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Micro-inverter Curtailment Strategy for Increasing Photovoltaic Penetration in Low Voltage Networks

Ognjen Gagrica, Phuong H. Nguyen, *Member, IEEE*, Wil L. Kling, *Senior Member, IEEE*, and Tadeusz Uhl

Abstract-- Transition towards smart distribution networks with high penetration of photovoltaics (PV) will involve incidental generation curtailment as an alternative to grid reinforcements. Micro-inverters are taking over popularity of string inverters in residential and some commercial areas mainly due to increased energy harvest. This paper demonstrates how micro-inverters with a modified overvoltage protection scheme could provide a reliable curtailment solution and accommodate additional PV capacity. Two wide-area curtailment schemes were proposed for a typical Dutch residential feeder with densely clustered PV. Firstly, a single worst-case scenario was used to demonstrate the capabilities of the proposed curtailment schemes: the distribution network operators can optimize between various priorities such as total feeder output, economic equality between connected parties, voltage levels, voltage unbalance and curtailment execution time. Secondly, a yearly comparison was made against conventional overvoltage protection and the results show 62-100% reduction in overvoltage losses.

Index Terms--Distributed power generation, inverters, photovoltaic systems, power quality, smart grids, voltage control.

I. INTRODUCTION

Low voltage (LV) networks are generally not designed for densely clustered distributed generation (DG). Increasing the amount of grid-tied PV generation is limited by so-called hosting capacity of the grid [1]. Voltage rise above limits in residential areas due to high penetration of PV generation is an issue that can be handled by imposing a power injection limit [2]. A conservative approach is to say that beyond this maximum injection point grid reinforcements (adding new transformers, reinforcing cables) are required if more connected parties are to benefit from PV generation. There are alternative local measures that can be taken to indirectly mitigate voltage rise through improving load matching [3] or measures directly aimed at voltage control [4].

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A. Impact of DG on Grid Voltage

Voltage levels along the feeder vary due to increase of impedance from transformer towards the end of the feeder [2]. With no DG connected, the end of the feeder has the highest voltage drop, but with introducing DG the situation is reversed and overvoltage first occurs at the end of the feeder. Overvoltage protection standards [7] impose fixed voltage limits, but with unequal voltage levels this creates unfair distribution of the problem, by having DG at the end of the feeder to trip more often than DG closer to transformer. When controlling the voltage locally the problem is the same, which is why some forms of responsibility (feed-in loss) sharing needs to exist between DGs. For this purpose wide-area DG coordination is used, based on voltage sensitivities to active and reactive power injection [5], [8], [9].

In LV networks DG is often single-phase while the network itself (European) is three-phase. Voltage rise in an unbalanced network is especially problematic as it can cause cascaded DG tripping [10]. Therefore, voltage control needs to ensure not only voltage limits on one phase, but also voltage balance between phases.

B. Voltage Control in Distribution Networks

Voltage can be controlled conventionally by distribution system operator (DSO) with solutions including adjustment of transformer tap or installation of voltage compensation devices. Locally from DG itself, voltage can be regulated by controlling active and reactive power. In case of on-load tap changers (OLTC) it is possible to coordinate DG and OLTC control [5]. In addition, it is possible to use battery-integrated PV and locally control voltage by absorbing excess active power [6].

The impedance of LV networks is predominantly resistive ($R \gg X$). As a consequence, voltage is more sensitive to variations of active than reactive power, so using reactive power to regulate voltage in LV is not effective [8], [9]. The inverter would have to be largely overrated for reactive capacity and it would work with low power factor which contributes to losses and deteriorates power quality. Active power variation can control voltage more effectively, but since the inverter by default operates in maximum power point tracking (MPPT) mode, voltage can only be lowered by curtailing power.

The curtailment has direct economic consequences for the PV owner. Nevertheless, if the overvoltage probability [11] is low, curtailment can be profitable, because it allows PV to feed some amount of power, rather than having no feed-in at all, due to inverter trip. Secondly, most state-of-the-art inverters have digital MPPT [12], which eases the implementation of curtailment algorithms. However, it needs to be understood how curtailment affects the electronic components and how its execution might be a reliability issue in module-level inverters (micro-inverters or AC modules).

C. Benefits of Micro-inverter Topology

Module-level power conversion is becoming an increasingly popular solution for residential and some industrial-size PV installations mainly because it addresses the efficiency issue that hinders central and string inverter topologies (Fig. 1). Due to the series connected modules and the chosen PV cell topology, module mismatch in a string system impacts the MPPT efficiency in such way that, if one module fails or underperforms, the inverter will condition the output of an entire array according to the poorest performing module [13], [14]. Possible causes of module mismatch are: partial shading, soiling from dust, debris and bird droppings, and module degradation. These causes are more pronounced in residential areas due to orientation constraints and localized shading [15]. Module-level MPPT using DC-DC converters (power optimizers) or DC-AC inverters (micro-inverters) can surpass the mismatch problem and provide increase in energy harvest. In studies that only focus on an estimation on the basis of partial shading, estimated yield gain is 10%-19.5% [13]-[16]. Actual measurements in a large field study involving 143 sites equipped with micro-inverter systems have shown an average of 16% energy yield gain comparing to string inverter systems [17]. In addition to providing increased energy yield, micro-inverters have the advantage of having less risk of system failure. 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 (Fig. 1, c).

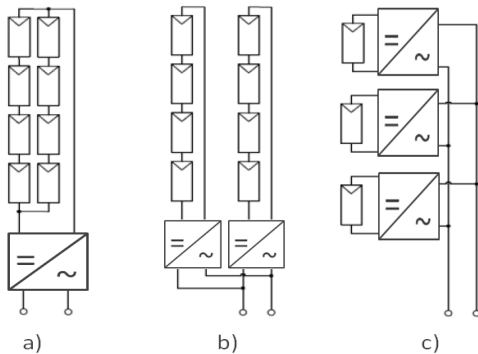


Fig. 1. Inverter topologies: central (a), string (b) and micro-inverter (c).

D. Contribution of the Paper

In this paper, the benefits of micro-inverter paralleled topology are explored for curtailment applications in order to increase PV penetration without changing the grid

infrastructure. In Section II an advanced curtailment method, in the form of a modified overvoltage protection scheme is proposed. This method avoids utilization of components with reliability issues and relies on tested inverter functionalities. By avoiding untested modes of operation, proposed curtailment is suitable even for the already deployed micro-inverters. The idea of voltage sensitivity impact on the power curtailment duration is presented in Section III, and based on it, two wide-area curtailment schemes are proposed. These schemes provide DSO with flexibility to optimize between various priorities such as total feeder output, economic equality between connected parties, voltage levels, and voltage unbalance and curtailment execution time. Methodology for calculating the annual overvoltage and curtailment losses is proposed in Section IV, offering a new idea of curtailment having a dualistic (preventive and wasteful) character with respect to overvoltage. A high PV penetration model for a typical Dutch LV feeder is presented in Section V. Simulated capabilities of the proposed curtailment schemes are presented in Section VI along with the annual comparison of curtailment effectiveness over conventional overvoltage protection.

II. CURTAILMENT MANAGED BY MICRO-INVERTERS

A. Micro-inverter Reliability Concerns

From the inverter logic point of view, implementation of curtailment requires either changing the input reference current [18], or ramping down the power output with a droop characteristic [9]. Component-wise, these actions can be achieved by changing the duty cycle of the transistors (MOSFET, IGBT) [19], or by controlling the DC link capacitance [20].

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 [21]. 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 [22]. Voltage rise due to PV peaks usually coincides with high ambient temperatures.

It should not be overlooked that in the process of increasing PV penetration not only newly installed inverters play a role, but also existing inverters with their associated warranty. If curtailment is adopted on a large scale, existing inverters must either be modified (hardware or firmware) or replaced. Firmware modification might seem less costly, but components are not tested for curtailment under elevated temperatures. This could produce unforeseen failure mechanisms and warranty could be questioned.

B. Remote Curtailment Management by DSO

Whether curtailment is going to be managed by the DSO is a matter of debate in a lot of countries. European advisory paper [23] elaborates on a range of problems concerning PV integration on a national level: insufficient framework for

implementation of local storage solutions and demand response; responsibility of DSO for financial compensation of curtailment losses to PV owners, and inability of DSO to access inverters remotely in order to manage power output.

Commercial state-of-the-art micro-inverters are deployed with data concentrators, which communicate to micro-inverters via mesh radio or power line communication while remote communication with users is done via internet. One concentrator can cover from tens to over a hundred micro-inverters. PV owners use them for monitoring and easy troubleshooting, manufacturers for more complicated troubleshooting and firmware updates. The same ICT infrastructure currently used by PV owners and manufacturers could be used by DSO in the future (Fig. 2) without additional cost, provided that business model, privacy and security are defined in the framework.

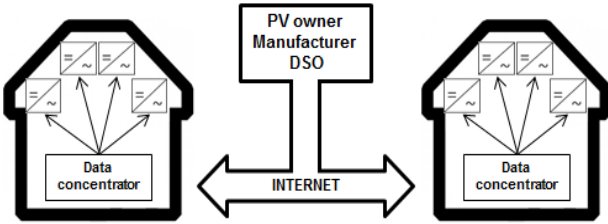


Fig. 2. Micro-inverter ICT infrastructure: presently used by PV owners and manufacturers and to be used by DSO in the future.

C. Module-level Tripping as a Curtailment Method

Each micro-inverter is technically an independent grid-connected generator, although formally it is part of one and the same PV system. This turns the PV array from monolithic into a segmented generator and allows part of the array to remain connected while the other part regulates the voltage by disconnecting.

The method can be described as a sequential, module-level tripping. Generator tripping has been widely employed on the transmission level and is recognized as the most effective way of resolving transient stability issues and sometimes to prevent overloadings [24]. Sequential breaker tripping schemes are used in transmission networks in order to limit fault currents and ensure reliable breaker operation [25]. The trip function already exists as anti-islanding/overvoltage protection in most PV inverters installed to date. Generator trip normally means an instant 100% loss of its capacity, but module trip is a partial reduction in capacity and this is where opportunity opens for the implementation of curtailment applications. The control algorithm is presented in Fig. 3.

Control range boundaries are determined by V_{START} and V_{STOP} parameters. V_{START} is kept slightly below the 1.1pu overvoltage threshold (i.e., 1.09pu). To achieve gradual curtailment, sequential tripping is proposed by introducing a trip time delay for each micro-inverter. To maximize energy output, the sequential tripping could be executed as an inverter restart, because after restart the inverter does not feed AC to the grid until it finishes its start-up procedure and closes the relay. Depending on the model, the start-up can take about 10-20s [26] which is considerably shorter than the downtime after an overvoltage event (standard minimum of three minutes [7]).

RMS voltage is checked in the loop with every trip, until V_{STOP} is reached. Such modified overvoltage protection scheme produces a “staircase” voltage response depicted in Fig. 4.

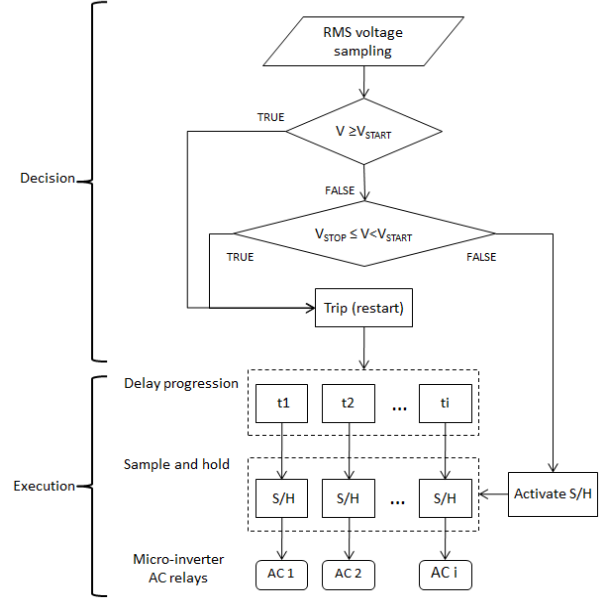


Fig. 3. Algorithm of voltage-controlled, sequential micro-inverter tripping.

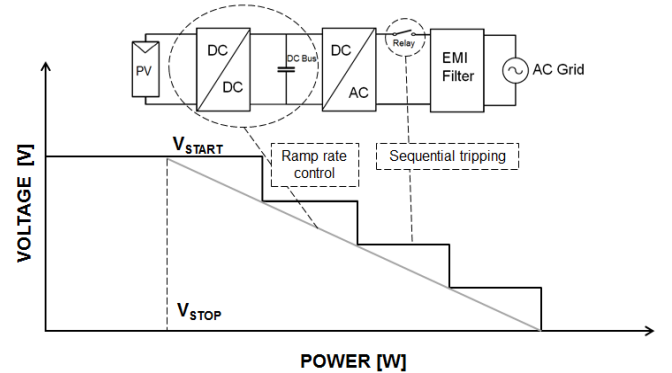


Fig. 4. Micro-inverter component utilization: ramp rate control via DC-DC stage and sequential tripping via AC relay.

The fact that each micro-inverter represents a power step of a PV system allows the curtailment to be “outsourced” from a DC bus to the AC relay. Therefore, a system level curtailment is achieved, but on the inverter level it is a trip event. This method is convenient for implementing curtailment into existing micro-inverter systems. Unlike curtailment, the inverter trip is a standard functionality tested by the manufacturer. Relays are not engaged in MPPT which is a fundamental inverter feature. Integrated micro-inverter relays are capable of 100,000 electrical operations at rated current [27]. Most commercial micro-inverters come in size 200-250W [28] with maximum output current about 1A, while relays are overrated to sustain 5-10A of continuous current [27]. Inductor coil is the key component in a relay and industry identifies inductors and resistors as the least fragile components in a power converter [22].

III. CURTAILMENT STRATEGIES

Curtaiment strategies are determined by parameters that can be configured for local action at the point of common coupling (PCC), or over a wide-area (multiple PCCs along the feeder). Algorithm considers two types of parameters: voltage control range and delay time step size. Locally, these parameters allow balancing between PV owner and DSO interests. In addition to local configuration, wide-area configuration allows balancing of internal DSO interests with respect to feeder output and response time. Trip delay and voltage control parameters can be assigned to micro-inverters via data concentrators.

A. Local Curtailment: Maximum Power vs. Voltage Priority

Changing the width of the V_{START} - V_{STOP} control range affects curtaiment losses. This concept is presented by the left chart in Fig. 5. In case of V_{STOP1} only two micro-inverters would be disconnected, while V_{STOP2} requires disconnection of five micro-inverters. Therefore V_{STOP1} would be used if green energy export is more favored than voltage level and V_{STOP2} in case of more strict voltage requirement. V_{STOP} should be determined by DSO based on their internal policy of allowed voltage rise above the nominal level. Another approach to favor green energy over voltage is to increase the delay time step between different power steps. Fig.5 shows that delay step t produces less energy represented by the hatched power-time surface, but it will bring voltage to required level faster. Since control algorithm uses RMS voltage, minimum value of t must not be less than the running average window of RMS calculation. In this paper, the window is over one cycle of fundamental frequency, or 0.02s and the step of 0.03s was assigned. Maximum t should be set in consultation with DSO.

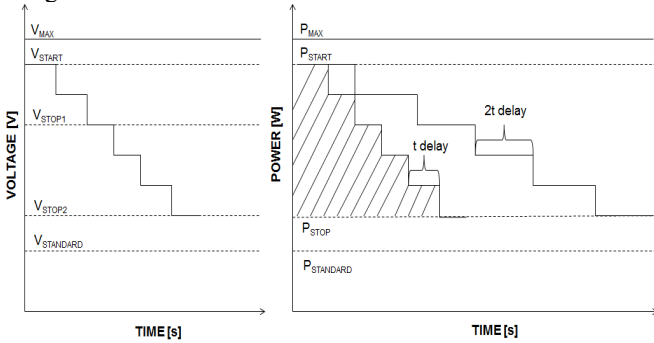


Fig. 5. Exported energy maximization vs. voltage priority by changing control range (left) and/or by changing delay time step (right).

B. Wide-area Curtailment

Having a flexibility to switch on/off each PV module in the feeder gives DSO an option to optimize over a wider area taking many issues into account. Just to name a few: strictness on voltage levels, feeder response time to disturbance, maximized output, equalizing curtaiment losses among PV owners or voltage unbalance.

1) Voltage Sensitivity Impact on Delay Step Duration

The sensitivity coefficients provide information on dependencies between load flow parameter variations. They are obtained from the load flow sensitivity matrix

$$S = \begin{bmatrix} 1 & 0 \\ 0 & |V| \end{bmatrix} \begin{bmatrix} \frac{\partial P}{\partial \delta} & |V| \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & |V| \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} = \begin{bmatrix} \frac{d\delta}{dP} & \frac{d\delta}{dQ} \\ \frac{dV}{dP} & \frac{dV}{dQ} \end{bmatrix} \quad (1)$$

where dV/dP and dV/dQ are voltage sensitivity and $d\delta/dP$ and $d\delta/dQ$ phase angle sensitivity to active and reactive power injection, respectively. In the predominantly resistive LV networks, $dV/dP \gg dV/dQ$. Even when power factor is lowered to 0.8, dV/dP is still three orders of magnitude higher than dV/dQ [8]. Because sequential tripping is targeted at micro-sized inverters, not originally designed for working under low power factor, only dV/dP is considered for the impact on delay step duration. Voltage sensitivity can be expressed differently as

$$\frac{dV}{dP} = \frac{\frac{dV}{dt}}{\frac{dP}{dt}} \quad (2)$$

where dV/dt and dP/dt represent voltage change rate and power injection rate. Voltage sensitivity increases with feeder length, suggesting that the same power injection rate produces higher voltage change rate.

Proper setting of delay step duration can decide whether curtaiment is successful or not. Success is defined by whether voltage drop rate caused by curtaiment is sufficient to counter the voltage rise rate. To prevent voltage rising to the point of overvoltage, curtaiment must satisfy

$$\frac{dV^+}{dt} \leq \frac{dV^-}{dt} \quad (3)$$

where dV^+/dt is voltage rise rate due to increase in injected power and dV^-/dt is voltage drop rate due to curtaiment.

Optimization study to determine the best delay step was out of the scope of this paper, however the general concept applied can be described: the sequential trip done at the end of the feeder should have shorter delay steps than the one at the beginning, otherwise condition (3) could be broken, leading to overvoltage. With this in mind, two possible curtaiment schemes are proposed: branch trip delay (BD) and branch-and-bus trip delay (BBD). In both schemes voltage control range is kept constant at each bus along the feeder.

2) Branch Trip Delay Scheme

The BD scheme is straightforward as it is just a copy of local setup of the last bus onto all buses. Delays only exist within local micro-inverter branch, but they will execute simultaneously on buses where voltage crosses the V_{START} threshold. This means that V_{STOP} is reached with fewer power steps and in shorter time, therefore BD should be used for strategies requiring fast response. Table I shows delay setup for each micro-inverter in the feeder. In this example, since the idea is to increase penetration to 8A per phase, there are eight micro-inverters with 1A maximum output. Note how delay sequences, although having the same progression, are phase-rotated on each bus (ABC, BCA, CAB, etc.). Since micro-inverters are single phase devices connected to 3-phase

network, having no phase rotation at each bus could create unbalances leading to cascaded tripping [10]. Having low granularity of control with maximum 24 steps (3 phases x 8 micro-inverters) is expected to lead to excessive curtailment which would be a disadvantage of BD, but faster execution is less likely to break condition (3).

TABLE I
BRANCH TRIP DELAY SCHEME [s]

	1	2	3	4	5	6	7	8
A1	0.03	0.12	0.21	0.3	0.39	0.48	0.57	0.66
B1	0.06	0.15	0.24	0.33	0.42	0.51	0.6	0.69
C1	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72
B2	0.03	0.12	0.21	0.3	0.39	0.48	0.57	0.66
C2	0.06	0.15	0.24	0.33	0.42	0.51	0.6	0.69
A2	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72
C3	0.03	0.12	0.21	0.3	0.39	0.48	0.57	0.66
A3	0.06	0.15	0.24	0.33	0.42	0.51	0.6	0.69
B3	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72
...
B14	0.03	0.12	0.21	0.3	0.39	0.48	0.57	0.66
A14	0.06	0.15	0.24	0.33	0.42	0.51	0.6	0.69
C14	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72

3) Branch-and-Bus Trip Delay Scheme

Table II shows the BBD delay setup. This particular BBD scheme is created with maximum granularity of control, which is achieved by not having any of two micro-inverters in the feeder trip simultaneously. Instead, the sequence is time shifted across each bus and phase creating 336 possible power steps (42 houses x 8 micro-inverters). The shortest delay starts at the end of the feeder (0.03s at A14) and increases towards transformer ending with 10.08s delay at C1. With so many delays used, satisfying (3) in BBD is a more complex task.

TABLE II
BRANCH-AND-BUS TRIP DELAY SCHEME [s]

	1	2	3	4	5	6	7	8
A14	0.03	1.29	2.55	3.81	5.07	6.33	7.59	8.85
B14	0.06	1.32	2.58	3.84	5.1	6.36	7.62	8.88
C14	0.09	1.35	2.61	3.87	5.13	6.39	7.65	8.91
A13	0.12	1.38	2.64	3.9	5.16	6.42	7.68	8.94
B13	0.15	1.41	2.67	3.93	5.19	6.45	7.71	8.97
C13	0.18	1.44	2.7	3.96	5.22	6.48	7.74	9
A12	0.21	1.47	2.73	3.99	5.25	6.51	7.77	9.03
B12	0.24	1.5	2.76	4.02	5.28	6.54	7.8	9.06
C12	0.27	1.53	2.79	4.05	5.31	6.57	7.83	9.09
...
A1	1.2	2.46	3.72	4.98	6.24	7.5	8.76	10.02
B1	1.23	2.49	3.75	5.01	6.27	7.53	8.79	10.05
C1	1.26	2.52	3.78	5.04	6.3	7.56	8.82	10.08

It can be seen from Table II that micro-inverters are disconnected in groups of three per branch position at each bus and when they finish one cycle from bus 14 to bus 1, the curtailment cycle is repeated on the next branch position.

Cycles repeat from branch position 1 to 8. This pattern allows both phase balanced curtailment and sharing of curtailment losses among PV owners. Management of different delay setup might seem like a complex task, but it is feasible considering the infrastructure presented in Fig 2. DSO could remotely select and activate the scheme. Data concentrators would upload the pre-programmed scheme to the micro-inverters.

IV. METHODOLOGY OF THE ANNUAL FEED-IN LOSS COMPARISON

The proposed curtailment method works as a modified overvoltage protection, so it was decided to compare the effects of its application against a baseline scenario-conventional overvoltage protection. Comparison is done for the annual load and generation data sets available in 15 min. intervals. The feed-in losses are differentiated as overvoltage losses and curtailment losses (Fig. 6).

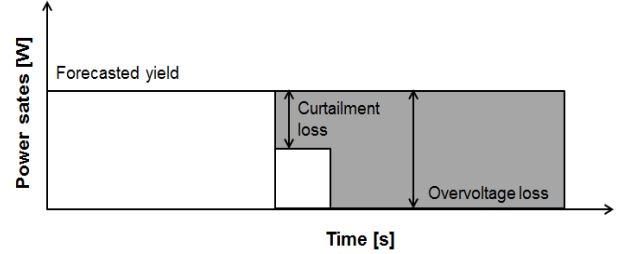


Fig. 6. Feed-in losses caused by overvoltage protection and curtailment

With a curtailment control designated to react within seconds, the simulation of annual data set takes unacceptably long. Because of that, a data filtering method is applied: the power flow first runs without curtailment in order to process the raw data set and filter out the power states that correspond to overvoltage and curtailment events. Filter triggers are based on voltage levels, $V \geq V_{MAX}$ for overvoltage events and $V_{START} \leq V < V_{MAX}$ for curtailment events. Next, power flow runs with curtailment using the filtered data set consisting only of event-related power states. Because the measured data was not available in resolution less than 15min it is assumed that the filtered event is the only event during the observed interval. In reality voltage surge due to change in power output is much more dynamic and can happen in less than 10s [19].

Conventional overvoltage event represents 100% feed-in loss during inverter downtime. Therefore overvoltage loss can be described as the sum of all annual overvoltage events

$$L_{ov} = \sum_{i=1}^k P_i t_{ov}; \quad (4)$$

where P_i - forecasted power at the moment of overvoltage, k - number of overvoltage events in a year, t_{ov} - duration of inverter downtime (most manufacturers use 5min). In the presence of the curtailment system each overvoltage event is preceded by the *preventive curtailment* event. Therefore the number of annual curtailment events is also k and curtailment loss is

$$L_c = \sum_{i=1}^k (P_i - P_{ci}) t_c \quad (5)$$

where P_c is power remaining after the curtailment event and t_c is curtailment duration under assumption that it is implemented

as a restart. Normally t_c is set at 10 sec. For the purpose of comparison, it is assumed that $t_c = t_{ov}$.

As explained in section II, curtailment is engaged at a fixed voltage level $V_{START} < V_{MAX}$. Such setup will produce curtailment events in this range, but not every forecast that crosses V_{START} necessarily leads to V_{MAX} . Every such curtailment is a *wasteful curtailment*. Therefore, to calculate total curtailment loss (L_{tc}), two curtailment event types need to be accounted for: preventive and wasteful curtailment

$$L_{tc} = L_c + L_{cw} \quad (6)$$

The former are already described in (5) while the latter are

$$L_{cw} = \sum_{j=1}^n (P_j - P_{cj}) t_c \quad (7)$$

where P_j – forecasted power during the curtailment, P_{cj} – remaining power after the curtailment, and n – number of the annual wasteful curtailment events. In this case the $t_c \ll t_{ov}$ condition stays, because these events, not being paired with overvoltage events, are not subject of direct comparison, but rather a factor that modifies the curtailment benefit. The energy benefit from introducing curtailment is then quantified as

$$E = L_{ov} - L_{tc} \quad (8)$$

V. MODELING OF A HIGH PV PENETRATION SCENARIO

A. General Modeling and Simulation Approach

For the general demonstration of capabilities of the BD and BBD schemes, a single worst-case (high generation-low load) scenario was simulated in discrete time domain. The scheme that provided a better yield was then selected for the annual feed-in loss comparison analysis. For that purpose a new simulation was performed using annual load and generation profiles.

B. Network Model

Typical Dutch three-phase LV network is used for the residential network model [29]. Four feeders extend radially from a 400kVA delta-star transformer (400/230V, X/R ratio=3.2, no OLTC), each feeder having 14 supply buses. 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, so it was included in the model. Each bus provides three-phase supply where each phase connects one house. Matlab/Simulink software is used for both network model and curtailment control model. It is computationally demanding to simulate curtailment on 168 houses with PV, so the model was reduced to one 14-bus feeder (Fig.6) with 42 houses, while the other three feeders were represented as occupied transformer capacity based on lump calculation of load and generation. Cables are modeled as RL branches and their characteristics given in Table III. Total feeder length is 0.49km.

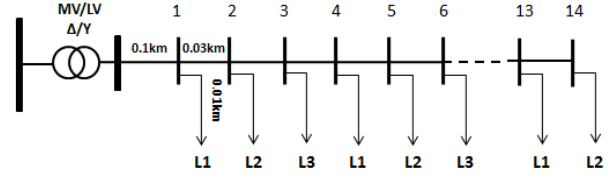


Fig. 7. Model of typical Dutch LV feeder with three alternately distributed load types.

TABLE III
CABLE CHARACTERISTICS AND LENGTHS

Cable type	Resistance [mΩ]	Inductance [μH]
0.1 km main cable	23.5	75
0.03 km bus-to-bus	7.05	7.5
0.01 km service connection	20.82	2.8

C. Generation and Load Model

1) Worst-case Scenario Model

Constant generation and load models are used. Micro-inverters are modeled as single-phase AC current sources controlled by a phase-locked loop (PLL). Their amplitude is 1A, which is realistic maximum AC output current for a 250W micro-inverter. Load at each bus is represented as lumped 3-phase load to account for three houses per bus. Three different load types (L1, L2 and L3) are used and alternately distributed along the feeder as shown in Fig 6. L1 and L2 are 360W and 650W, respectively. This data was derived from [30]. To account for a worst-case scenario 12:00 pm workday load of month of June is used. To create load diversity, L3 of 1200W is introduced and it represents average household peak demand according to [29]. Both generation and load are at unity power factor.

2) Annual Feed-in Loss Comparison Model

The model only differs in current source amplitude not being constant, but driven by annual net power flow data. Net flow data is obtained from load data in [30] and the inverter measurements, both provided in a 15-minute time resolution.

D. Increased PV Penetration Scenario

The assumption is that each of 168 houses has an equal PV capacity installed. Voltage trip limit is 1.1 pu. Under these conditions, load flow calculations showed that maximum allowed injection per phase is 5A at each house. At 6A overvoltages would occur on multiple buses along the feeder. The feeder presented in Fig. 7 is the test feeder where increased penetration to 8A per phase takes place while the rest of the LV node it remains at 5A. Each house in the test feeder is equipped with eight micro-inverters (8A). Having 42 houses with 8 micro-inverters gives DSO a maximum granularity of 336 power steps for wide-area control.

VI. SIMULATION RESULTS

A. General Capabilities under Worst-case Scenario

A constant high generation-low load scenario makes it easier to understand the capabilities of curtailment schemes on power output and voltages. In one simulation uniform low load (L1) was used in all buses and in another simulation different load types were used alternately as shown in Fig. 7. Control parameters and Simulink configuration are presented in Table IV.

1) Preservation of generation

Presented PV penetration model has voltage levels above 1.1pu in all buses. This would trip all PV in the feeder and there would be no preserved generation capacity. In this simulation such scenario is prevented by having micro-inverters with curtailment control engaged in all buses. Effects of BD and BBD on preserved generation after all buses reached 1.08pu level are shown in Table V for uniform load and in Table VI for different loads case. BBD provides 4A more than BD output on a feeder level. More indicative is the ability of BBD to curtail less power while preserving phase balance better than BD, and creating less economic inequality among PV owners. BD has four categories of curtailed users (2A, 3A, 4A and 5A) and preserved generation ranging 25%-63%. BBD has three categories of curtailed users (3A, 4A, 5A) and preserved generation ranging 38%-75%.

TABLE IV
SIMULATION PARAMETERS AND CONFIGURATION

Parameters	Simulink configuration
$V_{START}=1.09pu$	Solver: Ode45, variable step
$V_{STOP}=1.08pu$	Simulation type: discrete
Delay time step: 0.03s	Simulation step: 0.5ms
BD delay range: 0.03-0.72s,	
BDD delay range: 0.03-10.08s	

TABLE V
PRESERVED GENERATION IN AMPERES [A] FOR UNIFORM LOAD

Bus	BD				BBD			
	Phase A	Phase B	Phase C	Σ	Phase A	Phase B	Phase C	Σ
1	4	3	5	12	5	5	5	15
2	5	4	3	12	5	5	5	15
3	3	5	4	12	4	4	4	12
4	4	3	5	12	4	4	4	12
5	5	4	3	12	4	4	4	12
6	2	5	4	11	4	4	4	12
7	4	3	5	12	4	4	4	12
8	5	4	2	11	4	4	4	12
9	2	5	4	11	4	4	4	12
10	4	3	5	12	4	4	4	12
11	5	4	2	11	4	4	4	12
12	2	5	4	11	3	3	3	9
13	4	2	5	11	3	3	3	9
14	5	4	2	11	3	3	3	9
Total	54	54	53	161	55	55	55	165

TABLE VI
PRESERVED GENERATION IN AMPERES [A] FOR DIFFERENT LOADS

Bus	BD				BBD			
	Phase A	Phase B	Phase C	Σ	Phase A	Phase B	Phase C	Σ
1	6	6	5	17	6	6	6	18
2	5	6	6	17	6	6	6	18
3	6	5	6	17	6	6	6	18
4	6	6	5	17	6	6	6	18
5	5	5	6	16	6	6	6	18
6	6	5	6	17	6	6	6	18
7	6	6	5	17	6	6	6	18
8	5	5	6	16	6	6	6	18
9	6	5	6	17	6	6	6	18
10	5	6	5	16	5	5	5	15
11	5	5	6	16	5	5	5	15
12	6	5	5	16	5	5	5	15
13	5	6	5	16	5	5	5	15
14	5	5	6	16	5	5	5	15
Total	77	76	78	231	79	79	79	237

BD has four categories of curtailed users (2A, 3A, 4A and 5A) and preserved generation ranging 25%-63%. BBD has three categories of curtailed users (3A, 4A, 5A) and preserved generation ranging 38%-75%.

In case of different loads presented in Table VI, BBD maintains its advantages. Less power is curtailed due to more load being present. Another important observation is that variable load along the feeder has a beneficial effect on equalization among PV owners with both BD and BBD having only two curtailment categories of 5A and 6A. This is encouraging considering that in reality some level of stochastic variation is always present and it would be extremely rare to have a situation of 42 houses having same load at the same time.

2) Voltage Response

Both BD and BBD have the same V_{STOP} levels at each bus, therefore bus voltage levels almost match and are fairly equalized comparing to case without curtailment (Fig. 8). Significantly longer cable between transformer and bus 1 (Fig. 7) creates steep voltage increase comparing to other buses. Looking at Fig. 8 and Tables V and VI, it can be concluded that bus voltage equalization comes at the expense of unfair distribution of curtailment losses among PV owners.

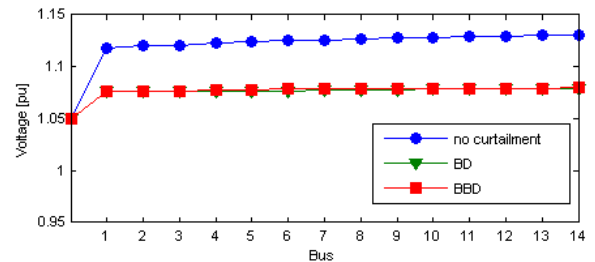


Fig. 8. Effects of curtailment on bus voltages.

Figures 9-13 show three-phase RMS voltage responses to BD and BBD schemes with different loads at bus 14. Note that in all four cases curtailment starts in the overvoltage range, although control setting is $V_{START}=1.09$ pu (Table IV). The reason for this is not because the algorithm failed to trigger at V_{START} , but due to constant generation model. Model is initialized with overvoltage state without gradual increase of power injection. The curtailment has a one-time delay of 0.5s due to PLL model initialization that takes 0.3s to complete. During the PLL initialization there are voltage transients that could be mistaken for voltage rise by the curtailment system.

BD executes faster in both load schemes, but it shows slight tendencies to create unbalance, especially in case of alternately distributed loads. Biggest voltage unbalance of 0.12% was recorded after BD scheme execution for different loads (Fig. 8). When it comes to accuracy relative to V_{STOP} both curtailment schemes perform well, BD with maximum error of 0.48% and BBD, having higher granularity of control, with maximum error of 0.32%. BBD having smaller power steps allows a smooth voltage ramp (Fig. 11-12), but it takes longer to execute.

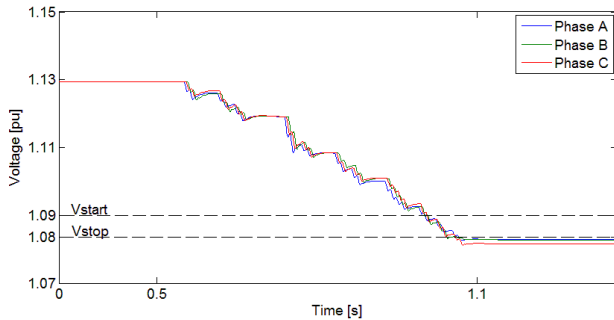


Fig. 9. Bus 14 voltage response to BD under uniformly distributed load.

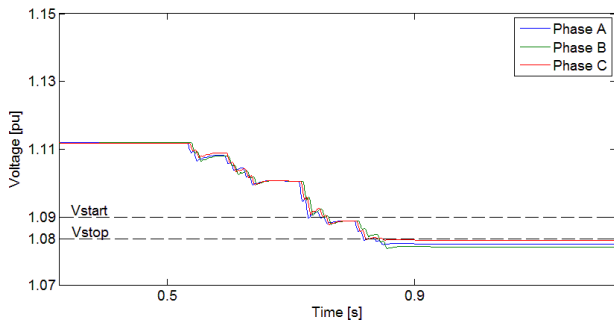


Fig. 10. Bus 14 voltage response to BD under alternately distributed load.

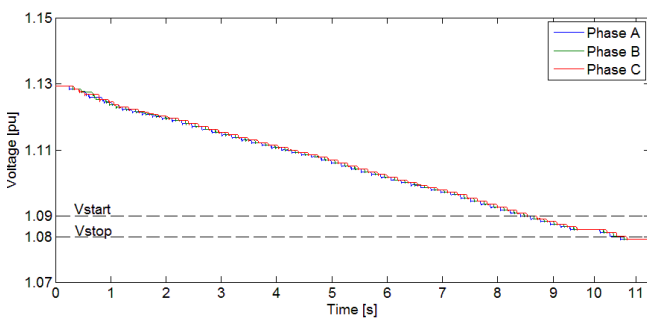


Fig. 11. Bus 14 voltage response to BBD under uniformly distributed load.

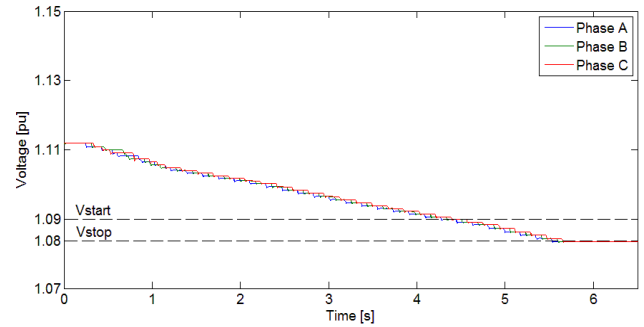


Fig. 12. Bus 14 voltage response to BBD under alternately distributed load.

It is almost similar to typical ramp rate control response, however, it is achieved not as an action of a single inverter, but as a resulting response from sequential tripping of multiple micro-inverters. This is demonstrated in Fig. 13: there is an ongoing curtailment between 4-6s with 21 power steps, although according to Table II only three micro-inverters at bus 14, branch position 5 are scheduled between 4-6s (5.07s, 5.1s and 5.13s). This shows how the entire feeder could be configured to carry out complex requests coming from a single bus.

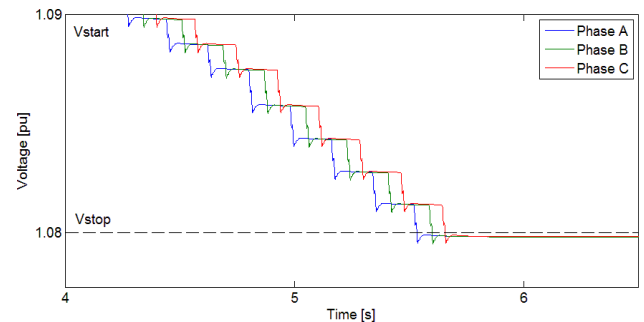


Fig. 13. Zoomed bus 14 voltage response to BBD.

3) Control System Response

Figure 14 shows on-off time series of micro-inverters at bus 14. They correspond to the 3A curtailment shown in Table VI. Delays displayed in Table II are applied, but there is a mismatch comparing to Fig. 14 even when 0.5s PLL delay is taken into account. Almost all delays are doubled, but the desired sequence is still achieved. This delay effect is caused by data transition rate handling given the constraints of the model (not fully discretized) and the solver (variable step). For a model containing over 300 different sample rates, Simulink is forced to maintain data integrity at the expense of data transition delay. In this paper the control system is developed to demonstrate the concept rather than the real-time target solution so the achieved response is acceptable.

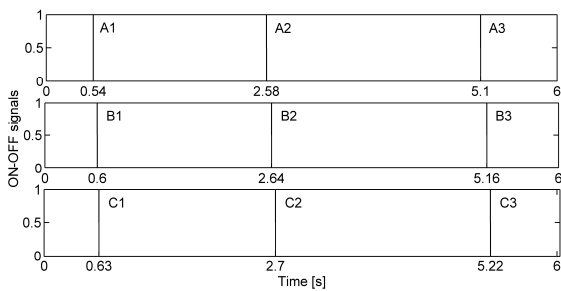


Fig. 14. On-off signal time series of micro-inverters at bus 14 (phases A,B,C) engaged during BBD under alternately distributed load.

B. Annual Feed-In Loss Comparison with Conventional Overvoltage Protection

Single case analysis revealed that BBD brings more benefits including more yield, hence it was chosen to be applied in the annual analysis. Using the methodology outlined in Section IV, comparison was carried out. Results presented here are for phase A, while results for other two phases are similar due to a balanced network model. Unlike single case scenario simulated in discrete time domain, these simulations are performed using phasors in order to reduce the simulation time.

Power flow analysis filtered the preventive and wasteful curtailment events from the annual data set as shown in Fig. 15.

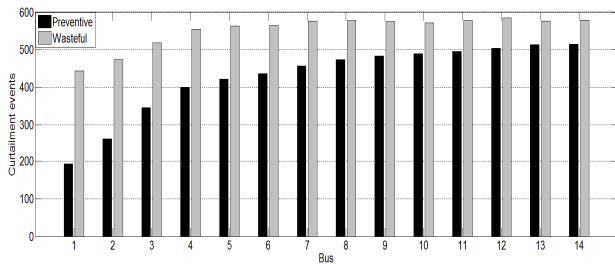


Fig. 15. Annual distribution of preventive and wasteful curtailment events at each bus.

It can be observed that, with the increased length of the feeder, the difference between the number of preventive and wasteful events becomes smaller. In other words, curtailment actions become more overvoltage-preventive towards the end of the feeder.

1) Curtailment benefits

The curtailment benefit is visualized in Fig. 16 as the difference between annual feed-in losses of overvoltage protection and curtailment. Curtailment was able to achieve max yield gain of 99.6%-100% at the first three houses which were practically not curtailed. Minimum yield of 62.3% was achieved at the last bus which experienced most intensive curtailment. In Fig. 17 it can be seen that the maximum wasteful curtailment does not go above 0.8kWh. It can be said that in the presented study curtailment has a highly preventive character that doesn't go below 96.8%.

Results for the entire feeder level are presented in Fig. 18. Curtailment brings 77.4% more yield than the overvoltage protection while wasteful curtailment share is insignificant.

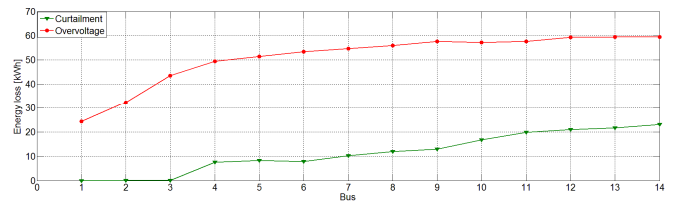


Fig. 16. Comparison of feed-in losses caused by overvoltage protection and BBD.

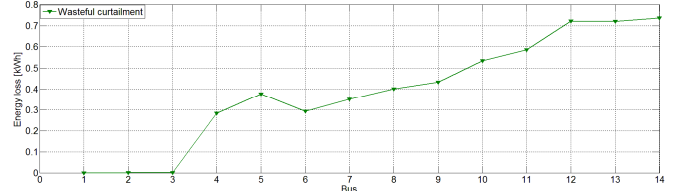


Fig. 17. Small presence of wasteful curtailment.

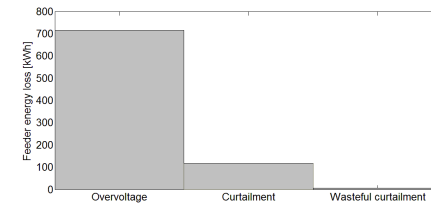


Fig. 18. Feed-in losses on the entire feeder level.

2) Voltage response

Bus 14 was selected for presentation of voltage response as it experiences the highest magnitudes and highest number of events. Once the data is filtered (Fig. 19), it is difficult to pinpoint the day or even month in which the event takes place because there is about 68 times difference in the offset between timestamps of raw and filtered data. The overvoltage prevention efficiency of curtailment is quite high with only a few instances out of 515 that curtailment was unable to successfully resolve. The situations such as the one at 3-3.25s occur because, over time, delay sequence deviates from default setting due to V_{START} level not being simultaneously reached in all buses. This further leads to incidental matching of trip times that are, by default, delayed. The underlying cause of such behavior is discussed in the next section.

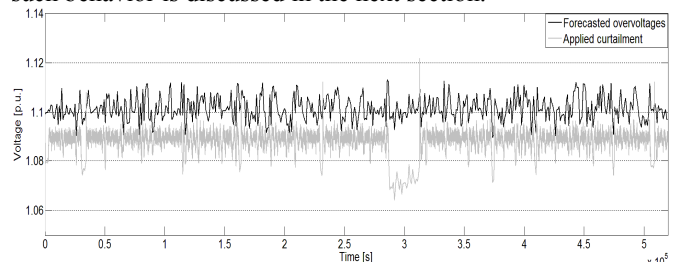


Fig. 19. Filtered, annual forecast of overvoltage incidents at bus 14 and their prevention by BBD.

VII. DISCUSSION

A perfectly synchronized curtailment action and fairly good distribution of feed-in losses among customers was demonstrated for BBD in a static, worst-case scenario. However, dynamic annual study demonstrated a different outcome. Inequality exists in feed-in losses judging by Fig. 16

and is most pronounced between the first and the last bus (22.4 kWh). The worst-case model with all buses simultaneously initialized in overvoltage is useful for demonstrating the effect of true (communication-based) coordinated curtailment, but that is not how BBD is presented in this paper. The BBD does not utilize communication between data concentrators, but only between data concentrator and micro-inverters. The annual net flow model revealed that, in reality, all buses never experience curtailment simultaneously, which distorts the default BBD delay scheme and leads to curtailment events being resolved into overvoltage. This however, happens very rarely on annual basis (Fig. 19).

VIII. CONCLUSION

In this paper, a successful PV penetration increase from 5A to 8A per house, for the case of Dutch LV feeder was presented without changing the network infrastructure. Micro-inverter topology can be utilized not only to turn PV into a more reliable energy source, but also to create a granular dispatch capability for voltage control and possibly other services of interest to DSO. Wide-area curtailment schemes were presented with ability to preserve 62%-100% of generation comparing to typical overvoltage protection. Curtailment schemes allow DSO to shift its strategy based on different priorities on feeder level such as: fast response, total feeder output, voltage levels and unbalance. Simulations performed for a balanced network model show that there is some potential for voltage unbalance to be investigated in the future. The economic equality among PV owners still remains an open question. Worst-case scenario provided a glimpse of what the results of coordinated curtailment action would look like, but to actually support that, the presented wide-area schemes must be further advanced with some form of coordination between buses. While proposed curtailment might not be able to handle equality among PV owners it is still a good step forward when compared to the baseline overvoltage protection. On the entire feeder over 550 kWh was saved by curtailment which could easily cover a monthly electricity bill of one household. From an implementation point of view, a more in-depth reliability study and an experimental confirmation would be needed to verify the viability of the sequential tripping method. Given the current level of ICT support that comes with commercial micro-inverters, already deployed PV systems could be easily retrofitted with curtailment functionality without changing MPPT or impacting reliability with untested modes of operation. This would allow an easy, cost-effective transition of module-level power electronics into a high PV penetration era.

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X. BIOGRAPHIES



Ognjen Gagrica was born in Novi Sad, Republic of Serbia in 1982. He received his MSc. in Environmental Engineering from the University of Novi Sad, Serbia in October 2008. From 2009-2012 he gained work experience in a couple of start-ups in the area of building energy management and smart grid. In October 2012 he entered a double PhD program conducted between AGH University of Science and Technology in Krakow, Poland, and Eindhoven University of Technology, Netherlands.

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Mr. Kling is involved in scientific organizations such as CIGRE and IEEE. He is the Dutch Representative in the CIGRE Study Committee C6 Distribution Systems and Dispersed Generation and the Administrative Council of CIGRE.



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