ARCHITECTURE OF ADVANCED DISTRIBUTION GRID VOLTAGE CONTROL METHOD UTILIZING EDGE COMPUTING SOLUTION

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ABSTRACT

Advanced voltage control methods have been developed during the recent years to increase the grid hosting capacity for distributed generation (DG), electric vehicles (EV), heat pumps (HP), etc. to be connected to weak distribution grids. One of such method was realized as hierarchical control architecture of primary, secondary, and tertiary controllers based on edge computing solution and demonstrated in a real-life distribution grid as a closed-loop demonstration in Denmark during year 2021. The generalized demonstration experiences and the proposed voltage control solution is critically analysed in the paper.

INTRODUCTION

The aim of the optimal voltage regulation demonstration project was to proof the long-term performance of a secondary voltage control solution, that could increase the hosting capacity, reduce losses, and increase voltage quality in medium voltage (MV) networks, and thereby postpone investments and extend the lifetime of existing components. The system has been controlling the voltage at a HV/MV substation between June 2021 and February 2022 autonomously. There is indication that the demonstrated system improved the voltage level and grid losses of the demonstration network. Additionally, no adverse effect due to the use of the system were observed, though there is an increase in daily tap operations from 7 to 9 tap operations. The automation system has been operating secure and robust way.

The hosting capacity assessment realized for the demonstration network shows excellent potential to enhance voltage control and hosting capacity in the distribution network. The secondary voltage control system has the potential to triple the hosting capacity of the demonstration network. All in all, the demonstration can be considered successful from feasibility and proof-of-concept perspective.

The paper will describe the overall control architecture of the demonstrated solution and the mechanisms how it may be integrated as a part of existing commercial grid automation and control center IT systems. The paper will also discuss about the technical capability to solve voltage issues, applicability, scalability, and regulatory aspects of such solution in different kind of grid circumstances. The benefits and drawbacks of selected control architecture are discussed as well. The paper will conclude the attractiveness of the proposed solution from practical and commercial perspectives.

VOLTAGE CONTROL CONCEPT

The share of DG is increasing in distribution grids. New wind power, photovoltaic and so on, are continuously being connected to the distribution network as new customers and among existing customers by transforming them as prosumers. During periods of high wind and/or high solar radiation, the production from wind turbines and/or photovoltaics increases, which may cause the voltage in the MV network to increase above the allowed limits, especially when the consumption is low and production is located in remote (electrical distance) locations. The voltage rise is one of the main barriers of the hosting capacity of distribution networks. Alternatively, DGs will be curtailed to maintain the voltage within the allowed limits. In extreme cases generators may not be allowed to connect to a weak network before the grid expansion has been realized and therefore increasing grid investment cost if the operational safety margin is not satisfied in all possible conditions.

On the other hand, during low production and high demand situations the voltage will drop and may eventually drop below allowed limits. Large new loads such as HPs and EVs may have highly correlated consumption patterns, which are increasing peak load. In similar way, the price-based control of prosumers or demand response will increase the peak loads in the distribution grid by increasing the correlation of consumption patterns among customers.

Hosting capacity enhancement

To increase the hosting capacity of the distribution network in such a way that it can host more load and more DG, without compromising voltage quality, a secondary voltage regulation system has been developed and demonstrated. The system is also minimizing network losses in the distribution system.

Due to the increasing amount of DG connected to the distributions network, the automatic voltage regulators (AVR) of on-load tap changer (OLTC) are set to maintain a fixed voltage at the MV busbar, rather than using a regulator with line drop compensation. This limits the hosting capacity of the network, due to voltage variations at the edge of the network caused by high load/no production and low load/high production situations. Line drop compensation is insufficient to handle complex voltage profiles caused by bi-directional power flows.

Therefore, the primary voltage control at the transformer station (AVR of OLTC) alone is not enough for the future requirements to maintain good voltage quality in all parts of the distribution networks having decreasing, increasing and both kind of voltage profiles.

Proposed architecture

With the increasing penetration of DG, it’s important to find new solutions to automatically solve voltage problems by optimally employing the transformers OLTC and other possible primary voltage controllers. The Figure 1 illustrates the basic idea of the proposed concept. The local automation system based on edge computing has been developed to host several functions to realize the secondary voltage control. Primary functions utilized in the demonstration are monitoring, state estimation, forecasting and optimal power flow algorithms. The basic idea is to monitor and estimate the whole MV distribution network and optimize the voltage control settings of AVRs based on that information. The concept and the optimization can consider multiple controllers, which are under direct control of DSO through ownership, connection requirement or a service contract. The automation solution is based on edge computing at HV/MV substation, remote reading of selected MV/LV substation measurements, grid analysis and optimization at edge computing platform and readjustment of control settings of primary AVRs.

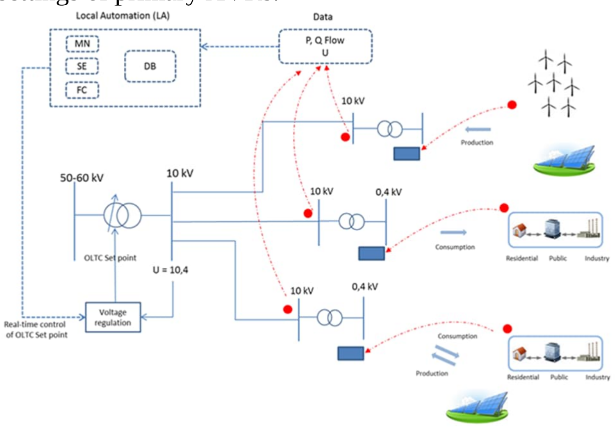

Figure1. Concept of advanced distribution grid voltage control.

Voltage controllers are realized as a hierarchical structure [1]. The basis of the control are the primary controllers (AVRs), which are reacting fastest of all control levels and typically associated to the physical resource realizing the control action.

On top of primary control level there exists a secondary control. The secondary control includes a near real-time coordination and optimization functionalities. The aim is to ensure proper response of all primary controllers in a specified grid area and to guarantee acceptable or even optimal voltage quality in all nodes of the grid and not only in the nodes where the primary controllers are located. Secondary control may include also multiple objectives in addition to voltage control, which typically are loss minimization, minimization of production curtailment and minimization of reactive power exchange with a TSO.

The highest control level is called tertiary control and it is typically a predictive controller, which tries to solve the challenges before they exist. The aim of the tertiary controller is to provide more freedom for a secondary and primary controller to maintain acceptable grid state in real-time. For that purpose, the tertiary controller may change the topology of the distribution grid or in future participate in local flexibility market.

DEMONSTRATION SETUP

A local automation system based on edge computing has been developed to host several functions to realize the secondary voltage regulation system. Primary functions utilized in the demonstration are based on monitoring, state estimation, forecasting and optimal power flow algorithms. Those algorithms are operated in the local automation system installed at the HV/MV transformer substation to perform four functions: (1) Monitor the distribution network in real-time by collecting measurements from substation and few strategically selected distribution transformers at the distribution network. (2) Estimate the state of the distribution network by utilizing the state estimation algorithm, the measurements collected and filtered by the monitoring functionality, the pseudo-measurements of aggregated load profiles of low voltage network customers, and the grid model. (3) Optimize the settings of primary voltage controllers of the network area by minimizing the cost function consisting of network losses, production curtailment, voltage deviation and number of tap changer operations within given network constraints and given control resources. (4) Adjust the control set-points to the AVR of OLTC dynamically. The voltage levels in complete MV network are controlled in near-real time to keep them on acceptable level not only at the substation but in all parts of the network.

Primary voltage control is realized decentralized way. Each controller is measuring a local voltage typically from terminals of the component. The most common such voltage controller in distribution grids is the AVR of OLTC in HV/MV primary transformers. Decentralized voltage control is applied many times for DGs as well. Reactive current of the generator is controlled by an AVR to maintain constant voltage. It is also good to realize that DGs have many other possible control modes like power factor control. It is not directly controlling voltage but will reduce the voltage rise, because the generator is consuming reactive power on high active power outputs. Depending on the size of the generator, the primary voltage control is mandatory, or it needs to have a capability for it based on grid codes for generators.

ANALYSIS OF THE PROPOSED SOLUTION

Primary control

Primary voltage controllers are helping a lot to maintain acceptable voltage quality in distribution grid. Traditionally the only voltage controller has been in the primary HV/MV transformer (AVR of OLTC). The penetration of DG and grid code requirement to have voltage control in the generator is increasing the hosting capacity. Similar approach could be easily implemented for EV charging points and inverter driven HPs as well. The reactive power controllability at rated power of the unit requires that the inverter is oversized, which increases the cost of investment. Inverters may also provide equal amount of inductive and capacitive reactive current, which is a benefit compared to synchronous machines, which have much more limited capability to provide inductive reactive current compared to capacitive current.

Weaker the distribution grid is, more the voltage control is increasing the hosting capacity. Voltage control with reactive power is quite effective in MV grid because the resistance-reactance ratio is about one and therefore significant reactance exists along MV feeders. LV grid connected voltage controller are less effective because the LV grid is mainly resistive. Voltage controllers are however enhancing the situation because the MV/LV transformer has reactance, where the reactive current may impact on voltage.

Voltage rises most for the generators located in the end of the feeders. Therefore, those generators would benefit the most, if voltage control is applied in all generators, also in all small LV grid connected generators. Otherwise, there is a risk that voltage rise would be too severe, and the generator needs to reduce its output to keep the voltage below the maximum allowed value. This kind of active power limitation based on measured voltage is common nowadays in solar power inverters. Customers of distribution grid are not in the equal position in a such case. Utilizing reactive power based voltage control and designing appropriate voltage settings for each generator is one possible way to reduce this negative impact (or allow the secondary control to optimize them in near real-time). The negative impacts of reactive power based voltage control (e.g. increased grid and inverter losses) may also be minimized by setting large enough deadband for reactive power around the nominal voltage. However, the primary voltage controllers are not able to solve this problem completely.

The cost of primary voltage control is very cheap for a DSO in case of requiring it from DGs, EV charging points, etc. Additional losses will be realized in DSOs grid and in inverters due to higher apparent power flows, but the cost of additional losses is low if the rated power factor is reasonable (e.g. about 0.95-1). However, the societal benefit is very high, if the primary voltage control is avoiding expensive grid enhancement investments.

One of the best aspects of primary voltage controller is its easy applicability. Therefore, they are very scalable. Primary voltage control is not dependent on any external systems, required information may be measured locally and the reactive power control may be realized independent from active power. Some inverters are capable of reactive power control even if the generator is not producing active power and therefore those inverters may support the grid all the time. Reactive power based voltage controllers have naturally more value in HV and MV grids compared to LV grids. In addition, the active power based voltage controllers should be utilized in DG to prevent dangerous overvoltage and to avoid utilizing voltage protection relays to trip the whole unit.

Grid regulation is supporting capital grid investments in most European grid regulations compared to operational expenditures. In practice, this means that privately owned distribution system operators (DSO), who want to maximize their profit, are favoring investments (capital expenditures), which have positive impact on their allowed profit. European directive 2019/944 [2] is however requiring grids to select the most cost-effective method to enhance the grid hosting capacity and to realize grid development plans. DSO should therefore investigate smart grid solutions (e.g. advanced voltage control) and compare them to traditional passive grid investments.

Secondary control

The secondary voltage control is enhancing the control of primary voltage controllers to keep good voltage quality in the whole distribution grid. For that purpose, the secondary voltage control requires good and grid-wide estimations of the grid state. To realize that cost-effectively, a distribution grid state estimation is commonly applied for this process. The accuracy of the state estimation may be improved to appropriate level by adding few additional current measurements for a strategically selected grid nodes (large generating units if not already measured and heavily loaded MV branches or customers) in addition to primary substation measurements (busbar voltage and feeder currents), and by applying load profiles of customers as pseudo-measurements for other nodes. Smart meter measurements are very valuable to improve the accuracy of load profiles, especially while the penetration of small-scale DG, EVs and HPs is penetrating and therefore continuously changing customer net load demand. Details of those methods are presented in [3].

The state estimation requires also an accurate and updated grid model to be accurate enough. Inaccuracies may be result of missing or incorrect information in grid model. When starting a project of secondary voltage control, the grid model validation should be the first task, because the correct information is extremely critical for the success of the control.

Challenges of grid model updating are related to grid topology and addition of new grid components and customers. The status of switching devices is maintained in real-time by SCADA from circuit breakers, remotely controlled disconnectors, and large generating units. The status of manually controlled disconnectors needs to be updated to SCADA/DMS (distribution management system) by grid operator based on information received from field crew. Critical information from secondary voltage control viewpoint is also the status of reactive power compensation units and off-load tap positions of MV/LV distribution transformers. The update of grid model to DMS from planning systems like network information system is typically realized as a batch process (e.g. once a day) to add or remove grid components and customers. The implementation of the secondary voltage control based on edge computing requires real-time information exchange between SCADA/DMS and platform to receive updates of the grid model. Alternatively horizontal IEC 61860 GOOSE communication between IEDs controlling switches and edge computing platform needs to be realized.

Secondary voltage control is adjusting the settings of the primary voltage controllers located in the control area. The area might be for example a MV or a LV grid. The adjusted settings are for example voltage, reactive power or power factor setting of primary controllers depending what type controllers are included. Also control delays may be adjusted especially for coordination (time grading) purposes to avoid unnecessary OLTC operations or to enhance response times of OLTCs. When the secondary control is applied for the reactive power management between DSO and TSO, the role of secondary control is to maintain appropriate reactive power reserves in continuously controlled resources like DGs and to decide which static reactive power compensation devices are switched on or off.

The settings of primary controllers are typically defined based on optimization, but much more simple and faster rule-based methods have been applied as well. The rule-based methods are following a control logic to response to voltage changes quickly and to coordinate control actions based on the status of the whole grid. The rule-based and optimization methods may be utilized together, while the rule-based method is bringing the distribution grid back to acceptable state and the optimization method is fine-tuning parameter settings to optimize the grid status. The benefit of this arrangement is that the rule-based method may respond very quickly compared to optimization method and it always finds a solution.

The commercial attractiveness of the secondary voltage control is attractive since it is mainly a software-based solution. Naturally the development of a software has a cost as well, but the implementation cost of a solution may be decreased to relative low level compared to completely hardware-based solutions like grid reinforcement. The actual software cost is difficult to evaluate because it strongly depends on the amount of development time. Most software libraries required for the solution may be found as open-source projects and therefore the software license cost is minimal. The cost of computing hardware is dependent on the architecture selected for the implementation. Hardware and platform maintenance naturally has a cost. Hardware and maintenance cost might be reduced by selecting edge computing platforms, which are built for multiple purposes. Extra measurement instruments, if existing measurements are not enough for the system, needs investments. However, those measurements have probably value for the overall grid operation as well. The communication cost consists of modem investments, communication services of telecommunication company, and realization and maintenance of cyber-security especially for inter-substation communication over public communication network. Communication to customer-owned DG units is also required. The utilization of secondary substation automation and smart meters, which many DSOs have already started to invest, would bring savings for the extra measurement and communication cost of the secondary control. The maintenance of secondary voltage control solution requires also dedicated configuration and engineering software. In addition to investments, the secondary voltage control has some operational cost as well like updating grid model and load profiles (but those are needed many other functions as well) and maintaining required knowledge to setup and operate the control system. The secondary voltage control is much more complex to build, engineer/configure, and maintain than the primary voltage control or the passive grid solutions. This is a clear disadvantage of the secondary voltage control solution, especially when the cost estimation is also very challenging.

Software-based solutions in general are very scalable and it is true in this case as well. The scalability requires that the engineering, configuration, and maintenance processes of the secondary voltage control solutions are well formulated and necessary tools to simplify and automate those exists. These processes may be compared to setting up a substation automation system. Necessary tools for the secondary voltage control solution are: (1) load profiling and profile updating/tailoring, (2) grid model validation, (3) engineering tools to parametrize and configure secondary controller, communication, automation, cyber security (this might be a generic IEC 61850 configuration tool, when the secondary control is part of substation automation), (3) logging and supervision, performance evaluation, alarms/events (e.g. part of SCADA or separate automation of cyber security supervision system), and (4) grid planning tools should include secondary control for analysis purposes.

Grid regulatory aspects are mostly similar than for the primary voltage control. Some additional grid code requirements are required for the control resources (generators, storage, etc.) to provide remote control possibility of controllers for a DSO (communication capability, access to controller and right to adjust the settings). Such requirements exist for large generating units, but the efficient utilization of the secondary control would require applying similar principles for small-scale resources as well.

The secondary voltage control may increase the hosting capacity remarkably in the case of a weak distribution grid.

In the demonstration grid, the additional hosting capacity for residential solar power was estimated to be three times higher than the hosting capacity of the passive grid. Therefore, the solution is commercially attractive from all stakeholders' viewpoint. DSO would get savings because the passive grid solutions are not needed. Customers would experience lower distribution grid tariffs and connection costs, and the equality of production customers would improve because less production curtailment would be required.

Tertiary control

Tertiary control is to further extend the capabilities of the secondary control. Tertiary control is typically a predictive controller, which optimize the operation of distribution grid for a following day. The aim of the tertiary controller is to provide more freedom for a secondary and primary controller to maintain acceptable grid state in real-time. For that purpose, the tertiary controller may change the topology of the distribution grid for example to shift some load or generating points from one feeder to another. The cost of changing grid topology is relatively high because that requires typically manual on-site switching actions by a field crew and therefore switching cannot be done very frequently.

Second future possibility of tertiary controller is to contract flexibility or purchase it via a local flexibility market. Therefore, the tertiary controller needs to predict how much, where and what time flexibility is needed. In this way, the DSO may increase for example the load demand close to DG, if the voltage rise is predicted to happen and cause production curtailment, if nothing is done. Naturally the opposite is possible as well. After predicting the flexibility requirements, the tertiary controller purchase flexibility from a local flexibility market, makes sure that requested flexibility is realized and later participates in flexibility validation and settlement phases. Now several companies are developing local flexibility markets, where also DSOs might buy flexibility. A good example of such market process is described in [4].

The cost of flexibility services is highly dependent on how often and how much flexibility services are needed. Therefore, a long-term view is needed to make a correct decision between buying flexibility or realizing grid reinforcement.

CONCLUSIONS

The idea of advanced voltage control methods in the distribution grids is mainly to postpone the necessary grid investments and continue using the existing grid infrastructure until the end of its useful lifetime. Therefore, the advanced voltage control methods should always be considered together with the design of a passive grid and not as a separate planning task. The advanced voltage control methods may extend the hosting capacity of the distribution grids for DG, EVs and HPs, which have not been able to consider in the past forecasts. The decision to solve the possible voltage challenges in the distribution grid by passive grid or advanced voltage control solution is realized after grid planning studies, which considers technical and economic aspects of all alternative solutions during the whole lifetime of existing grid.

The role of advanced voltage control solution from commercial viewpoint is to provide alternative solution for passive grids, when the grid infrastructure is still relatively young and other methods like network reconfiguration or similar are not providing good enough result. Voltage control solutions may be applied at all voltage levels from HV, MV and to LV. Most likely the first applications will be on rural MV grids, which have long feeders, radial structure, and less strong connection points for end-customers. In such networks the strengthening of the grid may require extensive investments for the passive infrastructure. The second possible application area are LV grids, which have a high penetration of DG, EVs and HPs. Required investments for a single LV grid are not extremely high, but the challenge might be the very rapid increment of the challenges. On such situation, DSO may not have enough time to realize all necessary investments (similar kind of LV grids are many), it is not clear enough how strong LV grid should be built or the original problem may be on MV side of the grid, which is waiting to be rebuild. In these cases, the postponing of LV grid investments with advanced voltage control solutions might be a wise decision and to provide acceptable voltage quality for end-customers at the problematic area.

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