REVIEW OF THE SMART OPERATOR IN THE FIELD

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ABSTRACT

The paper gives a review of the experience that has been gained in the field from operating an autonomous active central unit in a low-voltage grid. It can be concluded that the central intelligence – the Smart Operator- is suitable for voltage control in low-voltage grids. Compared to the grid operation without the Smart Operator the number of voltage limit violations are reduced to a minimum. The schedule-forecast (depending on weather forecast data) for the installed assets by the Smart Operator is of high quality since most of the time the schedule control leads to normal operation and an imminent limit violation is preventively averted. It can be derived that some assets are used more frequently of the Smart Operator and therefore are more valuable for an active grid control.

INTRODUCTION

The number of Distributed Energy Resources (DER) in Europe and the according feed in of power is significantly increasing. Especially in distribution grids this causes problems and voltage rise is one of the biggest issues. Consequently, the increasing power of DER requires reinforcement measures in order to achieve a safe, reliable and optimal grid operation. Instead of reinforcing grid assets in the conventional way, an active control of intelligent assets (on-load tap changer (OLTC), low voltage network switch) and local flexibilities (electric-vehicle charging station, battery storage and intelligent household appliances) is achieved by using a Smart Operator (SmOp) [1], [2].
After a successful validation phase of the Smart Operator and its self-learning algorithm in a laboratory of the Institute for High Voltage Technology at RWTH Aachen University [3], the Smart Operator is further validated in three German low-voltage grids with high feed-in from renewables [4]. The project consortium consists of RWE Deutschland, PSI, Horlemann Elektrobau, Hoppecke, Maschinenfabrik Reinhausen, Stiebel Eltron, RWTH Aachen University (RWTH) and University of Twente. This paper highlights the experience that has been gained from the autonomous control of the Smart Operator in one of the three low-voltage grids.

THE FIELD TEST REGION

The Smart Operator was put into operation in the field test region of Wertachau in June 2014. The SmOp uses optical fibre to communicate with the assets. 150 of the 202 households

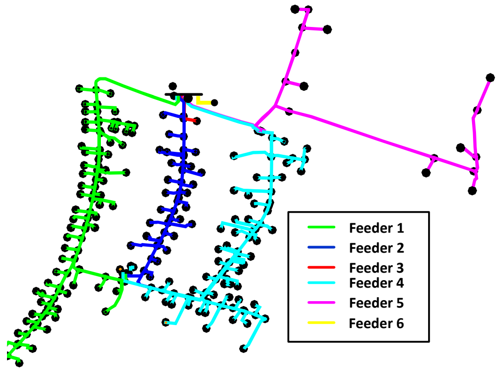

Figure 1: Topology of the field test region Wertachau

are equipped with smart meters. 23 of the households are equipped with a Home Energy Controller (HEC) [5]. In total, the field test region holds an installed photovoltaic (PV) power of about 200 kWp, 10 storage heaters and 8 hot water tanks. The controllable actuators of the Smart Operator include one OLTC, one battery storage, two charging stations, two network switches and the mentioned 23 HECs. Figure 1 shows the grid topology of the field test region and its 6 feeders.
An overview of the installed actuators of the field test region is provided in **Table 1**. The feeder numbers indicate the position of the actuators.

Table 1: Actuators and their location in Wertachau

Actuators	Amount	Feeder number
OLTC	1	-
Charging station	1 (up to 44 kW)	4
Battery storage	1 (150 kWh, 80 kW)	4
Network switch	2	(1-2), (2-4)

THE SMART OPERATOR

The Smart Operator is an autonomous active unitor centralized operation of a low-voltage grid based on a learning algorithm [2]. The goal of the SmOp is stationary voltage control and the avoidance of asset overloading. To achieve this goal, the SmOp includes a metering system, which is installed in the grid, to measure the state of the system and suitable actuators to affect the state.
The operating process of the SmOp consists of the execution of the steps shown in Figure 2 once every minute. First, measurement data is acquired by the smart meters installed in the field. The schedule control is executed, based on the system state that is determined by a state estimation utilizing the measurement values. Here, the predicted day-ahead schedule of each actuator is checked for validity for the current time slice. If there are limit violations, deviations from the planned behavior

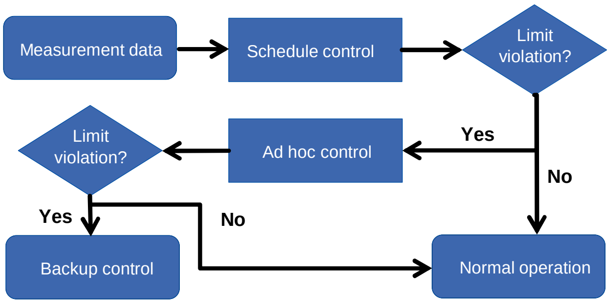

Figure 2: Process steps of the Smart Operator

must take place – an ad hoc control action is performed. If there are no limit violations, the actuators are switched accordingly and the cycle is ended. The ad hoc control tries to find a new solution when the quality of the schedule is insufficient. For this purpose, depending on the location of the limit violation, feeder control or grid control is available. In the first case, it is attempted to fix the limit violation only on the basis of the actuators in the affected feeder. If this is unsuccessful or more feeders are affected, a complete grid control is performed. In the grid control all actuators are being involved in the control, in particular the OLTC and network switches. If this is successful, the schedule is updated accordingly and the actuators are switched. Afterwards a dead time is active for the current quarter hour. On failed ad hoc control a simplified rule-based backup control is performed, which takes over the control in case of insufficient training data. With increasing operation in the field this backup system should rarely be used.

The applied algorithm, unlike many other solutions for grid control, is not based on a rigid set of rules. Rather, its actions are based on the experiences that are made during operation. These experiences are also dependent on exogenous variables such as global irradiance, temperature and time. It is therefore not possible to directly derive the concrete behavior of the Smart Operator from the current grid status (if condition x then set actuators y). This fact increases the complexity of validation considerably; however, it offers the advantage that the SmOp can respond flexibly to new grid use cases as well as novel actuators. Furthermore, the method allows, in the environment of a highly stochastic supply task, a sufficiently detailed 24-hour forecast to determine the planned actuator activity based on the ever-adapting experience base. This forecast is particularly important for the efficient use of actuators with time coupled restrictions (state of charge of battery storages, flexibility of a household). [2]

The objective function of the SmOp can be adjusted via a weighting term (the sum of the term equals one) so that either voltage control or avoidance of asset overloading is prioritized [2]. In the field test region, the objective function is set as follows:

- 80 % voltage control
- 20 % avoidance of asset overloading

Consequently, the focus is on voltage control. Individual voltage limits are assigned to each of the three different field test regions, as well as the feeders of the grids (deviating from the applicable standard DIN EN 50160 [6]). For this, recorded voltage profiles of the grids were analyzed before commissioning the field test grids. Based on the analyzed voltage profiles and the existing actuators in the grids, the voltage limits in the field test region Wertachau were set to +/- 5 % around the nominal voltage. The data management of the algorithm is chosen such that the parameters can be adjusted for each grid at any time.

FINDINGS

To validate the effectiveness of the Smart Operator in the field the following three aspects need to be examined:

- Voltage control
- Control behavior
- Utilization of the actuators

For the different field test regions individual voltage limits are defined to be abided by the active operation of the Smart Operator. One part of the assessment of the effectiveness of the SmOp in the field therefore is the study of voltage control.
The SmOp has different control modes for the active grid operation (see Figure 2). An evaluation of the control behavior shows which control mode the SmOp uses to fulfill the operational tasks.
Furthermore, an analysis of the actuator use by the Smart Operator is done. The analysis provides information about the reliability and the frequency of use of actuators. In addition, it is differentiated in which control mode the SmOp uses the actuators.

Voltage control

The following review of the violations of the self-defined voltage limits gives information about the effectiveness of the voltage control. The control mode of the SmOp is not considered at this point. The three phase voltages, which are minutely acquired by the smart meters, are averaged. All acquired voltage values of the second half of the year 2015 are validated.
Table 2 contains an overview of the voltage violations separated by month. The violation of the lower voltage limit (LVL) and the upper voltage limit (UVL) are differentiated as well. The number of the voltage values in the period of six months that do not violate the voltage limits is 99.98 % or higher. This means that the voltage is in between the limits +/- 5 % around the nominal voltage. Minimal proportions of violations to the lower limit occur in feeder 1 and 2 in some of the months. The minimum values are at about 217.4 V.

Table 2: Overview of the voltage limit violation

Month	LVL	No violation	UVL	Min Voltage @LVL [V]
07-15	0 %	100 %	0 %	
08-15	0.01 %	99.99 %	0 %	217.4
09-15	0 %	100 %	0 %	
10-15	0 %	100 %	0 %	
11-15	0.01 %	99.99 %	0 %	217.6
12-15	0.02 %	99.98 %	0 %	217.4

Control behavior

As main measure of the voltage control, the Smart Operator creates a schedule for the existing actuators - the schedule control. If an actuator is active due to a schedule control action, it can be assumed that an imminent limit violation is preventively averted. If during the operation the Smart Operator determines that the schedule control cannot meet the voltage limits at one point of time the ad hoc control action takes place. Thus the times of schedule control should dominate the times of the ad hoc control.

The total share of the ad hoc control with respect to the one-minute time slices over six month is 0.68 %. It can be concluded that the schedule control meets the operational task in over 99 % of the time. Table 3 shows the results of the ad hoc control processes.

Table 3: Number of Ad hoc controls (successful/overall)

Month	Feeder control	Grid control	Backup control
07-15	12/323	490/491	1/1
08-15	29/29	15/22	7/7
09-15	101/101	53/57	4/4
10-15	77/79	65/143	80/80
11-15	92/131	61/68	46/46
12-15	135/150	81/130	64/64
∑	**446/813**	**765/911**	**202/202**

Regardless of the ad hoc control mode, all given limit violations can be fixed. The effectiveness of the Smart Operator is reflected in the 100 % success rate of the ad hoc control. In feeder 1 the feeder control actions are performed by a network switch and in feeder 4 by the battery storage and a charging station. The feeder control succeeds in 55 % (446/813) of the cases. The success rate of the grid control is 84 % (765/977).

Figure 3 shows the number of ad hoc control actions per day as a histogram. In less than 12 days the number of ad hoc control actions is more than 30. At these days the forecast of the SmOp is not effective due to a low quality of the weather forecast. However, this number of days is only 7 % of the total number of days in the six months and therefore is rather small.

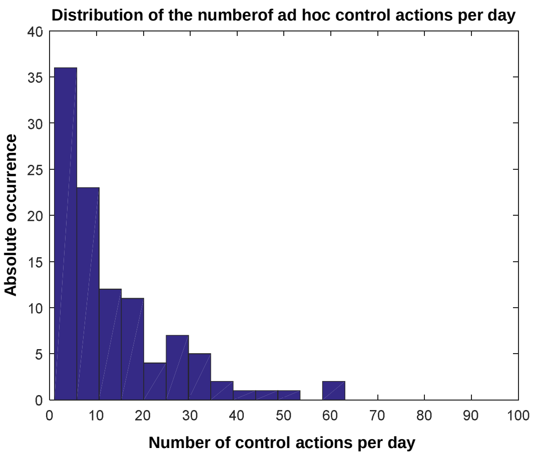

Figure 3: Distribution of the number of ad hoc control actions per day

Utilization of the actuators

The Smart Operator uses the actuators for schedule control and ad hoc control in order to control the voltage. Table 4 shows the proportion of the actuators in active state in the second half of the year 2015. With 69 %, the battery storage is the most active actuator. In general, the battery storage is defined as active if it generates or consumes a power unequal to zero). During its active state the operation is mainly triggered by the schedule control (99 %) as figure 4 shows. Only 1 % of the active state is triggered through the ad hoc control.

Table 4: Overview of the active state of the actuators

Month	Actuator	Active
07-15 to 12-15	Battery storage	69 %
	OLTC	9 %
	Network switch 1	1 %
	Network switch 2	0 %

In 9 % of the time the OLTC is not in its neutral position so that the OLTC is active and the voltage is actively controlled. However, with 267 tap changes throughout the six months, it is one of the rarely used actuators. 64 % of the tap changes are triggered by the schedule control.
The network switches are very rarely closed and therefore are rarely active (Network switch 1: 1 % and Network switch 2: 0 %). 97 % of the control actions of the first switch originate from the schedule control.

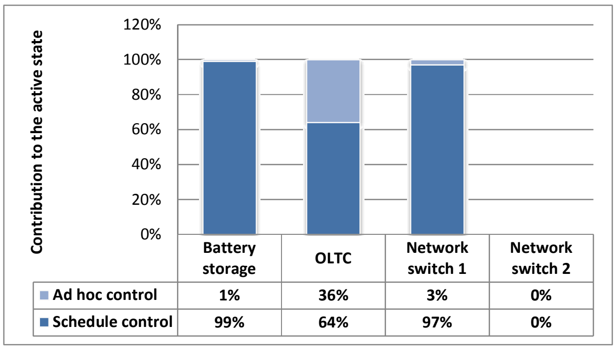

Figure 4: Control mode within the active state

COMPARATIVE VALIDATION OF THE SMART OPERATORS GRID CONTROL

An analysis of the grid state with Smart Operator control is compared to a fictive situation without having a Smart Operator installed in the grid, e.g. without having any actuator. For this an ex-post simulation with the help of the measurement data from the field test region is done for an exemplary day. Figure 5 shows the maximum voltage curves of the operation at feeder 4 with (green) and without (red) SmOp from 1.30 pm to 2.30 pm. Furthermore the busbar voltage (blue) and the defined voltage limit (magenta) are depicted. It is evident that the operation with the SmOp avoids voltage limit violations. Here, the Smart Operator uses the battery storage as a 10 kW load. All other actuators are not active. This additional load is almost the whole time successful in order to meet the voltage limit. However, at 1:50 pm and 2:14 pm the maximum voltage with SmOp also exceeds the voltage limit. Therefore, an ad hoc control is conducted.

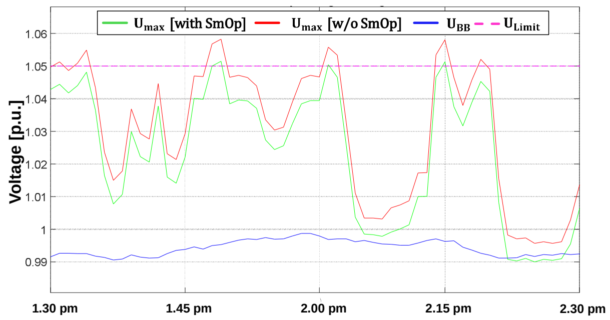

Figure 5: Voltage curve with and w/o SmOp in feeder 4

To avoid violating the limit around the time period of 1:50 pm, the network switch 1 is closed. Figure 6 shows the corresponding course of the control behavior. It can be seen that the closing of the network switch under the ad hoc control, respectively the dead time after the ad hoc control is carried out. At 2:14 pm the network switch is closed again for a moment. In the next minute, the current quarter hour has ended and the schedule control can comply with the limits again.

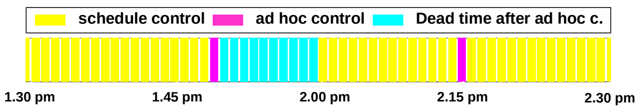

Figure 6: Course of control behavior with and w/o SmOp

The impact of the switching action of the network switch can also be observed in feeder 2 since it gets meshed with feeder 4. The maximum voltage with Smart Operator is increased in comparison with the operation without Smart Operator. However, the voltage limits are not violated, so that a valid condition exists also in feeder2.

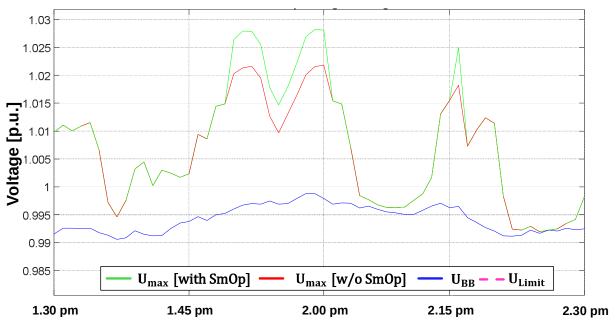

Figure 7: Voltage curve with and w/o SmOp in feeder 2

SUMMARY

To evaluate the efficiency of the Smart Operator the voltage control, the control behavior and the utilization of actuators were investigated in the field. The evaluation of the voltage control has shown that the voltage curves of the field test region Wertachau is predominantly maintained within the defined limits by operating with SmOp. Exceeding the voltage limits results in an ad hoc control operation, which transfers the voltage back into the valid range by utilizing the available actuators. The ad hoc control is performed in less than 1 % of the one-minute time slices. The actuators are predominantly operated in accordance to the schedule control. As a result, limit violations are being prevented. The quality of the forecasts that are created based on the experiences of the Smart Operator can therefore be considered as high.
Regarding the actuators, the following trends can be derived:

- **Battery storage** is primarily controlled by the schedule control. Due to the intertemporal behavior of battery storages this is to be seen as very positive. On average, the battery storage is operating in about 59 % of the one-minute time slices.
- The **OLTC** on average is active in less than 10 % of the one-minute time slices. It is mainly addressed through the schedule control. Despite the low activity of OLTC, voltage control is always successful.
- One of the **network switches** is always open. It can be concluded that the position of the switch is not useful for the Smart Operator. The other network switch is in average less than 2 % of the time slices. Again it is primarily controlled via schedule control.

The conducted analyses show that the effectiveness of the SmOp in the field is given. The SmOp conditionally uses different control modes such as feeder control or grid control to meet the operational task properly.

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