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LV distribution network voltage control mechanism: Analysis of large-scale field-test

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ABSTRACT

This work presents the results of an extensive large-scale field test of a local voltage control mechanism in Low Voltage (LV) distribution grids. The main goal of the voltage control system is to mitigate over- and undervoltages in the feeder, and for that the readily available flexibility of residential smart appliances is used. The advantage of the control system is that there is no need for a communication network between the different households within the LV network. The control system merely requires communication between the smart appliances within one household, and uses locally available measurements, such as the household supply voltage provided by e.g. a smart meter. The control system was rolled out in the LINEAR residential demand response pilot in 85 families, and was tested from December 2013 to September 2014.

1. Introduction

In recent years, three evolutions cause a decrease of predictability and an increase in variability of the power flows in the electricity system. Firstly, the share of intermittent renewable energy is growing [1]. Secondly, renewable energy generation is increasingly injected in a decentralized manner, in particular photovoltaic generation in residential neighborhoods [2,3]. Thirdly, there is an increase of the electrical load caused by a shift from fossil fueled systems towards high efficient electrical equipment for transport and heating [4]. Due to the combination of these three evolutions, distribution system operators (DSOs) are facing more complex power flows, as well as increased (local) peaks in production and consumption, on their turn influencing the (local) voltage. Controlling the voltage locally could help to maintain the grid within acceptable limits according to European EN50160 standard [5], and at the same time minimize, defer or even avoid grid capacity upgrades. Some local voltage control mechanisms to reduce overvoltages regarding distributed production have already been implemented. One of the widest adopted and most rudimentary measures consists of country-specific regulations requiring photovoltaic (PV) inverters to disconnect automatically when a maximum voltage limit is exceeded [6]. This mechanism however has significant drawbacks since it causes a lower yield of the installed PV installations and thus an increased return on investment period for the owners of the installations [7]. Additionally, this control mechanism may cause unwanted and uncontrolled voltage or frequency changes if there is high PV penetration [8]. A second method to decrease local voltage peaks due to PV injection is by a gradual curtailment of the PV inverters according to a piecewise linear droop curve. Instead of fully curtailing the PV output power when the voltage limit is exceeded, this voltage control mechanism lowers the active output power proportional to the deviation of the grid voltage. A third option for voltage regulation is the injection of reactive power into the grid [9–11]. A comparison between these three methods is given in [12]. Several lessons can be learned from the Distributed Energy Resources (DER) voltage control measures. One solution consists of adapting the above-mentioned grid voltage stabilizing methods developed for PV inverters, to loads with an inverter-type front-end, such as electric vehicle chargers [13,11]. Another approach is to use all of the flexibility of (smart) appliances in a Demand Response context to avoid voltage issues. Several methods are being developed to coordinate different loads and production units to optimize the power flows for a specific objective, e.g. minimal voltage deviations, valley filling or peak shaving [14,15]. These systems however have the

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drawback that a communication network is required that interconnects the components and all the smart loads.

This paper discusses the experimental validation of a voltage control mechanism for Low Voltage (LV) distribution networks that uses the available flexibility of the smart devices within one household [16,17]. The flexibility of all types of smart appliances is used, not only devices having an inverter-like front-end. The main advantage of the used control system is that it does not require a communication network between the different households within the LV network, nor does it require real-time coordination between households, fast-responding measuring equipment, etc. The developed control system only relies on communication between the different smart appliances within one single household, and only uses locally available measurements such as the household supply voltage. As a result, the proposed control system is easily installed and compatible with Demand Response infrastructure currently being developed, such as home gateways and smart meters.

The optimal configuration parameters for this algorithm were obtained through simulation (details in [16]) where the influence of each individual control parameter was studied in detail. Secondly, an extensive series of lab tests was performed to work out a robust and reliable communication protocol and to debug configuration issues. All technical details of the setup can be found in [18]. Finally, the developed and tested control system has been rolled out in a real life pilot in 85 existing households within the LINEAR project [19,20], tests running from December 2013 to October 2014.

The study was part of the LINEAR Smart Grids project, a large-scale research and demonstration project focused on the introduction of smart grids and demand response strategies at residential premises in the Flanders region in Belgium from 2009 to 2014 [20]. The focus of the project was finding solutions to match residential electricity consumption with available wind and solar energy while keeping the system in balance on all levels of distribution. Characterized by its scale (85 households) and its high level of integration, this pilot project gives a unique opportunity to test in the real life potential for demand response and to study user participation as described often in literature [21,22]. Working with existing household and users in real-life situations makes it possible to quantify effects such as response fatigue with users and flexibility.

2. Material and methods

2.1. Algorithm

The proposed voltage control algorithm is described in depth in [18]; in the following paragraph the basic working principles are briefly repeated. The algorithm uses the available flexibility of the smart devices within one household to control the voltage profile at the connection point of this household, by switching these devices on or off when the line voltage reaches a critical level. As a joint objective between all the households, the proposed mechanism controls the voltage profile of the whole feeder. The flexibility of different types of devices was used in the LINEAR pilot: smart wet appliances like tumble dryers, dishwashers or washing machines as well as Smart Domestic Water Heaters (SDWH) and electrical vehicles. The algorithm in itself however is not limited to these, and can be used with any type of flexible device.

In order to decide which devices to switch on or off, a hierarchical priority-based ordering scheme is used. The priority of a smart appliance is defined as a measure of the urgency to start. When the local voltage at the connection point of the house drops below a predefined lower limit (LDL), the appliances with lowest priority are delayed or if possible switched off. When the voltage exceeds a predefined upper limit (UDL), the appliances with the highest priority are switched on.

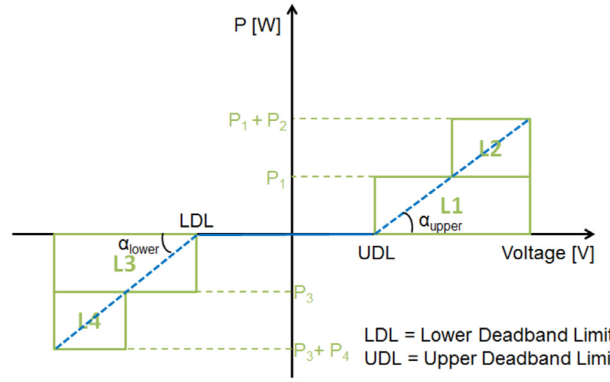


Fig. 1. Illustration of the switching scheme of the voltage control algorithm.

The priority attributed to these different appliances is calculated in the following way: when setting up a wet appliance or plugging in an EV, the user defines a deadline for the completion of the selected activity. Based on this information and the cycle time/charging time needed to finish the activity, a $t_{deadline}$ is calculated, the ultimate moment for which the appliance must switch on in order to fulfill the request and therefore guarantee user comfort. The flexibility window for this action is determined as the difference between this deadline and the configuration time of the device. For the other devices like a SDWH, the flexibility is in contrast monitored constantly and in an automatic way, without user interaction. The temperature of the hot water inside the water heater is carefully monitored, and based on these measurements together with the minimum and maximum water temperature, a State of Charge (SoC) of the heater's energy content is calculated [16]. After defining these input parameters, each appliance is then assigned a certain priority based on either its flexibility window (wet appliances and EV) or its SoC (SDWH). This priority acts as a measure of the urgency that these appliances should switch on; the closer to the deadline and the lower the SoC, the higher the priority, the farther away from deadline and the higher the SoC, the lower the priority of the appliance. The priority increases linearly with respect to time and SoC, as can be seen in the following formulas:

Electric vehicles and white good appliances:

$$priority(t) = \frac{100\,(t - t_{setup})}{t_{setup} - t_{deadline}}.$$

Smart Domestic Water Heaters:

$$priority(t) = \frac{100(SoC(t) - 100)}{SoC_{min} - 100}.$$

With t_{setup} the time at which the user programs or connects the device or EV, $t_{deadline}$, as explained above, SoC the state of charge of the water heater, and SoC_{min} the minimal allowed state of charge of the heater as set by the user.

The hierarchical device ordering scheme, based on which one or more devices are switched, is shown in Fig. 1. It shows that when the lower or upper voltage limit is reached, the Lower and Upper Deadband Limits (LDL, UDL) respectively, a load switches on or off, based on its priority. The respective smart appliances are graphically represented by the rectangles L1–L4. The height of these rectangles represents the power rating of the load. When a voltage higher than the UDL is measured, the device with the highest priority is switched on first, while during the detection of a voltage below the LDL, the device with the lowest priority is switched off or delayed first.

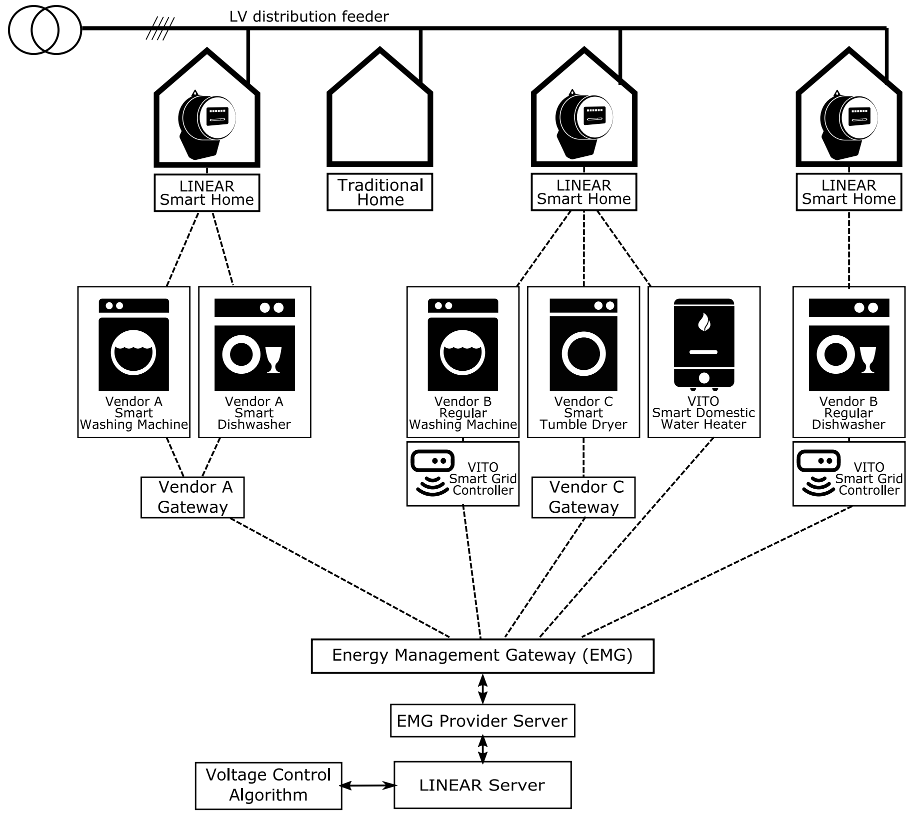


Fig. 2. Illustration of the technical setup of the appliances and communication channels during the pilot.

During extensive simulations (see [16]) based on historical consumption data, weather patterns and feeder structures, the ideal settings and parameters for the voltage control algorithm were determined. The biggest reduction in simulated voltage problems occurred when an UDL of +4% of the nominal voltage was applied, together with and a LDL of −4% of the nominal voltage. These parameter settings therefore were used when deploying the algorithm for the pilot.

2.2. Technical setup

The technical setup of the appliances and communication channels during the pilot is illustrated in Fig. 2. For each household a smart meter is installed to measure the consumed energy and to register the voltage at all phases at this connection point. These measurements are gathered together with all flexibility information of the devices in the house in a central point called the Energy Management Gateway (EMG). All this information is pushed each 15 min to a central server where the Voltage Control Algorithm is running. This algorithm decides which action each of the appliances should take, based on the household voltage and the hierarchical device ordering scheme, and these generated control actions are pushed back to the Energy Management Gateway, which distributes them back to the single appliances. In the pilot test the central server was an external server outside the household since also other experiments that required centralized control across all houses were conducted on this setup. However the algorithm can irrefutably also be run locally inside the household itself, therefore the system has no need for an external communication network. The flexible appliances used in the pilot were smart wet appliances, consisting of tumble dryers, washing machines and dishwashers, Smart Domestic Water Heaters (SDWH) and Electric Vehicles (EVs). The water heaters were exclusively developed in our own labs for these experiments [18]. Lastly, the electrical vehicles were plugged in to the wall with a smart socket–plug, which could be switched on or off depending on the desired action coming from the algorithm. For various reasons, see [20], the availability of the EVs suffered a lot from user response fatigue, which leads to the fact that the EVs did not offer their flexibility at their full potential in this field test. For that reason, the results of the EV-use will be omitted in the direct comparisons between different flexibility appliances. For any further details on the technical setup, we refer to [18].

2.3. Field test

After extensive testing in a closed lab-environment [18], the system was rolled out in the field in 85 households from 5 December 2013 onward. These were situated on different feeders in two different neighborhoods in the east of Flanders: one set in the community Brett–Gelieren (31 households) and the other set in the communities Hombeek and Leest (54 households). During a period of in total 187 active days between December 2013 and September 2014 the voltage control algorithm was active in these houses. During that time the voltage was accurately measured by the smart meters in each household and actively controlled by the use of the smart appliances participating in the project. Periods of three weeks active control were alternated with periods of three weeks when no control was applied. This makes it possible to do a thorough comparison between the voltage profiles in base case versus those during the voltage control.

Fig. 3 shows an example of the operations of the voltage control algorithm during the pilot. To interpret the figure it is important to know that the default behavior of this SDWH is to switch on whenever the SoC is lower than 60%. The figure clearly shows that the SDWH is instructed to start heating once the measured voltage crosses the upper limit. A period of 2 h is seen where the water heater is in a state of increased consumption because the upper

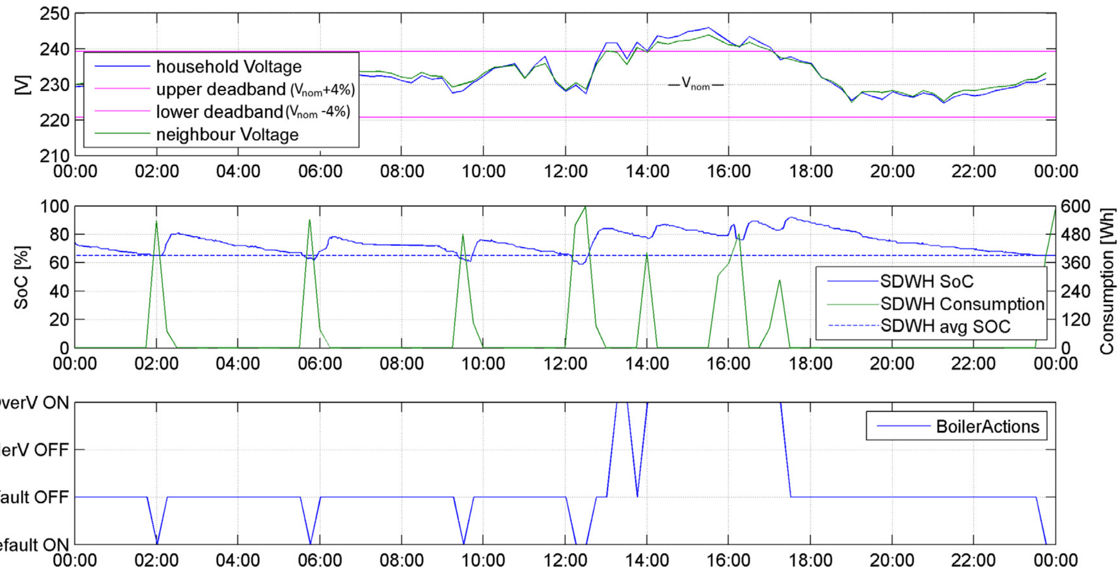


Fig. 3. The top chart depicts the measured voltage profile for 24 h one of the households participating in the pilot, accompanied by the voltage profile of the neighboring household. In the middle the SoC and consumption of the SDWH in this household are shown. At the bottom a visual representation of the actions that were sent to the SDWH during the day.

deadband limit was crossed. It is clear to see how the water heater was repeatedly switched on to consume more power and therefore to try to lower the voltage.

3. Analysis of results

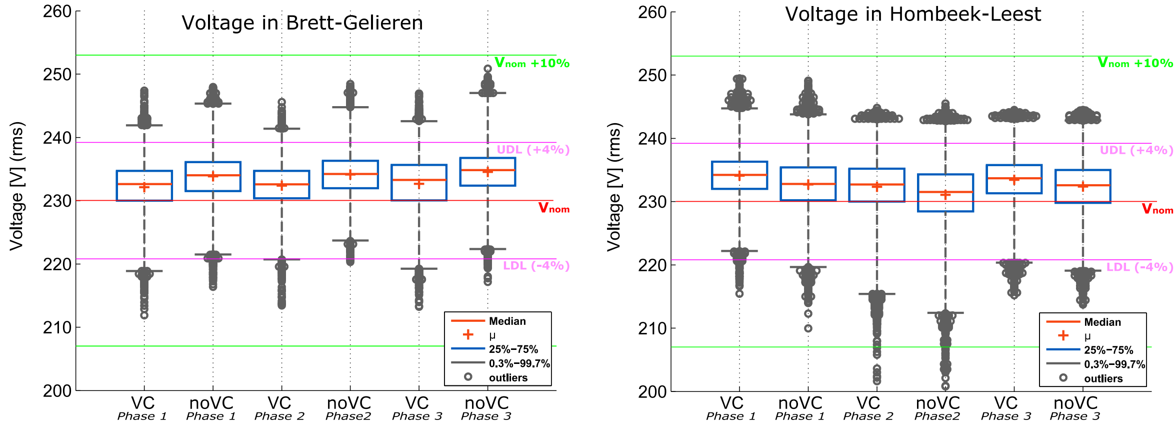
3.1. General results

Based on the fact that voltage profiles are highly correlated with climatological factors like the outside temperature as well as the amount of sunshine (a.o. due to the amount of PV on the rooftops of houses in these feeders) [23], the results from the voltage measurements are compared between days where the climatological factors are similar. Using data from the Belgian Center for Climate and Weather on the amount of sunshine during the day and the local temperature measurements in those neighborhoods, similar days were selected from both the period where the Voltage Control Algorithm was active ('VC') and where the VC Algorithm was not active ('no VC').

When we compare the voltage profiles for the households on similar days we notice a trend between the days when the algorithm was active and when it was not. The results can be seen in Fig. 4. We notice in the neighborhood of Brett–Gelieren explicitly that the days where the Voltage Control Algorithm is not active, the voltage is less confined in the top segment and reaches higher peaks over all the phases. The fact that we see a smaller percentage of the voltage profile exceeding the Upper Droop Limit in the Voltage Control case, can probably be assigned to the reaction of the algorithm, which switches on appliances once this threshold is crossed in order to lower the voltage again. In the case of the Hombeek–Leest neighborhood we see this effect much less clearly, due to the fact that in this neighborhood the houses of the pilot project were spaced much further apart form each other on the same feeder, diminishing their overall effect. Here, both the top segment of voltages of both the Voltage Control case and the reference case are very similar. Still the bottom segment is clearly more confined in the Voltage Control case. This could possibly be attributed to the reaction of the algorithm once again, which delays planned load at peak moments (low voltage) once the threshold is exceeded in order not to push the voltage more down, while in the reference case the unaltered, simultaneous use of different loads at peak moments may drive the voltage further down. However, although these clustered voltage profiles indicate some promising trends, it is clear that the Voltage Control algorithm and the available flexibility seem to fall short on many occasions to have an impact on the voltage profile on the total feeder. In the next paragraphs the root causes for this are investigated.

First of all, there is a significant discrepancy between the amount of time the algorithm detects a situation where action is required and the amount of smart appliance actions it can actually perform. The result of this analysis can be seen in Fig. 5. More than 95% of the voltage threshold crossings do not lead to an action (1161 measured actions vs. 30,461 threshold crossings), this is due to a lack of flexibility at that particular household at that particular moment. The main cause for this is the limited amount of appliances per household participating in the algorithm (on average 2 appliances/household), and because many of the smart appliances are not configured for action for the majority of the time. This is especially the case for the wet appliances, which were the vast majority of installed smart appliances in the pilot (93%). Firstly participants only used the smart option of the devices part of the time (smart configurations were between 30% and 50% of the time for the different types of appliances, for details see [20]), which partly impacts the availability of these loads. But secondly and most importantly, these type of appliances are only configured every few days, which only adds up to a handful of available hours every week. This greatly limits the overall availability of flexibility at the household at any given time during the day.

Analysis of the action logs showed a great discrepancy between the distribution of appliance types that were installed in the field test and the number of contributing actions each type had performed in the end (see Fig. 6). We see that most of the wet appliances perform poorly in fulfilling their flexibility role, in particular the washing machines and the tumble dryers. This can be attributed to the limited availability (handful of hours every week) of these appliances as explained before, but some additional aspects add to this ineffective performance. First, this flexibility period of wet appliances usually falls during the night (with deadline set in the early morning), where the least calls for action are made (as shown in Fig. 5). Secondly, each wet appliance can only participate with upward flexibility once every cycle: after a switch-on the machine is allowed to finish its work undisturbed in order not to compromise user comfort.



(a) Voltage profile in Brett–Gelieren.

(b) Voltage profile in Hombeek–Leest.

Fig. 4. Comparison between voltage profiles in both neighborhoods of the pilot. For all phases we see a comparison between days where the voltage control algorithm was active ('VC') and those where it was not active ('noVC'). The green line depicts the boundary between which the node voltage should be contained for 95% of the time according to the EU EN50160 standard [24]. Note that the whiskers of the box plot contain 99.4% of all measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

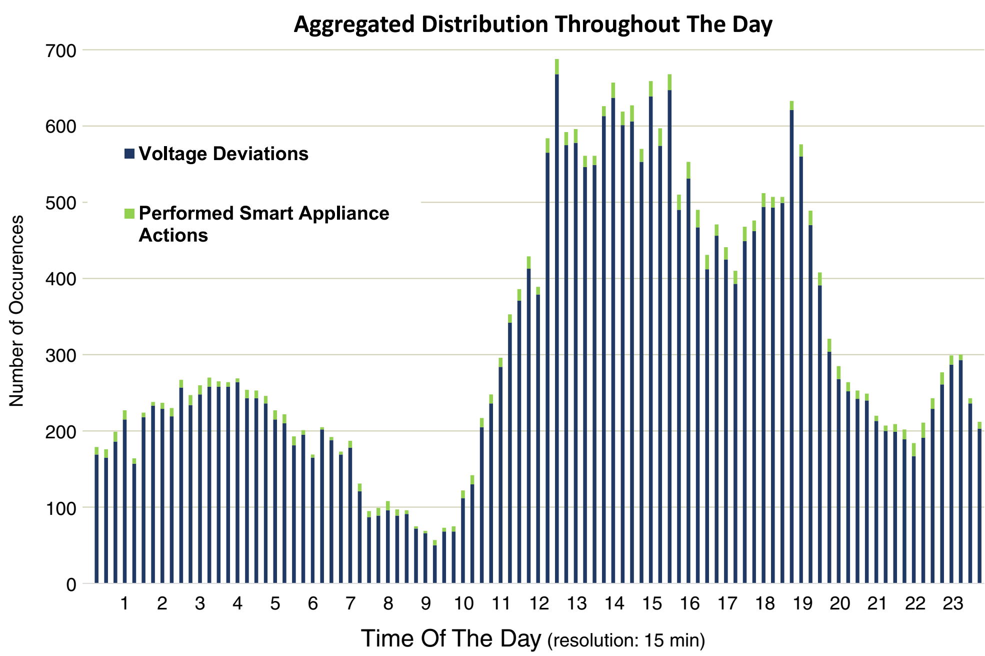


Fig. 5. Aggregated distribution throughout the day of the prevalence of voltage deviations and the performed smart appliance actions. The discrepancy between the amount of flexibility requested and flexibility given is due to the lack of flexible appliances at the right time on the right phase in each household.

The Smart Domestic Water Heaters on the contrary, show an excellent behavior compared to their prevalence in the study. While representing only 4% of the amount of smart appliances in this field test, they took more than 70% of the actions to their account. The reason for this is that Smart Domestic Water Heaters are available for 24 h a day; no user interaction is needed for this device. And additionally when a SDWH is used at one instance to solve an overvoltage issue, it can still be used in the next time slot for another section of upward flexibility, for as long as its maximum state of charge is not reached. This is a crucial advantage compared to the other appliances, since overvoltages are likely to recur quarter after quarter.

From the previous findings we can conclude that Smart Domestic Water Heaters are the most interesting smart appliances in a household to control the local voltage. The combination of large power, nearly 24/24 h availability and the possibility to intervene and take action multiple times a day without 'time out'-period makes the smart hot water buffer a particular useful tool to balance local voltages issues.

3.2. *Selective analysis of SDWH-potential*

The actual potential of a fully developed out-roll of Smart Domestic Water Heaters in a full neighborhood can be estimated by doing a sub-analysis of the field test results. The effect is investigated of running the voltage control algorithm in only the subgroup of houses where a SDWH was available.

To quantify the potential of a full roll-out of Smart Domestic Water Heaters in a neighborhood, we concentrate on the effect that controlling actions with these appliances caused. We isolate the instances where the measured voltage at the household exceeded our Deadband Limit (UDL or LDL) and looked at how the voltage behaved during the following quarter.

In Fig. 7, the characteristics of the voltage profiles are plotted for four different households that were all equipped with a SDWH, together with the sum of these profiles. The *y*-axis depicts the average drop the line voltage experiences after it has exceeded the UDL in the previous quarter, for both the default case as the

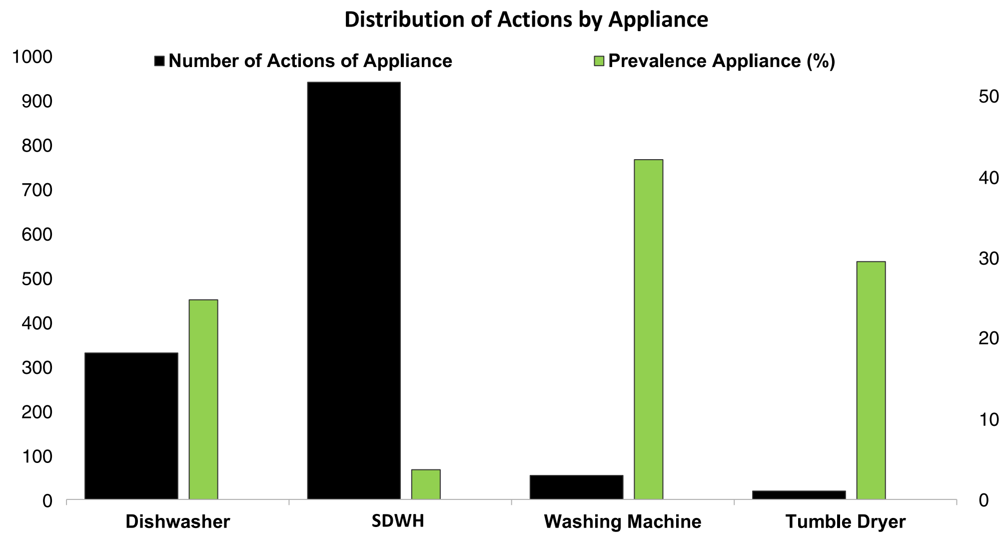


Fig. 6. Distribution of performed action by appliance type combined with prevalence of each appliance type in the study. Notice the impact the SDWH has for the limited number of appliances in this study.

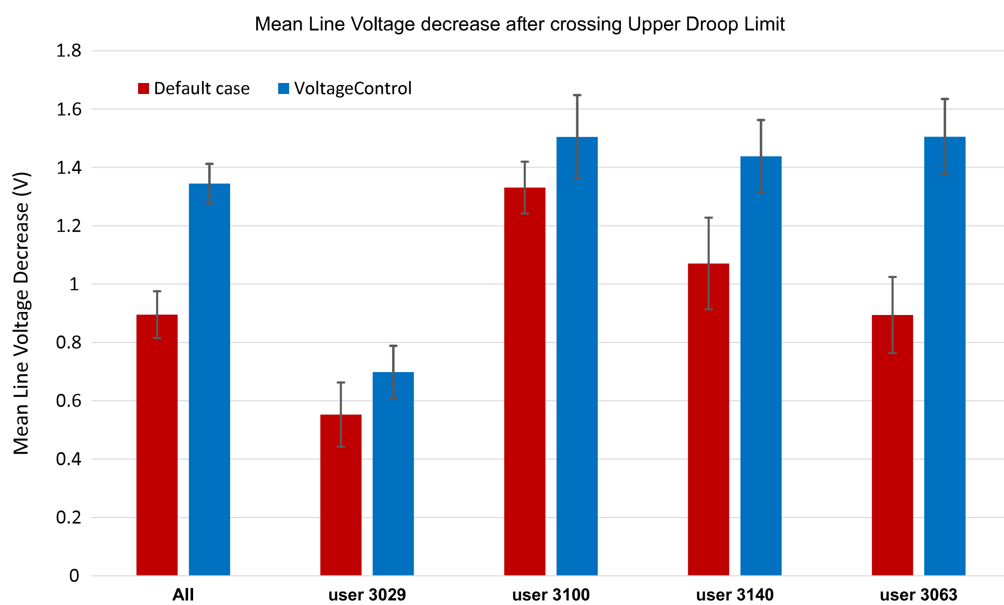


Fig. 7. Average line voltage drop for different households equipped with a SDWH for both reference case and Voltage Control case.

case when the voltage control algorithm is active. The averages are calculated over tens of thousands of data points, covering the whole testing period of the pilot and are based on the following formula:

$$\overline{\Delta V_{line}} = \frac{1}{n}\sum_{i=1}^{n} V_{line}(\tau_i) - V_{line}(\tau_i + 1)$$
$$\forall\, \tau_i\ :\ V_{line}(\tau_i) > 1.04\, V_{nom}.$$

With V_{nom} being the nominal voltage of 230 V, V_{line} the measured voltage by the smart meter, τ_i the time of overvoltage detection and $\overline{\Delta V_{line}}$ being the average line voltage drop after an overvoltage detection.

It can be seen in Fig. 7 that in the default case, when no directed action was applied to lower the voltage after reaching the critical level, still a positive drop is experienced of almost 0.9 ± 0.08 V as a result of uncoordinated external factors. In the Voltage Control case however, this average voltage drop is significantly higher, 1.4 ± 0.07 V on average. The error margins for both cases are given, and it can be seen that due to the proportion of the sample size, the measured difference is highly significant. An independent-samples t-test was conducted to compare $\overline{\Delta V_{line}}$ (average line voltage drop after an overvoltage detection) in the reference case and Voltage Control case. There was a significant difference in the scores for reference behavior (M = 0.895, SD = 0.080) and the Voltage Control case (M = 1.345, SD = 0.068); $t(2322) = -4.2803$, $p = 1.942 \times 10^{-5}$. These results suggest that when applying the algorithm in houses where a SDWH is available, the voltage can be lowered actively after an overvoltage detection.

As mentioned before, periods of uncontrolled reference behavior were alternated with periods of Voltage control every three weeks, to ensure a reliable measurement of the impact of the algorithm.

The influence of the active control of Smart Domestic Water Heaters by the voltage control algorithm in these households is significant. It shows that by controlling the heating cycle of the water heater, it is possible to actively control and influence the line voltage in case of overvoltages. The size of this influence however, has its limitations. This is mainly due to the ratio of the smart load versus the uncontrolled load within the household and additionally to the fact that direct neighbors are not using the system, which makes it much harder to achieve a change in line voltage. Clearly, the effect would be more profound on neighborhood level, and therefore increase the potential of this kind of control mechanism, if the size of the smart controllable load would be bigger. This could either be achieved by increasing the number of appliances controlled, or the number of houses connected to the control algorithm.

Even though the size of the effect is small, these results show that it is possible to actively influence line voltage with domestic appliances and it indicates that in those situations where Smart Domestic Water Heaters are widely used, the here proposed voltage control algorithm has potential.

4. Conclusion

We developed a voltage control algorithm that makes it possible to control the line voltage of a low voltage distribution grid by using the flexibility of household appliances. Based on the locally measured voltage it is decided whether or not action should be taken, and if necessary the smart appliances in the household are switched on or delayed their task in order to confine the line voltage within certain limits. The main advantage of this control system is that it only uses appliances available in homes for a general purpose like controlling the neighborhood voltage, but still can work independently for each household. There is no need for a communication network between the different households on the feeder, which avoids cost, has low technical complexity and which makes it ideal for scaling up to larger systems.

The developed mechanism was deployed in a pilot composed of 85 real households in the eastern part of Flanders, Belgium. The algorithm functioned correctly and had measurable interventions as shown in certain example cases. On the neighborhood level however, its effect was limited and not unambiguously detectable in voltage measurements. The absence of effect on general profile was due to the fact that a lot of overvoltage detections of the algorithm, opportunities for interventions, could not be met because no flexibility was available at that moment in that specific household. Specifically the wet appliances underperformed due to a lack of availability in real-life situations. The most successful and active apparatus in this study was the Smart Domestic Water Heater, since it has a large power, is available for 24 h/day and can be switched on and off when needed, as long as the comfort requirements are respected. When focusing our analysis to only the households with Smart Domestic Water Heaters, the effect of the controlling algorithm was very clear. It was shown that the algorithm was able to make a statistically significant difference in correcting the voltage profile when the threshold value was exceeded.

In conclusion it can be said that the potential of line voltage control by using the flexibility of domestic appliances is proven, but the focus should be on those appliances that can be online for a large portion of the day (if not 24/24). As our result show, Smart Domestic Water Heaters have a potential for controlling local voltage, but also Electrical Vehicles or smart heating and cooling systems could meet these requirements.

Acknowledgments

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