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Distribution grid planning considering smart grid technologies

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Abstract: Connection of distributed generation units, energy storages, and new loads into low-voltage grids leads to a constrained operation of the grids. Consequently, voltage limits violation and overloading of grid assets occur more frequently. To tackle these issues, distribution system operators (DSO) still employ traditional techniques in planning distribution grids to increase grid hosting capacity (HC). This implies a huge investment for the distribution grid operator. Nonetheless, smart grid technologies can be considered as alternative options for the DSO. Two methods, centralised voltage control and decentralised voltage control are compared technically and economically as an alternative to the traditional approach aimed at increasing grid HC.

1 Introduction

Due to increased installation of distributed generations (DGs) in low-voltage (LV) grids, distribution system operators (DSO) increase grid hosting capacity (HC) by means of traditional grid reinforcement [1]. This paper presents how smart grid technologies can be considered as planning alternatives to traditional approaches for solving voltage problems in the LV grid. This could eventually delay the investment associated with traditional grid planning. In this paper, the concepts of centralised voltage control (CVC) and decentralised voltage control (DVC) are presented. Both can be considered as alternative approaches to the traditional planning approach. An improved algorithm has been developed by the authors in [2, 3] to coordinate voltage control among smart grid technologies. The DVC strategy will be presented in this paper. Finally, the results of CVC and DVC strategies will be technically and economically discussed and compared with each other as well as with traditional grid planning.

2 Voltage control strategies

Application of an on load tap changer (OLTC) transformer in medium-voltage (MV)/LV substations is suggested in a lot of research for regulating voltage in LV grids. Furthermore, DG units can also support voltage in the LV grid in terms of reactive power support. Hence, both technologies contribute to a flexible operation of distribution grids. Traditionally, MV/LV transformers were operated at off-load tap and DG units were operated at constant power factor of one. DG units can contribute to voltage control by managing their active power 'curtailment' and reactive power. According to the German grid code, DG units connected to the grid should provide voltage support [4]. These methods are already implemented in the operation, however, are not yet integrated in distribution grid planning. There are two main strategies for voltage control, CVC and DVC, as shown in Fig. 1.

Fig. 1*a* represents a CVC strategy. In this strategy, there is a bidirectional flow of information between the control centre, distributed measurement and control asset over the grid. The state of the grid is measured and transmitted via a communication medium to the control centre. In the control centre the set points for each of the relevant grid elements are calculated and sent to the control units for execution. In the DVC strategy, there is no or very limited communication over the grid assets as shown in Fig. 1*b*. The set points for the control assets are estimated and executed based on the local measurements. The algorithm for the CVC strategy considered for the compression in this paper has been developed by the authors in [2, 3]. This paper focuses on the DVC strategy in detail.

2.1 DVC strategy

In this section, different applicable methods for DVC are described. Much focus is given to describing different methods with respect to DG units participating in voltage control, mainly curtailment and reactive power management such as cos $\varphi(P)$ and $Q(V)$. The voltage control by the OLTC transformer in the secondary station MV/LV is based on the common approach. This is to trigger tap changer operation when the measured voltage in the secondary side bus-bar of the OLTC transformer is not within the pre-determined bandwidth.

2.1.1 Reactive power management: DG unit support to control the voltage by reactive power is limited. This limitation can be due to the capability limits of the DG units and due to the effectiveness of the reactive power injection to the voltage based on the feeder characteristic such as R/X. As the R/X ratio is higher in LV grids compared to MV grids, the reactive power has relatively lower impact compared to active power on voltage in LV grids. However, it can be an economical option to control the voltage with the reactive power of the DG units as a first option rather than active power curtailment or traditional grid reinforcements. Provision of reactive power by DG units is mainly constrained by their operating power factor which is 0.95 or 0.9 depending on the installed capacity suggested in [4]. There are different methods of reactive power support to control the voltage in distribution grids. The section below focuses on the main ones.

2.1.2 Method A: cos φ *(P):* The traditional principle is to operate the DG units with a power factor close to $\cos\varphi = 1$. Currently, $\cos\varphi(p)$ is suggested as one of the methods to help the DSO in voltage control. Fig. 2 shows the characteristic curve according to which the DG units support the voltage in a feeder. Reactive power support in this method is based on the active power of the unit. DG units start to operate in capacitive mode once the active power of the respective unit reaches a pre-set value of $P_1 = 0.5P_n$. Hence, in this method it is assumed that there would be violation

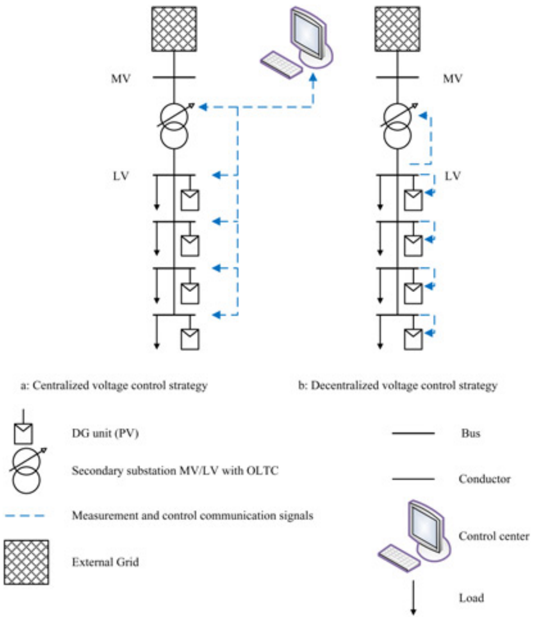

Fig. 1 *Voltage control strategies*

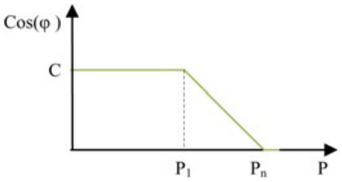

Fig. 2 *DG unit characteristic curve for method A*

of the upper limit of the steady-state voltage if the feed-in of the DG unit is increased to half of its nominal value. Equation (1) describes the set points mathematically

$$\cos\varphi = \begin{cases} c, & P < P_1 \\ K(P - P_1) + c, & P_1 \leq P \leq P_n \\ \cos\varphi & P > P_n \end{cases} \tag{1}$$

where K is

$$K = \frac{\cos\varphi - C}{P_n - P_1} \tag{2}$$

Based on the actual feed-in, the respective value for $\cos\varphi$ is determined according to (1) and (2). The values of reactive power are determined based on the following equation:

$$Q = \tan\left(\cos^{-1}(\cos\varphi)\right)*P \tag{3}$$

2.1.3 Method B: Q(*V*)*:* Providing reactive power as a function of voltage at the point of common coupling (PCC) is an alternative method where the DG units can participate in the voltage control of LV grids. Reactive power is consumed/provided when there is a difference between the voltage reference value V_{ref} and the actual voltage value V_{PCC} measured at the PCC. Fig. 3 shows the characteristic droop function for the reactive power of a DG unit.

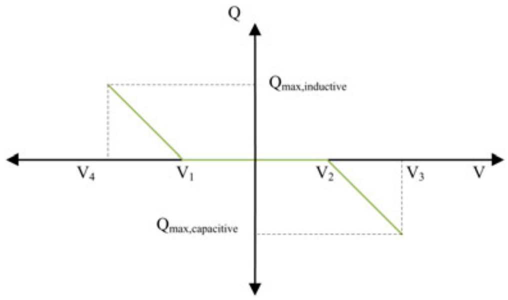

Fig. 3 *DG unit characteristic curve for method B*

Based on the characteristic curve shown above, the reactive power is calculated as per the following equation:

$$Q = \begin{cases} C_1\left(V_{\text{pcc}} - V_1\right) & V_4 < V_{\text{pcc}} < V_1 \\ 0 & V_1 \leq V_{\text{pcc}} \leq V_2 \\ C_2\left(V_{\text{pcc}} - V_2\right) & V_2 < V_{\text{pcc}} < V_3 \end{cases} \tag{4}$$

where C_1 and C_2 are the constants and can be calculated as per (5) and (6), respectively,

$$C_1 = \frac{Q_{\max}}{V_4 - V_1} \tag{5}$$

$$C_2 = \frac{-Q_{\max}}{V_3 - V_2} \tag{6}$$

Based on the equations above, the connected DG units in the grid provided reactive power at the time when there is a lower voltage problem due to the high load and less feed-in from the DG units. In the same way, the DG units consume reactive power at the time when there is a high voltage problem due to high feed-in and less load.

A deeper insight into the two aforementioned methods for reactive power management resulted in method B being more efficient than method A. The main drawback of method A is the assumption that the DG unit should start to support the voltage regulation in the grid once the active power of the unit is greater than half of its nominal capacity, regardless of the actual loading condition in the grid. Hence, DG units will reduce the voltage at the PCC even if there is no voltage problem. This causes many losses in the grid by unnecessarily providing reactive power. However, in method B the DG units support the grid voltage based on actual voltage at the PCC of the respective DG unit. Therefore, both actual generation and loading of the grid is considered.

2.1.4 Curtailment: The German Renewable Energy Act of 2014 defined a mechanism to control the active power of the DG units in case of system failure. According to this Act, the DG units should be remotely controlled, which implies that the mechanism required for the curtailment are already available. From the planning perspective, curtailment of active power of DG units is considered as an alternative option helping the DSO to control overvoltages and congestions in the grid [1]. A fundamental application of curtailment in the DVC strategy is based on droop functions. Fig. 4 shows the characteristic curve for active power curtailment of a DG unit.

As in the case study for DVC in the following section, curtailment is considered together with reactive power support. The characteristic curve for curtailment is therefore shown in Fig. 4 above together with the reactive power characteristic curve.

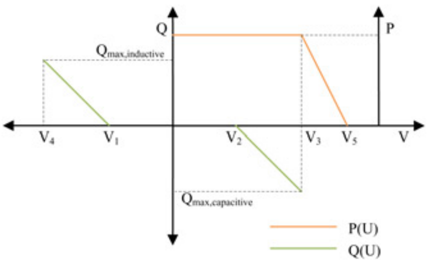

Fig. 4 *DG inverter characteristic curve for curtailment*

3 Case studies

The CVC and DVC strategies implemented here are shown in Fig. 1. The LV residential distribution grid model of the CIGRE [5] benchmark shown in Fig. 5 is chosen as a platform to perform the simulations. All relevant parameters of the cables and transformer are described in the CIGRE document [5]. Only the cable length between nodes 12 and 15 is changed with a factor of 5 and the cable length between nodes 7 and 18 is changed with a factor of 4. Two case studies are developed. In both case studies, all the parameters are the same. In case study B, however, 50% more PV units are distributed between nodes 4 and 15 compared to case study A of a total capacity of 80 kVA. Capturing the stochastic nature of DG units (in this case study PV units) and loads their profiles are represented by time series. The time series used for this simulation is developed in [6] for the duration of one year with hourly resolutions. The control limits for OLTC and DG units are described in Table 1.

The algorithm for CVC shown in Fig. 6 has been developed by the authors in [2, 3]. The algorithm consists of three blocks; block A describes the reactive power control of PV units, block B shows the substation voltage control and block C depicts the active power curtailment of the PV units. The algorithm takes minimum, maximum and LV substation voltages in the grid as input parameters for each time step. Moreover, the algorithms incorporate the feeder impedance method to select the PV units which will participate in CVC. A detailed description of the algorithm and parameter calculation can be found in [2, 3].

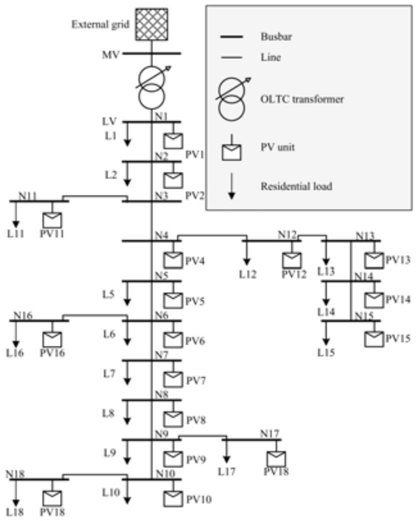

Fig. 5 *CIGRE – European benchmark for LV grid*

Table 1 Parameter set points for the assets in DVC

Assets	Parameters	Set points, p.u.
OLTC	dead band-upper limit	1.01
	dead band-upper limit	0.99
DG units	V1	0.94
	V2	1.07
	V3	1.09
	V4	0.91
	V5	1.10

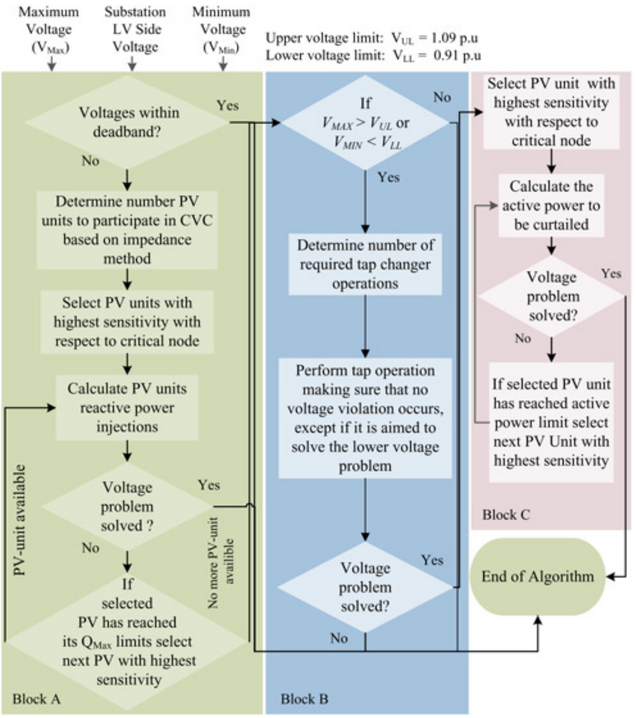

Fig. 6 *Centralised voltage control algorithm*

3.1 Results of the case studies

The technical result for case study B will be presented as it is the case with a relatively higher amount of PV units. The voltage duration curve for case study B is shown in Fig. 7. Without the intervention of any of the aforementioned voltage control strategies, violation of the upper voltage limit for a duration of 1080 h and lower voltage limit for a duration of 35 h in the studied year is observed. The voltage limit is according to EN 50160. Considering the application of OLTC in MV/LV substations the voltage limit of 10% is applicable for the LV grids. However, in this study the voltage interval of (1.09 and 0.91) p.u. is considered. The 2% is kept as a safety factor covering possible

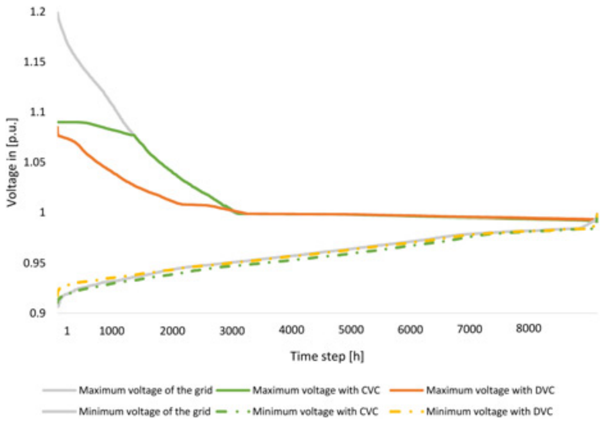

Fig. 7 *Maximum and minimum voltage duration curves with and without applications of CVC and DVC strategies*

Table 2 Summary of case studies results

Case studies/ strategies	Active power curtailment, kWh	Reactive power support, kVArh	Number of tap operations	Losses, kWh
Case study A – CVC	0	786	34	15,906.5
Case study A – DVC	2291.3	3165.8	453	15,638.3
Case study B – CVC	418	34,622	720	26,951.5
Case study B – DVC	53,800	6716	442	16,067

planning and operation errors such as the forecasting of future DG unit connection.

By implementing the CVC and DCV strategies shown by the green and orange curves in Fig. 7 above the voltage of the studied grid is kept within the maximum and minimum limits defined in the study cases. Both strategies demonstrate computability to increase the grid hosting capacity in terms of steady-state voltage limits in order to increase the integration of additional DG units. Table 2 technically compares CVC and DVC strategies in both case studies.

In both cases, the DVC strategy leads to a substantially higher curtailment of active power of the PV units. Considering a limitation of, e.g. 3% as an annually permissible energy curtailment for each PV unit imposed by the regulations in the planning of PV units. In case study A, the PV units connected at node 15 and in case study B, the PV units connected at nodes 15, 14 and 13 will already be reaching this limit. Consequently, defaulting the application of traditional grid reinforcement or the consideration of CVC. Methods of traditional grid reinforcement for calculation in this paper are based on the planning guideline in [7].

4 Economic analysis

The results of CVC, DVC and conventional grid planning (in this case upgrading the cables) are economically evaluated as alternative options for solving the grid HC problem. A comprehensive economic evaluation should consider not only the capital investment costs but the operational costs as well. For the planning of distribution grids the net present value (NPV) method can be used as a decision-making tool, whose value justifies the reason why a company should delay an investment. The overall NPV for each option can be calculated using the following equation:

$$\mathrm{NPV} = \mathrm{NPV}_1 + \mathrm{NPV}_{\mathrm{op}} \tag{7}$$

where NPV_1 and $\mathrm{NPV}_{\mathrm{op}}$ are the net present values of investment and operational costs, respectively. The annuity method is considered a suitable evaluation method for options with different life times [8]. Based on the annuity method, the NPV can be annualised as per (9) and (13)

$$A = \frac{i(1+i)^n}{(1+i)^{n-1}} \tag{8}$$

$$A_1 = \mathrm{NPV}_1 \cdot A \tag{9}$$

where A is the annuity factor, A_1 the annualised investment cost, i represents the interest rate and n is the asset lifetime. In this study, a lifetime of $n = 40$ years and $i = 8\%$ is considered. The active power curtailment, reactive power support and losses in the grid are considered as operational costs in this study. As the simulation is considered for 1 year T, the data of the system losses, reactive power support and curtailment are also considered for the duration of 1 year in time steps of 1 h Δt for each case study

$$C_{\mathrm{Losses}} = \left(\sum_{t=1}^{T} \mathrm{Losses}\right) \cdot \Delta t \cdot c_{\mathrm{losses}} \tag{10}$$

$$C_{\mathrm{c}} = \left(\sum_{t=1}^{t} \text{Curtailed power}\right) \cdot \Delta t \cdot C_{\mathrm{c}} \tag{11}$$

$$C_Q = \left(\sum_{t=1}^{t} |Q|\right) \cdot \Delta t \cdot C_Q \tag{12}$$

$$A_{\mathrm{op}} = C_{\mathrm{Losses}} + C_C + C_Q \tag{13}$$

The overall annual cost A_{total} for each option can be calculated as follows:

$$A_{\mathrm{total}} = A_1 + A_{\mathrm{op}} \tag{14}$$

The cost for the economic calculation is presented in Table 3.

Fig. 8 provides an economic comparison of three different options for increasing grid HC in both case studies.

It can be seen from the figure above that the application of the DVC strategy to increase the grid hosting capacity in case study A is the most economical option. If no annual curtailment restriction is imposed by the regulator during planning, the second most economical option is the application of the CVC strategy. The CVC strategy can also be the most economical option if there is a curtailment restriction imposed by the regulator. Traditional grid reinforcement is evaluated as the most expensive option for case study A. In case study B, the DVC strategy is evaluated as the most expensive option. This is due to the fact that in this case 50% additional PV units are installed compared to case study A, which leads to a higher amount of curtailment. The main cost component for the DVC strategy in case study B comes from the curtailment of active power. However, the application of the CVC strategy is considered the most economical option to increase the grid hosting capacity.

Table 3 Costs for economic analysis

Options	Costs
MV/LV – OLTC transformer	30,000€
LV cable	100 €/m
network losses (C_{losses}) [1]	0.079 €/kWh
reactive power compensation [1]	0.0087 €/kVarh
curtailment cost (C_{c}) [1]	0.2874 €/kWh
communication and control	10,000€/feeder for DSO

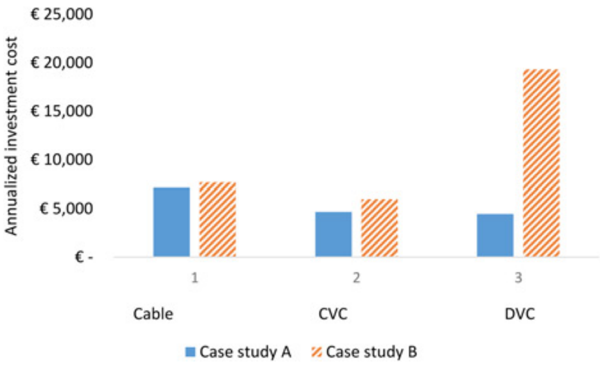

Fig. 8 *Summary of economic evaluation of the planning options*

5 Conclusion

This paper focused on the planning of distribution grids, mainly LV grids. It describes how increased installation of DG units in LV grids could challenge the grid hosting capacity in terms of the upper steady-state voltage limit violation. A traditional strategy to tackle this problem is to upgrade LV grids with additional lines/cables and/or transformers. The application of advanced communication and control technologies in LV grids under the label of 'smart grid technologies' enables a flexible operation of LV grids. This paper considered the concept of flexible operation of LV grids and reflects it in the grid planning phase. Hence, the application of smart grid technologies in LV grids is assessed as an alternative planning option to conventional strategies. Two different strategies CVC and DVC are presented in this paper. Both strategies are technically capable of solving an LV grid voltage problem as presented in the two case studies. The paper shows that regulation such as application of an annually curtailed energy limit greatly influences the choice of the grid planner. In the same way, the penetration level of the DG unit in a grid leads to different amounts of curtailments, which has a cost implication that could eventually impact the planners' choice of different alternatives.

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