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Final report from 28.10.2019

CEVSol: Cost effective smart grid solutions for the integration renewable power sources into the low-voltage networks

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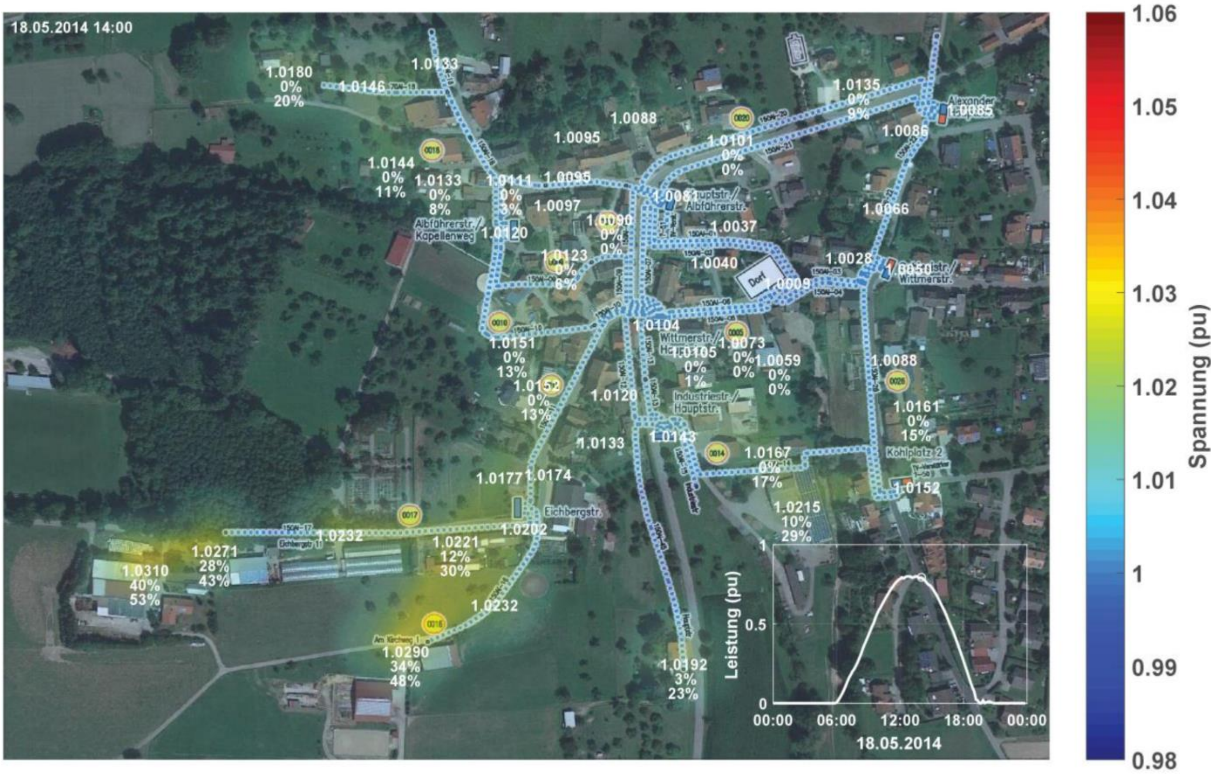

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Zusammenfassung

Während des CEVSol-Projekts wurde das technische Verhalten sowie die Wirtschaftlichkeit von Lösungen zur Spannungsregelung in Verteilungsnetzen mit großem Anteil an erneuerbaren Energien entwickelt und bewertet. Dies wurde auf der Grundlage von Analysen bestehender Verteilnetze durch Extraktion von approximierten / reduzierten Netzmodellen durchgeführt. Die Methodik wurde auf nationale sowie auf ein deutsches Verteilnetz angewendet.

Die Projektinhalte bieten eine Vision und einen Vergleich verschiedener Technologien zur Spannungsregelung auf der Grundlage ihrer Vor- und Nachteile sowie eine Klassifizierung der technischen Methoden zur Durchführung der Spannungsregelung in den verschiedenen Kategorien der Niederspannungsverteilnetze. Die Durchführung basiert auf der vorgeschlagenen Methodik, die bereits ein breites Spektrum technischer Lösungen abdeckt, um eine klare vergleichende Analyse zwischen verschiedenen Lösungen und deren Kombinationen zu erhalten.

Die erhaltenen Ergebnisse und Arbeiten der Vorjahre, die auf ZHAW_Matpower basierten, wurden mit den Ergebnissen dieses Berichts in Verbindung gebracht, die mit einer speziell entwickelten OpenDSS-Umgebungen erzielt wurden. Dies ermöglicht einen fairen technischen und wirtschaftlichen Vergleich zwischen den Ergebnissen der Lastflussberechnungen in Matpower (P (U), Q (U) und PQ (U)) und den zusätzlichen Funktionen der OpenDSS (LVR, OLTC, Gitterverstärkungen). Darüber hinaus ermöglicht der Ansatz der Verwendung der Lastflussberechnungen von Matpower in der OpenDSS-Umgebung die technische Bewertung verschiedener Kombinationen der bereitgestellten Spannungsstabilitätsmaßnahmen, z. PQ (U) zusammen mit OLTC / LVR. Diese Ergebnisse wurden verwendet, um die Methoden für verschiedene Kategorien von Niederspannungsverteilungsnetzen zu klassifizieren und die Rangordnungsmatrix zu erstellen.

Résumé

Au cours du projet CEVSol, les performances techniques ainsi que l’efficacité économique du contrôle de la tension dans un réseau de distribution avec une grande part d’énergie renouvelable ont été développé et étudié. Cette étude a été réalisé en analysant des réseaux de distributions existants pour extraire des modèles approximés / réduits. Cette méthodologie a été appliquée au réseau national ainsi qu’un réseau de distribution Allemand.

Le contenu du projet donne une vision et une comparaison de différentes technologies pour le contrôle de la tension, basé sur leurs avantages et inconvénients et sur la classification des méthodes techniques dans le but d’appliquer le contrôle de la tension dans différents réseaux de distribution à basse tension. La méthodologie proposée couvre un large choix de solution technique, permettant une analyse comparative claire entre les différentes solutions et les combinaisons de solutions.

Les résultats obtenus et les travaux des années précédentes basés sur ZHAW_Matpower ont été confondus avec les résultats de ce rapport, obtenus avec des environnements OpenDSS spécialement conçus à cet effet. Cela permet une comparaison technique et économique équitable entre les résultats obtenus à partir des flux de charges avec Matpower (P(U), Q(U) and PQ(U)) et les fonctions supplémentaires apportées par OpenDSS (LVR, OLTC, renforcement du réseau). De plus, l’approche consistant à utiliser les calculs de flux de charge de Matpower dans l’environement OpenDSS permet d’évaluer la viabilité technique de potentiel combinaisons de mesures de stabilité de la tension fournies comme par exemple PQ(U) avec OLTC/LVR. Ces résultats ont été utilisés pour classifier les méthodes pour différent réseaux de distribution basse tension et ainsi générer une matrice de comparaison.

Summary

During CEVSol project, the technical performance and economic efficiency of solutions for voltage control in distribution grids with large fractions of renewables was developed and evaluated. This was carried out based on the analysis of existing distribution grids by extracting approximated/reduced grid models. The methodology was applied on national and one German distribution grids.

Project content provide a vision and comparison of different technologies for voltage control based on their advantages and disadvantages and classification of technical methods for performing voltage control in the various low voltage distribution grids categories. It was carried out based on the proposed methodology, which covers a wide range of technical solutions, to have a clear comparative analysis between different solutions and the combinations of them.

The obtained results and work from the previous years that were based on ZHAW_Matpower, were conflated with the results of this report, which were achieved with purpose-built OpenDSS environments. This allows fair technical and economical comparison between the results gained from the load flow calculations in Matpower (P(U), Q(U) and PQ(U)) and the additional functionalities provided from the OpenDSS (LVR, OLTC, grid reinforcements). Additionally, the approach of using the load flow calculations from Matpower within the OpenDSS environment allows the technical assessment of different combinations of the provided voltage stability measures e.g. PQ(U) together with OLTC/LVR. These results were used to classify the methods for various low voltage distribution grids categories and to generate the ranking matrix.

Main findings

- PV would not cause too many voltage problems in distribution grid with short feeders in the future. Whereas, the EV fast charging stations will have the bigger impact on voltage violation
- Modern inverters have the abilities to control the active and reactive power with respect to the actual grid voltage. This fact introduces new opportunities not only for the DSO, but also for the regulatory authority
- The relative voltage rise 3–5 % caused by the totality of all generating stations in a considered network defined in DACHCZ without load and control options should be discussed or revised in the future. New voltage control strategies allow significantly increase grid hosting capacity of RES not violating voltage limits

Contents

Abbreviations

APC	Active power control
DG	Distributed Generation
DR	Demand Response
DSM	Demand side Management
DSO	Distribution system operator
EE	Energy Efficiency
EMS	Energy Management Solution
ESS	Energy Storage System
EV	Electric Vehicles
FACTS	Flexible Alternating Current Transmission Systems
HAN	Home Area Network
HV	High Voltage
LV	Low voltage
LVDG	Low voltage distribution grid
LVR	Line Voltage regulator
MV	Medium Voltage
NLTC	No-load Tap Changer
OLTC	On-load Tap Changer
RES	Renewable Energy Source
RPC	Reactive power control
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition

1 Introduction

1.1 Background information and current situation

Taking into account the objectives of the Swiss energy strategy for 2050[1], a considerable increase in the installation of Distributed Generation (DG) is forecasted. Due to the fact, that this strategy pursues radical changes in the power generation sources of the future, it is expected that a considerable share of present nuclear based generation will shift to renewable sources.

The integration of DG has changed the assumption of having only mono-directional power flows on low voltage (LV) distribution grids, where electricity was flowing from medium voltage (MV) grids to end-customers through the LV grid. The actual distribution grids were built in radial form defining the highest voltage node of the LV grid at the MV/LV transformer secondary side, and the lowest voltage node at the last connection point served by the string. The impact of this policy influences the actual distribution grid, aggravating unexpected issues in defined regions with high penetration of renewable energy generation. Among the aforementioned problems, some of the most important implications to be considered are thermal overloading of lines, power quality issues and violations of voltage limits.

1.2 Purpose of the project

In this project, the technical performance and economic efficiency of solutions for voltage control in distribution grids with large fractions of renewables was developed and evaluated. This was carried out based on the analysis of existing distribution grids by extracting approximated/reduced grid models. The methodology was applied on national and one German distribution grids.

1.3 Objectives

The main goals described on the final report are achieved results from previous stages with a proposed method for the estimation of the most cost-effective solutions of voltage control for a specific low voltage grid category. The main motivation behind this work is to enable the integration of a large amount of renewable energy sources without expensive grid extensions, to fulfil the given power quality standards [2],[3] and to protect the infrastructure from possible overloading.

2 Methodology

Optimisation of low voltage systems makes it necessary to apply systems analysis and dynamic multi-step methods to observe reciprocal interconnections and behaviour of low voltage system elements over time and space. A characteristic feature of systems analysis is that for selecting an optimal solution for voltage control purposes, sophisticated systems must be investigated within the development process. To realize this kind of approach, modelling methods of the existing low voltage system development was used. They must adequately reflect real systems characteristics and perform system technical, economic and ecological criteria calculation. Besides, effective optimization methods are required to solve optimization tasks with discrete variables.

In the literature, there are many results about analysing positive and negative aspects about renewable sources impact on distribution grids with possible solutions to control voltage within the acceptable boundaries. However, provided solutions with different technologies do not provide a clear comparative analysis between different solutions in middle and long-term horizon. To overcome this particular drawback, this final report provides an extended method [4] for the estimation of the most cost-effective solutions of voltage control for a specific low voltage grid category, which was elaborated for the various grid categories and a number of technical methods for performing voltage control in the distribution grids.

The proposed approach presented here is based on the basics of large technical system development management: the problems of optimal development plan selection, sustainable development methods and development optimization criteria with attention to low voltage grid issues. The development process is dynamic, the creation or reconstruction of system objects and elements is performed in different locations of the system and at different time moments. The relative efficiency of development plans in development process is variable - it means that decisions have to be taken considering long-time period. In real tasks, development plan variations can reach a big amount of combination. Therefore, new methods of optimization have to be developed. Sustainable development management is a sophisticated activity because of uncertainty of the future. To overcome this condition for estimation of most cost-effective solutions for a voltage control, a dynamic management method is proposed.

The simulation of low voltage power grids is particularly challenging due to uncertain information about load patterns, non-symmetry between phases, rapid and unpredictable fluctuations of renewable energy sources (RES). In addition, the simulation of novel control mechanisms and elements, acting on renewable energy production and other converter-based production devices requires a flexible simulation environment. To overcome these issues and observe realistic behaviour of low voltage grid with different solutions for voltage control, dynamic simulation is organized in interaction with the ZHAW developed and OpenDSS [5] simulation environments with a tailored capability to perform quasi-static time series simulations (QSTS). The main advantage of using QSTS simulation is its capability to properly assess and capture the time-dependent aspects of power flow, taking into account the behaviour of different solutions for voltage control in a yearly basis. QSTS produces sequential steady state power flow solutions where the converged state of an iteration is used as the beginning state of the next timestep. The resulting integrated simulation between development management and simulation environments is proposed.

2.1 Description about methodology – ZHAW_Matpower/OpenDSS engine approaches for Voltage control investigation

Development planning can be binarily classified as static or dynamic according to the tasks that are going to be solved. In the static planning tasks, the planners seek the optimal set for the single time period (for instance, single year) with a focus on the final optimal network state for the pre-defined future single period. This deliverable focus on the multiple years' consideration of optimal and most cost-effective solutions for voltage control strategy identification for the whole planning period, which is classified as dynamic (see Figure 1):

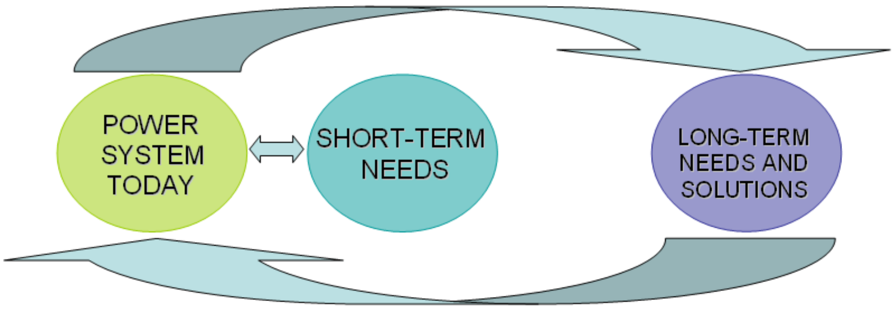

Figure 1 Planning horizons

The basics of the step-wise development management approach are established from the following main factors (see Figure 2):

- Time levels / voltage levels / loads, generation etc. modelling;
- Decision-making for advanced stage (horizontal information flow) in uncertain conditions only for the nearest time period of 2-5 years;
- Estimation period shall correspond to the average life-cycle period, approximately within 20 to 30 years;

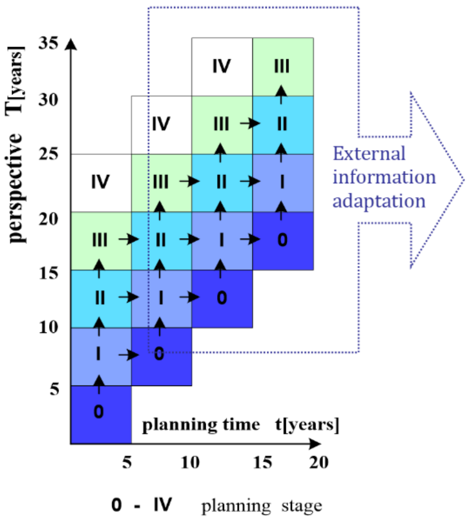

Figure 2 Development Planning Structure

To realize this particular approach, modelling methods of the existing system development were supplemented with new technical regulation and market economic regulation criteria and functionalities (see Figure 3):

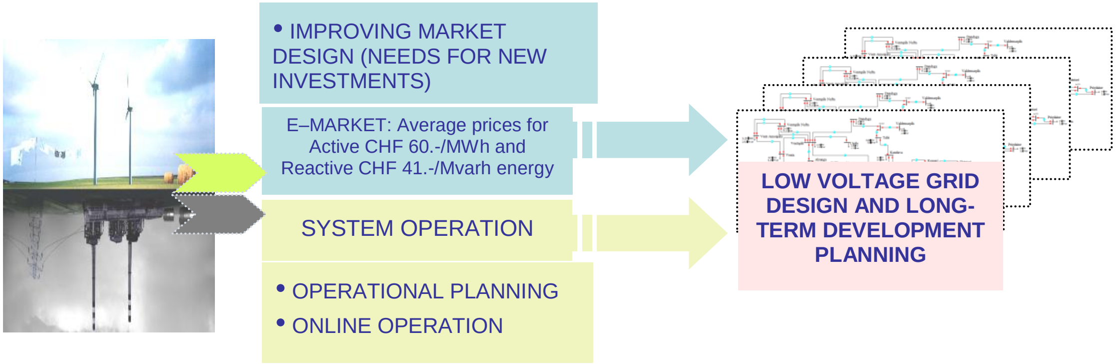

Figure 3 Low Voltage System analysis modification

The modelling methods must adequately reflect real low voltage systems characteristics as much as possible, as well as include flexible generation incorporation, and perform system technical, economic and ecological criteria calculation. Moreover, effective optimization methods are required to solve optimization tasks with discrete variables.

Benefits that may be recognized for the sake of the availability of the well-planned low voltage system are denoted to technical as well as to electricity market aspects, increasing grid-hosting capacity, which is in fact closely connected to economic efficiency issues.

Connection of all characteristics will lead to low voltage systems sustainability that is identified as the fact that up to now in designing process of electrical power systems not enough attention has been drawn to consequences of the made decisions. Taking into consideration the aspects mentioned above, the implementation of the proposed dynamic method and tool for low voltage system sustainable development analysis will increase the accuracy of low voltage systems development scenarios and decisions to solve thermal overloading of the lines, power quality issues, and violations of voltage boundaries in the future.

2.1.1 Long-term planning method

Development planning is a process to determine an optimal strategy to expand the existing low voltage network to meet the demand of the possible load growth and the proposed generators, while maintaining reliability and security performance of the grid. The general objective of the low voltage network development planning task is to determine ‘where’, ‘how many’ and ‘when’ new element/devices must be added to a network in order to make its operation viable for a pre-defined horizon of development planning, with costs minimization for optimal expansion/development plan determination.

Main concepts of development planning are based on: Development Action (D-action); Development Step (D-step); Development Plan (D-plan). The essences of the parameters are explained on Figure 4.

$$\boxed{\overbrace{e(t-1)}^{Existing\ state} + \overbrace{(\dots\ \dots\ \dots)}^{\mathrm{Re}alized\ D-action(s)} = \overbrace{e(t)}^{New\ state}}$$

Figure 4 Development state formation

Development plan formation is a complicated process that requires extensive studies to determine many new network elements. Creation of the optimal development plan will ensure adequacy of the grid, generation and demand in the future.
Electricity market affects not only power system operation as whole, but also its development practices. It is determined by the condition that electricity generators are independent from transmission and distribution operators and their interests differ. This fact creates higher uncertainty conditions and time resolutions accuracy for the perspective forecasts than before and power system development planning and optimization is hampered. For low voltage network sustainable development solutions, the estimation period must be assumed longer than economic life cycle period – advisable up to 30 years. While selecting optimal development plans under uncertainty, it is necessary to formulate: information package set, representing information credibility range – prognosis, credibility estimation criteria and comparable development plans.
If the compromise between network estimation problems and development aggregated results has not been reached to match the quality of the planning, the results will be impaired. The following factors lead to solution to compile both the AC and DC models:

- For short-term analysis, including intermitted generation and market conditions, of several years and due to subject to initial information availability, the full AC model can be used;
- Considering the complexity and dimension of development and optimization tasks, as well as information uncertainty conditions, the appropriate method for the steepest calculating of power flows for criteria definition is simplified by the DC method.

The objective function for the low voltage network development plan displays and integrates the technical and economic parameters as well as the power supply reliability, ecological, etc. parameters (can be seen in Figure 5).

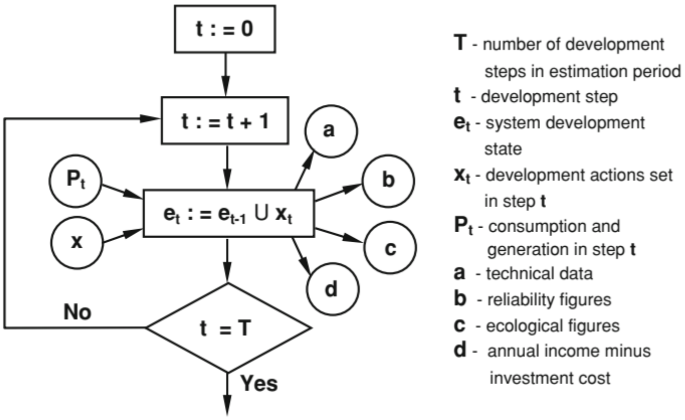

Figure 5 Estimation process of multi-step D-plan

Optimization incorporates the methods and algorithms, by which the maximum for objective function F is determined, usually with many variables, observing supplemental conditions, including limitations which are expressed by equalities or inequalities. In tasks on technical systems, development variables are development actions (D-actions), but technical criteria are limitations, such as maximal allowed line capacity, etc. For development optimization tasks, multiple criteria are defined (can be seen in Figure 6).

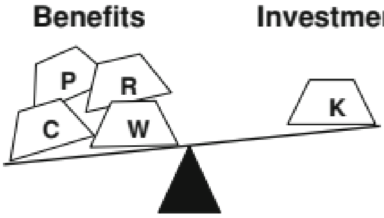

Figure 6 Cost Benefit analysis of D-actions

There are capital investments on one side of scales required for D-actions realization, while on the second side there are benefits gained by the D-actions performed:

- Operation and maintenance costs reduction (C);
- Overload reduction, over and under voltage violation reduction, power quality improvement (P);
- New consumers and generation connection, increasing grid hosting capacity (W);
- Power supply security improvement (R), etc

Part of this gained benefit has monetary value but there are such benefits, which can hardly be evaluated financially. However, it is still required to initiate the optimization. The economic estimation of D-actions is a thorny task. The D-actions must be estimated applying the method which is named as economic life cycle concept. Capital contributions efficiency is estimated observing operation, maintenance, and technical costs, caused by emergency situations/faults and others. When estimating D-action, its criterion calculation must not be based on only 1-year figures; the criterion must reflect the whole economic life-cycle of the object.

The objective function in (1) represents the gained benefits welfare, minus the investment cost in new solutions (Classical Grid Reinforcement, Active Power Curtailment, Reactive Power Control, On-load Tap Changer, Line Voltage Regulators, Battery Energy Storage Systems, Demand Side Management, Solid-State Transformers etc.). The objective function is a network development plan g quality criterion, denoted as $F(T,g)$ and is calculated by following formula:

$$\max F(T,g) = \max_{g \in \{G\}} \sum_{t=1}^{T} (SW(t,e(t),g) - IC(t,e(t),g)) \quad (1)$$

where: t – development step serial number;

T – number of development steps in estimation period;

g – development process;

$\{G\}$ – set of all possible development plans;

$SW(t,e(t),g)$ – gained benefits in development step t, development state $e(t)$ and development process g;

$IC(t,e(t),g)$ – investment costs in development step t and development state $e(t)$ and development process g.

To consider the impact of highly variable renewable energy source and loads to technical and economic criteria, each development state should be observed at a minute base. Application of minute calculation allows taking into account the major trends of production and consumption during the day, taking into account consumption time shifting, demand side management and demand response programs, distributed generation, and capture the time-dependent aspects of power flow.

The application of QSTS simulations requires more data to represent the time-varying PV output coincident with time-varying load. The time series data is often difficult to obtain as the measurement equipment at the feeder and PV plant will need to be upgraded with higher time resolution capability. The necessary data set can become very large depending on the resolution and length of simulation desired and simulation processing times can increase quickly and become burdensome. Details of voltage regulation controls, such as intentional delays, also need to be represented.

Each development process is characterized by number of realized development actions and its realization moment, as well as by each development action realization type. Figure 7 represent small example with 2 development actions, development step 1 year and 16 development states. The total number of development plans in this example will be 16.

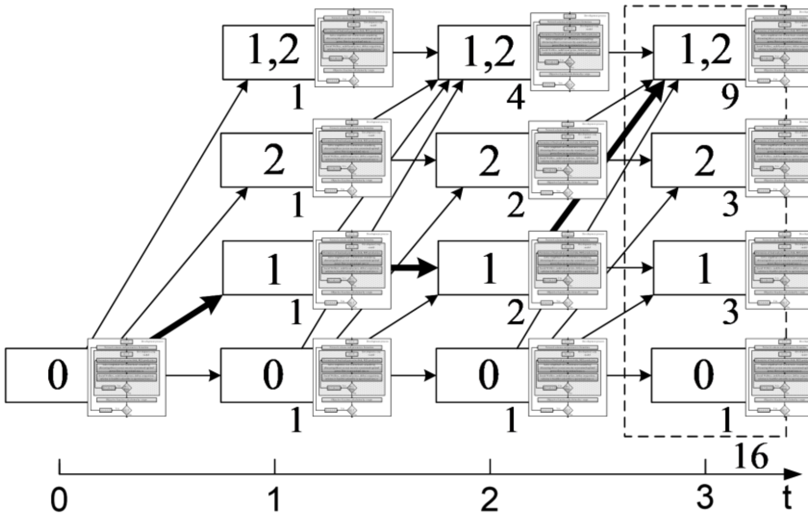

Figure 7 Development states forming scheme example

In real tasks, the number of comparable development plans attains astronomic quantity, therefore it is required to apply specialized dynamic optimization methods in low voltage system sustainable development management process. Within the frame of electric power system dynamic optimization task, power flow calculation must be performed with high-speed and certain accuracy. Due to this factor, it is necessary to use specialized methods.

2.1.2 Modelling technique

The main point of this part is to demonstrate the method based on the deterministic concept with a dynamic low voltage planning with technical and market economic regulation principles. The mathematical model of the low voltage system and its development process configuration and network dynamic behaviours introduction in hardware will provide the capability to calculate and assess system criteria for decision making. To provide hardware operation on the given task, data are required as well as corresponding software that includes the optimization algorithm. Taking into consideration the calculation dimension, the applicable methods must be operable with a relatively high speed and similar requirements are also applied to the data. Development modelling should include network dynamic behaviours and represent the network's real processes as much as possible. Based on the main functioning factors defined above, the following functional specifications of the proposed method are considered (see Figure 8).

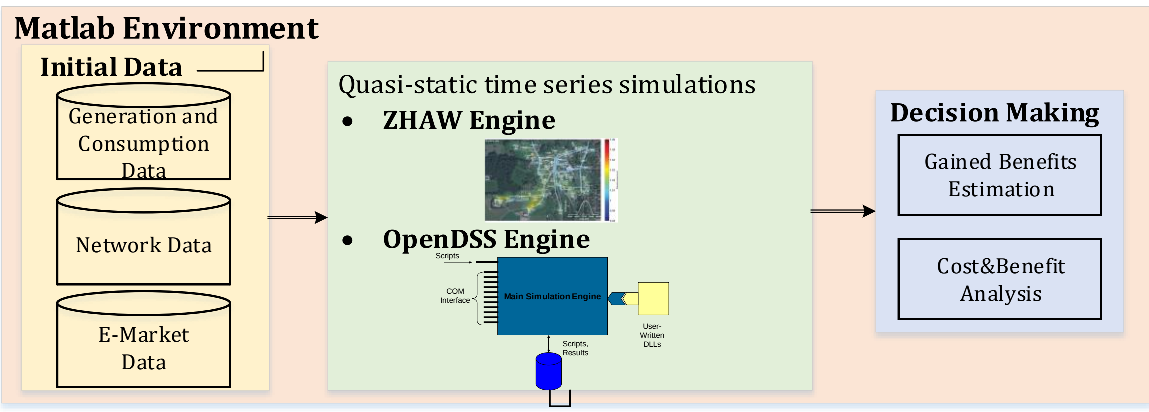

Figure 8 Functional specification of the proposed method

Development model functional specification consists of the tree main blocks:

- **First block** contains the necessary input data from generators, consumers, network elements and e-market information. The input data may be classified into 4 groups:
  1. group - data that within the whole calculation process is unchangeable;
  2. group - data that is specific for each development step;
  3. group - data that are specific for each development state;
  4. group - data that are used for analysis of the results.
- The **Second block** is concerned with obtaining the results for scenarios formed by the user, where QSTS algorithm is implemented throughout ZHAW and OpenDSS engines. Obtaining of the results by the presented modelling and simulation have to be always motivated by the best effort to achieve valuable results, since those, when applied to the development planning processes, may considerably influence decisions, and thus path of system development and its degree of optimality.
- **Third block** could be regarded as decision making. Decision making by itself is a complex procedure, and in this deliverable under the decision making is assumed focus on gained benefits and investment cost estimation, based on the objective function.

Additionally, in order to analyse and compare the future investments in low voltage grids, a set of metrics are defined that show the gained benefits. This metric shows how DSOs could benefit or detriment from the investment in the new solutions.

- **Economic criteria:**

The major economic efficiency ratios are Net Present Value (NPV), Internal Profit Rate (IRR) and Pay Back Period (PB). Net Present Value ratio complies with discounting or monetary value reduction in accordance with discount rate. Discounting is done using the average cost of capital (WACC) for grid investment, which was set by UVEK for the year 2018 at 3.83% [6]. NPV value is expressed in monetary value units. If NPV > 0, then D-action is economically effective; and the higher NPV, the more effective D-action is. But, if NPV < 0, then D-action is not effective; it is not paid back and causes losses. If NPV = 0, then D-action is paid back but is not profitable. In addition to the NPV criteria, IRR is used additionally that demonstrates accumulative capacity of D-action (income accumulation speed), and the higher IRR value is, the faster the D-action will be paid back. IRR value is expressed in percentage. According to the situation available in credit resources market and basic principles of investment policy, the D-actions are considered as economically efficient if IRR >3.6% [7].

The payback period of the contributions (investments) is the needed time until the total system income taking into account monetary value reduction during the period equals the total costs of the system. In order to consider the D-action as economically efficient, its payback period shall be shorter than the D-action technical life cycle (depreciation period). The less payback period, the more favourable D-action from economic viewpoint. In order to estimate these ratios in the preliminary stage of D-actions, cash flow shall be calculated for the whole economical per year life-cycle of respective D-action. If cash flow is calculated including D-action and excluding it, then the ratios of economic efficiency of the D-action can be estimated.

- **Technical criteria:**

Technical criteria depend on the specific system. In dynamic models for development optimization, technical parameter limitations are assumed as a boundary condition. In CEVSol project technical limitations was assumed as D-action plan feasibility.

The described method above was implemented during project and comparative results was received at final stage of the project. Most of the technical analysis was done with ZHAW developed engine [4] in Matpower environment [8] and OpenDSS [5].

3 Control of voltage in distribution grids

3.1 Investigation of new options for control of voltage in distribution grids

3.1.1 Grid enhancement

Investments in grid enhancement are the common way to improve the voltage regulation at the end of a string. Although, the results denoted by this technical solution are easily tangible, but its investments tend to be high arousing the necessity of new solutions. In the CEVSol project, the costs are assumed in range from 150 to 400 CHF/m for grid reinforcement [9][10][11]. For other voltage control solutions implementation, additional costs are assumed in addition to capital expenditures [12]:

Table 1 Additional costs for voltage control solutions implementation

Various jobs for technology implementation	15%
Unforeseen costs	10%
Project Planning costs	10%
Construction Management / NIS Adm. Work	8%

3.1.2 Voltage Control with on load Tap changers (OLTC)

For the OLTC impact investigation, a voltage regulator with a standard control range of ± 5% or ± 20 V was used. The control range comprises 11 steps with 4 volt deadband. This corresponds to a gradation of ± 5 steps and is implemented on the primary side of the transformer. Per stage, the secondary voltage thus changes by ±1.2%. The advantage of the OLTC is that it only changes the voltage amplitude. The price for a OLTC with a standard control range was assumed according to [13]

Table 2 Capital costs for OLTC

Assumed OLTC costs		
250kVA	27’000	CHF
400kVA	31’000	CHF
600kVA	35’000	CHF
800kVA	37’000	CHF
1000kVA	41’000	CHF

3.1.3 Voltage Control with Line Voltage Regulators (LVR)

For the LVR impact investigation, a voltage regulator with a standard control range of ± 6% or ± 24 V was used. The control range comprises 9 steps with 5-volt deadband. This corresponds to a gradation of ±4 steps and is effective on the primary side of the LVR. Per stage, the secondary voltage thus changes by ±1.5%. The advantage of the voltage regulator is that it only changes the voltage amplitude. As a result, there is no active power limitation of the PV system and the entire produced power can be fed in. The disadvantage of the voltage regulator is when the regulator reaches its maximum or minimum position. The voltage can still cause limit violations. The price for an LVR with a standard control range of ± 6% is currently between CHF 10'000 and CHF 30'000, depending on the controller performance. In addition to the standard control range of ± 6%, an extended control ranges can be selected for a surcharge. The surcharge depends on the controller power and the desired control range.

Table 3 Capital costs for LVR

Assumed LVR costs		
20kVA	11'000	CHF
110kVA	23'000	CHF
175kVA	26'000	CHF
250kVA	29'000	CHF

3.1.4 Voltage Dependent Active and Reactive Power Control with PV Inverters

The voltage dependent active and reactive power control (PQ(V) control) using PV inverters can be implemented according to the specification of the local distribution system operator and is already possible for several products on the market [14]. A possible control ramp, implementing the PQ(V) control with a mean value at 1.03 pu is depicted in [15]. While the active power curtailment and the underexcited reactive power injection beyond 1.01 pu counteracts voltage rise at the node (e.g. high PV feed-in), the overexcited reactive power injection below 0.99 pu reduces the voltage reduction (e.g. due to EV charging) in the LVDG. The PQ(V) control with different control methods has been implemented in the Matpower load flow calculation software and was applied to the different real grids in Switzerland and Southern Germany. The technical feasibility was evaluated by comparing the maximum voltage at the weakest node in the LVDG without PQ(V) control and with PQ(V) control. The respective costs of the control methods were estimated and thus the most appropriate solution suggested for these grids.

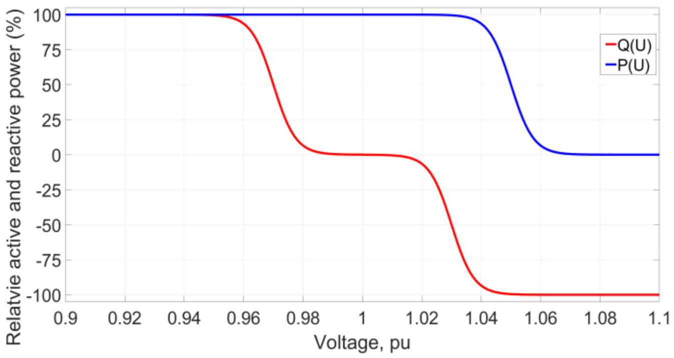

Figure 9 Example of a control figure implementing the PQ(V) control of a PV inverter according to the line voltage. In this example 50% of the control bandwidth is reached at 1.03 pu.

3.1.4.1. Costs for PQ(V) control

In order to deploy reactive power while simultaneously keeping the active power output at 100% the apparent power output of the PV inverter needs to be oversized according to:

$$S_{inv} = \frac{P_n}{\cos(\varphi)}$$

For the maximum reactive power control at cosφ = 0.9 the apparent power of the inverter thus has to be oversized 1.11 times. Since this oversizing does not manifest a monetary advantage for the plant owner, it has to be reimbursed by the DSO.

Active power curtailment over time results in a tangible yield loss of the PV plant and thus a cost share induced by the PQ(V) control. Further active power losses may be caused by the heat dissipation on the power lines due to the additional reactive power circulation in the LVDG.

Certain control strategies may cause excessive reactive power in the LVDG, which needs to be supplied by the medium voltage grid. This compensation is usually charged by the medium voltage grid operator if the cosφ at the corresponding transformer is lower than 0.92.

In the analysed grids the costs for yield losses were accounted for with 60 CHF/MWh and the costs for reactive power compensation were estimated at 41 CHF /Mvarh.

3.1.5 Voltage Control with Demand Side Management

The planning and implementation of the utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility load shape i.e., changes in the pattern and magnitude of a utility load. Demand-side management encompasses the entire range of management functions associated with directing demand-side activities, including program planning, evaluation, implementation and monitoring. Opportunities for demand-side management can be found in all customer classes, including residential, commercial and industrial, and wholesale [16]. As main activity of demand and load control or efficiency increase, the DSM include all events that are related with demand side. The NERC report [17] promote the DSM model for American energy system conditions. Therefore, in the scope of the CloudGrid project and European energy system and market conditions, a vision for DSM architecture was proposed, where the difference is set in Demand Response (DR) actions change.

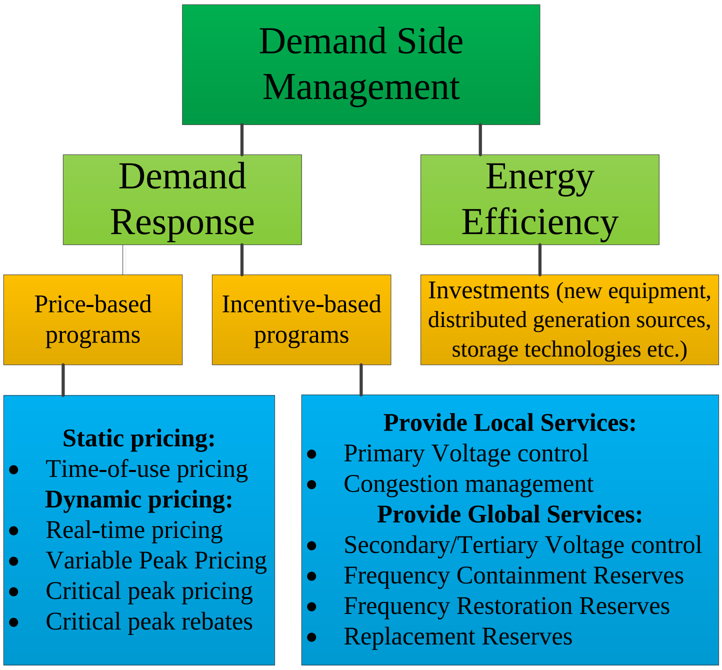

Figure 10 Demand Side Management categories

While energy efficiency (EE) programs are focused on technological process innovation and optimization in order to decrease the passive consumption, DR programs can be moved in time and depends on the consumer flexibility. DR provides the ability to stabilize transmission and distribution grids by reducing consumption peak level and utilization for congestion management. For short term stability questions. it is possible to use DR for global frequency and local voltage control. In addition, DR can impact market prices [18].

A number of EU and other national projects have demonstrated the utilisation of RES and DER flexibility within individual categories of grid connected devices, such as various types of domestic load, EV charging, storage with distributed generation [19]. The main challenges associated with smart grid operation are a coordinated approach and an optimal energy management strategy with respect to multiple objectives, where two main outcomes are [20]:

- With a new energy management solution (EMS), the wasteful use of energy will be decreased, and further utilisation of RES will be provided.

- With the developed EMS, a two-way digital communication between DSO and common household devices could enable smart energy system and advanced smart grid component management, giving the prosumers a tool to improve their energy efficiency and actively participate in electricity market for lowering their costs of energy consumption.

Proceeding aims and possibilities of DSM potential participants several DSM approaches can be highlighted [19]:

- Load and consumption analysis-based approach. A list of task can be created by analysing the customer behaviour with the aim to decrease load consumption and optimize customer daily load. Such initiative will lead to an increase of energy efficiency. This approach is the passive DSM part.
- The feedback system, which consists in informing the consumer about the system constraints. It focuses solely on providing feedback on the electricity use. This approach represents a first step towards DSM implementation.
- The price-based approach, which requires behaviour change on the customer side triggered by price signals.
- And the system capacity-based approach, which does not rely on the price sensitivity of customers but on other system forecasts. In this approach, the customers indicate their preferences to a third-party player (aggregator [21] or system operator) and consent to let this player take the control of smart appliances. For larger customers, this can include contracts for load shedding.

The availability of a flexible amount of resources between price-base and incentive-based approaches is changing during the time and depends on the availability of controllable appliances, energy prices, weather conditions. In a case of price-based approach, the active consumer/prosumer is motivated to decrease his consumption in hours with high prices and shift it to hours with lower prices. Such conditions do not always exist, due to the reason that energy prices during the day, week or longer time period could be flat or with small price gaps. In this case, the active consumer/prosumer could provide a flexible amount of resources for local and global services through incentive-based approaches and receive additional income with overall power system efficiency improvement.

Figure 11 and 12 present total home area network (HAN) consumption in 10 second time scale, which represents home active power consumption behaviour per month with pronounced consumption per working days and weekends without PV generation. The total consumption in July and August was 200kWh and 227kWh, respectively.

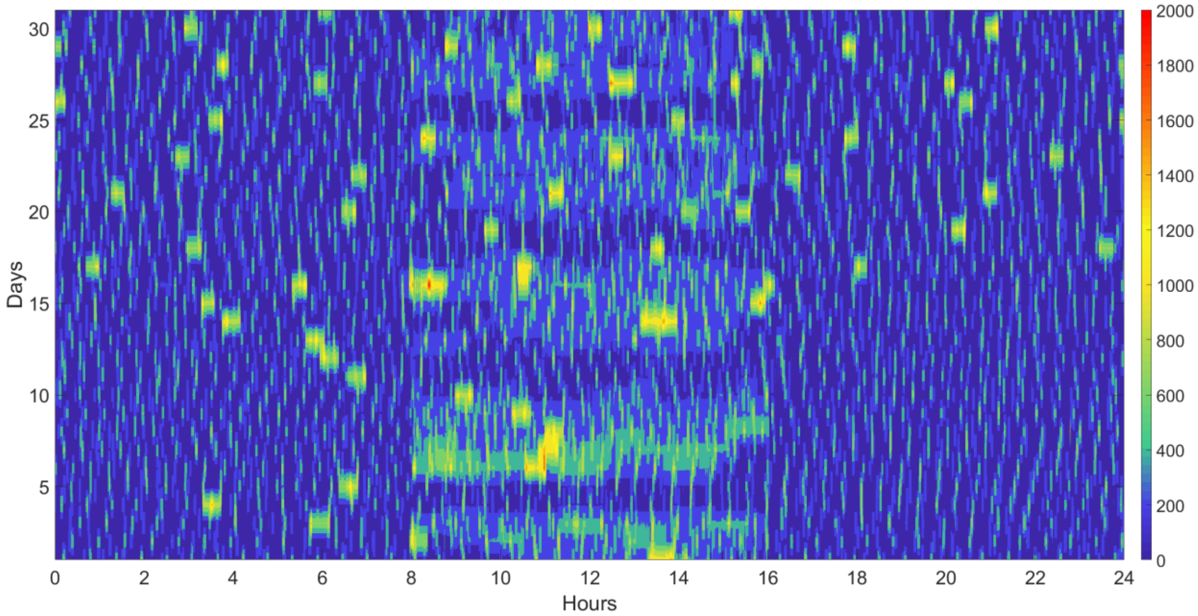

Figure 11 Total HAN consumption distribution in July with 10 second scale

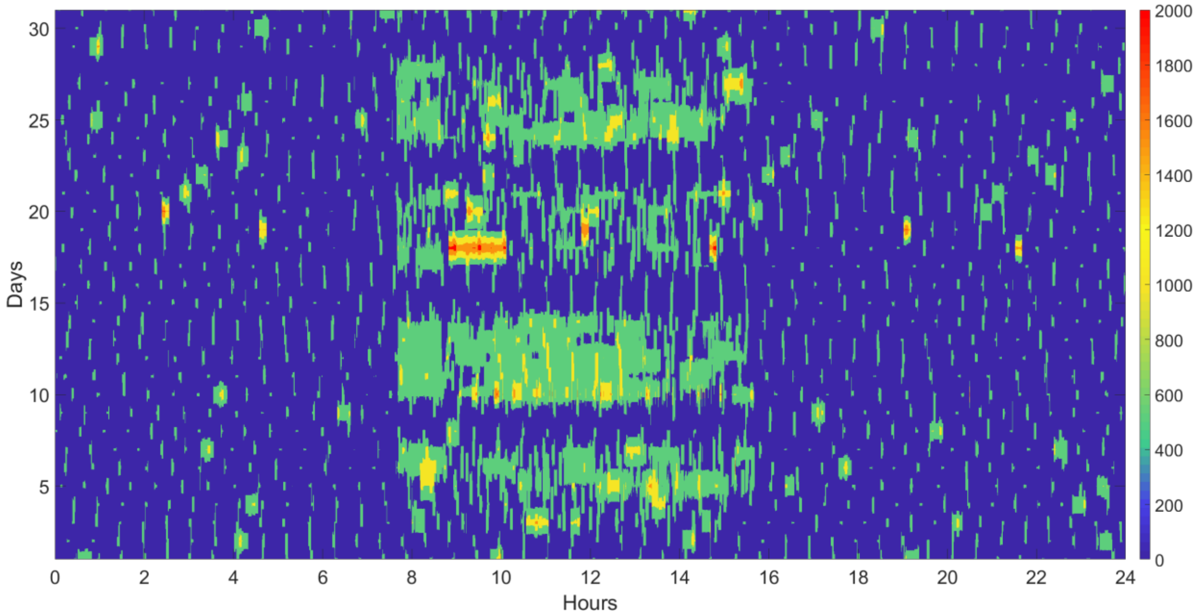

Figure 12 Total HAN consumption distribution in August with 10 second scale

Due to high volatility of local demand in low voltage grid and uncertain availability during time, using flexible loads for the local voltage control does not seem to be a reliable solution. Extension of existing demand with thermal loads (hot water boilers, heat pumps) will allow to utilize PV produced energy and decrease voltage violations in the grid. However, such extension will not provide certain and stable solution in long-term. Based on these findings, the use of DSM for voltage control in LVDG is not considered within the CEVSol project.

3.1.6 Voltage Control with Battery Energy Storage Systems

The voltage dependent active power control ($P\_{BESS}(V)$ control) using BESS inverters can be implemented according to the specification of the local distribution system operator. A possible control ramp, implementing the $P\_{BESS}(V)$ control with a mean value at 1.06 pu is depicted in Figure 13. Active power charge beyond 1.05 pu counteracts voltage rise at the node (e.g. high PV feed-in). The $P\_{BESS}(V)$ control has been implemented in the Matpower load flow calculation software and was applied to the Artificial grid presented in Chapter 3.2.7 for a Hamlet grid type with 1510m long NS-GKN 3x150/150 cable line. It was assumed that all BESS accumulated energy during voltage violations was used to cover consumption. The technical feasibility was evaluated by comparing the maximum voltage at the weakest node without and with $P\_{BESS}(V)$ control. The respective costs of the control method were estimated and presented in Table 4. Costs per usable kilowatt hour including battery inverter costs are assumed in range from 700 ÷ 4200 CHF/kWh [22].

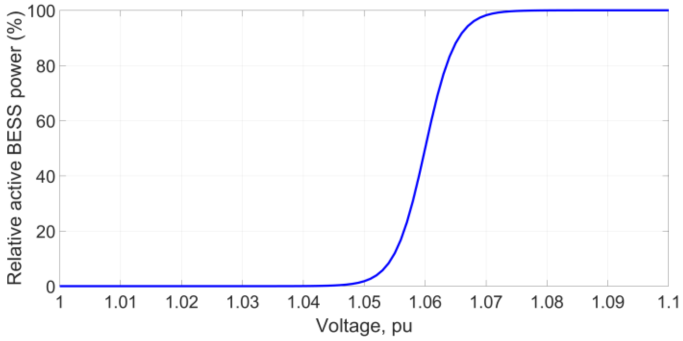

Figure 13 Example of a control figure implementing the $P\_{BESS}(V)$ control of a BESS inverter according to the line voltage. In this example 50% of the control bandwidth is reached at 1.06 pu.

Table 4 Investigated BESS costs for voltage control purposes of the Hamlet type grids[1]

Installed PV, kW	PV production, MWh	Voltage_PV PCC max	BESS Power, kW	BESS max Energy per day, kWh	BESS Energy per year, MWh	Voltage_PV_BESS PCC max	BESS Costs[2], CHF/kWp_PV	BESS Price[3], CHF/kWh
100	106.37	1.067	12	28	0.60	1.055	197 ÷ 1180	3.30 ÷ 19.79
120	127.65	1.084	27	86	4.42	1.057	501 ÷ 3006	1.36 ÷ 8.17
140	148.92	1.101	44	158	11.73	1.058	788 ÷ 4730	0.94 ÷ 5.65
160	170.20	1.117	60	240	21.60	1.059	1049 ÷ 6291	0.78 ÷ 4.66
180	191.47	1.133	77	339	33.30	1.059	1320 ÷ 7920	0.71 ÷ 4.28
200	212.74	1.148	94	444	46.35	1.060	1555 ÷ 9332	0.67 ÷ 4.03
220	234.02	1.163	111	553	60.44	1.060	1759 ÷ 10553	0.64 ÷ 3.84
240	255.29	1.178	128	663	75.35	1.060	1935 ÷ 11610	0.62 ÷ 3.70
260	276.57	1.191	145	776	90.94	1.061	2088 ÷ 12531	0.60 ÷ 3.58
280	297.84	1.205	163	889	107.07	1.061	2224 ÷ 13342	0.58 ÷ 3.49

Discharge BESS accumulated energy during voltage violations also an option to feed or charge the EV at home during the evening and night and thus reduce the overvoltages and undervoltages problems during the day.

[1] BESS is investigated only for voltage control purpose
[2] Investment costs for installation of BESS to prevent voltage violations
[3] Price for payback BESS in particular case, taking into account 10 years long battery lifetime

3.2 Grids under investigation

The definition of grid classes is given by the aggregation of several sectors of the distribution grid that provide similar services. Each class consists of the grid itself and the types of consumers and distributed producers. Table 5 shows the subdivision of the arbitrary distribution grids into categories of grid sections:

Table 5 Investigated grids

Grid class	**Identification**
Industry	N/A[4]
Small industry	N/A
Shopping centres near the city outskirts	“Einkaufszentrum Rosenberg” (Stadtwerk Winterthur)
Urban area with multi-family houses	Ilanz (Repower)
Urban areas with business centres or schools	Stadtwerk Winterthur with business centres and schools
Village Centres	Knonau (EKZ), Dettighofen (EKS)
Village peripheries	Dettighofen (EKS)
Hamlets	Weiler (Stadtwerk Winterthur)

3.2.1 Hamlets (Stadtwerk Winterthur)

The analysed grid is in Winterthur and represents the grid class *Hamlets.* The study examined the 6-bus distribution network system shown in Figure 14. The system can be arbitrarily extended and subsequently analyzed. It was examined how much two photovoltaic systems (108.7 kWp on bus 105 and 70.7 kWp on bus 106) would affect the voltage at the respective node. It is to be conceded here that such a topology with a 527 m long overhead line and a wire diameter of 5 mm is considered an exceptional situation by the local grid operator [12],[23]. At Stadtwerk Winterthur, an existing overhead line, in the case of planned work, is usually not replaced by a new overhead line. The overhead line is replaced by a corresponding cable. In the following, the replacement of the overhead line with a 150 mm^2 low-voltage cable was examined, analysed and the costs determined for comparison with the other solution variants. Due to the new construction of the track, the cable length is extended by 94 m because the new route cannot be built identically to the course of the overhead line.

[4] Small and medium industrial grids was neglected in investigation due to short lines and powerful connections. Voltage violation is not expected with high share of PV

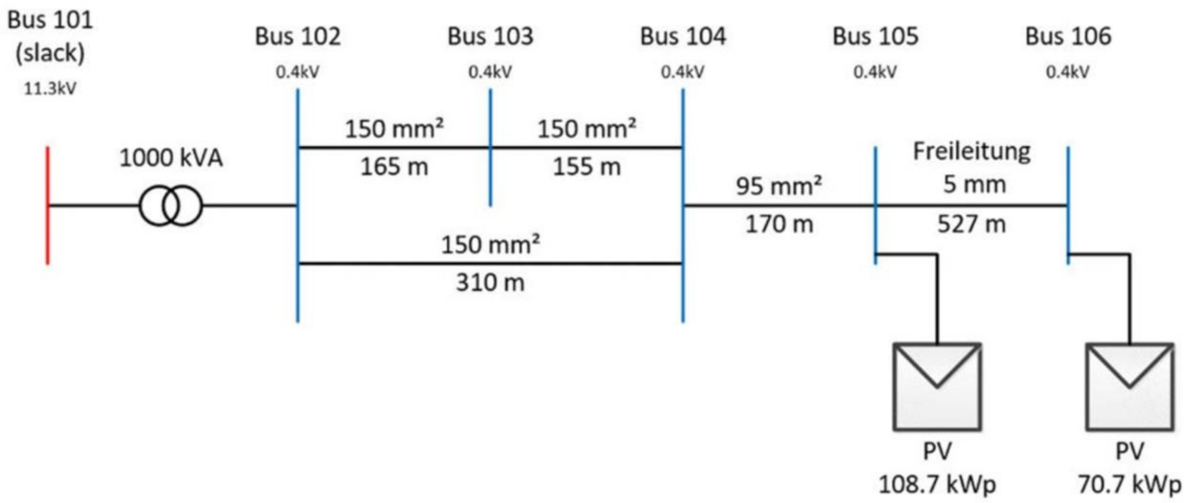

Figure 14 Single line diagram of the LVDG in Winterthur.

Table 6 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVarh	Voltage PCC max/min	Losses MWh/MVarh	Costs per Year Difference with base case, CHF	Investment Costs, CHF
Initial grid, no PV	1734.6/594.5	0.996/0.938	20.77/31.14	N/A	N/A
Base case, PV no ctrl.	1558.4/596.6	1.217/0.938	29.29/33.28	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	1561.1/646.3	1.161/0.938	32.05/34.82	2199.7	5'000
PV Q(V) ctrl. (Mean 1.03 pu)	1560.7/633.9	1.164/0.938	31.63/34.52	1667.3	5'000
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	1579.0/636.6	1.053/0.938	27.16/32.68	2876	5'000
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	1579.1/626.3	1.053/0.938	26.82/32.46	2459.7	5'000
OLTC, PV no ctrl.	1558.3/596.4	1.217/0.953	29.19/33.05	-14.2	53'218
LVR, PV no ctrl.	1558.5/596.7	1.205/0.952	29.38/33.32	10.1	33'748
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	1562.9/647.3	1.160/0.952	31.97/34.75	2348.7	38'748
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	1562.2/639.3	1.164/0.952	31.69/34.55	1978.7	38'748
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	1579.1/636.7	1.053/0.938	27.26/32.72	2886.1	38'748
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	1579.2/626.4	1.053/0.952	26.92/32.51	2469.8	38'748
LVR_v2, PV no ctrl.	1558.6/596.7	1.181/0.949	29.53/33.38	16.1	29'854

1st Grid Reinforcement[5]	1554.4/595.1	1.097/0.946	25.32/31.81	-301.5	93'150 – 248'400
2nd Grid Reinforcement[6]	1552.8/595.2	1.069/0.948	23.71/31.89	-393.4	118'650 – 316'400

The weakest node and its connection box were identified after performing a load flow calculation over one year. The maximum voltage at the weakest node was 21.7% over the nominal voltage (see Table 6). The best performance showed the PQ(V) control strategy with a mean value of 1.02 pu, where the voltage could be reduced by 13%absolute and 2nd Grid Reinforcement where the voltage could be reduced by $14.7\%_{absolute}$

[5] Reconstruct line 5 (621m) with 95 mm^2 cable R_0=0.194Ω/km X_0=0.086Ω/km

[6] Reconstruct line 5 (621m) and 4 (170m) with 150 mm^2 cable R_0=0.124Ω/km X_0=0.086Ω/km

3.2.2 Dettighofen

The analysed grid is in Dettighofen, Southern Germany (see Figure 15) and represents the grid class *Village Periphery.* The allocation of PV plants was performed according to the real grid provided by the DSO EKS.

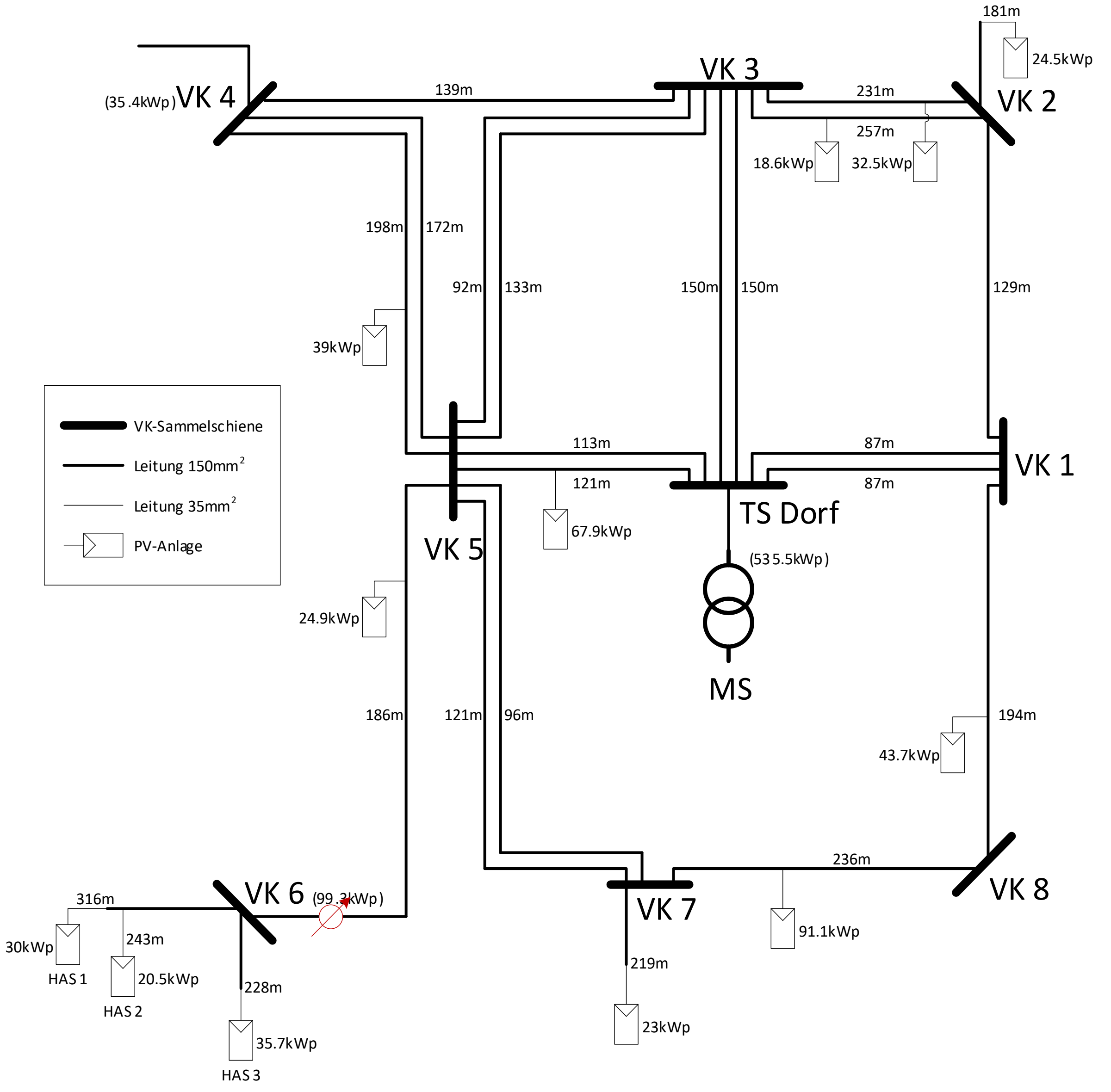

Figure 15 Single line diagram of the LVDG in Dettighofen, Southern Germany. The grid is connected to the medium voltage grid with a 400 kVA transformer and features 33 PV plants with a cumulative nominal power of 535.5 kWp.

Table 7 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVArh	Voltage PCC max/min	Losses MWh/MVArh	Costs per Year Difference with base case	Investment Costs
Initial grid, no PV	429.37/171.83	1.000/0.985	1.87/2.73	N/A	N/A
Base case, PV no ctrl.	-215.14/183.99	1.071/0.985	12.23/14.89	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	-213.58/256.60	1.050/0.985	13.45/16.05	3070.61	13'388
PV Q(V) ctrl. (Mean 1.03 pu)	-214.44/233.84	1.054/0.985	12.92/15.59	2085.85	13'388
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	-213.41/256.95	1.031/0.985	13.43/16.03	3095.16	13'388
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	-214.02/234.07	1.038/0.985	12.88/15.54	2120.48	13'388
OLTC, PV no ctrl.	-214.96/184.22	1.057/0.985	12.41/15.13	20.23	40'238
OLTC, PV with Q(U) ctrl. (Mean 1.02 pu)	-213.58/256.60	1.050/0.985	13.44/16.05	3070.61	53'626
OLTC, PV with Q(U) ctrl. (Mean 1.03 pu)	-214.44/233.84	1.054/0.985	12.92/15.59	2085.85	53'626
LVR, PV no ctrl.	-215.08/184.01	1.047/0.985	12.28/14.90	4.42	29'854
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	-214.51/235.62	1.031/0.985	12.85/15.62	2154.63	43'242
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	-214.79/217.45	1.038/0.985	12.58/15.30	1392.86	43'242
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	-214.52/235.83	1.031/0.985	12.85/15.62	2162.64	43'242
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	-214.79/217.51	1.038/0.985	12.57/15.29	1395.32	43'242
Grid Reinforcement[7]	-215.74/184.04	1.057/0.985	11.63/14.94	-33.95	89'100 – 237'600

The weakest node and its connection box were identified after performing a load flow calculation over one year. The maximum voltage at the weakest node was 7.1% over the nominal voltage (see Table 7). The best performance showed the PQ(V) control strategy with a mean value of 1.02 pu, where the voltage could be reduced by 4%$_{absolute}$ and properly located LVR, where the voltage could be reduced by 2.4%$_{absolute}$

[7] Reconstruct line near VK 6 (594m) with 150 mm^2 cable R_0=0.124Ω/km X_0=0.086Ω/km

3.2.3 Ilanz

The grid is located in Ilanz, Canton of Grisons (see Figure 16) and represents the grid class *Urban neighbourhood with apartment buildings*. The PV plants were considered according to the local DSOs estimations, which amount to 41 PV plants with a total nominal power of 788.5 kWp connected to the 630 kVA transformer in the future.

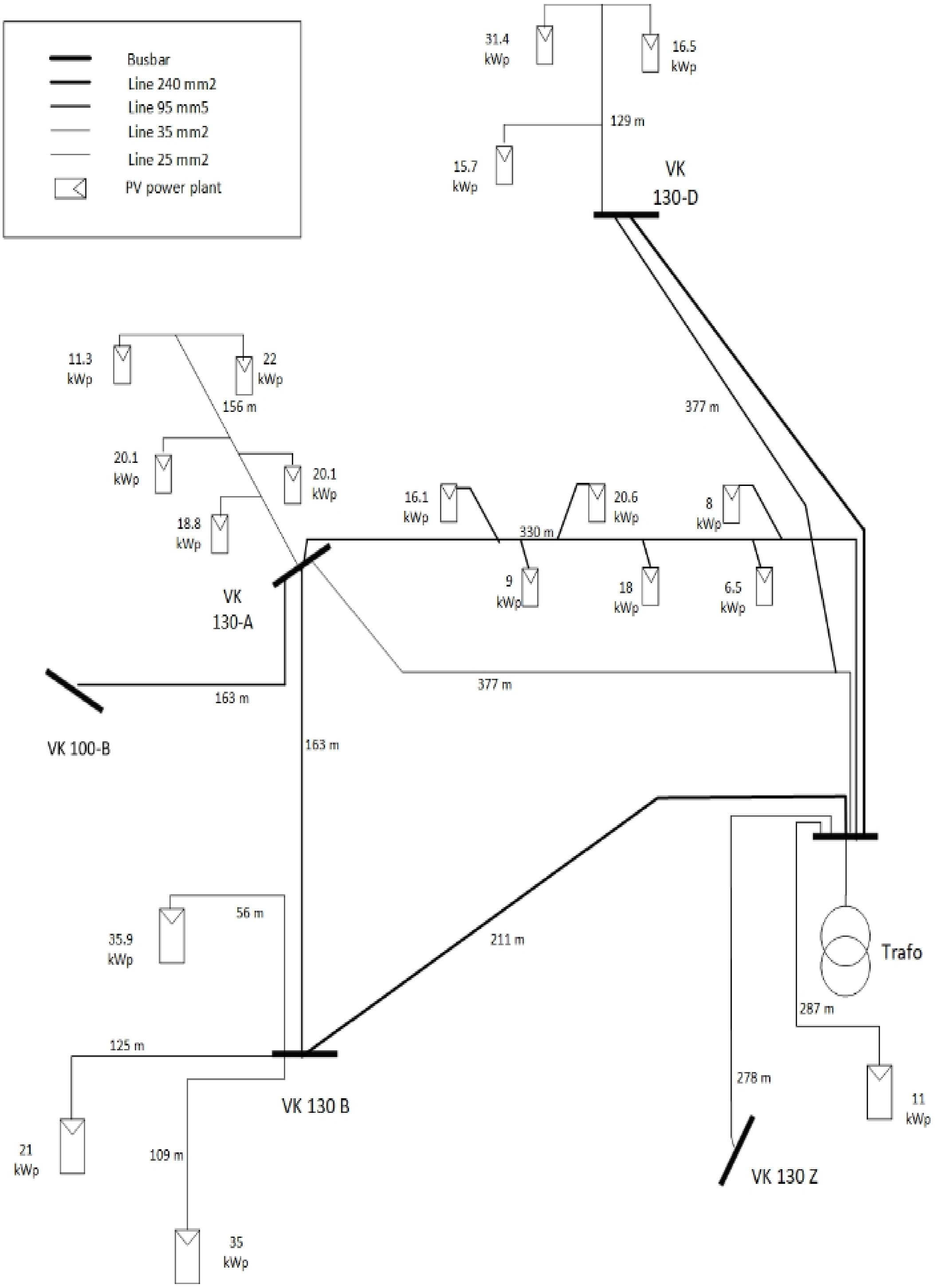

Figure 16 Single line diagram of the LVDG in Ilanz, Canton of Grisons. The scenario of 41 PV plants with a cumulative power of 788.5 kWp was considered to be connected to the 630 kVA transformer.

Table 8 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVarh	Voltage PCC max/min	Losses MWh/MVarh	Costs per Year Difference with base case	Investment Costs
Initial grid, no PV	781.35/313.31	0.993/0.971	11.86/8.93	N/A	N/A
Base case, PV no ctrl.	-41.11/324.16	1.050/0.971	20.63/19.78	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	-40.25/370.73	1.034/0.971	21.49/20.61	1960.97	19'713
PV Q(V) ctrl. (Mean 1.03 pu)	-40.66/355.15	1.039/0.971	21.09/20.26	1297.59	19'713
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	-40.25/370.82	1.034/0.971	21.49/20.61	1964.66	19'713
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	-40.67/355.15	1.039/0.971	21.08/20.25	1296.99	19'713
OLTC, PV no ctrl.	-41.11/324.16	1.050/0.971	20.63/19.78	0	45'430
LVR, PV no ctrl.	-41.11/324.16	1.049/0.973	20.63/19.78	0	29'854
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	-40.46/362.56	1.035/0.973	21.27/20.43	1613.4	49'567
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	-40.77/349.22	1.039/0.973	20.97/20.15	1047.86	49'567
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	-40.47/362.50	1.035/0.973	21.27/20.42	1610.34	49'567
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	-40.78/349.18	1.039/0.973	20.96/20.14	1045.62	49'567
Grid Reinforcement[8]	N/A	N/A	N/A	N/A	N/A

The weakest node featured a maximum voltage rise of 5% above the nominal voltage (see Table 8). By applying a PQ(V) control with a mean of 1.02 pu the maximum voltage can be reduced to 3.4%. OLTC and LVR technology implementation did not bring significant improvements in particular grid du to highly distributed PV plants across the grid.

[8] Urban area has strong grid and reinforcement is not necessary

3.2.4 Knonau

The analysed grid is located in Knonau, Canton Zurich (see Figure 17) and represents the grid class *village center*. This LVDG consists of two separately feeded grids with two transformers. The first grid contains two PV plants of 354 kWp and 85 kWp nominal power respectively. The second grid contains two PV plants of 10 kWp each. Since no estimation of future PV penetration is available for the second grid, it was assumed that a total of 400 kWp PV will be installed in the future, which corresponds to the transformer apparent power. This power was randomly allocated to nodes in the grid with another 38 PV plants of 10 kWp each.

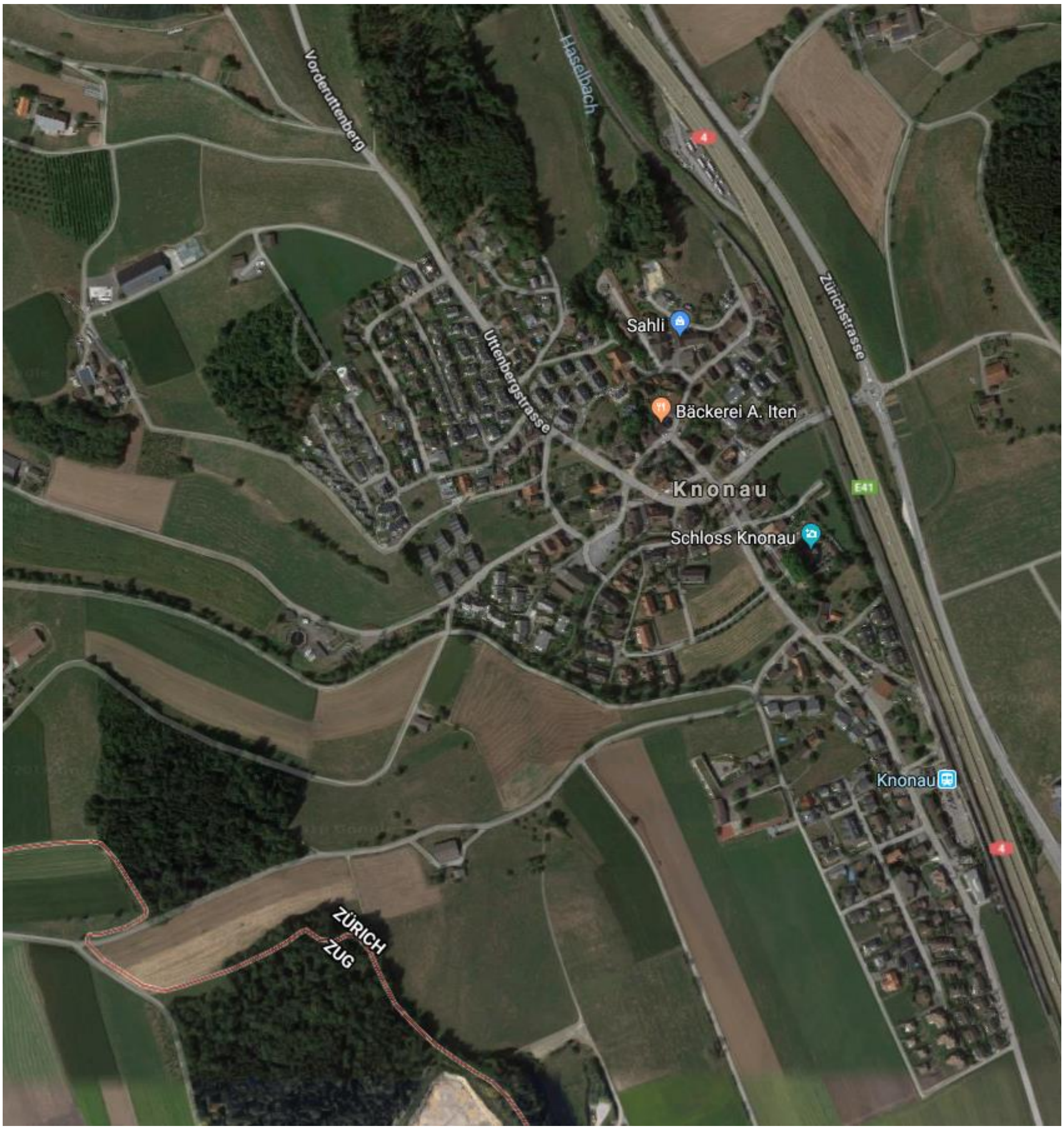

Figure 17 Geographical location of the LVDG in in Knonau, Canton Zurich.

Table 9 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVarh	Voltage PCC max/min	Losses MWh/MVarh	Costs per Year Difference with base case	Investment Costs
Initial grid, no PV	1273.57/246.89	0.999/0.957	26.21/28.45	N/A	N/A
Base case, PV no ctrl.	397.12/249.51	1.037/0.957	25.71/31.07	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	397.28/261.42	1.029/0.957	25.79/31.16	497.91	20'975
PV Q(V) ctrl. (Mean 1.03 pu)	397.15/257.65	1.031/0.957	25.74/31.11	335.54	20'975
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	397.26/261.53	1.029/0.957	25.78/31.15	501.22	20'975
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	397.15/257.63	1.032/0.957	25.74/31.11	334.72	20'975
OLTC, PV no ctrl.	397.21/249.80	1.036/0.959	25.80/31.37	17.29	80'476
LVR, PV no ctrl.	397.12/249.51	1.027/0.962	25.71/31.08	0	59'708
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	397.12/249.96	1.022/0.962	25.69/31.07	18.45	80'683
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	397.11/250.41	1.024/0.962	25.70/31.07	36.3	80'683
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	397.12/250.12	1.022/0.962	25.69/31.07	25.01	80'683
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	397.11/250.41	1.024/0.962	25.69/31.07	36.3	80'683
Grid Reinforcement[9]	N/A	N/A	N/A	N/A	N/A

The weakest node featured a maximum voltage rise of 3.7% above the nominal voltage (see Table 9). By applying a PQ(V) control with a mean of 1.02 pu the maximum voltage can be reduced to 2.9%. Two OLTC technology implementation to both transformers did not bring significant improvements in particular grid du to highly distributed small-scale PV plants across the grid. The best performance showed the two LVR technology implementation where the voltage could be reduced by $1\%_{\text{absolute}}$

[9] Urban area has strong grid and reinforcement is not necessary

3.2.5 Stadtwerk Winterthur with schools

The analysed grid is located in Winterthur, Canton Zurich (see Figure 18) and represents the grid class *Urban areas with business centres or schools*. Since no estimation of future PV penetration is available for the grid, it was assumed that a total of 795 kWp PV will be installed in the future, which corresponds to the 800-kVA transformer apparent power. This power was randomly allocated to nodes in the grid with 15 PV plants.

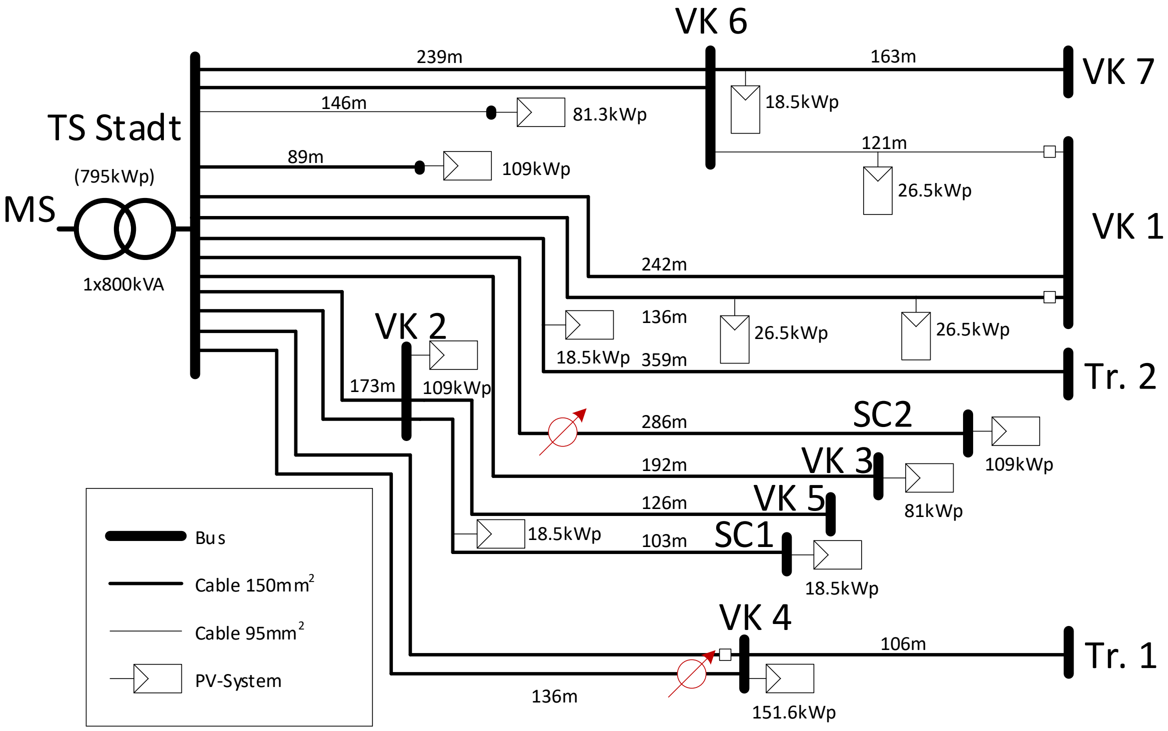

Figure 18 Single line diagram of the LVDG in Winterthur.

Table 10 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVarh	Voltage PCC max/min	Losses MWh/MVarh	Costs per Year Difference with base case	Investment Costs
Initial grid, no PV	1562.27/262.42	0.997/0.969	20.78/21.63	N/A	N/A
Base case, PV no ctrl.	591.86/262.39	1.033/0.971	22.39/21.60	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	592.05/291.15	1.022/0.971	22.57/21.86	1190.56	19’875
PV Q(V) ctrl. (Mean 1.03 pu)	591.96/280.74	1.026/0.971	22.48/21.74	758.35	19’875
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	592.05/291.15	1.022/0.971	22.57/21.86	1190.56	19’875
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	591.96/281.09	1.026/0.971	22.48/21.74	772.7	19’875

OLTC, PV no ctrl.	591.96/262.57	1.025/0.971	22.49/21.77	13.38	48’026
LVR, PV no ctrl.	591.88/262.40	1.026/0.978	22.30/21.60	1.61	63’602
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	591.93/273.62	1.019/0.979	22.45/21.68	464.63	83’477
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	591.90/269.57	1.021/0.979	22.43/21.68	296.78	83’477
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	591.93/273.62	1.019/0.979	22.45/21.68	464.63	83’477
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	591.90/269.57	1.021/0.979	22.43/21.65	296.78	83’477
Grid Reinforcement[10]	N/A	N/A	N/A	N/A	N/A

The weakest node featured a maximum voltage rise of 3.3% above the nominal voltage (see Table 10). The best performance showed by applying a PQ(V) control with a mean of 1.02 pu the maximum voltage can be reduced to 2.2%. OLTC technology implementation can reduced voltage to 2.5%. By applying the two LVR technology the voltage could be reduced by $0.7\%_{absolute}$

[10] Urban area has strong grid and reinforcement is not necessary

3.2.6 StadtWerk Shopping centre

The analysed grid is located in Winterthur, Canton Zurich (see Figure 19) and represents the grid class *Shopping centres near the city outskirts*. Since no estimation of future PV penetration is available for the grid, it was assumed that a total of 1816 kWp PV will be installed in the future, which closely corresponds to the 2x1000 kVA transformer apparent power. This power was randomly allocated to nodes in the grid with 59 PV plants.

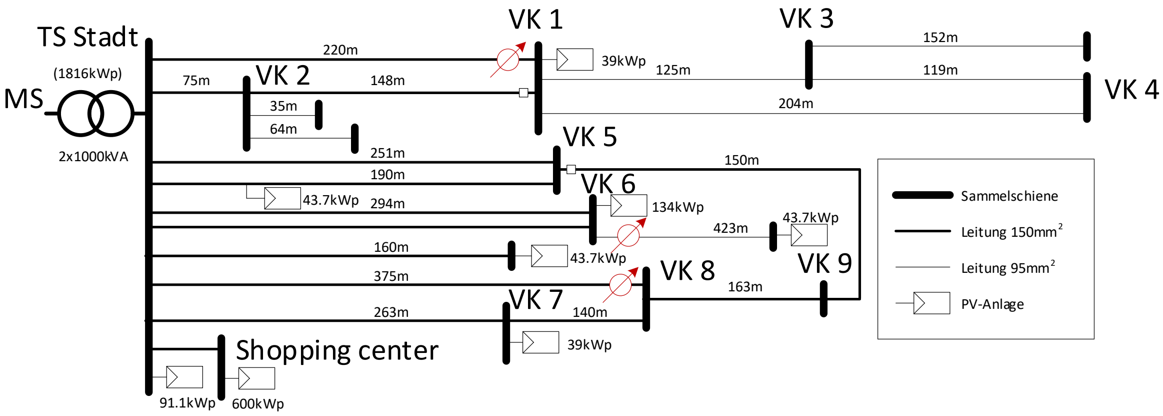

Figure 19 Single line diagram of the LVDG in Winterthur.

Table 11 Summary of grid behaviour over one year for the case without any control (Base case) and with different control strategies.

Control Strategy	Total Active and Reactive energy delivered MWh/MVarh	Voltage PCC max/min	Losses MWh/MVarh	Costs per Year Difference with base case	Investment Costs
Initial grid, no PV	6649/1212	0.996/0.940	69.17/183.25	N/A	N/A
Base case, PV no ctrl.	4431/1160	1.084/0.942	71.07/131.98	Base case	N/A
PV Q(V) ctrl. (Mean 1.02 pu)	4437/1279	1.056/0.943	75.05/135.21	5239	45'400
PV Q(V) ctrl. (Mean 1.03 pu)	4433/1252	1.059/0.943	73.38/133.95	3892	45'400
PV PQ(V) ctrl. (Mean P(1.05) Q(1.02) pu)	4438/1281	1.047/0.943	75.03/135.18	5381	45'400
PV PQ(V) ctrl. (Mean P(1.05) Q(1.03) pu)	4435/1252	1.048/0.943	73.19/133.81	4012	45'400
OLTC, PV no ctrl. [11]	N/A	N/A	N/A	N/A	N/A
LVR, PV no ctrl.	4431/1160	1.048/0.942	71.32/132.06	19.31	89'562
LVR, PV with Q(U) ctrl. (Mean 1.02 pu)	4434/1213	1.043/0.943	72.98/133.37	2353	134'962
LVR, PV with Q(U) ctrl. (Mean 1.03 pu)	4432/1190	1.043/0.942	71.88/132.55	1290	134'962

[11] OLTC control is not applicable in cases with parallel connections

LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.02) pu)	4434/1213	1.042/0.943	75.03/135.18	2353	134'962
LVR, PV with PQ(U) ctrl. (Mean P(1.05) Q(1.03) pu)	4431/1190	1.042/0.942	73.19/133.81	1230	134'962
Grid Reinforcement[12]	4425/1158	1.0598/0.942	65.01/129.71	-442	107'550 – 286'800

The weakest node featured a maximum voltage rise of 8.4% above the nominal voltage (see Table 11). The best performance showed by applying a PQ(V) control with a mean of 1.02 pu the maximum voltage can be reduced to 4.7%. By applying the three LVR technology the voltage could be reduced to 4.8%$_{absolute}$.

[12] Reconstruct lines near VK 1, VK 4, VK 6 (717m) with 150 mm^2 cable R_0=0.124Ω/km X_0=0.086Ω/km

3.2.7 Artificial grid

For a wider spectrum of investigations, an artificial grid (see Figure 20) was implemented for different voltage control strategy analysis, changing grid topology, line length variation from 10m till 1510m, installed PV from 0 till 280kWp, and load variation from 165kW till 63kW. The load was adjusted according to the line length and maximal allowable current value for the cable type NS-GKN 3x150/150 with 70% loading: longer line, smaller load.

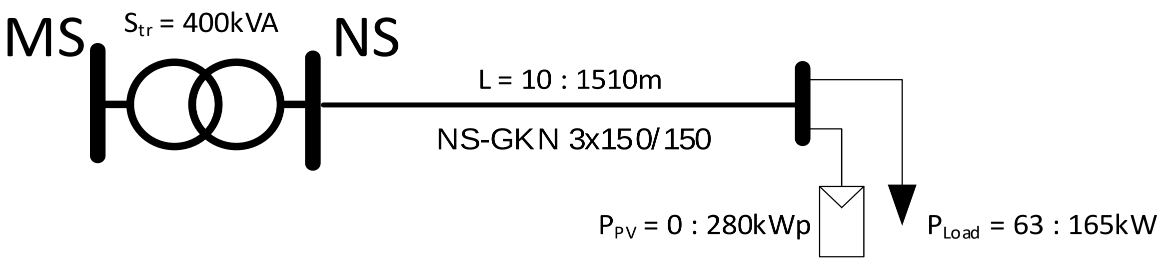

Figure 20 Single line diagram of the Artificial LVDG

Figure 21 present investigated grid behaviour without voltage control and represent maximal voltage in PCC, active and reactive energy losses with costs for losses per Year. At shorter distances (<460m) installed PV (280kWp) not violate voltage. At longer distances (1510m) voltage violation appear at 80 kW installed PV.

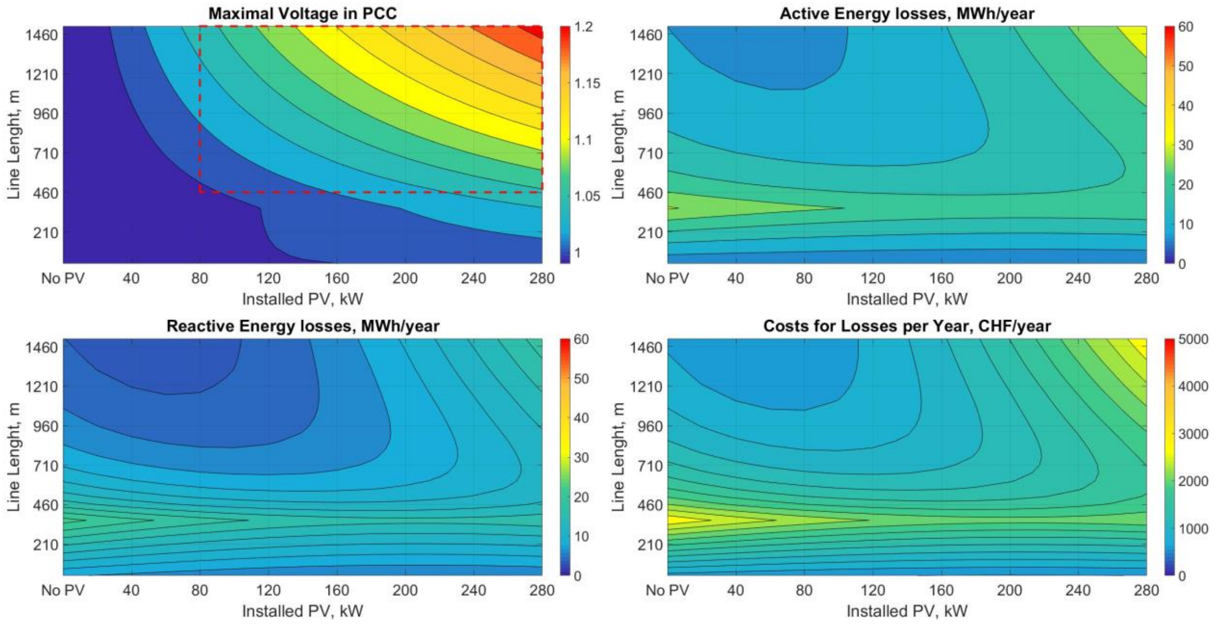

Figure 21 Artificial grid behaviour without voltage control[13]

[13] Costs for yield losses were accounted for with 60 CHF/MWh and the costs for reactive power compensation were estimated at 41 CHF/Mvarh

Figure 22 present investigated grid behaviour with PV Q(U) control and additionally represent necessary investments for oversizing PV and cover additional active and reactive losses. Current voltage control solves voltage violation problem partly, increasing grid hosting capacity from 80kWp till 220kWp and allowing increase distance from 460m till 1210m.

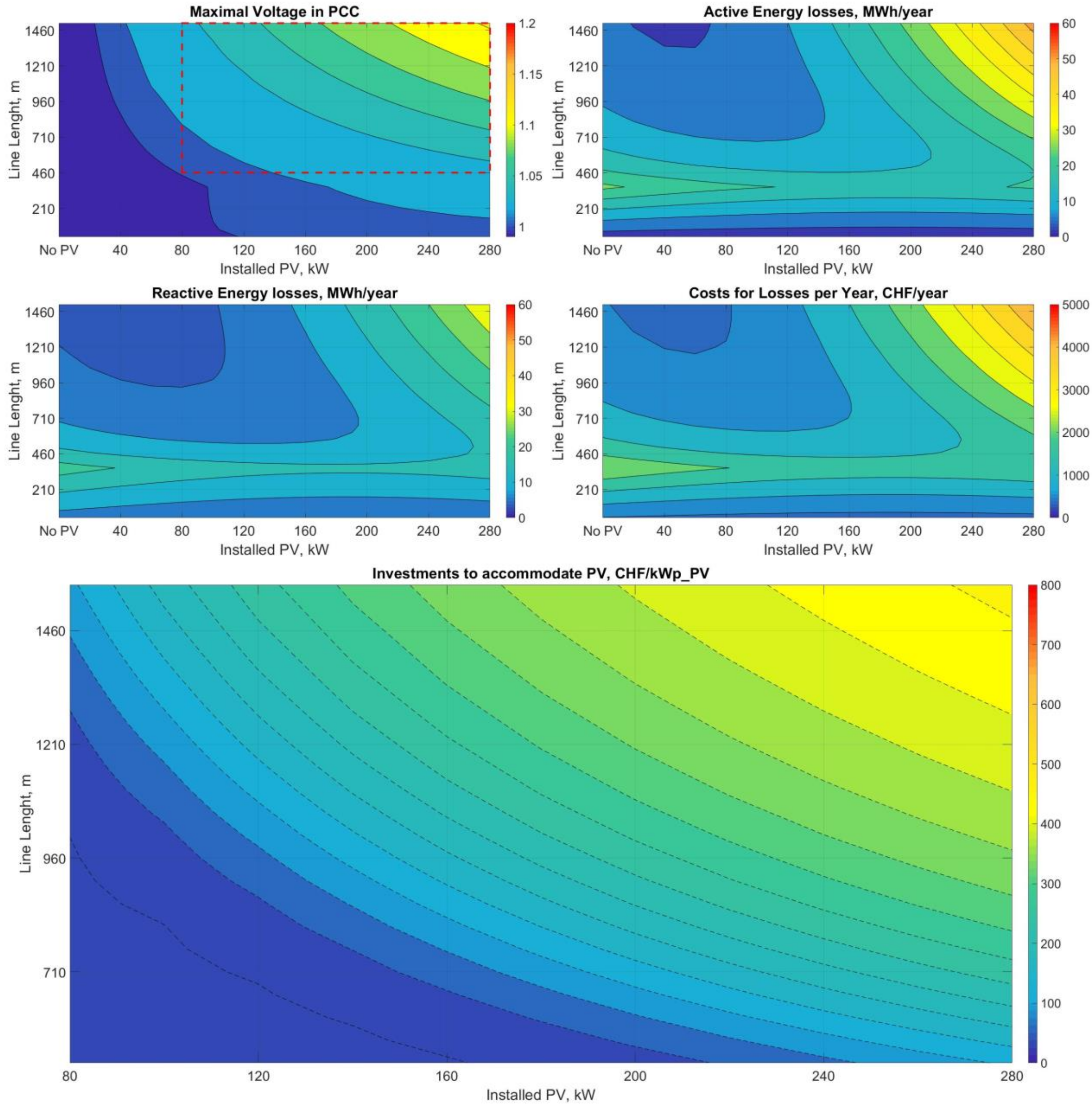

Figure 22 Artificial grid behaviour with PV Q(U) control[14]

[14] Investment costs for oversizing of PV are assumed 250 CHF/kWh. Costs for yield losses were accounted for with 60 CHF/MWh and the costs for reactive power compensation were estimated at 41 CHF/Mvarh

Figure 23 present investigated grid behaviour with PV PQ(U) control and additionally represent necessary investments for oversizing PV and cover additional active and reactive losses with reimbursed of active power curtailment. Current voltage control solves voltage violation, increasing grid hosting capacity from 80kWp till 280kWp and allowing increase distance from 460m till 1510m, however investments to accommodate high share of PV increases significantly.

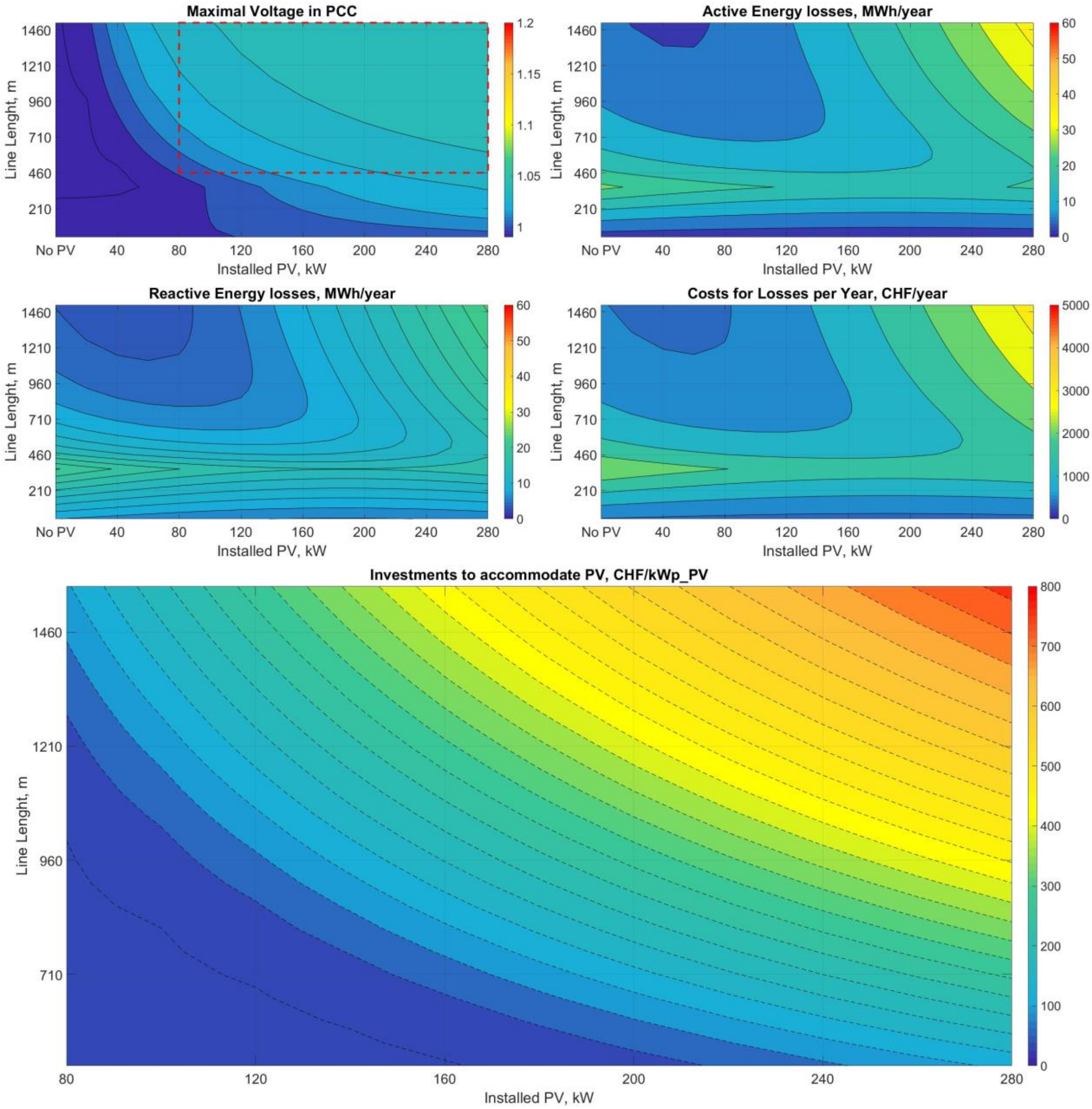

Figure 23 Artificial grid behaviour with PV PQ(U) control[15]

[15] Investment costs for oversizing of PV are assumed 250 CHF/kWh. Costs for yield losses were accounted for with 60 CHF/MWh and the costs for reactive power compensation were estimated at 41 CHF/Mvarh. Reimbursed of active power curtailment were accounted for with 50 CHF/MWh

Figure 24 present investigated grid behaviour with LVR control and additionally represent necessary investments for device installation and cover additional active and reactive losses. Current voltage control solves voltage violation partly, increasing grid hosting capacity from 80kWp till 220kWp and allowing increase distance from 460m till 1100m. This solution and costs are suitable for cases with concentrated generation. In the case of highly distributed generation, the necessary investment will increase depending on the network topology.

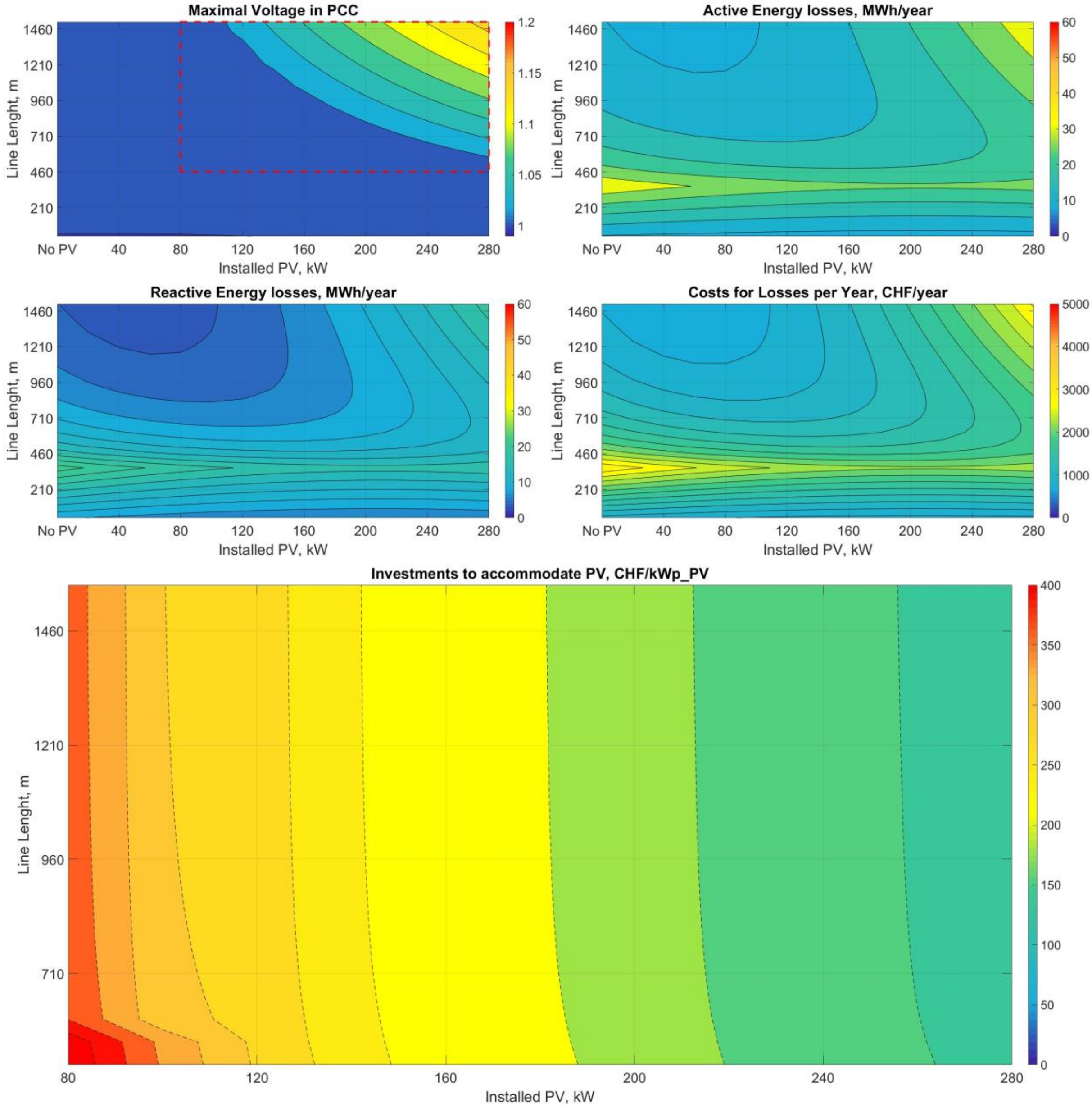

Figure 24 Artificial grid behaviour with LVR - Mintap=0.94 Maxtap=1.06[16]

[16] Investment costs of LVR are assumed according to Table 3 with additional costs from Table 1

Figure 25 present investigated grid behaviour with grid reinforcement and represent necessary investments for reconstruction and cover additional active and reactive losses (losses reduction). Current voltage control solves voltage violation partly, increasing grid hosting capacity from 80kWp till 220kWp and allowing increase distance from 460m till 1150m.

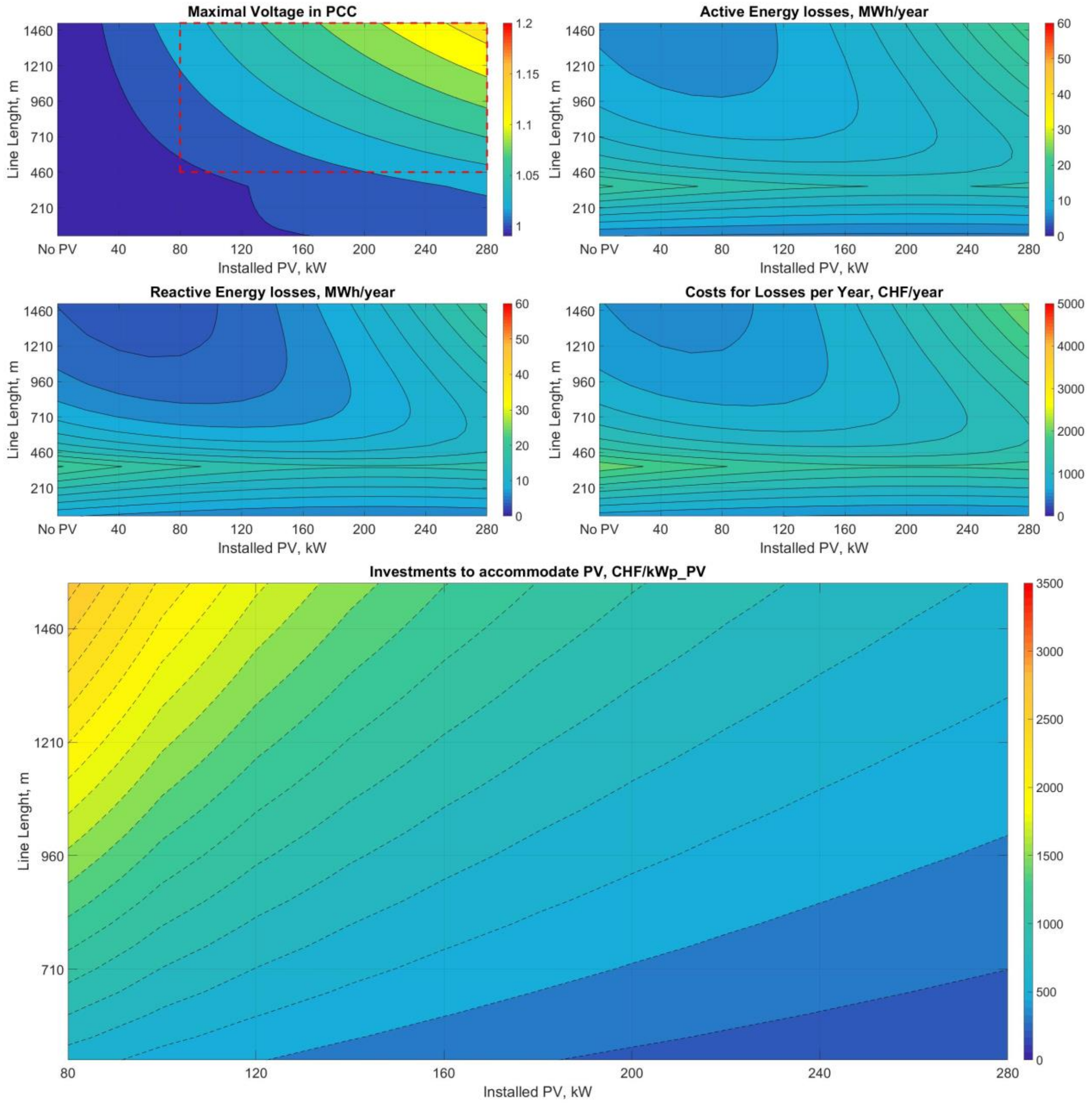

Figure 25 Artificial grid behaviour with first grid reinforcement[17]

[17] Reconstruct NS-GKN 3x150/150 cable with NS-GKN 3x240/240 cable R_0=0.0754Ω/km X_0=0.072Ω/km, the costs are assumed 150 CHF/m

Figure 26 present investigated grid behaviour with extended grid reinforcement and represent necessary investments for reconstruction and cover additional active and reactive losses (losses reduction). Current voltage control solves voltage violation, increasing grid hosting capacity from 80kWp till 280kWp and allowing increase distance from 460m till 1510m. Costs for particular reinforcement are assumed 30% higher than previous ones.

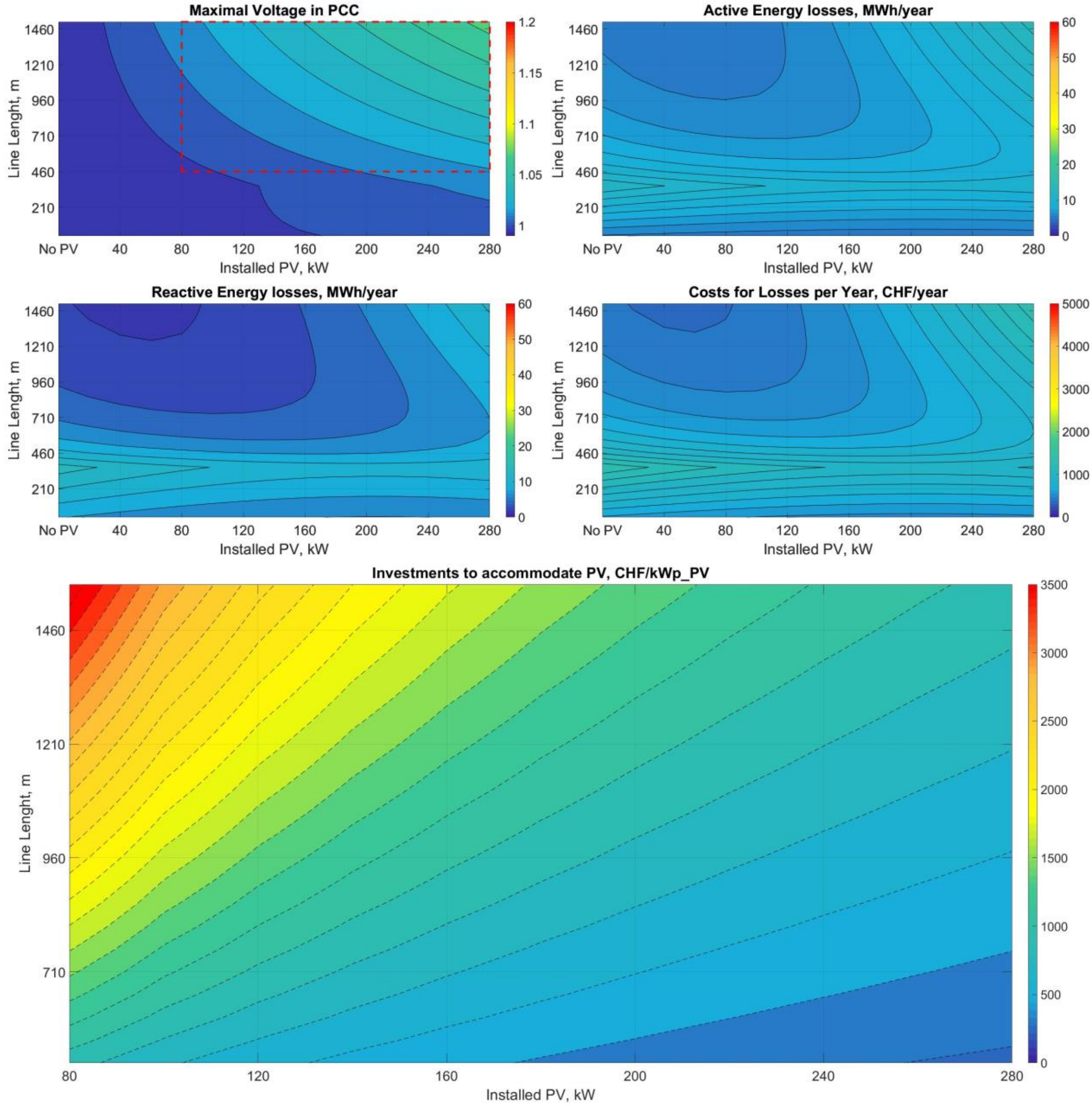

Figure 26 Artificial grid behaviour with second grid reinforcement[18]

[18] Reconstruct NS-GKN 3x150/150 cable with two parallel NS-GKN 3x240/240 cables R_0=0.0754Ω/km X_0=0.072Ω/km, the costs are assumed 200 CHF/m

Figure 27 present investigated grid behaviour with BESS and represent necessary investments for investments and cover additional active and reactive losses. Current voltage control solves voltage violation, increasing grid hosting capacity from 80kWp till 280kWp and allowing increase distance from 460m till 1510m.

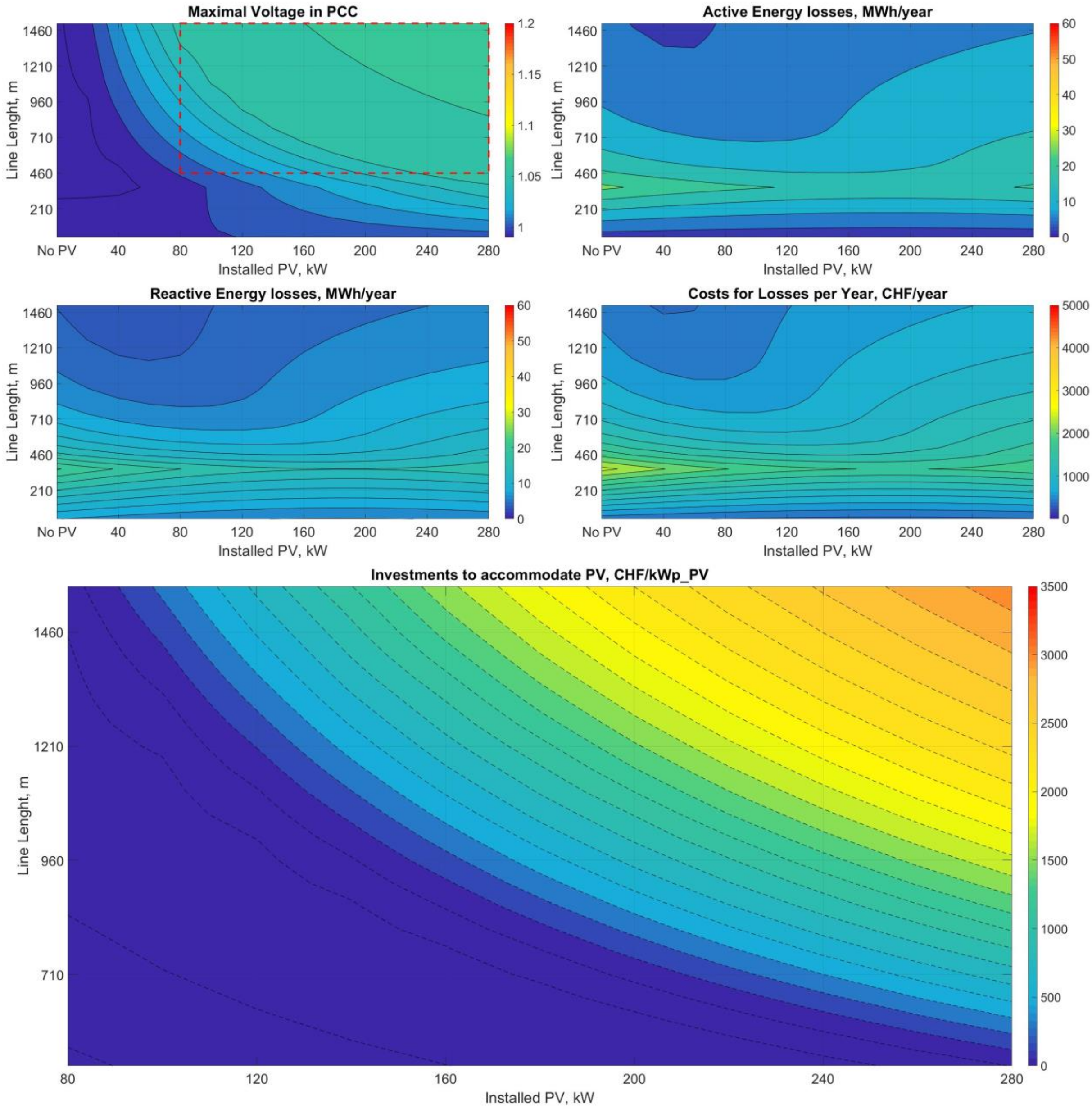

Figure 27 Artificial grid behaviour with BESS[19]

[19] Investment costs for installation of BESS are assumed 700 CHF/kWh to prevent voltage violations

3.3 Comparison of different technologies for voltage control based on their advantages and disadvantages

3.3.1 Classical Grid Reinforcement

This classical method to avoid voltage violations may result in a simple, but in most cases, expensive solution. Although, other type of issues like overcurrents, short circuit currents, losses on the line and stability of the system also lead to the requirement of grid reinforcement, these investments in grid reinforcement represent a major economic effort for the DSO. Accordingly, there is a need to develop new and smarter solutions that might resolve the grid problems at a lower cost. Calculations presented in the study of the distribution grid, which was developed by the Federal Ministry for Economic Affairs and Energy in Germany, show that a reduction of 3% of the annual energy injection into the grid of wind power plant and photovoltaic systems, may decrease the grid reinforcement costs by 44% at the high, medium and low voltage level [24]. Despite the many years of experience in grid expansion projects, the mentioned method continues having weaknesses, some of which are the unavoidable transformer's disconnection involved in the intervened area, the need to reroute power flows, the reduction of the available infrastructure in order to fulfill N-1 criterion and errors derived from civil works that might lead to disturbance of the operating grid. Nevertheless, in some cases this method provides the best economical solution.

Table 12 Line reinforcement

Advantages	Disadvantages
• Experience and Know-How • Could be performed at the end of the actual distribution line life cycle	• Elevated price (Not in every case) • In some cases, switchgear is not possible to improve further • Impact on other infrastructures, like civil infrastructure in urban areas • Long time for planning and development of the project • Limitation of the infrastructure during works decreasing accomplishment of the N-1 criterion capabilities • Public support

The previous problem may be solved by installing a circuit dedicated to connecting distributed generation. In this case the generation circuit will be provided with its own transformer, which allows the possibility to be equipped with OLTC and thereby simplifies voltage control. This solution plays an important role in circuits, where load density is low compared to the generation level.

Table 13 Dedicated circuit for distributed generation

Advantages	Disadvantages
• Solution with low control complexity • Better Voltage Control by means of OLTC, due to separation of demand and generation behavior	• Elevated price • Higher inefficiency, due to parallel grids not able to carry demand if needed

This solution is technically easy to install and not so expensive regarding the improvements provided. The quantity of reactive power to be required by the grid, might change seasonally, demonstrating the requirement of one shunt capacitor that could be manually connected to the grid. However, this capacitance might be also achieved installing multiple shunt capacitors between the same connection points. This configuration exhibits the advantage to allow a more sensitive voltage control but on the other hand, the costs of the solution increase. This simple method may be implemented into regions with a predictable seasonal change of the charge, which may result in a decrease of voltage violations of the grid.

Table 14 Shunt capacitors and reactances

Advantages	Disadvantages
• Experience and Know-How • Reduced losses on the grid	• Discrete steps • Until now manually connected to the grid • Low or non-supervision through SCADA

3.3.2 Tap Changers

Tap changers are a traditional component of the actual HV/MV transformers, which enabling voltage control on the distribution grids, but at the same time, its effect involves has an impact on large areas of the distribution grid. The lack of selectivity on the voltage control might regulate decrease the frequency of voltage violations over a part of the grid, but, increasing them in other parts of the affected region. In the distribution grids of the future, voltage control must be developed locally, using the principle of selectivity. This stimulates the investment in new MV/LV transformers with voltage control capabilities based on tap changers. In contrast to the classical grid reinforcement, innovative measures are available that may be suitable for reducing additional costs. The use of Tap changers in MV/LV transformers should be mentioned as one of the popular methods of the DSO to be implemented at the moment.

In NLTC type of Tap Changers it is not allowed to make voltage adjustments while the transformer is under load. For that reason, it represents a limitation to the reaction time of this technology, and also additionally, it has to be taken into account, that the disconnection of a distribution transformer curtails the energy supply to all of the customers tied to it. For that reason, this technology is only used in LV transformers in which it is possible to perform the required disconnection.

Table 15 No-load Tap Changer (NLTC)

Advantages	Disadvantages
• Technology already used in some LV applications • Control of steady state voltage	• Transformer must be turned off if tap position changes • No independent string voltage regulation • Slow reaction time • Discrete steps

On-Load Tap Changers are well known on the applications of HV/MV transformers, where it is normally installed on the high voltage winding due to its lower current level. The quantity of current that a Tap Changer can control is one of its main characteristics when selecting the right device for a defined application. This is based upon the fact that these devices are built to withstand a defined amount of current, while making the change of position. The arc imposed to the contacts generates wearing implying a maintenance operation to be performed during the life cycle of the transformer, what forces the distribution transformer to be taken out of operation.

Table 16 On-Load Tap Changer (OLTC)

Advantages	Disadvantages
• Well-known technology on HV/MV Transformers • Small device • Automatic adjustment possible • Control of steady state voltage • Losses reduction	• No independent string voltage regulation • Slow reaction time (several seconds) [25] • Discrete steps • Contact's wearing (Due to arcing) (1) • Low short circuit tolerance (2) • Change of the transformer's impedance • Not feasible for radial feeders with high number of branches and long distribution lines • Slow reaction to temporary voltage changes

[1]*Mechanical contacts*

[2]*Thyristor based*

Behaviour of LVR based on the configuration provided by OLTCs installed in an autotransformer at any node of the grid. Comparing this device with a MV/LV transformer equipped with an OLTC, it is important to notice that the use of LVR helps to improve voltage profiles locally and reduces losses on the distribution lines, while the distribution transformer with OLTC acts in a wider manner. However, the optimal location of the LVR depends on topology assumptions and the load/generation behaviour forecasts.

Table 17 Line Voltage Regulators (LVR)

Advantages	Disadvantages
• Small device • Automatic adjustment possible • Control of steady state voltage • Losses reduction • Local voltage regulation • Can be used as temporary solution to solve grid issues	• Slow reaction time (Seconds) • Discrete steps • Contact's wearing (Due to arcing) (1) • Low short circuit tolerance (2) • Change of the transformer's impedance • Slow reaction to temporary voltage changes • Topology dependent • Studies of the grid needed in order to define optimal location

[1]*Mechanical contacts*

[2]*Thyristor based*

3.3.3 Active Power Regulation

LV grids with high level of decentralized generation are characterized for increased voltage values, which are usually caused by the active power injection of photovoltaic power plants. This behaviour implies a direct relationship between the voltage level on the grid and the quantity of active power injected into the system. This means that voltage control mechanisms may be derived from the active power control. With an Active Power Curtailment scheme, the DSO restricts the active power injection in problematic circuits of its system, where over voltage violations may appear. In order to do so, different grades of curtailment may be implemented, whereby the complexity level of the application is indirectly proportional to its control requirements to implement it. Additionally, the implementation of this method by the DSO causes disadvantages to the owner of the affected power plant, e.g. the diminishing of its power yield, which is directly proportional to the turnover produced by the power plant. On the other hand, the opportunity to offer active power curtailment as negative power reserve

emerges, which might result in a profitable opportunity for the customer in a liberalized power market. In that case, the size of the power plant will determine if the market actor can offer this service by himself or through an aggregator.
The level of complexity of power plant shut-down case is relatively low for the DSO in comparison to the other Active Power Curtailment schemes explained on this report, due to the fact that there is no need of dedicated power or voltage control on it. The inverter of a power plant, which is intended to operate under this scheme, is relatively simple and is going to be sized according to the capacity of the power plant.

Table 18 Power plant shut-down

Advantages	Disadvantages
• Experience and Know-How • Low complexity Voltage Control • No need for the converter to be oversized • Possibility to offer this as ancillary service for the DSO • Control of steady state voltage	• Reduction of power yield • Discrete regulation • Slow reaction to temporary voltage changes

Although a deliberate reduction on the power production of a power plant is not optimal for the power supply business, when taking into account the increase in the installation of photovoltaic power plants on the low voltage grid with the same power peak production at midday, it represents a problem for the DSO, who will experience elevated voltage levels on its grid. This implies investments of the DSO in the grid in order to keep this phenomenon under control. A study of the ZHAW compares the total loss of energy production in a year according to different levels of power limitation on the inverter. The respective results show that a limitation of 70% on the generated power results in a total loss 4.4% of the annual production, while a limitation of 60% leads to 10.4% losses and 80% to 1.0% [26].

Table 19 Regulation of active power generation

Advantages	Disadvantages
• Experience and Know-How • No need for the converter to be oversized • Power yield reduction to just 4% in a year by a limitation of 70% • Converter is already an essential device in photovoltaic power plants • Control of steady state voltage • Fast control capabilities (ms)	• Higher complexity of voltage control compared to a shut-down (for DSO) • Higher capital costs • Loss of yield is topology dependent, therefore, it must be studied in every single case

3.3.4 Reactive Power Regulation

This approach to voltage control has been used for several years on HV grids. Thanks to a high X/R ratio this technology displays effective results on HV grids, but in contrast, this ratio is relatively low on LV grids, which implies a lower influence on the voltage behaviour, when applying this approach. For this reason, it is important to maximize the use of the reactive power used on the grid. Although, this technology helps to avoid voltage violations, it is also important to mention that a higher reactive power flow on the circuits will lead to higher losses on the lines as well as an increased load on transformers and lines.

Table 20 Automatic control of capacitor banks

Advantages	Disadvantages
• Experience and Know-How • Stand-alone capabilities • Adapted to actual conditions of the system • Control of steady state voltage	• Less effective solution compared to its results in transmission systems • Might increase losses due to reactive power injection • Discrete steps • Voltage and current measurement requirement • In stand-alone case might interfere with the system restoration measures of the DSO

Nonetheless, this solution plays an important role on the distribution grids of today, due to the fact that reactive power control could be performed by power electronics devices. Additionally, taking into account that every PV power plant counts already with inverters based on power electronics, which are able to consume/produce reactive power, this approach encourages a better use of the assets, providing an added value to the decentralized generation. Furthermore, the feeding of reactive power as a function of the voltage has been proven for some time in the high and medium voltage. Therefore, depending on the local conditions, more generating plants can be connected to an existing distribution network, with this requirement and the according dynamic network support [27].

Table 21 Reactive Power Control on PV Inverters

Advantages	Disadvantages
• Experience and Know-How • Stand-alone capabilities • Adapted to actual conditions of the system • Decrease probability of voltage violation • Converter is already an essential device in photovoltaic power plants (No Q(V) control on standard solution) • Control of steady state voltage • Fast control capabilities (ms) • Continuous voltage regulation • In cases of high demand (EVs) can prevent undervoltages violations	• Might increase losses due to reactive power injection • In stand-alone case might interfere with the system restoration measures of the DSO • Might require inverter oversizing • Complicates grid management for the DSO • Requirement of addition of Q(V) control on standard solution

3.3.5 Power Electronic Based Solutions, including storage

Distribution grid operator are searching for innovative solutions to solve the growing control problems attached to the integration of decentralized generation. Between One of these technologies are FACTS, which could to be transferred from Power Transmission Systems to Power distribution systems. FACTS were originally conceived to be implemented on transmission systems, although, nowadays some studies suggest the use of these technologies and its benefits in order to solve the constantly growing problems in the distribution grids.

When regarding the most common topologies of these devices, three can be identified as most important. The first topology to be mentioned is the shunt connection to the grid by means of a coupling transformer, which is intended to serve to voltage control. The second one is the parallel connection to the grid of these devices, which is used to control current flux, and finally, the third topology represents a combination of the two previous topologies, which provides the advantages of the both previously described solutions, but as drawback to these advantages, this technology is characterized by a high price and just a few practical experiences. Overall, power electronic based solutions come with an inverter based on power electronics to control the energy flux to be injected or absorbed from the grid. And an ESS like an inductor, capacitor, battery or a combination of the previous devices that provides or stores the energy required to be injected into the grid. With this in mind, power electronic based solutions act locally, where they are installed under different principles

Table 22 Power Electronic Based Solutions

Advantages	Disadvantages
• Multifunctional device that balances loads, Sags, voltage oscillations and reduces losses • Continuous voltage regulation	• Due to the high R/X ratio of LV grids the voltage regulation using reactive power less is effective than in HV grids • High costs • Deep studies of the grid must be performed, in order to define feasibility and optimal installation point • Requirement of high-speed protection (fuses), blown fuses must be replaced manually • Energy limited to the capacity of the ESS • Injection of harmonics into the grid, therefore requirement of filters to correct this problem

3.3.6 Demand Side Management

The influence of the load behaviour connected to the distribution grid is also a point to consider, when searching for solutions regarding voltage control. Excess of active power injection into the grid locally increases the voltage levels, meanwhile active power consumed on the system locally reduces the voltage levels. Accordingly, this approach might be implemented based on the management of energy assets like batteries and the change in load behaviour, e.g., in an industry where a process with a high energy consumption is rescheduled. Thanks to changes in regulation and a liberalized market, prices might incentivize users to shift load peaks so that they overlap with the energy generation peaks. Furthermore, this approach is reinforced by high investments in smart devices which may receive real time information of the energy market prices and, according to its programming, act automatically to activate loads, or conversely, disconnect unnecessary loads. Additionally, creating a cluster of high energy consuming devices like heat pumps and electric vehicles and at the same time allowing bi-directional communication with these devices simplifies load shedding schemes. Accordingly, electromobility is covered as DSM in the next subchapter in further detail.

Table 23 Demand side management

Advantages	Disadvantages
• Better use of energy • Consumers being part of the solution • Local voltage control • Possibility to sell DSM as ancillary service	• Requirement of communications • Access to market prices • Installation of Smart Meters • There is no guarantee for the required load adjustment to be performed

3.3.7 Wide Voltage Regulation (Centralized control)

The wide voltage regulation method acts as a voltage control method for energy assets (Reactive power voltage controllers, active power voltage control, Batteries among others) on a distribution grid. With the implementation of this additional measurement points, the DSO obtain a detailed overview of the voltage profiles on the system instead of just one point. This becomes essential for strings with a high integration of DG, where voltage profiles might increase along the string inducing voltage violations. According to the state variable measures received from the sensors, the DSO might intervene with the topology of the system to improve voltage profiles in a specific region of its grid.

In addition, one might implement more intelligent protection and control schemes. This helps the DSO to improve selectivity of protections and becomes relevant for a failure localization system, which further improves enhances its time response and minimizes the out of operation time of the system.

Table 24 Wide Voltage Regulation

Advantages	Disadvantages
• Better knowledge of the state variables of the grid • Protection selectivity increases • Better failure localization • Improvement of time response in case of failures on the grid	• Requirement of costly communications on DSO level • Investment in voltage sensors • Complex control schemes • Concerns regarding security, safety and reliability (Hackers)

The disadvantage of this method relies upon the necessity to implement communications to automatize it. Communication technologies implies higher complexity in control schemes, and include uncertainties regarding security, safety and reliability. Until now the use of communications for this kind of applications on LV grids are not common and for that reason, these technologies must be adapted to the requirements of the LV grid and tested in pilot projects in order to demonstrate its capabilities and benefits to the DSOs.

3.3.8 Electromobility

A study performed in the Austrian distribution network “Smart Grids Model Region Salzburg”, describes the challenges of the integration of electromobility. Of the mentioned project, it is important to highlight that the integration is strongly dependent on the individual patterns of mobility for each user, specific vehicle characteristics and the communications infrastructure that is used [28]. For the application of this technology, there are some philosophies of energy use, in which batteries installed in EV might be used in DSM systems. This concept is based on the behaviour of vehicle owners that shows, that for an important number of hours during the day the vehicle is not used and therefore, might be operated by the DSO to locally adapt the load to the actual generation of a part of the grid, which may be understood as an active power voltage control. The massive use of EVs could therefore be seen as an enormous distributed ESS. This distributed ESS combined with the PV integration growth allows an improved self-consumption ratio of PV systems, which consequently means a reduction of the energy reserves usage. For example, during the day the battery installed on the EV might be charged and subsequently be used in order to provide a part or the complete amount of energy required for the user at home. On the other hand, the infrastructure of our buildings is nowadays not able to adopt the integration of a considerable number of EVs [29]. This suggests an important investment in grid reinforcement, communication infrastructure and civil works on buildings in order to adopt this technology.

The study by Navigant on the topic of electromobility [30] study shows how the investment requirement per capita in 2015 - 2030 is spread over the different network area classes. Due to different network charge calculations and different structural characteristics of individual network areas, no direct statement can be derived from this on the amount of future network charges. The balancing effect that charging control has on the distribution of grid construction investments is even more pronounced, given the per capita figure. With 6 million electric cars in the uncontrolled case, people in rural areas pay 61 euros four times as much as the people in the city. With 15 million electric cars and net charging control, people in rural areas would only pay around 40 percent more for grid expansion than people in the city.

Table 25 Annual per capita distribution network investment 2015-2030 in urban, semi-urban and rural areas [30]

Annual per capita investment in € (2015-2030)	6 million electric cars		15 million electric cars	
	uncontrolled	controlled	uncontrolled	controlled
urban	14	11	40	28
semi-urban	23	13	52	24
rural areas	61	33	99	39

The future investment identified in this study are for the grid levels, low and medium voltage, on average well below the historic investments in electricity distribution grids in Germany including high voltage levels. In addition to the positive effect of charging control in terms of the amount and distribution of investment requirements, there is another potentially relieving effect: As Fraunhofer ISI has determined for a suburban area with low investment requirements, the market upturn in electromobility can possibly lead to a reduction of network charges per kWh [31]. The fixed costs of the distribution network are distributed over a larger amount of electricity consumed, thus reducing the specific network charges per power unit consumed. However, the effectiveness of this mechanism depends on whether electromobility in a given area leads, above all, to better utilization of the existing network, or high additional investment is necessary.

Charging PV electricity for the rooftop at home into a second stationary home battery is also an option to feed or charge the EV at home during the evening and night and thus reduce the overvoltages and undervoltages problems during the day.

Table 26 Electromobility

Advantages	Disadvantages
• Local DSM adjustment • Improvement of own consumption ratio of PV systems • Reduction of energy reserves • Reduction of CO_2 emissions	• Strongly dependent on user's mobility patterns • Communications infrastructure • Grid Reinforcement • Investment in civil works on buildings

4 Results and discussion

4.1 Classification of technical methods for performing voltage control in the low voltage distribution grids

The combination of different technologies increases the efficiency of the voltage control system. This work presents a palette of possible solutions to voltage boundary violation problems, although, none of these solutions can be identified suitable to every possible topology of the distribution grid. The optimal solution regarding voltage control in LV grids shall be a combination of technologies that allows different grades of selectivity and that is capable to adapt to the topology necessities of the grid.

The topology of the system influences the voltage profile on LV grids. Nowadays, it is no longer possible to assume unidirectional energy fluxes directed from the MV grid to the loads and decreasing voltages along the strings. The integration of photovoltaic DG with a high integration level changes the topology of the grids, causing voltage profiles to decrease or increase depending on the quantity of active power injection into the string.

Due to the low ratio X/R of LV grids, reactive power regulation as voltage control is less effective in LV as in HV grids. This indicates a more moderate effect on the distribution grid with solutions based on reactive power regulation. On the other hand, this ratio is the reason why technologies based on active power regulation are more suitable to provide solutions to the LV grid problematic.

The concept of selectivity can be applied to the voltage control context as the capacity of a device to improve the voltage profile locally with minimal influence on other strings of the distribution grid. e.g. an OLTC located at the MV/LV transformer affects the voltage profile of all the strings attached to it. Meanwhile, an LVR can act locally at specific nodes that exhibit voltage violations with less influence over other strings.

Although, all the solutions summarized in this report have the capability of mitigating voltage violations in order to avoid the grid reinforcement as an objective, there are still cases where it is inevitable.

The action of voltage control technologies in the distribution grid might negatively influence other essential problems of the grid like congestion. It happens in cases in which active power is injected into the grid in order to improve the voltage profile on that node. As a result, the voltage profile might be improved, but a consequence of this action congestion issues might appear on this part of the grid.

The proportional relationship between the active power infeed and the likelihood of over-voltages to appear on the grid, is directly related to the active power density installed in a region. This concept defines the type of grid according to the quantity of load per area resulting in a division of the distribution grids into two rural areas and urban areas. An urban area is characterized for small line distances, high population density and high concentration of DG. Urban areas have therefore a high concentration degree due to the fact that they represent 10% of the surface of Switzerland with 50% of the total load of the country. A rural area is characterized for long line distances, a low population density and therefore low concentration of DG. Rural areas have therefore a low concentration degree due to the fact that they represent 90% of the surface of Switzerland with 50% of the load of the country [32]. The behaviour of the voltage violations on the types of distribution grids mentioned above is totally different, due to this behaviour being influenced by the growth in the DG. Until the year 2010 the share of DG in Switzerland was marked for an important contribution provided by the rural surfaces 90% and just 10% on urban areas. According to the definition above, it is inferred that overvoltage violations are more likely to appear in rural areas than in urban areas, due to the ratio between low consumption and high generation.

Because of its simple topology, voltage control in rural distribution grids is easier to implement. This kind of grids are more likely to exhibit overvoltage boundary violations in any case where they were implemented through cables. On the contrary, voltage control in urban distribution grids tends to be more complicated, due to the fact that a mixture of overvoltages and undervoltages characterizes these grids at the same time. For this type of grids, a combination of voltage control technologies acting over a big area of the grid and other technologies acting selectively over dedicated nodes are suggested.

The installation of new assets on the grid are required in order to integrate new decentralized generation and to improve the efficiency of the voltage behaviour of low voltage systems. However, some of these assets might be operated under an intelligent regime in order to provide new solutions to the distribution power system. Flexibility is the characteristic of the market players to adapt its behaviour in order to avoid congestions or events that could endanger the operability of the power system. Contrary to other curative procedures already performed for the DSO like redispatch, this process is performed in advance in order for the DSO to detect potential hazards on the basis of prognosticated power flows of the system. Taking into account that the offered flexibility normally involves the restriction in the comfort level of the player, it must be economically compensated for the player that take advantage of the performance of this flexibility. A flexibility framework leads to a more effective operation of the already installed assets of the distribution system. Additionally, the flexible behaviour of the market players reduces the need of a higher distribution capacity of the system, thanks to its voluntary cooperation in the solution of a potential hazard for the system. In the scope of this work those hazards are specifically related to voltage violations. Consequently, the combination of some of the technologies already described on the previous chapters like DSM, smart meters, power curtailment and ESS may be unified under this framework.

Modern inverters have the abilities to control the active and reactive power with respect to the actual grid voltage. This fact introduces new opportunities not only for the DSO, but also for the regulatory authority. The DSO should have the possibility to operate the grid in a wider voltage range up to the 1.1pu. Therefore, if the voltage reaches 1.1pu, the feed-in power of the inverter has to be decreased linearly to zero as it is already implemented by the Austrian authority in TOR D4 [33].

The DSO VKW (Voralberger Energienetze GmbH) mentioned during a meeting that PV would not cause too many voltage problems in distribution grid in the future. Whereas, the EV fast charging stations will have the bigger impact on voltage violation in their opinion. This economical issue can be solved by limiting the charging power.

4.2 Economic evaluation of different smart grid technologies for typical grid classes

In the matrix elements, the typical characteristics are mentioned, e.g. investments, which are required to accommodate a given percentage of PV power generation relative to local consumption in the distribution network.

Table 27 Economic evaluation of different smart grid technologies for typical network classes[20].

	Alternative Solutions							
Grid type	Grid Reinforcement	PQ(V) ctrl	Q(V) ctrl	LVR	OLTC	BSS	DSM[21]	Other
1: Industry[22]:	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2: Small industry:	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3: Shopping centres near the city outskirts	55÷155	65÷80	60÷80	45÷55	N/A	>500	N/A	LVR/PQ(V) 85÷100
4: Urban area with multi-family houses	Strong grid	50÷70	50÷70	40÷50	50÷60	Strong grid	N/A	LVR/PQ(V) 80÷100
5: Urban areas with business centres or schools	Strong grid	40÷60	40÷60	75÷85	55÷65	Strong grid	N/A	LVR/PQ(V) 110÷120
6: Village Centres	Strong grid	30÷35	30÷35	70÷80	90÷100	Strong grid	N/A	LVR/PQ(V) 90÷100
7: Village peripheries	160÷450	90÷130	90÷125	50÷60	70÷80	>350	N/A	LVR/PQ(V) 120÷150
8: Hamlets	490÷1700	390÷430	Infeasible solution	Infeasible solution	Infeasible solution	>2'200	N/A	LVR/PQ(V) 570÷610

[20] Presented results are based on investigated grids and achieved technical solutions for 25-year estimation period, CHF/kWp_PV
[21] There is no guarantee for the required load adjustment to be performed. Not sustainable solution
[22] Small and medium industrial grids was neglected in investigation due to short lines and powerful connections. Voltage violation in current grids is not expected with high share of PV

5 Conclusions

The obtained results and work from the previous years that were based on ZHAW_Matpower, were conflated with the results of this paper, which were achieved with purpose-built OpenDSS environments. This allows fair technical and economical comparison between the results gained from the load flow calculations in Matpower (P(U), Q(U) and PQ(U)) and the additional functionalities provided from the OpenDSS (LVR, OLTC, grid reinforcements). Additionally, the approach of using the load flow calculations from Matpower within the OpenDSS environment allows the technical assessment of different combinations of the provided voltage stability measures e.g. PQ(U) together with OLTC/LVR.

Based on the proposed method, which already covers a wide range of technical solutions, a clear comparative technical and economic analysis was carried out between different solutions and the combinations of them. These results were used to classify the methods for various low voltage distribution grids categories and to generate the ranking matrix.

6 Outlook and next steps

The relative voltage rise 3–5 % caused by the totality of all generating stations in a considered network defined in DACHCZ [2] without load and control options should be discussed or revised in the future. New voltage control strategies allow significantly increase grid hosting capacity of RES not violating voltage limits

EV charging stations will have the bigger impact on voltage violation. Charging PV electricity for the rooftop at home into a second stationary home battery to feed or charge the EV at home during the evening and night and thus reduce the overvoltages and undervoltages problems during the day

CEVSol project investigations were done with local control assumptions, without centralized and decentralized control approaches. Additional research and development activities in the field of Co-Simulation are necessary to simulate cyber-physical systems, combining LVDG, Information and Communication Technology and Electricity Market domains behaviours. Outline a path to increase medium and low voltage grid-hosting capacity for distributed energy resources and electrical charging infrastructure, throughout flexible resources and retail market design, increasing utilization of grid infrastructure and in the long-term, prevent costly grid reinforcements

Additional research and development activities are necessary in fields of mathematical models of the low voltage system and its development process simulations, extending existing models with wider capabilities – centralized/decentralized control options with PV/EV equipment functionalities (Q(U), PQ(U), P(U,f))

7 National and international cooperation

As part of the CEVSol project:

- Through discussions with the two project partners EKZ and EKS, two distribution grids were identified and assigned to one of the network classes. The shopping centers have a detailed and precisely measured low-voltage distribution network in Knonau (EKZ), which corresponds to the network class *village center*. The EKS provide the data of a distribution network “Dettighofen” in which larger PV systems are present, which reflects the network classes *Village Centres* and *Village peripheries*.

- At the start of this project during international meetings, the DSO VKW (Voralberger Energienetze GmbH) mentioned during a meeting that PV would not cause too many voltage problems in distribution grid in the future. Whereas, the EV fast charging stations will have the bigger impact on voltage violation. This economical issue can be solved by limiting the charging power.
- The associated international partners were the ZAE Bayern and the Vorarlberg power plants VKW. CEVSol had access to the results and insights from the local subprojects and master theses and incorporate this knowledge optimally in the SFOE project.
- ZHAW, in cooperation with the electricity companies of the canton of Schaffhausen AG (EKS), analyzed the low-voltage grid in the municipality of Dettighofen and carried out various simulations. Dettighofen is a border near Municipality and is therefore in the supply area of the EKS. Simulations showed that the upper voltage limits were determined according to the technical rules for the assessment of Grid repercussions D-A-CH-CZ in the western part of the network are not complied with. On the basis of the analyzes, several studies were published in which it was examined whether the problematic voltage increases by means of the PQ (U) control can be avoided. It could be shown that with this control strategy the voltage limits be maintained even during the day with the highest PV performance (worst-case scenario).
- Successful collaboration between ABB (PGGA), EKS and ZHAW bring possibility to organize and teste a pilot installation in Dettighofen. The main motivation behind this work has been to enable the integration of a large amount of renewable energy sources without expensive grid extensions, to fulfil the given power quality standards and to protect the infrastructure from possible overloading; all this ideally in a minimum intrusive way with regard to the end-customers and at minimum cost. In addition, the installation shall be as easy as possible, ideally without any prior grid model analysis. This comprises a low-voltage line-voltage regulator (LV-LVR) equipped with a new functionality, which combines the voltage regulation with a coordinated reactive power (factor) control (RPC) and active power control (APC) of PV inverters. Besides the direct and indirect voltage control functionality, it also includes an active power limitation as a backup function in order to protect the involved infrastructure from temporary overloading. Thus, more fluctuating renewable energy sources can then be installed in the grid. The developed solution is based on an existing dry transformer acting as an LV-LVR extended with an additional control logic running on an inexpensive remote terminal unit (RTU) and using a wireless communication to the PV invertors in order to coordinate the power production according to the actual conditions in the grid.
- Through discussions with the Stadt Winterthur, two distribution grids were identified and assigned to one of the network classes. The shopping center “Einkaufszentrum Rosenberg” (Stadtwerk Winterthur), which corresponds to the network class *Shopping centres near the city outskirts* and Stadtwerk Winterthur grid, which corresponds *Urban areas with business centres or schools*
- ZHAW in collaboration with Stadt Winterthur, DEPSYS and NovaVolt bring possibility to organize pilot at Winterthur, combining different technologies and proposing technical solutions for smart distribution grid management with high share of electric vehicle charging stations, preventing costly grid reinforcements.
- ZHAW strengthen collaboration with academic and industrial partners. Was submitted H2020-ECSEL-2018-1-IA-two-stage proposal with acronym: EMERGE Essential Means for Enabling Resilient low-voltage Grids in European power systems with involvement 8 consortium partners: ZHAW (CH), EKZ(CH), NovaVolt AG (CH), Stadt Winterthur (CH), DEPSYS (CH), RISE (SW), IPE(LV), NTNU(NO).

- Was submitted H2020 Call LC-SC3-ES-1-2019 with topic: Flexibility and retail market options for the distribution grid proposal with acronym: GOLDNET Grid Optimization for enabling resilient Large Distributed energy NETworks, taking into account previous submission drawbacks and involving new partners to the consortium (18 partners), strengthening collaboration between academia/industry and utilities.

8 Publications

- F. Carigiet, F. P. Baumgartner, P. Korba, R. Knecht, M. Koller, and M. Niedrist, "*Optimisation of the Load Flow Calculation Method in Order to Perform Techno-Economic Assessments of Low-Voltage Distribution Grids,*" in Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, 2017, pp. 2181–2187
- Knecht, Raphael; Carigiet, Fabian; Schwab, Alain; Korba, Petr; Baumgartner, Franz, 2018. *Techno-economic evaluation of voltage dependent active and reactive power control to reduce voltage violations in distribution grids* [Paper]. 35th European Photovoltaic Solar Energy Conference and Exhibition (35th EUPVSEC), Brussels, 24 to 27 September 2018. DOI: https://doi.org/10.21256/zhaw-4035
- F. P. Baumgartner, C. Messner, C. Seitl, G. Lauss, F. Carigiet, R. Bründlinger, T.I. Strasser *Analysing the Voltage Stability of Photovoltaic Inverters Reactive Power Control in the Laboratory Including the Distribution GRID Transformer* [Paper]. 35th European Photovoltaic Solar Energy Conference and Exhibition (35th EUPVSEC), Brussels, 24 to 27 September 2018. DOI: 10.4229/35thEUPVSEC20182018-6EO.2.6
- Cyril Allenspach, Reto Högger, Artjoms Obushevs, Helen Reist and Petr Korba, *Implementation of Quasi-Static Time Series Simulations for Analysis of the Impact of Electric Vehicles on the Grid* [Paper], 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 7 to 9 October 2019, status: accepted

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