Tie open point relocation as possible replacement for the step voltage regulator

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Abstract

The increase in distributed energy generation, such as photovoltaic systems (PV) or combined heat and power plants (CHP), poses new challenges to almost every distribution network operator (DNO). In the low-voltage (LV) grids, where installed PV capacity approaches the magnitude of household load, reverse power flow occurs at the secondary substations. High PV penetration leads to voltage rise, flicker and loading problems [1]. These problems have been addressed by the application of various techniques amongst which is the deployment of step voltage regulators (SVR). SVR can solve the voltage problem, but do not prevent or reduce reverse power flows. Therefore, the application of SVR in low voltage grids can result in significant power losses upstream. In this paper we present part of a research project investigating the application of remote-controlled cable cabinets (CC) with metering units in a low-voltage network as a possible alternative for SVR. A new generation of custom-made remote-control cable cabinets has been deployed and dynamic network reconfigurations (NR) have been realized with the following objectives: (i) reduction of reverse power flow through the secondary substation to the upstream network and therefore a reduction of upstream losses, (ii) reduction of the voltage rise caused by distributed energy resources and (iii) load balancing in the low-voltage grid. Secondary objectives are to improve the DNO's insight into the state of the network and to provide further information on future smart grid integration.

1 New remote-controlled cable cabinets

A cable cabinet (CC) is a low-voltage grid equipment, where feeders are connected to each other via busbars. Cable cabinets usually have fuses which are used for both the protection to isolate faults and for the reconfiguration in the network. In case of faults or maintenance the network reconfiguration is generally conducted by manually plugging or unplugging the fuses.

Figure 1 One of the cable cabinets prior to hardware implementation

A traditional cable cabinet is depicted in **Figure 1** and illustrates one of the cable cabinets prior to implementation of the new remote-controlled cable cabinets with metering units. The traditional cable cabinet cannot be switched nor are important data (voltage, current, power flow) measured.

As part of the research project, all relevant cable cabinets in the network were modified and replaced with a new generation of off-the-shelf remote-controlled cable cabinets specifically designed by the project team. The hardware components were manufactured specifically for the project and therefore custom-made parts were ordered from various specialized suppliers located in different countries in the European Union.

Figure 2 Prototype of the custom-built remote-controlled cable cabinet

One of these custom-built remote-control cabinet is shown in **Figure 2**. This CC consists of three main parts: On the top left is the normal classical CC and on the bottom left are the switches. On the right-hand side is an antenna for the communication system, a central processing unit

(CPU) for handling all the data measurements, and other essential electronic parts for the functioning of the whole system. Some important components of the hardware implemented are fuses (200A), copper busbars and cable conversion current transformers, for measuring current, voltage, power flow as well as power factor for each feeder.

1.1 Step voltage regulator

For this project the DNO acquired and installed a step voltage regulator in order to be able to compare its behaviour with the solution based on the "online network reconfiguration". It was configured to control the voltage at the LV node at 1+/-0.04p.u. in 9 steps with an additional voltage per tap of 2% **(Figure 3)**.

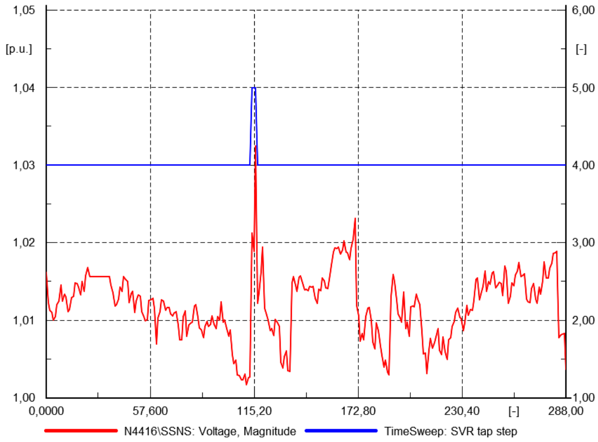

Figure 3 Change in LV grid voltage over one day and VSR tap step

The use of the step voltage regulator solves the voltage rise and voltage drop problem. However, it does not solve the problem of reverse power flow, which can cause to high losses in the transformers and upstream into the medium voltage grid (MV). In this research project, one of the objectives was to reduce reverse power by dynamically reconfiguring the tie open point so that power generated in the LV network is directly consumed in neighbouring network areas of the same LV network.

2 Project phases

The research project was conducted out in two phases:
Phase 1 - Hardware implementation,
Phase 2 - Software implementation.
In the following section both project phases will be described.

2.1 First project phase – Hardware implementation

The first step of the project was to replace each relevant cable cabinet with the new remote-controlled cable cabinet and to equip the secondary substation in the network area (**Figure 4**) with a metering, communication and switching devices. The implementation of a switching system allows dynamic reconfiguration of the network, i.e. change the tie-open points and thus have flexible feeders in the network area.

The installed metering system records the voltages of all relevant nodes and the active and reactive power flows of the branches connected to these nodes. The communication system enables the synchronous transmission of measurement data from each feeder in the electrical network to the control room. This data is used for state estimation and determination of switching sequences. The switching commands to the cable cabinets can be issued in real time from the control room.

Figure 4 Low voltage grid with 2 Secondary stations (N) and seven cable cabinets (KV)

The deployed remote-controlled cable cabinets allows the grid operator to operate one voltage level downstream in the grid than normal, i.e., in the low-voltage grid. The main benefits for a network operator are:

- Improved power restoration after faults.
- Dynamically change the switching configuration of the secondary substation.
- Especially with the introduction of remote-control capability to the cable cabinets, on-line configuration management becomes an important part of LV distribution automation. The DNO can realize remote-controlled reconfiguration of the LV feeders to achieve the desired power flow pattern by connecting feeders with high generation to feeders with high consumptions.

2.2 Second project phase - Software implementation

As already mentioned, the remote-controlled CC supports the use of dynamic network reconfiguration. Before network reconfiguration it is important to know the state of the network. The network under consideration (**Figure 4**) consists of two areas separated by a tie open point. Voltage, power flow and switch status measurements are available at each CC and secondary substation. There are 66 PV-plants in the network and in the control room measurements are only available for one PV generator referred to as the reference PV. The total annual customer energy consumption of the network is approximately 3.1 GWh. Further data of the network is provided in **Table 1**.

Secondary Station	Domestic Connections	peak-load	PV-power	Back-feed
N4416 (SVR)	30 (Industry)	89,4 KW	118,7 KW	>200W/m²
N4347	102 (Households)	158,7 KW	140,3 KW	>500W/m²

Table 1 Basic data of the LV network

There are no smart meters available for each customer. It is therefore necessary to estimate the state of the network before performing online network reconfiguration. In the simulation software PowerFactory developed by the consortium partner "DIgSILENT", some algorithms for the estimation of generation and loads were implemented. In the next section, some details will be provided.

2.2.1 Estimation of loads and generation

Since the available measurement data set is not redundant, a classical state estimator could not be applied [2] [3]. Therefore, a simplified state estimator was developed specifically for this project in the PowerFactory simulation software using the DPL scripting language. It can perform several tasks namely:

- Estimation of the PV generation of each plant
- Estimation of the consumer active and reactive power.
- Determination of switching sequences for network reconfiguration.

First of all the PV-generation is estimated based on the data from the reference generator and historical data from all the generators. For each plant, data is available on the capacity and total generation in kWh in the previous year. The following assumptions are made in this estimation:

- That the tilt and shadow factors are implicitly considered by considering the annual energy and data from previous years.
- The reference plant does not exhibit any shading during the day. Possible shading of the other plants is not considered.
- It is further assumed that the solar irradiance at the location of the reference PV plant is valid for the entire sub-grid under investigation. The network area has only a small geographical extent, so that this approximation can be used. Rapid cloud migration can lead to strongly differing feed-in values under certain circumstances. This has not been considered in the present work.

Finally, the loads are then estimated based on the measurements from CC, secondary substations and the estimated values of the infeed of each PV plant. Basically, the following steps are performed:

- Plausibility check by considering the correlation between the switching state and the measured values and compliance with Kirchhoff's theorem for all cable distributors.
- The current measurement topology is analysed to identify sub-grids that are uniquely defined by a set of measurements and can be estimated independently using a scaling algorithm. Depending on the state of the switches a maximum of 32 sub-network areas can be identified.
- The branch metering values identified for each sub-area are used to automatically create and configure sub-feeders for the feeder-based load estimation. The feeders thus created define exactly which power flows in and out of the corresponding sub areas. Depending on the switch status a maximum of 52 feeders can be created for sub-grid under investigation. Due to the cascading of the measurements used, it possible to identify some grossly inaccurate measurements. The measured values for voltages and currents were used to evaluate the accuracy of the estimation procedure. With this analysis some measurements errors were identified and corrected.

2.2.2 Network reconfiguration

Distribution power systems are electrically separated via tie open points, which are strategically positioned to archive a certain goal, e.g., balance loads to reduce losses. Network reconfiguration can, therefore be performed by changing the state of switch devices, taking into account the need not to lose the radial nature of the system. Reconfiguration of the network moves loads and generation from one part of the network to the other. The network can be reconfigured using one of the following objectives [4] [5]:

- Reduction of the reverse power flow
- Relieve the network of overloads and voltage limit violations. To measure the degree of constraint violations or compare two network states, voltage and loading performance indices were used.
- Reduction of losses of the network.

For the network configuration, the DNO specified rules and preconditions to follow, e.g., the tie open points can be changed only to the nearest geographic cable cabinet. This means, if the tie open point is at any arbitrary point in time in the cable cabinet “KV1110” and any of the switching preconditions specified by DNO are fulfilled, the switching algorithm (**Figure 5**) will switch either to the tie open point upstream (KV1713, KV1722) or downstream (KV1113). In the next time interval, the tie open point can be adjusted further, so that at one point in time, the optimum tie-open point will have been set.

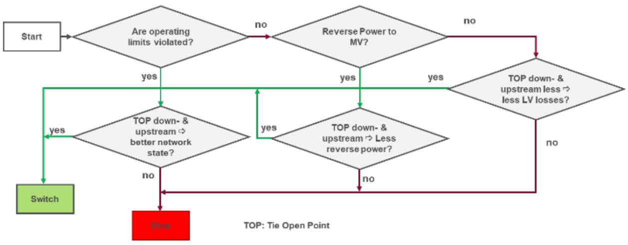

Figure 5 Process flow for the switching algorithm

Numerous test network reconfigurations base on the remote-controlled cable cabinets were carried out by the DNO. The quality of the algorithm for proposing switching actions was checked using these test switching actions.

3 Results

In order to show the added value of the remote-controlled cable cabinets, results for a day in which the electrical surplus in energy occurs only in one of the two neighbouring grid areas will be investigated. This is the case according to **(Table 1)** when the solar radiation is above 200 W/m² and below 500 W/m².

3.1 Accuracy of the estimation

PV generation and consumer power were estimated based on the available measurements. There values were used with the load flow to determine the state of the network. To assess the accuracy of the estimation algorithm, the estimated values were compared to the corresponding measured values. It is important to keep in mind the fact that a measurement error (0.5%) is provided by the manufacturer and also that a slight divergence of the values is tolerable.
Considering the network reconfigurations carried out by the DNO on different types of days (clear sky, bad and variable weather) branch flow and node measurements were compared to estimated values.

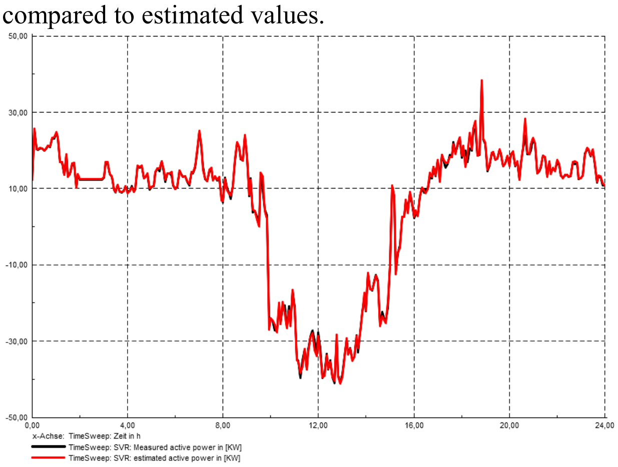

Figure 6 Measured and estimated active power through the SVR

Figure 6 illustrates the measured and estimated active power flow through the SVR. These results indicate that the estimation algorithm provides accurate results with an error less than 5%. Some outliers were observed, and further analysis will be performed in the future.
The plausibility check of the substations and the CC for compliance with Kirchhoff's theorem indicated that this is not fully satisfied within the expected accuracy interval. The following factors which could not be quantify have an impact on the accuracy of the results: (i) accuracy of the metering equipment (ii) accuracy of the communication (iii) missing measurements for street lighting (iv) unbalance of the 3-phase network because of unbalanced PV infeed (the estimation procedure assumes that the network is balanced).

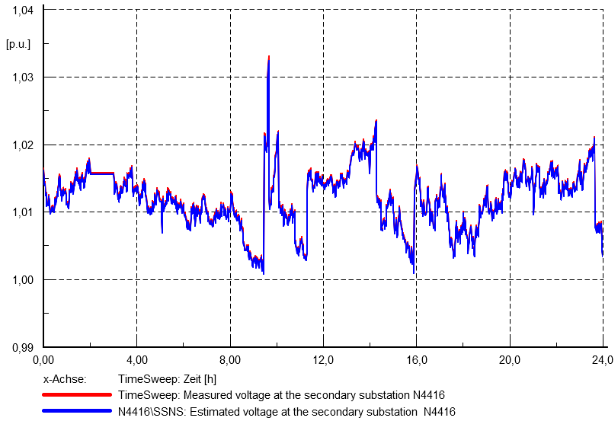

Figure 7 Measured and estimated voltage at substation N4416

Figure 7 illustrates the results of the estimated and measured voltages at the LV busbar of the secondary substation. These results indicate that the maximum difference between the estimated and measured voltage values is less than 0.003 kV (3 volts). The maximum differences between measured and estimated voltages after network reconfiguration is about 1.8%.
The expected voltage problems (voltage rise) could not be observed in the area of the network under consideration, however with increasing integration of distributed energy resources in the future this might be the case. In more than 99.8% of the cases studied here, there were no voltage problems, so that SVR was idle. Therefore, it could not be validated whether moving the tie-open point to mitigate voltage increases due to distributed energy resources is an alternative to the SVR.

3.2 Network reconfiguration to reduce reverse power flow

For network reconfiguration, a meta-heuristic technique was implemented, but because of the small size of the network and only ten possible tie open points, the meta-heuristic technique was not used. Instead, a search algorithm estimating the reverse power for each possible tie open point was used. Reducing the reverse power in one area of the grid by network reconfiguration can lead to an increase of reverse power in another part of the network. However only the total reverse power to the upstream grid is of interest. If the total reverse power can be reduced in the next point in time by a pre-defined value, then network reconfiguration is performed. In this section, results obtained with metering data for a period of one selected day are presented. Only the results for a tie open point with smallest reverse power for the selected day are presented. **Figure 8** illustrates the reverse power flow through the step voltage regulator for the normal network state (blue curve) and for the tie open point at CC “KV1723”.

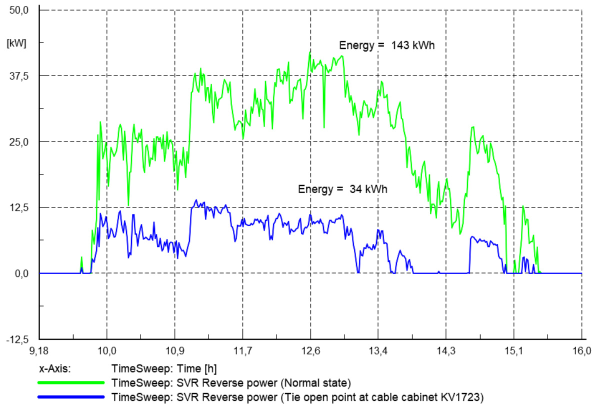

Figure 8 Reverse power flow through SVR

With the approach of the tie open point relocation, the reverse power in the area N4416 can be almost completely avoided with increased reverse infeed of the area N4347 into the medium voltage grid. **Figure 9** illustrate the total reverse power again in normal network state and for the tie open point at CC “KV1723” indicating a substantial reduction of the reverse power flow.

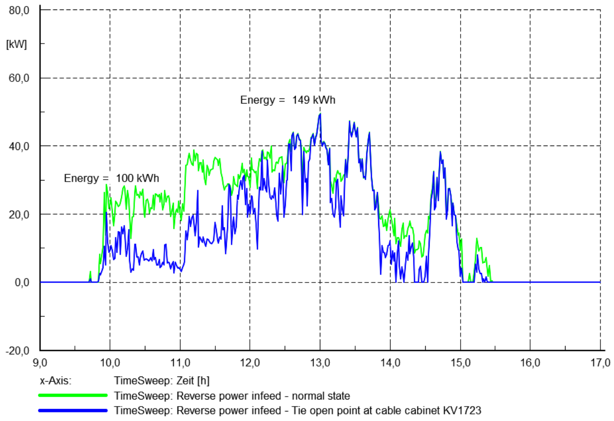

Figure 9 Reduction of reverse power flow

The first conclusion we can draw from this research is that; the use of the tie open point relocation method has proven it's effectiveness in terms of reverse power compared to the installation of a step voltage regulator.

3.3 The power losses

In general, the reduction of losses is mainly achieved by implementing low-loss asset procurement strategies. Optimizing the tie-point or load balancing between feeders is one of the ways to reduce losses. By using dynamic network reconfiguration scheme, it is possible for the DNO to consider seasonal load and distributed generation variations as well as load growth. The use of dynamic network reconfiguration can be costly due to the fact that tie-open circuit breakers deteriorate frequently and therefore need to be replaced every few years. In this research project the used switch can withstand up to 10.000.000 switching cycles. There are currently no examples implemented in Germany to dynamically reconfigure the LV network periodically or based on given conditions.

The losses due to reverse power upstream could not be analysed since the upstream network was represented by an equivalent external grid model. This is a topic for future analysis. Therefore, only losses within the grid area under consideration could be analysed. The normal tie open point of the investigated LV network was strategically selected based on minimum losses. Several network reconfigurations under different network states were performed and it was observed that by moving the tie open an increase in the losses as indicated in **Figure 10** for CC in KV1723 were observed.

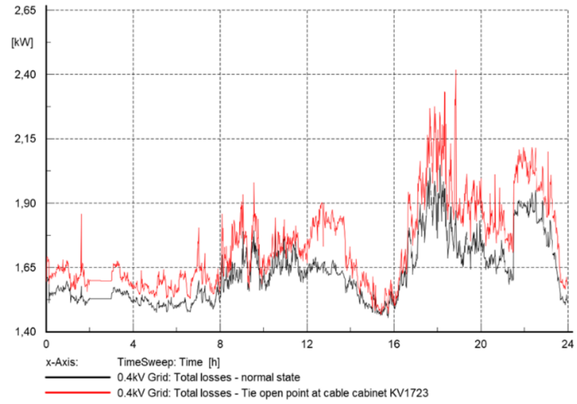

Figure 10 Impact of tie open point on losses

4 Outlook

This paper describes the implementation of advanced remote-controlled cable cabinets with metering units and how this was used to reconfigure the network to reduce losses and reverse power flow. The use of such technology has enabled the distribution network operator to gain more visibility of what is happening in the low-voltage network, and to manage the process of 'feeder switching' from the control room in real time, without the need for electricians on site. This saves a lot of time and money.

However, there are still many issues to be addressed. The comparison of the dynamic network reconfiguration with SVR has not been possible because expected voltage problems did not occur. As the amount of distributed energy in the grid area under consideration is expected to increase, this comparison can be performed in the future.

Due to expected harmonic issues, reconfiguration of tie open point was limited to the next geographically located cable cabinet. This could be changed in the future if harmonics do not present a problem, so that the strategy of

changing the tie open point to any suitable one can be realized in a single step.
The state estimation results are expected to improve as more smart grid meters are deployed and taken into consideration.

5 Literature

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