigation control was switched ON (right chart on **Fout! Verwijzingsbron niet gevonden.**), the neutral current was reduced. This was not the case in the basic scenario, which means that the unbalance mitigation control successfully reduced the (voltage) unbalances, created by unsymmetrical PV injection.

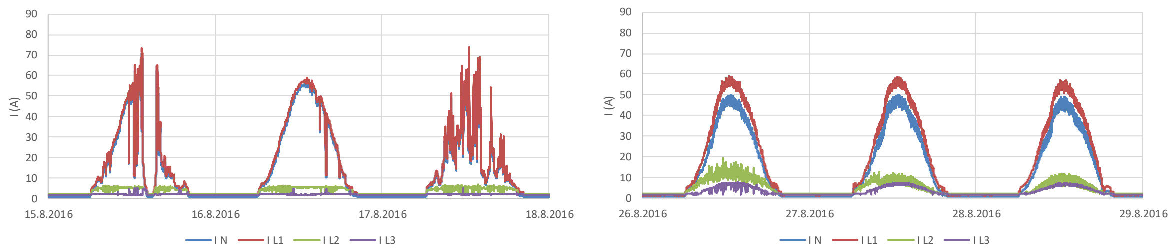

Figure 20: Reduction of the neutral current in case of unbalance control activation

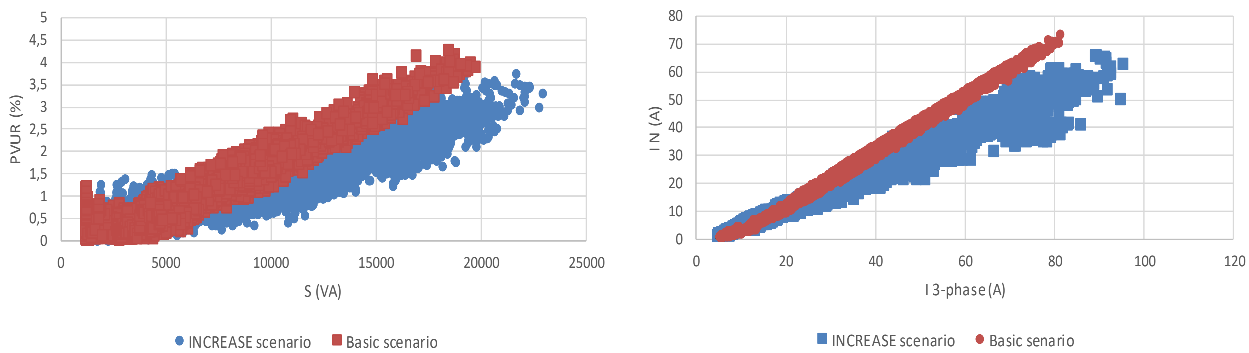

Figure 21: Impact of the unbalance control on maximal phase voltage differences and neutral current

Proper response of the unbalance mitigation control is further confirmed in **Fout! Verwijzingsbron niet gevonden.**22, which shows results of correlation analysis. On the left chart, the correlation between the phase voltage unbalance rate (PVUR) factors, indicating the voltage unbalance, and total apparent power has been analysed. The results indicate that in the INCREASE control scenario, PVUR values are reduced. As an example: in case of 15,000 VA, the PVUR is almost halved.

On the right chart of **Fout! Verwijzingsbron niet gevonden.**22, a correlation between neutral current and total three phase current is noticeable. Also in that case, it is very clear that the unbalance mitigation control is proper operational. As an example: at a 3-phase current of 80 A, the neutral current is reduced by about 20 A.

The Austrian field trial confirmed that the unbalance mitigation control performs according to the concept, defined within INCREASE. As controllable inverters were introduced, voltage unbalances were reduced if the unbalance mitigation control was activated.

Using such controllable inverters could be a good solution for increasing PV penetration in networks facing voltage unbalances. The Austrian field trial shows also that PV inverters with unbalance mitigation control do not further deteriorate voltage unbalances, but improve the situation. A more significant improvement of the voltage unbalances may be achieved by increasing the share (total power capacity) of such controllable inverters.

1.5 Regulatory framework and business modelling

In INCREASE, we have developed innovative solutions for the control of distributed renewable energy sources and of demand response units. The supervisory control level, the scheduling control, is in charge of the flexible energy portfolio optimization, where demand response units' flexible energy is optimized to maximize the value of the ancillary services (AS) provided in the electricity markets and prevent grid conflicts of interest.

The outcome of the control of flexible energy sources is highly dependent on the rules and boundary conditions within which the system operates. These rules encompass the technical, economic, market and regulatory provisions and define the framework specific for each country in which the control solutions are deployed.

In the report D5.3[2], entitled "Enabling frameworks for INCREASE solutions" we investigated the viability of the INCREASE control solutions and key INCREASE AS provided within the current framework conditions in the INCREASE partner countries. While the low voltage (LV) grid of the Slovenian distribution system operator (DSO) Elektro Gorenjska (EG) served as the basis for previous assessments in the INCREASE report D5.2[3], entitled "Report on short-term market mechanisms for AS provision", in the report D5.3 an assessment for a representative European grid was the basis for overall policy conclusions. With purpose of application of the INCREASE solutions within a wider EU region, data was gathered from several DSOs in central, southern and northern region. A representative grid was created as a synthetic grid based on a questionnaire about typical network settings and parameters in different European regions comprising typical amount of feeders per transformer station, size of loads connected per feeder, and typical loading of the transformer and lines in the network. In the representative grid, the impact of INCREASE technologies implementation was analyzed using the scenario approach. Sensitivity of those results to key drivers was also analyzed

The results of report D5.3 reflect the energy market's undergoing a dramatic change. The European Commission has published an ambitious legislative proposal to redesign the electricity market (the Winter Package). The idea of the new legislative proposal is to increase the security of supply and ensure that the electricity market will be better adapted to the energy transition. The transition will bring in the market a multitude of new producers, in particular of renewable energy sources, as well as enabl full participation of consumers in the market notably through demand response. The new electricity market design being developed will allow innovative companies with new business models to emerge and compete on the market. Already now we see the emergence of new market players, such as aggregators or industrial companies starting to offer secondary or tertiary reserves via smart control of demand response measures. In most European countries however the consumers are not enabled to offer their flexibility. This report will contribute to this discussion putting the INCREASE solution in a broader context of needed regulatory, economic or market preconditions.

The report D5.3 builds on the INCREASE reports D5.1[4] and D5.2. In the latter, the INCREASE value analysis methodology is described, based on a technical analysis where MAS control strategy operation is simulated in a typical distribution network, using Evaluation Scenarios. These scenarios covered the problem space in which MAS control operates, reflecting different operating stages of LV networks, e.g. with different penetrations rates of DRES and demand response or different seasons. The simulated

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[2] Report D5.3 can be downloaded from the INCREASE website: http://www.project-increase.eu
[3] Report D5.2 can be downloaded from the INCREASE website: http://www.project-increase.eu
[4] Report D5.1 can be downloaded from the INCREASE website: http://www.project-increase.eu

outcomes of the MAS control strategies provided operating schedules of DRES- and DR-units and thus the physical properties of the four key grid challenges of INCREASE. Based on the technical analysis an economic, environmental and operation security assessment was made for different business cases that enables a broader view on possible benefits to the society than classical cost-benefit assessment. These assessments were made with the value analysis tool (VAT), a MATLAB based computing tool, created in INCREASE using value analysis scenarios defined in the project. These scenarios comprised a series of parameters that describe the assumptions used in our value analysis.

Several of these assumptions were specific to the Slovenian LV grid, whereas in case of other assumptions, e.g. profit sharing, typical market values were used. The analysis in report D5.3 presented the results of the calculation of the break-even point for various actors and the associated business models that connect them. Sensitivity analysis has been used to investigate the impact of various assumed values in order to enable the implementation of the proposed INCREASE solutions in the selected EU countries.

In report D5.3, we presented business cases with positive revenues for an aggregator implementing INCREASE solutions. We found that the aggregator has a successful business case if his costs are distributed among a sufficient number of DR units in his pool. In case of the aggregator's pool size of 10.000 DR units, the costs were spread across enough units to achieve annual profit in the operation. Scenarios with lower level of integration of PV and DR units were less profitable, which can be problematic for the aggregators with smaller DR pool sizes. There the aggregator became profitable only with increased energy prices or by including the PV units in his business portfolio as well.

For all of the pool sizes, an increased level of integration (PV and DR) lead to better cost distribution and more favorable conditions for the aggregator. Other factors such as higher market prices (e.g. on the reserve markets) would promote his profits. Under the realistic cost assumptions employed in the investigated business models, flexibility from DR units alone was hardly profitable for small DR pools. When PV units are included in the aggregator's pool, also smaller aggregation pools were profitable. This meant the aggregators should strive to include PV units in the portfolio when operating smaller DR unit pools.

Overall, the results showed that the EU grid was more profitable than the Slovenian DSO grid, even when accounting for Slovenian personnel costs that are below the EU average. Also for small pool sizes, it was possible to secure sufficiently large flexible energy portfolio sizes (i.e. above 1 MW, the minimum bid size in several reserve markets). However even smaller flexible energy portfolio sizes may lead to profitable business cases for the aggregator and therefore the market requirements regarding the minimum bid size should not be prohibitive. The energy market of the future will therefore be characterized by a multitude of market actors with different business portfolios and costs structures. Only an inclusive approach will lead to the needed transition of the EU energy systems.