HOLISTIC COORDINATION OF SMART TECHNOLOGIES FOR EFFICIENT LV OPERATION, INCREASING HOSTING CAPACITY AND REDUCING GRID LOSSES

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ABSTRACT *— This paper presents the results of investigation, performed in the SysTec laboratory of Fraunhofer IEE within the transnational access (TA) of European Research Infrastructure supporting Smart Grid (ERIGrid) project. The coordinated operation of Smart On-Load Tap Changer (OLTC) transformer and photovoltaics (PV) inverters is investigated, and the symmetric voltage control algorithm approach is proposed to increase the efficiency of control during PV generation periods.*

INTRODUCTION

The penetration of Renewable Energy Sources (RES) and Electric Vehicles (EV) is expected to increase over the next decades. The 2018 Edition of the REN21 Renewables Global Status Report [1] reveals a global energy transition well underway with record new additions on installed renewable energy capacity, rapidly falling costs, increases in investment and advances in enabling technologies.

Voltage rise is the most critical constraint for the integration of distributed generation (DG) in rural electric distribution networks. The distribution system operator (DSO) is responsible for maintaining voltage limits, however the DSO does not have direct access to the DG. A distributed and coordinated control scheme, considering the transformer substation as a hub[1] of the grid, should help the DSO to deal with the integration challenges allowing a cost-efficient integration of high shares of DG and EV.

Coordinated voltage control concepts can delay grid reinforcement costs while increasing the DG hosting capacity of electric distribution networks. A lack of coordination, on the other hand, can cause the undesired operation of equipment and additional losses. The coordinated control has to maintain a high level of quality of supply while achieving economic benefits in comparison to network reinforcement.

CONTROL STRATEGIES

In order to cope with the voltage fluctuations promoted by DG and EV different voltage strategies can be applied depending on the body of research:

The project “Aktives intelligentes Niederspannungsnetz” [2,3], has defined five control strategies depending on the used components:

Conventional: Neither the majority of installed PV plants nor the local network stations are participating in voltage control in the distribution network or provide information for operational control. The only exception is the use of measurement value estimates to determine the forecast for network feeding from PV plants [4].

Active inverters: PV inverters vary their active and reactive power depending on set characteristic curves [5,6].

Smart Substation: There is the option of controlling the inverters from the local network station and process inverter measured values for use in the network control station.

Active Substation: Voltage is controlled using the controllable distribution transformer with OLTC only using the measured values in the station directly. Measurement results of this system are presented in [3].

Active and Smart Substation: Voltage control using the controllable distribution transformer with OLTC and inverters. In addition, there is the option of using measured values from the inverters and the local network station in a harmonized control concept. Test results are shown in [7].

More recently, a different group of researchers have investigated the last control concept for increasing the PV hosting capacity of low voltage (LV) grids [8]. In this case, instead of a communication-based coordination between OLTC and inverters they propose a local control approach.

However, another group of researchers, that have

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[1] *Understood as “a common connection point for devices in network”.*

developed and tested a new smart distribution transformer [9], have identified that a lack of communication-based coordination between distribution transformer with OLTC and the inverters can prevent the use of advanced algorithms able to reduce power losses in case of a reversal in power flow [10,11].

On the other hand, in the project "DG DemoNet – Smart LV Grid" [12,13], real tests of solution approaches for central and distributed monitoring, management and control concepts were performed in selected low LV networks in Salzburg (Austria). Final validation results and the key findings are described in [14].

At "DG DemoNet", three control "stages" were investigated [15,16]:

Local control (stage 1): The simplest stage just performs a local control of the transformer's OLTC using busbar voltage while PV inverters are operated according to their default Q(U) and P(U) control independently.

Distributed control (stage 2): While inverters are operated the same way as in stage 1, actual voltage measurements delivered from selected smart meters are used for distributed voltage control of the transformer's OLTC.

Coordinated control: The transformer is controlled the same way as in stage 2. In addition, the inverters' Q(U)-control can be adapted dynamically by the controller to reduce voltage spreading (the difference between the highest and the lowest voltage in the grid considering all three phases).

According to these researchers, the technical as well as the economic benefits of the developed solutions depend on the individual grid. Since only three grids were investigated, it may be difficult to evaluate the benefits of the developed solutions as well as their potential for future grids.

In this paper, it is proposed a set of test cases that aims to improve the current knowledge regarding the coordination of the technologies capable of providing a voltage balance in the LV-network, avoiding technology discoordination that can cause the undesired operation of the distribution transformer with OLTC and the limitation of the hosting capacity of electrical networks.

COORDINATED VOLTAGE CONTROL

In this section, a symmetric algorithm for coordinated control considering smart transformer with OLTC and PV-inverters is explained. As it is demonstrated in Figure 1, the coordinated voltage controller with implemented symmetric voltage control algorithm receives, by means of Modbus, all measurements obtained from the LV side of the transformer and each of the 4 PV inverters and, for its part, sends commands for tap action.

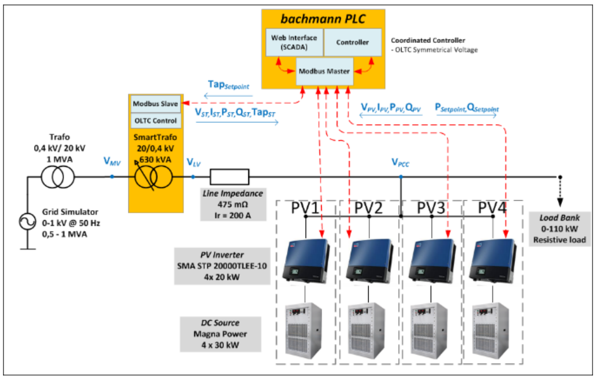


Figure 1. Diagram of the control communication system

The goal of this control is to maximize the voltage reserve in the system. That is, to keep the maximum and minimum voltages within the LV network as far as possible from the statutory limits (±10%). The control acquires the voltage measurements from different points along the LV network, i.e. load, PV inverters and transformer. From these measurements, maximum and minimum voltages are obtained. Then, the average voltage is calculated and compared to the voltage set point (230V). If the average voltage deviates from the set point, over the dead band value, then the OLTC control is activated in order to bring the average voltage back to the set point value.

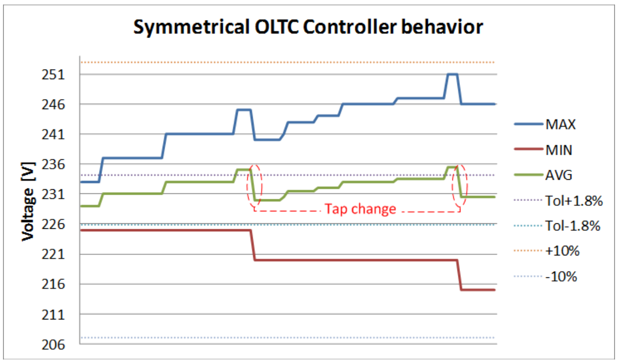


Figure 2. Symmetrical voltage algorithm

The proposed parameters for the coordinated controller are presented in the Table 1:

Voltage set-point [V]	230
Dead band [%]	1.8
Time between tap changes [s]	3.5

Table 1. A set of parameters for the controller

The standard EN 50160 [17] states that the supply voltage has to remain in the range of ±10% of the rated operating voltage.

Regarding PV inverters with rated power above 8 to 10 kW, they are usually connected by three phases to the grid and can operate in all four quadrants thus being able to inject or absorb reactive power while active power is fed into the grid.

In case of normal load conditions, the voltage at the end of the line is lower than the voltage at the transformer side. The situation changes when there is feed-in from PV inverters because voltage can be increased at the end of the line comparing to the voltage at the transformer. By additionally absorbing reactive power the overvoltage can be limited somehow. That property of PV inverter is described in the Figure 3.

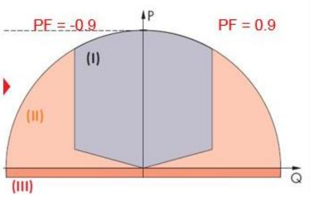


Figure 3. PV reactive power limits

Taking into account that LV networks have a radial nature with a predominantly R/X ratio, reactive power in comparison to active power has lower impact on the voltage value. Nevertheless, in LV distribution systems with high R/X ratio reactive power absorption can also be effective, especially when taking the transformer impedance into consideration.

TEST SET-UPS

The SysTec laboratory of Fraunhofer IEE was used to test a coordinated controller in a recreated laboratory configuration as shown in Figure 4.

In order to investigate the coordination of different technologies under real load and distributed generation, the smart distribution transformer with OLTC is connected to the grid with 4 PV inverters and a resistive load on the LV side. The measurements are taken in several points along the LV network in order to achieve the whole LV profile.

Figure 4. SysTec laboratory of Fraunhofer IEE

80kWof generation is distributed between four PV inverters with reactive power capabilities that can be installed at various position within the LV grid. To emulate PV panels DC sources with 30 kW each were used with a constant voltage source configuration.

The smart transformer is a 630 kVA 20/0.4 kV Dyn5 transformer, with a short-circuit voltage of 6% and no-load losses of 600 W. The OLTC regulates the voltage in +/-4 steps of 2.5 % each.

Two different LV-network configurations were built to evaluate a set of generation levels from PV inverters:

Set-up 1, described in Figure 5, represents different feeders, where generation units are spread out along distribution network, and a load bank is connected at the end of one of the feeders.

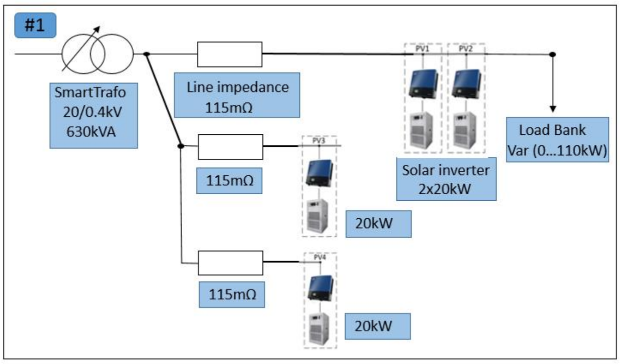


Figure 5. Set-up 1.

Set-up 2, described in Figure 6, shows a single feeder with a set of generation units connected at the same electrical point, and a load bank at the end of the feeder.

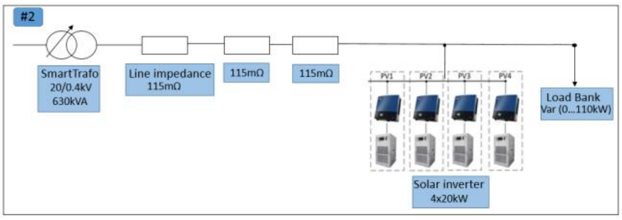


Figure 6. Set-up 2.

The main characteristics of all the test set-ups are:

- The network is predominantly resistive.
- The system is absolutely balanced.
- Resistive load steps are discrete and static.
- Each inverter acts as a measurement point for the control loop, as well as the control box of OLTC.

CONTROL STRATEGIES

Three voltage control strategies have been performed at the SysTec laboratory:

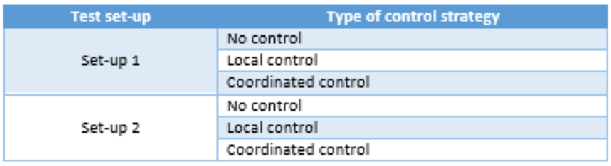
First, no control is applied. The system operates as a passive network with connected PV inverters.

Second, a *conventional local (non-coordinated) control* is used for the smart transformer with OLTC and the PV-inverters. There is no communication between the voltage controller located at the transformer and the inverters. Each local resource works on its own, taking into account local available voltage measurements and trying to balance it locally with the help of the controller integrated in each device.

Third, a *coordinated control* scheme, based on the symmetric algorithm, is applied to coordinate the behavior of the transformer with OLTC and PV inverters.

TEST CASES

The test objective is to experimentally verify the ability of each *control strategy* to maximize the hosting capacity in all the proposed *test set-ups*.



Test set-up	Type of control strategy
Set-up 1	No control
	Local control
	Coordinated control
Set-up 2	No control
	Local control
	Coordinated control

Table 2. Proposed control strategy for different set-up

For the laboratory experiment, the percentage of loads and PV generation levels are selected in order to approximate them to a daily consumption and PV energy generation profile, as shown in Figure 7.

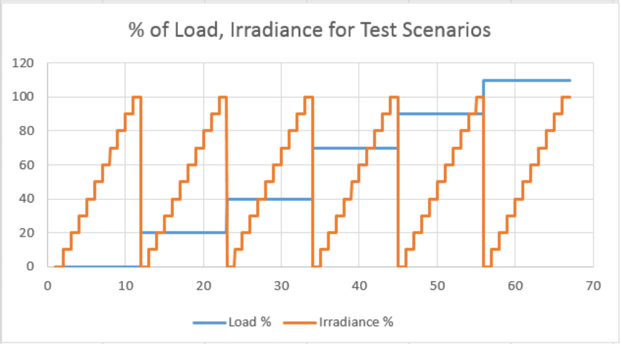


Figure 7. Proposed consumption and generation scenarios for the experiment.

TEST RESULTS

Set-up 1

For all control strategies and each *PV generation - Load* scenario, the voltage value remains within permitted boundaries. There is no problem to integrate all the power injected by inverters.

Set-up 2

Set-up 2 is the worst case in terms of system behavior during feed-in from PV inverters without coordinated voltage control, whose voltage profile is shown in the Figure 8.

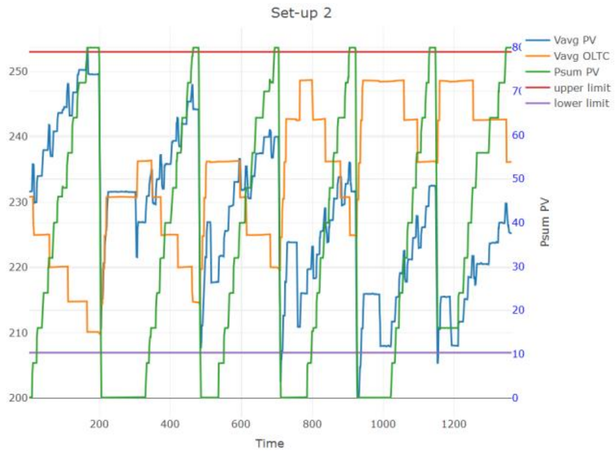
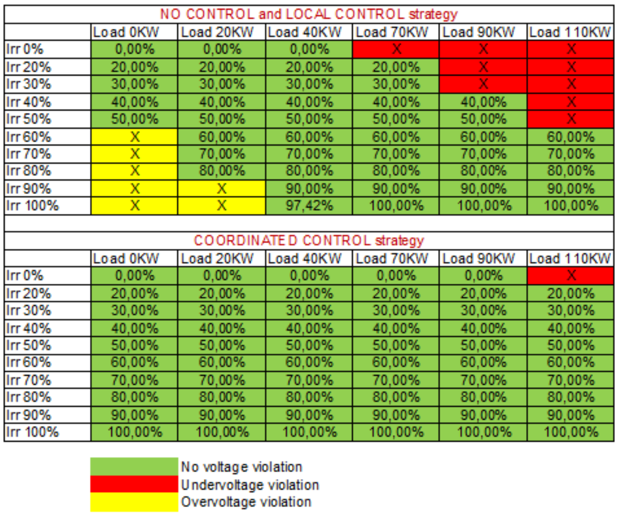


Figure 8.Behavior of the Set-up 2 under coordinated control

The results for this network configuration are summarized in Table 3, where the percentage evaluation of the hosting capacity is demonstrated for both base and control cases (local and coordinated).



NO CONTROL and LOCAL CONTROL strategy

	Load 0KW	Load 20KW	Load 40KW	Load 70KW	Load 90KW	Load 110KW
Irr 0%	0,00%	0,00%	0,00%	X	X	X
Irr 20%	20,00%	20,00%	20,00%	20,00%	X	X
Irr 30%	30,00%	30,00%	30,00%	30,00%	X	X
Irr 40%	40,00%	40,00%	40,00%	40,00%	40,00%	X
Irr 50%	50,00%	50,00%	50,00%	50,00%	50,00%	X
Irr 60%	X	60,00%	60,00%	60,00%	60,00%	60,00%
Irr 70%	X	70,00%	70,00%	70,00%	70,00%	70,00%
Irr 80%	X	80,00%	80,00%	80,00%	80,00%	80,00%
Irr 90%	X	X	90,00%	90,00%	90,00%	90,00%
Irr 100%	X	X	97,42%	100,00%	100,00%	100,00%

COORDINATED CONTROL strategy

	Load 0KW	Load 20KW	Load 40KW	Load 70KW	Load 90KW	Load 110KW
Irr 0%	0,00%	0,00%	0,00%	0,00%	0,00%	X
Irr 20%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%
Irr 30%	30,00%	30,00%	30,00%	30,00%	30,00%	30,00%
Irr 40%	40,00%	40,00%	40,00%	40,00%	40,00%	40,00%
Irr 50%	50,00%	50,00%	50,00%	50,00%	50,00%	50,00%
Irr 60%	60,00%	60,00%	60,00%	60,00%	60,00%	60,00%
Irr 70%	70,00%	70,00%	70,00%	70,00%	70,00%	70,00%
Irr 80%	80,00%	80,00%	80,00%	80,00%	80,00%	80,00%
Irr 90%	90,00%	90,00%	90,00%	90,00%	90,00%	90,00%
Irr 100%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%

🟩 No voltage violation
🟥 Undervoltage violation
🟨 Overvoltage violation

Table 3.Benchmarking of three strategies with different levels of PV generation - Load

Due to the feed-in of active power from the PV inverters, there is a reverse flow that can exceed the upper/lower voltage limits. It was observed that only 50% of PV penetration is safely integrated without any additional control (*no control*), while higher penetration levels become unacceptable, exceeding the ±10% V_{nom} band. The same situation is observed with the local control (*non-*

coordinated), because the load is not enough to exceed the dead band of 1.8%[2] in any scenario, since maximum system load does not overcome the 17% of the rated transformer power. The application of the *coordinated control* allows the reduction of the voltage deviations and the increase of PV penetration up to 100 % in a worse case (110kW load).

CONCLUSION

A symmetric voltage regulation approach has been tested with the aim of coordinating technologies on the LV side. It was demonstrated that the coordinated control of smart transformer with OLTC and PV inverters, as described in this paper, offers new possibilities to increase the hosting capacity whilst fulfilling statutory limits.

With the coordinated voltage control, the usability of the network can be increased without enhancing the infrastructure, but increasing the effectivity of the control strategies; avoiding measures as PV curtailment or repowering of distribution/transmission lines.

It was also proved that the higher the control level is, the more information from the grid is necessary and the more complex the algorithm becomes. However, the impact of the controller on the voltage levels through the LV grid turns to be more effective.

Based on the outcome of this research, a hierarchy of coordinating technologies with the aim of enhancing the renewable hosting capacity of the LV distribution grid and reducing losses is suggested. The smart transformer with OLTC should act as the main voltage controller in the LV grid (master), whilst other voltage regulators should be configured as grid following units (slaves).

The objective for future research is to include distributed storage units (V2G, batteries) in an unbalanced LV network with dynamic loads and a higher reactive power.

Acknowledgments

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[2] Which leads to a tap change operation.