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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.

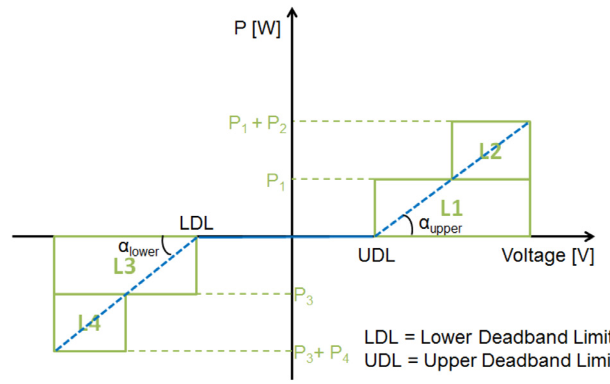

Fig. 1. Illustration of the switching scheme of the voltage control algorithm.

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.