INFLUENCE OF DIFFERENT FRAMEWORK CONDITIONS ON THE EFFECTIVENESS OF CONTROL CONCEPTS IN DISTRIBUTION GRIDS

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ABSTRACT

Conventional methods of on-load tap changer transformer (OLTCs) based voltage control in low Voltage (LV) distribution grids turn out to be more and more difficult. This is due to constant growth of distributed infeed (e.g. from photovoltaic systems) and the emergence of new electric load types (e.g. electric cars, heat pumps). New concepts to face these challenges are based on distributed voltage measurements within the grid (provided e.g. by special smart meters over power line communication (PLC)). As such control concepts are dependent on the availability of measurements, the impact of controller- and measurement-system parameterization as well as external factors such as delay time and package loss need to be investigated. This study demonstrates the impact of such framework conditions on measurement based control strategies and outlines a methodology to test such conditions.

I. INTRODUCTION

The increasing penetration of rural low voltage (LV) grids with photovoltaic (PV) units and the changing behaviour of customers due to “new” loads like E-cars lead to problems concerning voltage band violations. Conventional methods of voltage control with on-load tap changer transformers (OLTCs) based on bus bar voltage measurement turn out to be more and more difficult.

Approaches were introduced in [1] to enhance the efficiency of control algorithms of OLTCs. These new concepts are based on distributed voltage measurements within the grid (provided e.g. by special smart meters over power line communication (PLC)). It was shown via simulations and a field trial that the advanced control concepts support the network operation and increase the hosting capacity under certain circumstances [2].

The effectiveness of “smart meter based” control concepts is dependent on certain framework conditions like controller settings, moving averaging time of the smart meter measurements as well as transmission speed and data loss rate of the PLC. Within this study a potential way of investigating the influence of these factors on the basis of simulative sensitivity analyses is proposed and demonstrated.

II. METHODOLOGY

The focus of this study lies on quantifying the influence of internal and external factors on the effectiveness of a smart-meter based grid control strategy. The following factors are considered:

- Internal factors:
    - moving averaging time of the smart meter measurements,
    - integration threshold value of the grid controller,
- External factors
    - delay time of the PLC,
    - loss probability of data packets over the PLC.

In order to investigate the influence a LV grid simulation environment was set up which also includes active components (i.e. OLTCs), grid controllers and communication channels to distributed sensors. The simulation environment is based on the loose coupling of software components, which are responsible for the simulation of different aspects [3]. E.g. for the simulation of the behaviour of the power grid the commercial power flow calculation program PSS®SINCAL was used. The used controller algorithms were developed to run on an embedded controller.

The final set up of the simulation environment consists of five single components, so-called clients, which are coupled over a simulation message bus (SMB). The structure resulting simulation environment is shown in Figure 1 [3, 4].

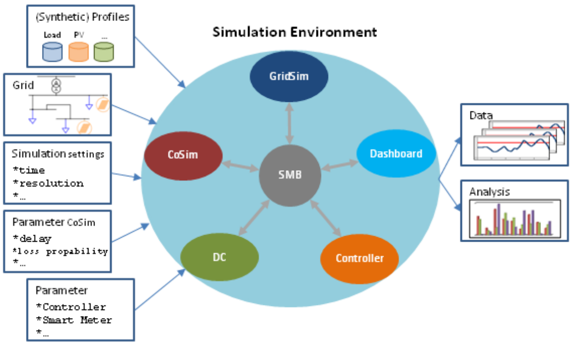

Figure 1: Structure of the simulation environment

- SMB… Simulation Message Bus for coupling of the components [3, 5].
- DC…Data Concentrator: representation of the embedded controller hardware
- CoSim…Communication Simulation: representation of the PLC channel [6]
- GridSim…Grid Simulation: representation of the LV power grid and smart meter measurements [4]
- Dashboard: optional web based tool for configuration and observation of the running simulations
- Controller: Implementations of the control algorithms [1, 7]

III. SIMULATION SCENARIOS AND BENCHMARKS

Scenarios

The grid scenarios used within this study are based on data from a database, which provides daily profiles of generation and load data for a wide range of consumption and generation scenarios in a high time resolution (seconds) [8].

The following generation (PV) scenarios were considered in the controller evaluation: sunny, unsettled and cloudy. Each PV feed-in scenario was tested with three different load scenarios: Summer/Workday, Transition/Sunday, Winter/Sunday. This lead to a total of 9 simulation scenarios investigated within this study [9].

The number of scenarios is not able to allow an interpretation of the presented results as statistically significant. To achieve this, a much higher number of scenarios have to be considered. Still the analysed scenarios allow having a first impression of the influence of internal and external factors on the effectiveness of a smart-meter based grid control strategy and show the applicability of the presented methodology.

Test LV Grid

The grid used within this study represents a typical LV grid in a rural area: from three feeders are 37 households supplied. 21 PV-plants in this grid area stress the network with an installed capacity of over 80 kWp. The grid topology and parameters are presented in more detail in [9].

The limitation on only one LV Grid has to be considered when interpreting the results of the simulation campaign. On an extension to a set of different (real) Grids is currently worked on.

Benchmark criteria

Two benchmark criteria were used evaluate the performance of the control strategy:

Voltage quality: The voltage quality achieved with a control strategy was evaluated based on the grid meeting the EN50160 during operation: "*95% of the 10 minute average voltage values are within ±10% of the nominal voltage*". The medium voltage level was assumed to be fixed at 20 kV. The voltage quality of the grid was assessed under stricter conditions than suggested in EN50160 reducing the allowed a deviation from ±10% to ±5%.

Control efficiency: Control efficiency was established based on the total number of required tap changes, with less required tap transitions constituting higher control efficiency.

Investigated Controller/ Communication Parameters

1) Integration threshold value of the grid controller

The integration threshold value (ITV) of the grid controller constitutes the time and magnitude of a voltage violation (given as [Vs]) before an OLTC step is initiated. An example is shown in Figure 2.

When the voltage of the transformer busbar is exceeding the given voltage limit (the so called "deadband", starting from point 1 in Figure 2) the controller starts to integrate the voltage time area above the limit. If the given ITV is exceeded, a change of the tap position is initiated. At the same time, the current integration level is set to zero (point 2). If the limit is again crossed, the integration is restarted (point 3), if the limit is met again, the integration is paused (point 4) and if the nominal voltage value is reached, the current integration value is set to zero (point 5).

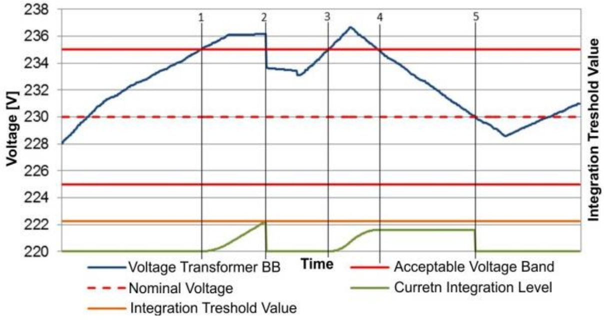

Figure 2: Example to explain the integration threshold value (ITV)

2) Moving averaging time of the smart meter measurements

The smart meter averaging time (T_{SMM}) results from the moving average function embedded in the EGDA (Express Grid Data Acquisition) of the Siemens AMIS Smart Meter. The current average value at a time-point t_x can be calculated as follows;

$$U_{t_x} = \frac{1}{T_{SMM}} \cdot \int_{t_x - T_{SMM}}^{t_x} u(t)\,dt \qquad (1)$$

IV. RESULTS

Influence of smart meter averaging time and integration threshold on controller performance

Figure 3 and Figure 4 depict the results of the 9 investigated scenarios using daily profiles regarding the benchmark criteria. The x- and y axis constitute parameter combinations (T_{SMM} / Integration threshold (ITV)), while the z-axis constitutes the achieved voltage quality, controller efficiency for all scenarios under a given parameter combination for each time slot. To point the results out, only the min, max and mean values from all simulated Scenarios and time steps are shown within the figures.

Figure 3 depicts the impact of T_{SMM} and ITV on the voltage quality. A quality of 100% means in this context, that 100% of the 10 minute average voltage values are within ±5% of the nominal voltage. Therefore given a voltage quality above 95% the voltage quality requirements are met (coloured green and yellow), while a quality below 95% constitutes a violation (coloured orange and red).

The results suggest that an increase of the T_{SMM} and ITV will lead to a decrease of the voltage quality in the grid. This is due to the fact that the controller will not be able to react in time (either because the received values are too coarse (due to long averaging time) or because its reaction time is too slow (due to a high integration threshold).

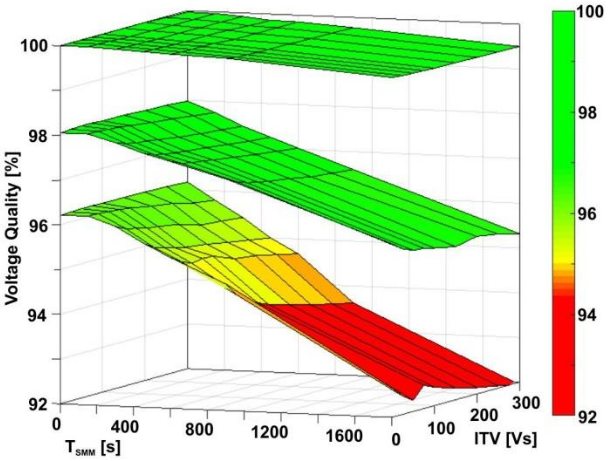

Figure 3: Results regarding voltage quality considering T_{SMM} and ITV variation (fixed parameters of communication channel)

The load/generation scenario also has an impact on the performance of the control strategy. While the max and average voltage quality always met the voltage criteria, load and generation scenarios exist where it is violated. To achieve a sufficient voltage quality within all scenarios, the smart meter averaging time should not exceed 600 seconds (10 minutes). Given a low integration threshold (100 [Vs]) the smart meter averaging time can be increased up to 900 seconds (15 minutes).

Figure 4 depicts the impact of the two parameters on the control efficiency (number of OLTC operations). For a better depiction the z-axis is scaled logarithmically.

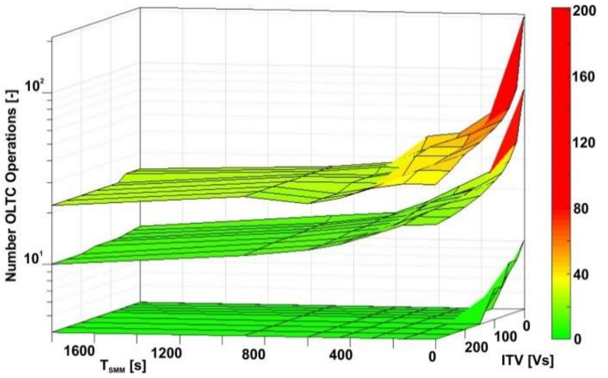

Figure 4: Results regarding OLTC operation considering T_{SMM} and ITV variation (fixed parameters of communication channel)

The least amount of OLTC operations is 4. The number of operations is strongly influenced by the integration threshold. This is not surprising, as the threshold defines the controllers' sensitivity towards voltage violations.

Influence of communication channel behaviour on controller performance

In a second investigation the influence of delay time of the PLC and loss probability of data packets over the PLC on the controller was investigated.

In a first step an optimal (lossless) channel is assumed to isolate the impact of latency on the controller. In a second step the chance of package loss is increased > 0. For each of those two cases the impact on the quality of the controller is investigated.

To link smart meter averaging time and communication channel performance a new variable is introduced. Let q denote the transmission quality.

To establish q, the average number of packages (Q) a controller receives during a smart meter averaging time needs to be calculated.

Q depends on the smart meter averaging time (T_{SMM}), the mean delay (T_{MD}) and the probability of package loss on the channel (LP). In addition it has to be noted that each packet needs to be transmitted over the communication channel twice. This leads to T_{MD} doubling and LP increasing by the power of two. Q can be established as:

$$Q = \frac{T_{SMM}}{2 \cdot T_{MD}} \cdot \left(1 - LP\right)^2 \tag{2}$$

Let Q_0 denote the number of packages required for the transmission of all smart meter values. In the case of the investigated low voltage grid Q_0 is 81 measurement values given by the number of Smart Meters (27) times the number of measured phases (3).

Based on Q and Q_0 q can be established

$$q = \frac{Q}{Q_0} = \frac{1}{Q_0} \frac{T_{SMM}}{2 \cdot T_{MD}} \cdot \left(1 - LP\right)^2 \tag{3}$$

Considering the analysed scenarios a transmission quality $q > 1$ guarantees a good controller performance. Looking only on voltage quality Figure 5 shows that $q > 0.5$ would be already sufficient.

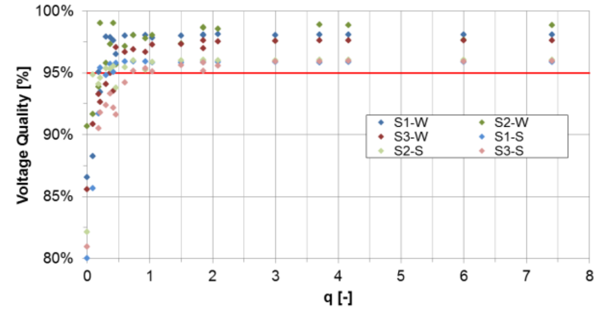

Figure 5: Impact of transmission quality on voltage quality for 6 of the considered 9 scenarios

Based on equation (3) the degrees of freedom to increase controller's robustness against weak communica-

tion channel behaviour can be summarized as follows.
The easiest way is a pre-selection of critical nodes to decrease the number of communicating Smart Meter (Q_0). Additionally an appropriate measure is an increase of smart meter value averaging time (T_{SMM}) as long as the expected voltage quality is ensured. (see Figure 3). Generally more difficult is the improvement of communication channel behaviour itself. Nevertheless decreasing delay time (T_{MD}) and loss probability (LP) of course lead to higher transmission quality.

V. CONCLUSION

The following conclusions have to be seen under the limitation of the small amount of simulated scenarios and are based only on one test grid. Despite that some interesting outcomes can be outlined:
The results suggest that the smart meter averaging time has a strong impact on the control strategy. While a too long averaging time will result in a violation of the voltage band, the transmission of instantaneous smart meter values will lead to a drastic increase of OLTC operations, while not impacting voltage quality noticeably. Our results suggest a smart meter averaging time between 5 and 10 minutes.
The integration threshold will impact the laziness of the controller and thus the severity of a voltage violation before the controller reacts. For the investigated scenarios an integration threshold of 25 [Vs] -150 [Vs] resulted in good control efficiency (4 tap operations per day) while maintaining a sufficient voltage quality. It should be noted, that the smart meter averaging time has a stronger impact on the overall performance of the control system than the integration threshold.
The analysis of the influence of delay time of the PLC and loss probability of data packets over the PLC suggests that these parameters cannot be investigated independently, but need to be set into the context of the other system parameters, especially the smart meter averaging time. This lead to the definition of the transmission quality q, which denotes the relative number of the average transmitted packages within a certain smart meter value averaging time. In order to achieve a sufficient quality of the controller q should be > 1 meaning that the controller receives at least one value from each sensor per averaging interval. This also means that (up to a certain point) latency issues on the transmission side can be resolved by increasing the smart meter value averaging time.

VI. OUTLOOK

This study investigated the impact of several system and communication parameters on a specific OLTC control strategy. The proposed methodology could be used to evaluate other smart meter based control approaches and their sensitivity towards such system parameters.
In order to increase the validity and statistical significance of the presented results the proposed analysis is currently performed under additional scenarios and a range of different LV grid topologies.

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