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Theme 2: Opportunities and Challenges with Operation using Flexibility

Robust coordinated voltage control in low-voltage networks validated through an experimental study – collaboration of an on-load tap changer and a battery energy storage

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Abstract: This study proposes a robust and completely independent coordinated voltage control (CVC) method for low-voltage (LV) networks as a solution for the overvoltage problem created by distributed generation. The CVC coordinates an operation of an on-load tap changer transformer at a secondary substation and a redox flow battery energy storage at a customer supply point in an LV network based on real-time measurements of the LV grid. The novelty of this CVC is that control decisions are based on relatively simple deterministic logic, which is fast to execute, does not require a detailed grid model, and provides always a solution, has minimal need of information exchange between components of the control system, and it may operate independently without supervision of control centre or information exchange between CVC solution and IT systems of the control centre. This study presents the developed CVC method and explains the practical aspects of implementation for robust and independent solution. The CVC was developed, implemented and tested at the smart grid laboratory of the TU Dortmund University as a part of a master thesis. The most relevant outcome of this master thesis is presented in this study.

1 Introduction

The core principle of electricity distribution has been that electricity is produced in centralised units and then distributed to a customer through transmission and a distribution network. However, the distributed generation (DG) has moved a part of the generation to the distribution grid. When this DG exceeds the load at a consumer supply point, electricity is transmitted from the customer to the grid, creating a reverse power flow. In weak distribution networks, the reverse power flow can cause the voltage at the customer supply point to rise over the tolerated limits and become the limiting factor for the hosting capacity of a DG [1]. The tolerated voltage limits vary in different countries. In Finland and in several other European countries, limits are defined by the European standard EN-50160 [2].

One or a combination of the following methods can be used to decrease the maximum voltage at a customer supply point; decreasing the impedance of the feeder by increasing the size of the conductor [1], adjusting the voltage of a low-voltage (LV) network by changing off-circuit taps of a medium-voltage (MV)/LV transformer [1], adjusting the voltage of an LV network by changing tap ratio of an on-load tap changer transformer (OLTC) at a primary substation [1], adjusting the voltage of an LV network by changing the tap ratio of an OLTC at a secondary substation [3, 4], adjusting voltage of an LV network by installing a line voltage regulator on a feeder [1, 4, 5], allowing active and reactive power control of a DG [1, 4], installing or using existing battery energy storage (BES) in an LV network for voltage control [1, 6], placing active or passive reactive power compensators on a feeder [1] and adjusting loads in a network in order to control voltage [1].

This paper proposes a robust centralised voltage control (CVC) method for LV networks as a solution for the overvoltage problem that was developed, implemented and tested as part of master thesis and further details of the study can be found in the master thesis [7]. The goals of this CVC method are that it must be robust and require only minimal communication within the network. The CVC method coordinates the operation of an OLTC at a secondary substation and a redox flow battery energy storage (BES) at a customer supply point in the LV network. The study compares the developed CVC method with other OLTC-based solutions. The compared solutions are a remote-control method and a fixed set point control method. Only the most relevant outcome of the study is presented in this paper. The comparison is based on laboratory experiments conducted at the Smart Grid laboratory of TU Dortmund University [8].

2 Coordinated voltage control (CVC)

The logic of the developed CVC algorithm is presented in Fig. 1.

The control algorithm receives the voltage measurements V_{M1}, V_{M1}, …, V_{Mn} from a network. This could be done for example using smart metering technology. From those, the CVC calculates the maximum voltage $V_{M\max}$ and the minimum voltage $V_{M\min}$. By changing the tap position of an OLTC, the CVC maintains the maximum and minimum voltages between the tolerated $V_{T\max}$ and $V_{T\min}$ voltages. If the voltage difference between the maximum and the minimum measured values is higher than the voltage difference between the tolerated maximum and minimum values, an OLTC does not change the tap position.

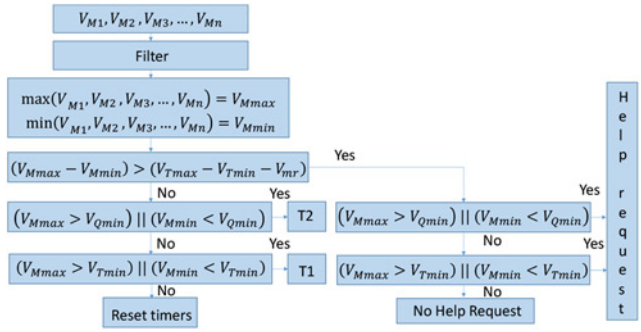

Fig. 1 *CVC algorithm [7]*

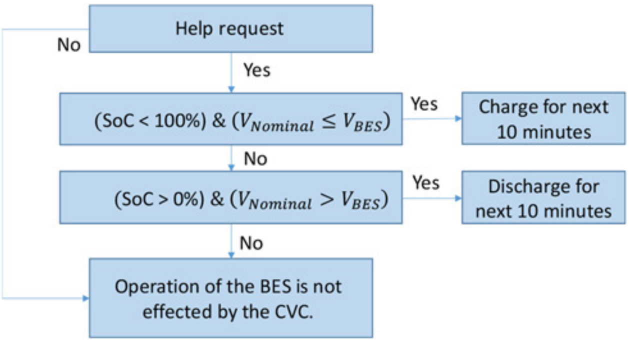

Fig. 2 *Voltage control logic of the battery energy storage in the CVC [7]*

The reason for this is that the voltage limits would not be within tolerance in any possible step position.

An OLTC is a discrete component and the CVC could run into situations, where the control algorithm executes continuously tap changes without reaching the steady position [1]. This can happen in a situation, when the voltage difference between the maximum and the minimum measured values are close but not over the voltage difference between the tolerated maximum and minimum values. In this case, if $V_{M\max} > V_{T\max}$ or $V_{M\min} < V_{T\min}$, a step position change can lead to continuous tap change operations. In order to prevent such behaviour, the CVC has a margin parameter *mr*. The margin value is given in percentages, from which together with the voltage set point V_{set}, the margin is calculated in voltages V_{mr}. The tolerated voltage difference in (1) is decreased by V_{mr}.

$$\left(V_{M\,\max} - V_{M\,\min}\right) > \left(V_{T\,\max} - V_{T\,\min} - V_{\text{mr}}\right) \tag{1}$$

Whether an OLTC does tap position changes, is determined by (1). If an OLTC cannot change the tap position, it initiates a help request to other devices in the network that are also able to control voltage. However, the need for voltage control of additional devices is tested with the same conditions that are used to test the need for step changes.

The CVC has the ‘tolerated voltage’ threshold and the ‘quick return’ voltage threshold. Exceeding the tolerated voltage threshold initiates timer T1 and exceeding the quick return voltage threshold initiates timer T2, in which T1 > T2. In conclusion, if $V_{M\max} > V_{T\max}$ or $V_{M\min} < V_{T\min}$, and condition of e.g. (1) is not exceeded, OLTC initiates timer T1 for a step position change to a convenient direction. If either $V_{M\max} > V_{Q\max}$ or $V_{M\min} < V_{Q\min}$, the CVC initiates a timer *T2* for a quicker step position change to a convenient direction. The appropriate value of the margin and timers depends on the network and the transformer type.

To prepare for a case of communication error or fault in the grid, the CVC algorithm has a deadband filter. Measured voltages are filtered with the deadband filter, so possible faulty measurements are not taken into account in control. However, the possibility of missing measurement at the most significant meter location, for example at the point with the highest voltage, exposes the algorithm to faulty actions.

3 BES control

The energy storage used in this thesis is a redox flow battery. Part of the logic of the CVC presented here would locate at the BES. This logic waits for the help request shown in Fig. 1 that initiates the voltage control of the BES. A part of the logic located at the BES is illustrated in Fig. 2.

The logic at the BES waits for help requests to be sent from the centralised logic of the CVC. In practice, this means that the CVC remotely controls a relay of a smart meter. The state of this relay is an indicator, whether the help request is on or not. The BES would read the state of this relay. After initiating the voltage control the logic verifies if a state of charge (SoC) of the BES is not full and if a voltage measured at a connection point of the BES is higher than the nominal voltage. If these conditions are true, the logic will initiate a charge of the BES for the next 10 min. If the conditions are false, the logic will check if the SoC of the BES is not 0% and if the voltage measured at a connection point of the BES is lower than the nominal voltage. If these conditions are true, the logic will initiate discharge for the next 10 min. If neither of the previous combinations is true, the operation of the BES is not affected by the CVC algorithm.

The time of both control actions depends on the expected time of extreme load conditions of a network. A 10-minute value for the time of control actions is set as an example. If the time of control actions is longer, the possibility of the unnecessary contribution of the BES increases. If the time of the control actions is shorter, the possibility of unnecessary on and off switching of the voltage control of the BES would increase, therefore increasing short term exceeding of ±10% range of the nominal voltage.

4 Methodology

The CVC has been tested at the laboratory of TU Dortmund University. For the study [7], the CVC was tested in several situations, however, from these only the most relevant outcome is presented in this paper. The topology of the measurement network is presented in Fig. 3.

Two groups of power amplifiers were used to emulate load and generation at the end of the feeders. As the generation, a power amplifier with a power setpoint of 92 kW was used. As the load. a power amplifier with a power setpoint of 35 kW and a resistor with the power of 100 kW was used. The charging power of the BES was 30 kW. Tolerated voltage values for the CVC were $V_{M\max} = 248$ V and $V_{M\min} = 212$ V. The margin used was 2.4% of the nominal voltage. The 10/10 kV OLTC transformer was used to produce MV variations. The 10/0.4 kV OLTC transformer was used as an MV/LV transformer. A cable emulator that consisted of NAYY 4 × 150 cables was used to emulate the LV grid.

The CVC was programmed in Node-RED, a JavaScript-based programming tool. The program runs on a computer that was connected to the communication network of the laboratory. The program acquired measurement data with intervals of 1 s and stored the data in an SQLite database. The voltage measurement at the 10/0.4 kV secondary side was measured with voltage measurements of the OLTC. Voltage and current measurements at BUS1 and BUS2 were measured with KoCos EPPE CX power quality analysers. Both OLTCs and power quality analysers were connected to the laboratory’s communication network via Modbus TCP.

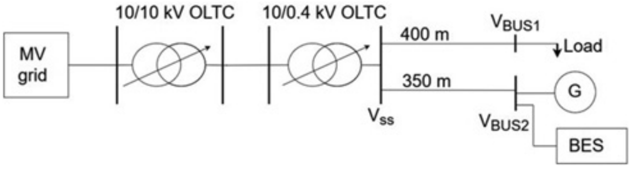

Fig. 3 *Network topology for test condition*

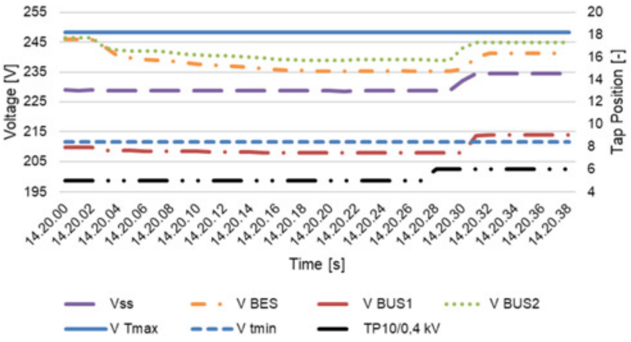

Fig. 4 *Measured voltage*

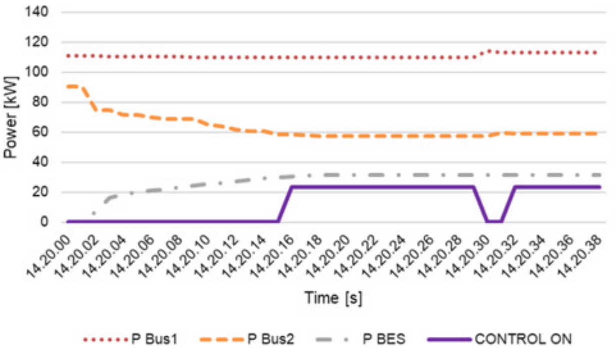

Fig. 5 *Measured power*

5 Results

The results of the experiment are presented in Figs. 4 and 5.

Voltages and tap position changes are shown in Fig. 4. The different power values and whether the voltage control of BES is on are shown in Fig. 5. The tap position of the 10/0.4 kV transformer TP10/0.4 kV is drawn in black. The tolerated maximum $V_{T\mathrm{max}}$ and minimum voltages $V_{T\mathrm{min}}$ are marked in blue. If the controlled voltage is exceeding these limits, the tap change timer is initiated. The controlled voltage is the voltage at the secondary substation V_{ss}, the voltage at BUS 1 V_{BUS1} and the voltage at BUS 2 V_{BUS2}. The power values measured from busses P_{BUS1} and P_{BUS2} are shown in Fig. 5. P_{BUS1} is power flow to the bus and P_{BUS2} is power flown from the bus. P_{BES} is the BES charging power. *CONTROL ON* is an indicator, whether CVC allows OLTC to do tap changes or not. There can be seen a voltage difference between V_{BUS2} and V_{BES}, because of the connection cable of the BES.

In Fig. 4, before 14:20:12, the voltage difference between measured the maximum and the minimum values of voltage is too high for OLTC to be able to fix the situation. If it would step up tap position, the voltage would exceed the maximum tolerated voltage and OLTC would end up doing continuously tap changes, i.e. hunting behaviour. The CVC sends the help request for BES at 14:20:02. In this test condition, there is a BES connected to the same bus which has high production. After receiving the help call, the BES SoC in order to bring voltage V_{BUS2} down. At 14:20:16, the voltage has come down enough for the OLTC to initiate the timer for a tap change. At 14:20:31, voltages are restored within a tolerated limit after the step-up operation of OLTC.

6 Discussion

Results in this paper demonstrate that the CVC with the cooperation of an OLTC and a BES can solve situations that the CVC with only an OLTC would not be able to solve. However, there are constrictions using a BES for voltage control. Whether a BES can contribute enough load or production for voltage control is situational. It depends on the network topology, production in the network, load in the network, use purpose of a BES and SoC of a BES. If a BES is already full, it cannot contribute as a load and vice versa.

The BES voltage control attempts to bring the voltage at the connection point of the BES closer to the nominal voltage parameter of the voltage control of the BES. This voltage control of the BES works properly, if the nominal voltage of network is set correctly. The assumption that 230 V is the best possible solution, might not fit all networks. In a network that has a high load and relatively not so high production, a higher nominal voltage parameter for voltage control of the BES would improve the voltage control.

The voltage control of the BES can contribute correctly to voltage control, if the BES is in the same feeder with voltage rise problem and the voltage at the connection point of the BES is above the nominal voltage or if the BES is in the same feeder with voltage drop problem and the voltage at the connection point of the BES is below the nominal voltage. This would be the general case. This CVC method does not have cooperation with the HV/MV OLTC, which can result in unnecessary tap operations and voltage fluctuations at a customer supply point. Coordination can be done by having different timers for cascading OLTCs [9]. Another approach is to create a system witch communication between two OLTCs.

7 Conclusion

The experiment presented here shows that the CVC can increase the hosting capacity of an LV network. In comparison to the CVC solely with an OLTC as an available component, the CVC with an OLTC and a BES cooperation is available to solve a wider range of voltage variations.

Further development of the CVC includes the implementation of a DG as a part of the CVC, reactive power control of the BES for a primary way to affect voltage, taking operations of an OLTC at a primary substation into account, more precise definitions of the margin used in the CVC and adding memory to the control of the CVC.

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