Sustainable transition to high PV penetration: Curtailment retrofit for the already deployed micro-inverters

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Abstract:

Increasing photovoltaic (PV) capacity in low voltage networks is limited by occasional congestion, resulting in unacceptable voltage levels. Network managers and policy makers are getting aware of this problem and various technical recommendations are given. Of special interest are ancillary services (reactive power control and active power curtailment) that could be provided by the "smart" inverters. Most PV inverters deployed to date are solely designed to maximize power output. To make the transition towards smart inverters, they either have to be replaced or retrofitted. Retrofit can be a more sustainable option, especially if it can be done only by software intervention ("soft retrofit").

This paper presents a curtailment method suitable for the already deployed micro-inverters without needing to replace them. Sequential module-level tripping is an optimized overvoltage trip scheme that achieves curtailment on a system level, without modifying the functionality of individual micro-inverter unit. The proposed method was simulated for an increased PV penetration scenario for a Dutch LV network. The annual feed-in losses of curtailment were compared against conventional overvoltage protection. Depending on the location of PV in the distribution network, 62-100% less feed-in loss was achieved with the proposed curtailment method.

Keywords:

Inverters, Photovoltaic systems, Sustainability, Voltage control, Curtailment.

1. Introduction

1.1. PV penetration and overvoltage in LV networks

In a worldwide expansion of grid-connected generation, specific challenges exist depending on the type of distributed energy source, but also depending on network topology, impedance characteristic and nominal voltage levels. Photovoltaic (PV) sources are characterized by generation profiles that experience peaks around noon and minimum values in the early morning and evening hours. For convenient use of existing built infrastructure, PV is a popular renewable energy choice in residential areas supplied through the low voltage (LV) network. However, residential load profiles with typical evening peaks and low midday values have a temporal mismatch with PV generation profiles [1]. Poor load matching implies that unused power is flowing through the network causing occasional congestion and overvoltage. In a scenario with an attractive feed-in tariff, the prosumer does not see this as an immediate problem and is happy to export the excess energy. However from the point of distribution system operator (DSO) the problem grows as more and more prosumers connect their PV to the grid. If no mitigation action is undertaken both the DSO and the prosumer get affected. DSO traditionally react to these problems by imposing a power injection limit [2] and proclaim that in order to connect more PV, network reinforcements must be implemented (adding new transformers, reinforcing cables). Given the time and resources it takes to put such measures into effect, this limitation may turn into a long wait for connection or even permanent loss of opportunity for prospective prosumers.

1.2. Voltage rise mitigation options

The network reinforcements should be kept as a last resort due to being time consuming and financially burdening. Instead, a range of alternative methods to increase PV capacity should be investigated [3]. Voltage levels can be controlled directly at transformer side, either manually via off-load tap changers, or automatically using on-load transformer tap changers (OLTC) [4]. In most feeders tap regulation is manual and supply to customers must be interrupted in order to change the tap. In terms of application OLTC is still considered a novelty.

Another option is to control voltage by varying active and reactive power (V(P), (V(Q)). The impedance of LV networks is predominantly resistive and active power is strongly coupled with voltage. Voltage sensitivity to active power variation (dV/dP) is much higher than to reactive power (dV/dQ), so using V(Q) in LV is not as effective. In a comprehensive voltage sensitivity study for radial LV radial feeders it was shown that even when power factor is lowered to 0.8, dV/dP is still three orders of magnitude higher than dV/dQ [5]. Nevertheless, V(Q) is usually given priority in residential LV because customer is not charged for its consumption.

In order to improve the voltage profile DSO can install custom power devices (CPD) [6] in strategic points in the feeder. Their operation is largely based on V(Q). CPDs are still considered expensive for widespread use. It is desirable to make the PV grid integration a seamless process by minimizing or even eliminating burden on DSO. This is possible if solution comes in a distributed manner, acting from multiple PV connection points. Since PV is an inverter-based generator, various opportunities lie in adapting inverter operation to achieve the same goals as with CPDs.

1.3. Emergence of smart inverters

The PV inverter designs for LV networks did not immediately anticipate network capacity problems. The focus was on making use of feed-in incentives by maximizing power output. This is why most inverters deployed in the world today only have maximum power point tracking (MPPT) function and basic overvoltage/undervoltage and anti-islanding protection. To maximize active power output they operate at a fixed power factor near unity. However, the connection requirements are evolving and becoming more demanding in terms of inverter capabilities [7]. Active power curtailment (APC) and reactive power support are new functionalities (ancillary services) that define the so-called "smart inverter" [8]. Some functionalities will require replacement of already deployed inverters with new inverters, but in some cases it is possible to perform retrofit only by modifying inverter firmware ("soft retrofit" in further text). While it sounds attractive that enabling ancillary service is only a software domain problem, in reality it can bring some undesirable impacts on the parties involved if not assessed from multiple aspects.

In this paper a soft retrofit of micro-inverters is proposed. The motivation is to solve the voltage rise problem by applying APC. The idea of sustainable retrofit is introduced. This is no attempt to quantify the sustainability of retrofit, rather the term "sustainable" is used to point out a technological pathway that is non-disruptive and cost-efficient for multiple parties involved, especially when a large scale retrofit action is undertaken. For this purpose, section II discusses several aspects of inverter retrofit: control strategy, warranty, availability of remote access and grid interaction between different inverter generations. Section III introduces micro-inverters as specific inverter niche with good pre-requisites for a sustainable retrofit. Also a novel APC method is presented as a means of carrying out the micro-inverter retrofit, that could serve as basis for future manufacturers' recommendations. In Sections IV and V modelling and simulation of a high PV penetration scenario is presented. The effectiveness of the proposed method to maintain voltage limits while accommodating additional PV capacity is demonstrated.

2. Sustainable inverter retrofit

Given the previous description of smart inverters, the transition towards high PV penetration can also be viewed as a transition from the already deployed, MPTT-only inverters towards smart inverters. The process of transition is driven by the adoption of new grid codes. Usually a commissioning date is established after which every new inverter must have smart functionalities while inverters installed prior to that date must either be replaced or retrofitted with new functionalities. In addition to commissioning time, the PV plant capacity can be used as criteria for mandating new functionalities. Such is the German directive VDE-AR-N-4015 [7].

In order to meet only one of the requirements in [7], the ordinance for frequency-dependent APC (Systemstabilitätsverordnung- SysStabV) has been issued, requiring a retrofit of 315,000 PV plants. The total estimated retrofit costs are: €65-175 million for retrofitting and €20 million for administration, all borne by the electricity consumers ([9], [10]). Massive, regulative-driven retrofit of PV inverters is a rarity in the industry, therefore the technical guidelines that proceeded from SysStabV directive are a benchmark example. The three technical guidelines of APC are all soft retrofit, in fact the goal was to avoid replacement in all cases [9].

Large retrofit actions such as these can impact multiple parties: DSO, prosumers and inverter manufacturers. Sustainable retrofit is discussed from the aspect of:

- control strategy (V(P) or V(Q))
- reliability and warranty
- availability of remote access
- grid interaction between already deployed and newly installed inverters

2.1. Active vs. reactive power control

If the chosen strategy is V(P), it must be known that the inverter by default operates in MPPT mode, so voltage can only be lowered by curtailing power. The curtailment has direct financial impact on feed-in revenue. If the need for it doesn't arise too often, curtailment can still be a profitable option because it allows PV to feed some amount of power, rather than losing all feed-in due to inverter voltage trip.

In [11] V(Q) was assessed as the most cost-effective option however authors state that they have assessed it as a "green-field" project, meaning there are no already deployed systems involved and that inverters are oversized for reactive power from the beginning. Old inverters would have to reduce active power output in order to accommodate reactive power otherwise failure is likely to happen due to exceeding their rating. Therefore, in a soft retrofit scenario reactive power will also lead to feed-in losses as shown in Fig. 1.

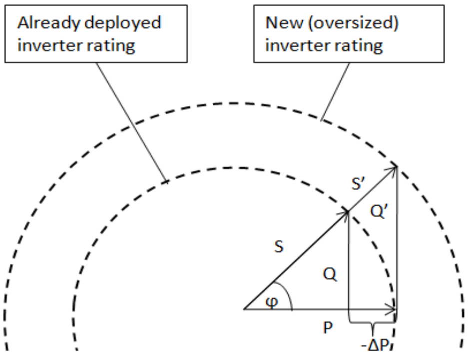

Fig. 1. Retrofit for reactive power (Q) comes at the price of active power loss (ΔP). Only oversized inverter can support the same amount of active power (P).

Reactive power is competitive if inverter is replaced and this can be considered sustainable only if inverter is due for replacement because of age. Since this paper deals with retrofit, replacement was not viewed as an option. Due to dominant effect of V(P) in LV networks and a supporting case from the industry in the domain of frequency-active power control [9], a V(P) control strategy was chosen for the retrofit objective.

2.2. Reliability and warranty

In the present day most inverters are digitally controlled which enables easier implementation of various MPPT algorithms [12]. The expectation is that control algorithms for soft retrofits should also be relatively easy to implement. However, from the manufacturer's viewpoint this is not just a software domain problem. These soft changes can impact the reliability of existing components, especially if the inverter application is in severe environmental conditions. Industrial survey on the reliability of power converters portrays capacitors and transistors as the most fragile components, whereas extreme ambient temperatures are the main source of environmental stress [13].

V(P) implementation requires varying the transistor duty cycle in the DC-DC boost section while V(Q) requires the same in the DC-AC section [14]. In addition, V(Q) increases voltage stress on the DC link capacitors [15]. Retrofit for V(P) seems less invasive, however it is still a new, untested functionality. Inverters manufactured prior to the grid code change went through accelerated life tests, but only for MPPT regime. It can be suspected that implementing V(P) and, especially V(Q), in inverters worn out from environmental stress, could produce unforeseen failure mechanisms and warranty could be questioned.

Some manufacturers will openly state that already deployed inverters cannot be retrofitted for V(Q) [10]. In fact, in the absence of regulative obligation manufacturers' practices can be very strict in terms of changes in product application. For example, the practice of AC coupling is useful for enabling grid-connected inverters to work in standalone mode during blackouts. AC coupling is far less invasive as it doesn't require any change in the inverters themselves rather it just allows PCC switching between different grid-forming sources (switching between grid source and battery-based source or a backup generator). Despite that, some grid-tie inverter manufacturers will not provide warranty if their product is used in AC coupling [16]. In a regulated, large scale retrofit, manufacturers are obliged to come up with recommendations for installers who perform the retrofit [9].

2.2. Availability of remote access

Implementing remote communication in distributed generation is important for the operational efficiency of distribution network. Two-way communication for the purpose of monitoring and control is an integral part of smart grid technology. In Germany in 2012 it became mandatory for inverters to have a remote control access enabled for DSO. All inverters under 30kW must have it otherwise they would have to limit active power down to 70% regardless of grid conditions [11].

In one manufacturer recommendation [17] there are both local and remote options for interfacing computer with inverter. Depending on product version remote access is not always an option. In [9] a sensitivity analysis of retrofit cost to inverter size and commissioning date was performed. A generalized trend is presented in Fig. 2. It can be observed that:

- In the same capacity category, older inverters will incur more cost
- For the same commissioning date, smaller inverters will incur more cost
- Earlier commissioning dates (i.e. 5 years earlier) will do more than double the cost for smaller inverters

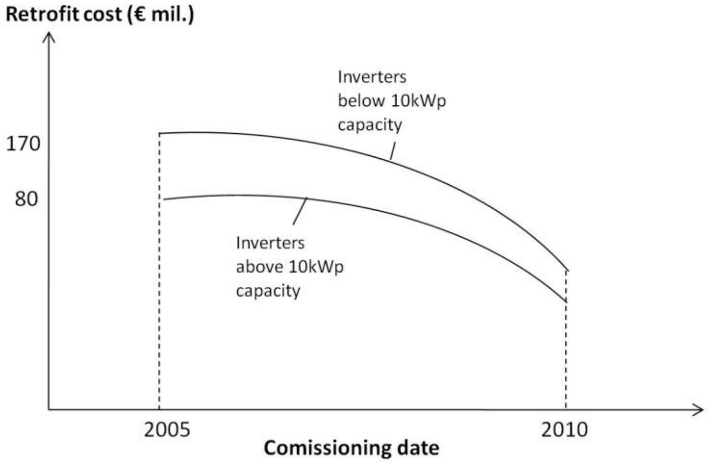

Fig. 2. Soft retrofit costs as a function of commissioning date and peak size.

Such trends could very well be due to higher number of small inverters dominated by lack of remote communication. If only local interfacing is available then installers must spend fuel for transport to and back from the PV plant location. Also, the cost of administering fieldwork operation grows. Remote access would reduce the fuel costs and CO_2 emissions associated with retrofit. Focusing on inverters with more recent commissioning date that already have remote access as part of the standard commercial package is probably a low-hanging fruit of sustainable retrofit.

2.3. Grid interaction between old and new inverters

The prosumers are not necessarily responsive to DSO retrofit requests [18], making the retrofit hardly a one-off task. It is successive with temporal and spatial displacement. Different generations of inverters and different manufacturers can exist in the same feeder. In some case retrofit will be possible in some case not. Inevitably this leads to having a mix of inverters with and without new functionalities, connected to the same LV circuit. This is a rarely discussed transitional aspect, but the problem it can cause is very similar to a well-known problem: when multiple PVs on the same feeder engage in a voltage control, unequal sharing of feed-in losses occurs [19]. This problem exists in both V(P) and V(Q) control, but only V(P) is discussed further.

As the feeder length increases, so does the dV/dP [5]. The same amount of power injection will cause higher magnitude voltage variation. If all inverters use uniform voltage threshold to trigger the curtailment, then inverters towards the end of the feeder will trigger earlier than inverters closer to the transformer. In Fig. 3 inverters A and B export at peak power and both have curtailment functionality. Inverter B engages curtailment at two instances in time. Curtailment at B also has an effect on lowering voltage at inverter A, which doesn't engage its curtailment. In other words, voltage rise that is caused by both inverters gets to be solved by only one of them at the price of unfair feed-in opportunity.

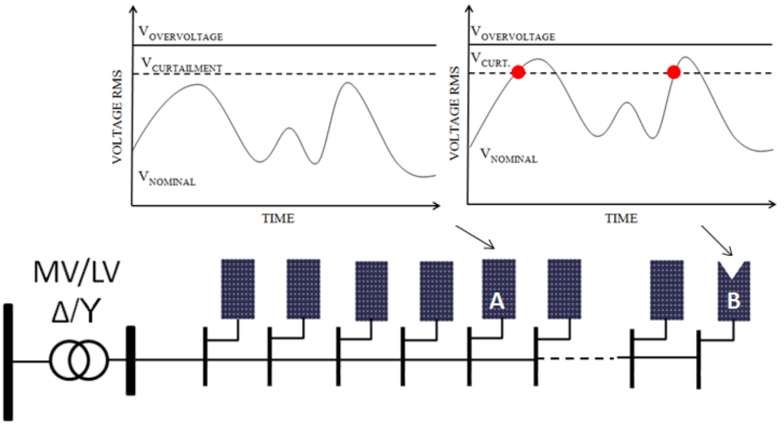

Fig. 3. Interaction between inverters on the same feeder: unequal voltage-controlled curtailment.

Identical situation from system state point of view is if inverter B is curtailment-capable and A is not. The same network state and variables, only the context of the problem is different. The position in the feeder can only make it worse or better for the engaged inverter, but the fact that one inverter start curtailment and the other doesn't is enough to cause the problem. To avoid this, retrofit should be approximated to a one-off action per feeder rather than have large temporal gaps between retrofits during which unequal feed-in losses would occur. Without information and communication technologies (ICT) infrastructure equally available and unified communication standard between different inverter brands this will be difficult to achieve in feeders with high PV penetration. Alternatively some hindsight planning in PV deployment could separate different inverter brands from the same feeder, but such practices are unknown and could interfere with purchasing freedoms.

3. Micro-inverters: a niche for sustainable curtailment retrofit

3.1. State of the art

Micro-inverter implements all conventional inverter features on a single PV module level. Effectively each module in a PV array becomes an independent plant hence micro-inverters are also known as AC modules. Micro-inverter concept was known since the '80, but the state of power semiconductor technology was such that it was not feasible to mass produce them. It has been little more over half a decade that they have made a come-back accompanied with the latest ICT [20] and since then it is increasingly penetrating the worldwide market. According to [21] the worldwide megawatt shipments will increase 306% in 2013-2017 period. Micro-inverter shipments in France will reach 35 MW in 2015 which will cover 13% of residential PV inverter market for that year.

With each PV module being independently connected to the grid (Fig. 4), the overall system reliability is improved. In case of a string inverter failure there is 100% string loss while in case of a micro-inverter failure it is limited only to one module. Also MPPT is carried out on module level which takes care of the module mismatch inefficiency that typically affects string inverter systems [22].

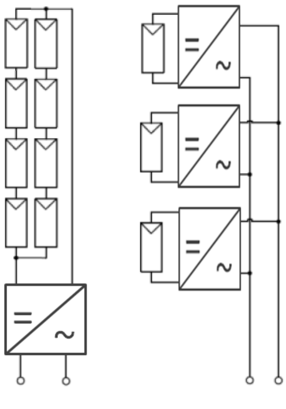

Fig. 4. Inverter topologies: string (left) and micro-inverter (right)

In case expansion of PV capacity no inverter resizing (replacement) is needed as system can be modularly expanded and more flexibly respond to different incentive scenarios. For example, one could start with couple of modules if self-consumption is preferred compensation model, and easily expand the system when the feed-in remuneration becomes more favorable.

Each micro-inverter has some type of embedded communication and a data concentrator to manage the entire set of micro-inverters. Locally data concentrators can do read/write operations on micro-inverters either via power line communication [23] or mesh radio [24]. Remote access to concentrators is enabled via ethernet port and is used by prosumers and manufacturers for monitoring and troubleshooting of each PV module. This communication infrastructure gives a good starting point for soft retrofit and for the future needs of DSO for remotely operated distributed generation (Fig. 5).

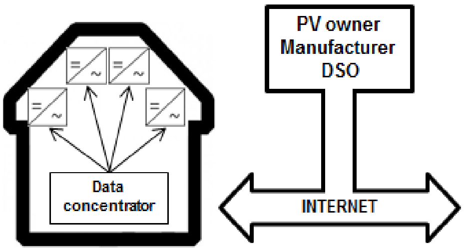

Fig. 5. Multiple parties accessing the micro-inverter communication infrastructure

Unlike conventional inverters that are housed indoors, micro-inverters are mostly exposed outdoors beneath the PV module. Being directly exposed to the ambient temperatures can increase their failure rate [15]. Voltage rise due to PV peaks usually coincides with high ambient temperatures and it is at these times that inverter must deliver voltage control. Implementing untested functionalities like curtailment carries added risk for micro-inverters, hence alternative curtailment method is proposed that avoids modification of default MPPT operation of transistors.

3.2. Sequential module-level tripping

Overvoltage protection switch exists as mandatory element in all PV plants. At a defined voltage threshold it operates by disconnecting the PV plant from the grid, causing 100% feed-in loss for the duration of DSO-specified overvoltage clearing time (3-5 minutes). This event is known as "voltage trip". In a series (string) connected module topology (Fig. 4, left) it is unavoidable to lose entire PV branch during voltage trip. Via micro-inverters each module has the potential to be tripped independently, causing only partial loss (module-level trip). However, the grid code doesn't differentiate between topologies and requires 100% plant disconnection (usually at V_{MAX}=1.1pu). In order not to violate the grid code the proposal is to introduce voltage trip range starting at a lower voltage level (i.e. V_{START}=1.09 pu) and stop at a desired voltage level (i.e. V_{STOP}=1.08 pu).

In addition to voltage control range, a PV plant dynamic response competitive to droop curtailment is proposed. Droop characteristic is typically represented as linear function $\Delta V=f(\Delta P)$. As described in section 2.2, droop curtailment changes the transistor operation on both plant level (string inverter) and module level (micro-inverters). The proposed retrofit takes the concept of linear power curtailment from a plant level and transforms it into an equivalent sum of discrete power steps on module level. Each droop function can be approximated by a staircase function, where each discontinuity represents a single module trip (Fig. 6). Different trip time steps (t,2t, etc) allow the "ceiling" of different droop lines. Each droop line has its own corresponding trip time sequence, hence the name "sequential module-level tripping" (SMT) is used. A trip function is executed by the protective switch which unlike transistors and capacitors, has a passive role in the inverter steady-state operation. So on the individual inverter level there is no change in transistor operation, but on the plant level the same curtailment effect is achieved (Fig. 6). Varying the V_{STOP} settings allows the DSO to prioritize between maximizing PV output and achieving desired voltage level.

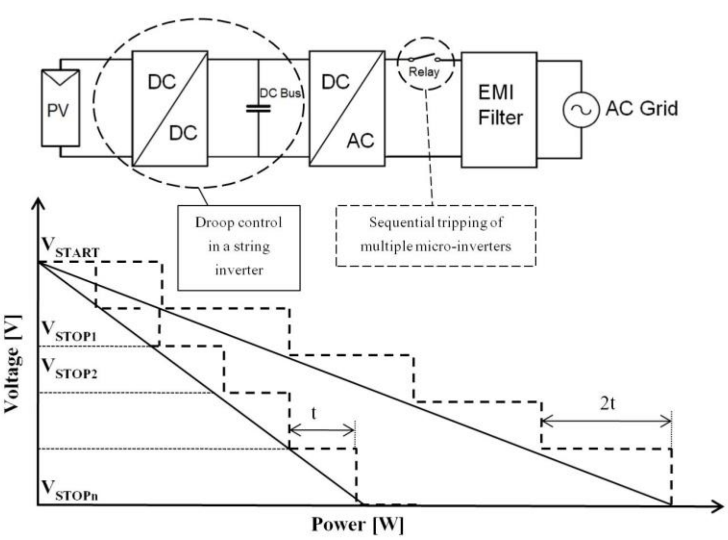

Fig. 6. Conventional curtailment (ramp voltage response) with transistor utilization and sequential tripping (staircase voltage response) with AC relay utilization.

4. Load and network modelling

The primary goal of the simulation was to demonstrate the effects on voltages and annual economic impact of SMT if applied in multiple PV systems that are located in the same neighbourhood. Simulation does not reveal the impact on micro-inverter components, as this will be shown in another study. That being said, there are no detailed generation and load models, but net flow model is used as depicted in Fig. 7.

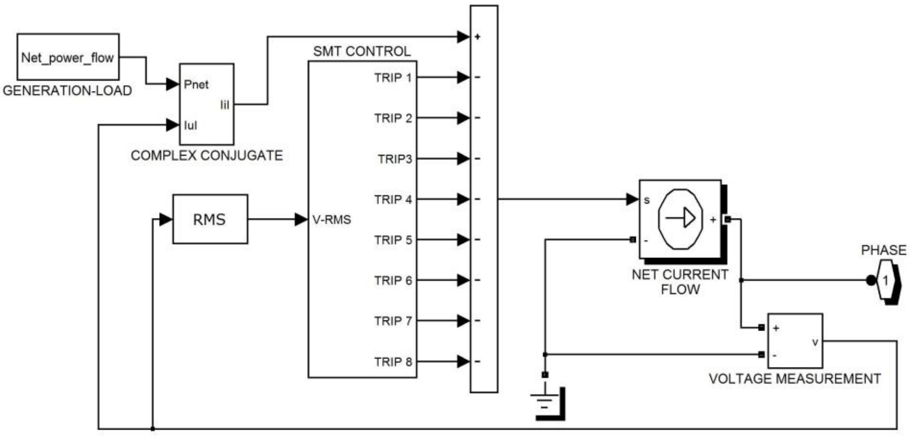

Fig. 7. Net power flow model of a single house incorporating SMT control.

Annual net power readings are obtained from real load and PV generation profiles available in 15 min intervals. Net power is presented to the model in a complex form. Current amplitudes are computed from the complex conjugate block. Each PV plant in the test feeder is equipped with eight micro-inverters. Standard micro-inverter output power is about 250W (or max. output current about 1A). The SMT controller incorporates curtailment by adjusting the net power flow. Using a desired trip delay sequence and voltage control range, eight trip signals (-1A steps) can be issued to adjust the power flow.

The SMT was simulated in Matlab/Simulink. For this purpose a typical Dutch residential network was modeled as a test environment. Four feeders extend radially from a 400kVA delta-star transformer , each feeder having 14 supply buses. Each bus provides three-phase supply, where each phase connects one household. Therefore, there are 42 household loads connected on one feeder. In Fig. 8 is a single-phase representation of the feeder with three different load types representing different customer groups and three different cable sections. Total feeder length is

0.49km. All cable sections were modeled as series RL impedances. In most of MV/LV transformers in Dutch grid, the transformer tap is set to 1.05pu to compensate for voltage drop along the feeder. This prevents undervoltage during peak demand hours, but increases the chances for overvoltage during peak generation hours.

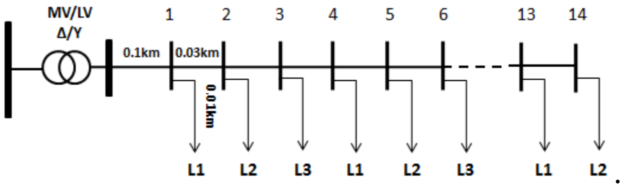

Fig. 8. Model of typical Dutch LV feeder with three alternately distributed load types.

5. Simulation results

The starting point for simulation is that maximum allowed PV capacity at each of 42 houses was 5A. The neighbourhood in the test feeder decides to increase to 8A per house. This leads to overvoltage in all buses. When SMT curtailment is applied voltage level in all buses is kept within limits and is also flattened which suits the minimization of distribution losses (Fig. 9).

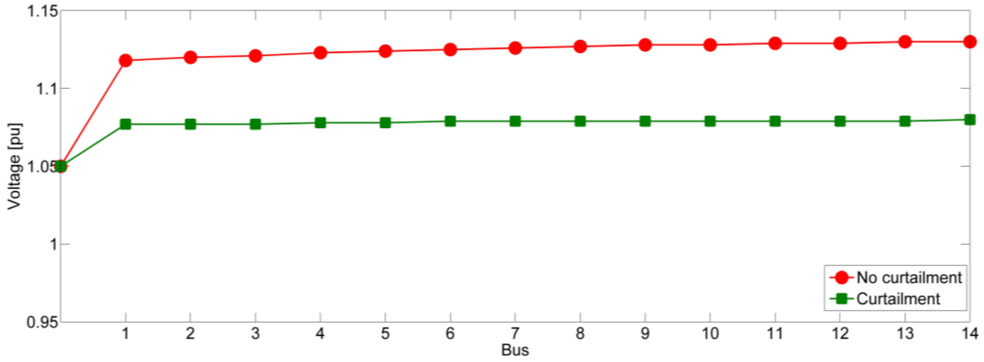

Fig. 9. Effects of SMT curtailment on bus voltages.

Conventional overvoltage protection was chosen as a baseline overvoltage mitigation method and compared against SMT. Fig. 10 shows power flow and voltage measurements taken at bus 14 during several random overvoltage/curtailment events that happen throughout the year. It can be seen that SMT maintains better energy yield (presented by positive net flow) in situations where it is otherwise brought to zero due to voltage trip. The trip clearing times represented in Fig. 10 are solely function of voltage, while in real application they are controlled by a timer. In feed-in loss calculations a realistic 5 minute clearing times were applied.

On an annual level SMT was able to decrease feed-in losses in every bus (Fig. 11). A maximum decrease of 99.6%-100% was achieved at the first three buses. Minimum decrease of 62.3% was achieved at the last bus which experienced most intensive curtailment. On the entire feeder level 550 kWh (77.4% feed-in loss decrease) were saved compared to overvoltage protection.

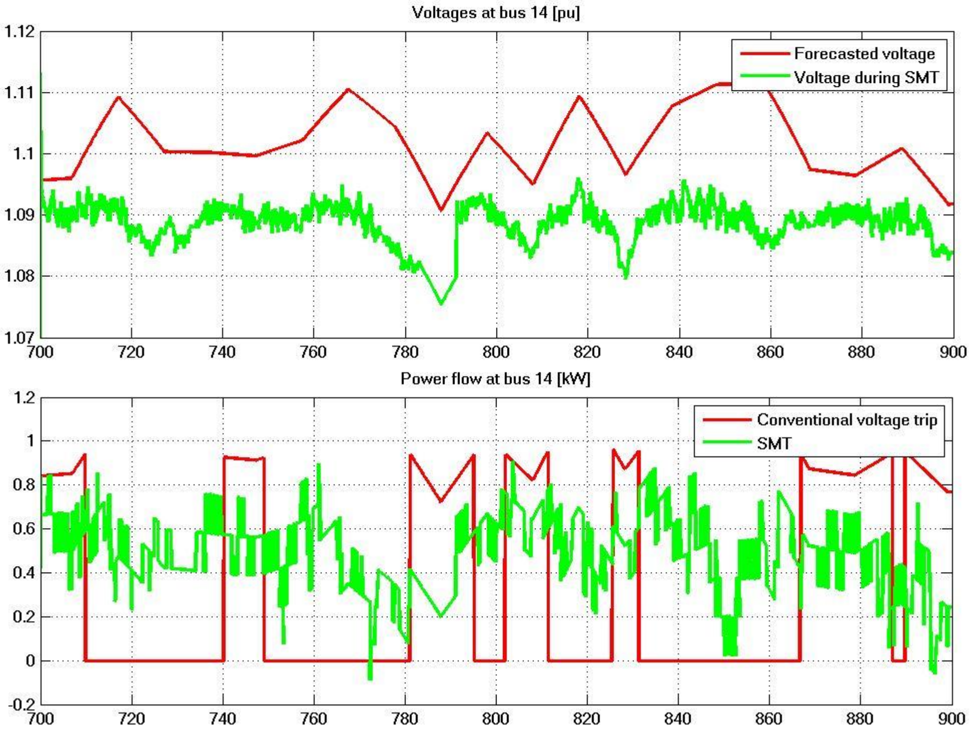

Fig. 10. Random overvoltage/curtailment events and positive effects of SMT.

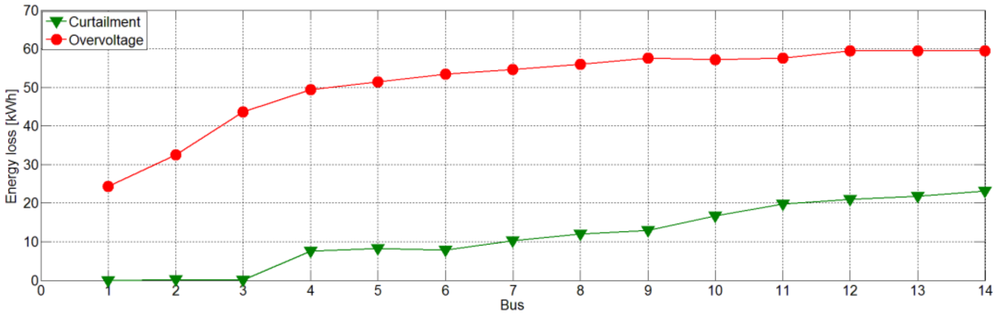

Fig. 11. Comparison of annual feed-in losses caused by overvoltage protection and curtailment.

6. Conclusion

This paper suggested several sustainability aspects to consider when carrying out the inverter retrofit for a high PV penetration scenario. In addition to DSO and prosumers, the manufacturers are highlighted as an important party in the process. Micro-inverters were chosen as a technological niche where the described sustainability issues could be met with a positive resolve. A unique curtailment method that avoids utilization of transistors was applied in feeder with increased PV penetration. Sustainability of retrofit was not quantified, however the effectiveness of curtailment was compared against basic inverter protection and quantified in annual load flow simulations. Depending on the location of PV in the distribution network, 62-100% less feed-in loss was achieved with the proposed curtailment method. Also voltage levels are maintained within operational limits. High-level outcome of proposed scheme that is presented in this paper should be complemented by more detailed studies in the future. One of them could be to assess the component reliability impact of SMT against conventional droop curtailment.

Acknowledgments

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