SOFT CURTAILMENT FOR VOLTAGE LIMITING IN LOW-VOLTAGE NETWORKS THROUGH REACTIVE OR ACTIVE POWER DROOPS

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ABSTRACT

The increasing share of small-scale distributed generation (DG) units can lead to over-voltage problems in low-voltage networks. In order to solve this issue, the DG units are sometimes equipped with Q/V droops, which is analogous as in the transmission network. This paper shows that the impact of reactive power on the voltage profile is limited in the considered low-voltage networks. The main reason is that in resistive networks the voltage is mainly linked with active power, not reactive power. Another, indirect, effect comes from the Q/V linkages in the overlaying networks, which is unknown and often counteracted by designated devices. Therefore, an effective way to avoid voltage limit violation in low-voltage networks is by implementing P/V droops in the DG units. A special variant of this is the voltage-based droop control that enables, without communication, to firstly change the output power of the dispatchable DG units and, only when necessary, also that of the renewable energy sources.

Index Terms— microgrids, distributed generation, droop control, curtailment

1. INTRODUCTION

With the advent of large amounts of distributed generation (DG) units, the power system undergoes major changes, especially at the distribution level. Therefore, the microgrid concept has been developed [1, 2]. Microgrids enable a coordinated integration of the DG units in the electrical power system and capture the emerging potential of DG [3]. Opposed to the conventional synchronous generators, a large share of the DG units is not directly connected to the electrical network, but use converter-interfaces. These converter-interfaced DG units lack the rotating inertia the conventional grid control is based on. Also, islanded microgrids have very different characteristics in comparison with the conventional electrical power system, such as their small scale and the possibly high share of renewable and volatile energy sources.

Therefore, for islanded microgrids, new control strategies for the converter-interfaced DG units have been developed. In order to avoid single points of failure and to increase the reliability of the microgrid, the usage of communication for the primary control is often avoided. This has led to the development of droop-based control strategies. The P/f droop control [4–6], with many variants, is widely used as it is similar to the conventional grid control. This control strategy is based on the inductive character of the lines leading to a linkage between the active power and the phase angle (thus dynamically also the frequency). However, as many microgrids are low-voltage networks, the lines are often mainly resistive, implying a P/V linkage. Therefore, the so-called reversed droops, P/V droops, have been developed [7]. A variant of this strategy, the voltage-based droop (VBD) control presented in [8], combines P/V droop control with dc-link voltage droops. With this VBD control strategy, the power changes of renewable energy sources can easily be delayed (to more extreme voltage conditions) compared to those of the dispatchable DG units. This can lead to an optimized integration of renewable energy sources, which can enable a higher share of renewables in the network.

In the grid-connected microgrids, the DG units are generally equipped with a conventional grid-following control strategy. The units track the terminal voltage to obtain a reference current. In this case, the injected power is independent of the state of the network. Therefore, voltage problems are becoming a major issue, especially in the low-voltage networks. To solve this, investments can be made in more and stronger lines. Also, hard curtailment or soft curtailment can be included. Hard curtailment consists of on-off control, which can lead to a loss of the potential renewable energy, as the storage capacity is limited. This paper focusses on soft curtailment through active power and reactive power changes of the grid-following units on one hand and through VBD control on the other hand.

2. METHODS TO AVOID VOLTAGE-LIMIT VIOLATION

2.1. Network investments

Grid-upgrades are the historical approach to deal with the increasing demand. However, with the large increase of DG in the network, this demands for very large investments in the

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power system. Hence, the smart grid paradigm proposes to deal with the networks capacity in a smarter way to limit the required investments. Some solutions provided are demand response or curtailment of the DG units' output power. This paper focusses on measures in the DG units.

2.2. Hard curtailment

For hard curtailment, the whole DG unit is disconnected in case the grid voltage exceeds a certain level, which is known as on/off control. This leads to a significant loss of the revenue, as generally, the units did not need to turn off entirely to solve the voltage problem. Also, a significant amount of available renewable energy is lost, as the storage capacity is generally limited or absent.

2.3. Soft curtailment

Another method is to use soft curtailment for voltage limiting in low-voltage networks.

2.3.1. Q/V droops

In the transmission network, the voltage is controlled through reactive power changes of the generators or by using specific devices such as capacitor banks. Because of the experience in this strategy, analogous methods are pursued in the low-voltage networks. However, from a theoretical point of view, there are limitations to this method. The power flow from a voltage source $\underline{E}_1$ to $\underline{E}_2$ through a line impedance of $R + jX$ equals:

$$P = \frac{E_1}{R^2 + X^2}\left[R(E_1 - E_2\cos\delta) + XE_2\sin\delta\right] \quad (1)$$

$$Q = \frac{E_1}{R^2 + X^2}\left[-RE_2\sin\delta + X(E_1 - E_2\cos\delta)\right], \quad (2)$$

with E_1 and E_2 the rms voltages and δ the phase angle difference between the voltages. In the transmission network, the line impedances are mainly inductive, thus, R may be neglected. Further, δ is typically small, hence, it is reasonable to assume that $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. Therefore, the flow of reactive power is proportional to the voltage magnitude difference:

$$Q \approx \frac{E_1}{X}\left[(E_1 - E_2)\right]. \quad (3)$$

For this reason, the output voltage can be regulated by changing the reactive power, e.g., in a droop as shown in Fig. 1. Therefore, new converters are sometimes equipped with Q/V curtailment strategies, e.g., the voltage support based on reactive power in [9]. The effect of Q/V droops in a 10 kV networks is also studied in [10].

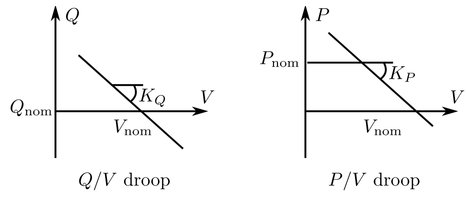

Fig. 1. P/V or Q/V droops (without constant-power band)

This paper focusses on low-voltage networks (230 V). These networks are predominantly resistive ($X \approx 0$ in (1) and (2)), such that the voltage magnitude mainly depends on the active power of the units:

$$P \approx \frac{E_1}{R}(E_1 - E_2) \quad (4)$$

Therefore, the impact of Q/V droops on the voltage profile is limited in low-voltage networks. Still, the reactive power can to some extent modify the terminal voltage, as:

- the lines are not perfectly resistive, always some inductance is present in the lines
- the PCC voltage (between the considered microgrid and the rest of the network, which is significantly more inductive than the microgrid itself, as shown in Fig. 2) is affected by the reactive power changes.

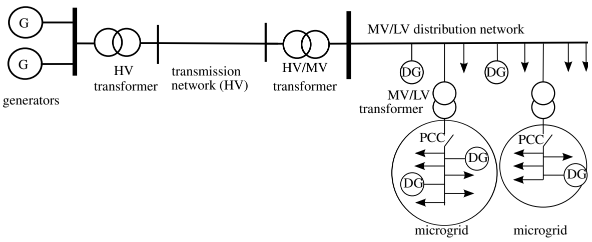

Fig. 2. Microgrid connected to utility through PCC

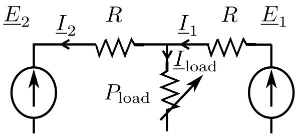

Fig. 3. Microgrid topology, low-voltage microgrid

Because of the latter reason, an indirect effect of Q on V is present. To verify this, the simple network of Fig. 3 is considered. It consists of a radial low-voltage network with resistive lines, a DG unit with voltage $\underline{E}_1$ (Thévenin equivalent) and a strong utility network $\underline{E}_2$. Only active-power loads are considered. The DG unit is equipped with a Q/V droop to consume reactive power when its terminal voltage becomes too high. In first instance, this does not influence the voltage of the resistive network. However, the consumption is balanced through reactive power generation in the high-voltage network. As shown above: $Q \sim \Delta V$, such that $\Delta V = E_2 - E_1$

increases. At first sight, this seems to indicate that the PCC voltage will increase as well. However, it is ΔV, not V_{PCC}, that increases. In order to demonstrate the influence of Q on V_{PCC}, the control strategy of the central generators should be considered. The large central generators are equipped with Q/V droops as well. A negative droop is present such that for an increasing reactive power (delivered reactive power is positive), these units will lower their terminal voltage. Hence, V_{PCC} clearly decreases. In this way, the DG unit's terminal voltage will lower compared to the case without Q consumption and Q/V droops can be effective, but to a limited extent.

A disadvantage of this method is that it is an indirect control. The microgrid's influence on the rest of the network is limited. However, one should not consider the whole network as voltage is a local phenomenon, opposed to network frequency. On the other hand, reactive power control does not involve active power changes, thus, the costs or revenue-losses are limited. One should also take into account that the current magnitude changes because of the reactive power control, which may restrict the delivered active power, again, indirectly.

2.3.2. P/V droops

As discussed above, in predominantly resistive networks, the terminal voltage of the DG unit is directly affected by its active power. Therefore, the required active power change for a given voltage change is lower compared to the reactive power change in the previous case. To lower the voltage, the delivered active power of the DG units should decrease. For dispatchable DG units, this is easily done by decreasing the fuel intake. It often means less income from active power delivery and an operation that differs from the nominal operation, which is generally most efficient. Lowering the generated power can also be implemented by deviating from the maximum power point operation, shifting the local load or using storage equipment. There are several ways to encourage the voltage control by the DG units. Firstly, this ancillary service can be encouraged by the grid operator by means of incentives. Secondly, it may also become obliged for voltage limiting. The central generators have to participate in the primary control. Presently, this is generally not the case for small DG units. However, with the increasing penetration of DG, this becomes an unsustainable situation. Thirdly, even without intervention of the operator, over-voltage conditions induce shut down of the units, which leads to a significantly higher loss of power generation compared to the soft curtailment. Hence, soft curtailment leads to less revenue loss compared to full shut-down.

2.3.3. VBD control

The VBD control delays the changes of active power of the renewable sources compared to those of the dispatchable DG units. This delay refers to changes of power triggered by more extreme terminal voltages.

The previous controllers are mostly implemented as grid-following controllers as depicted in Fig. 4. These controllers can be implemented in grid-connected microgrids. The injected current of these units is actively controlled. The VBD control is implemented as a grid-forming control strategy as shown in Fig. 5 and is applicable in both grid-connected and islanded microgrids. The delivered active power is controlled by a control loop that enables active power sharing between the DG units in the network. The terminal voltage is actively controlled.

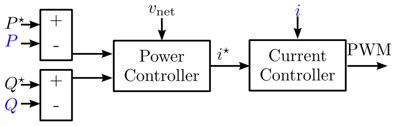

Fig. 4. Grid-following controllers

The voltage-based droop control is based on two control strategies shown in Fig. 6, with their operation dependent on the rms voltage [8]. Key in this control strategy is that it operates without communication and is based on the intrinsic characteristics of the considered microgrid such as the resistive lines, lack of rotating inertia, and the high share of renewables. In a voltage band around the nominal voltage, only the V_{g}/V_{dc} droop control strategy is applied, keeping the generated power constant and where V_{g} is drooped with V_{dc}, the dc-link voltage of the power source. V_{g} is the terminal voltage of the DG units, analogous to V in the grid-following P/V controllers. If the voltage exceeds this band, also a P_{dc}/V_{g} droop controller is turned on, which changes the generated power P_{dc} and avoids violation of the voltage limits. Therefore, this band is called the constant-power band.
The width of this band $2b$ depends on the characteristics of the power source. For variable, controlled (often non-renewable) power sources, a narrow constant-power band can be handled. Therefore, small variations of V from its nominal value V_{nom} address the P_{dc}/V_{g} droop controller to change P_{dc}. This enables to fully exploit the power control characteristics of the power source and the unit acts dynamically to limit the voltage changes. For non-variable or slightly-variable power sources (often intermittent renewable units), P_{dc} is determined externally and therefore, a wide constant-power band can be applied. In this way, changing the output power of these power sources is delayed and is only addressed to limit too large voltage variations in the microgrid.

For the reactive power control, a Q/f droop controller is

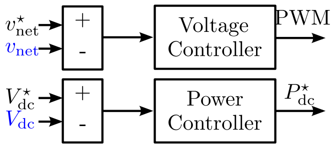

Fig. 5. Grid-forming controllers

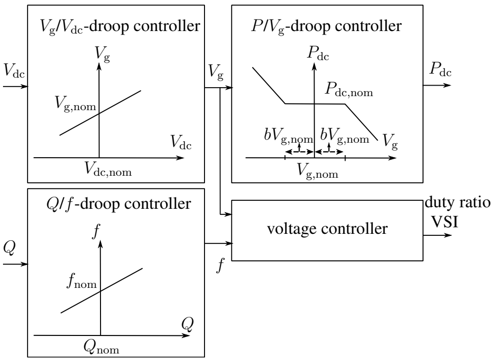

Fig. 6. Voltage-based droop control consisting of $V_{\mathrm{g}}/V_{\mathrm{dc}}$ droop control combined with $P_{\mathrm{dc}}/V_{\mathrm{g}}$ droop control and constant-power bands

applied. Opposed to grid-following controllers, no PLL is required for synchronisation as the Q/f droop takes care of this.

2.3.4. Combination of control algorithms

The VBD control is designed for islanded operation but can be implemented in a grid-connected network as well. It is a grid-forming control, like the conventional large central generators. Furthermore, based on the VBD control approach, the constant-power bands can be implemented in the grid-following Q/V and P/V droop controllers as well. In this way, the DG units only react on voltages that exceed a certain threshold voltage. Furthermore, the reaction of the renewables can be delayed to more extreme threshold voltages compared to that of the dispatchable DG units. Also, a combination of P/V and Q/V droops may prove to be beneficial by exploiting the benefits of both.

3. CASE STUDIES

Avoiding voltage-limit violation through reactive and active power changes is compared for the following control strategies: conventional grid-following (gr-foll) control, grid-following Q/V droop control, grid-following P/V droop control and grid-forming (gr-form) VBD control.

3.1. Strong network

In this case, the microgrid is connected to a strong utility network $\underline{E}_2$ that is modelled as a 50 Hz voltage source of 230 V rms, which is not affected by the microgrid. The network is shown in Fig. 3.

Resistive microgrid lines

The microgrid lines are resistive, here 3 Ω. A large line resistance is chosen as it emulates the virtual output impedance method [11]. Hence, the 3 Ω value is a combination of the real line resistance and the resistive virtual output impedance of the DG unit. A load of 2 kW is connected to the network.

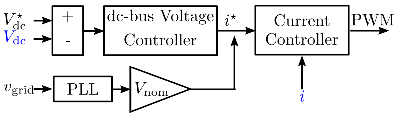

Fig. 7. Implementation of grid-following controller through PLL

The nominal power P_{nom} of the DG unit equals 3 kW. The rest is injected into the utility network. The simulations are preformed in Matlab/Simulink including the Plecs library to model the DG units upto the level of the converter switches.

First, an undispatchable grid-following controller is studied. The implementation of this controller is shown in Fig. 7. The terminal voltage is tracked by using a Phase-Locked Loop (PLL). As power-factor-one control is generally implemented, the injected current is in phase with this voltage. The rms current is determined by a dc-link voltage controller keeping the dc-link voltage constant. The dc input power is determined externally, e.g., using maximum power point tracking and as such equals P_{nom}.

Table 1. Study of influence of control strategy: resistive lines

Case	P (kW)	Q (kVAr)	V_{DG} (V)
Gr-foll, undispatchable	3	0	271.0
Gr-foll, P/V	1.9	0	248.7
Gr-foll, Q/V	3	-2.2	266.1
Gr-form, VBD ($b = 0$ %)	1.7	0	245.2
Gr-form, VBD ($b = 5$ %)	2.1	0	252.6

Second, in the grid-following control algorithm, a P/V droop is included to restrict the delivered active power to the network based on the terminal voltage:

$$P = P_{\mathrm{nom}} - K_P(V_{\mathrm{g}} - V_{\mathrm{g,nom}}), \qquad (5)$$

with $V_{\mathrm{g,nom}} = 230\mathrm{V}$ rms and $K_P = \frac{P_{\mathrm{nom}}}{50\mathrm{V}}$. Table 1 shows that the P/V droops avoid voltage limit violation, whereas the undispatchable DG unit would shut down due to the overvoltage occurrence.

In the third case, a Q/V droop is included in the grid-following control algorithm:

$$Q = Q_{\mathrm{nom}} - K_Q(V_{\mathrm{g}} - V_{\mathrm{g,nom}}), \qquad (6)$$

with $Q_{\mathrm{nom}} = 0$ VAr and $K_Q = K_P$. Even without influence of the utility network, this control strategy slightly influences the terminal voltage. This is due to the network line resistances and the changed rms current. Compared to the undispatchable DG unit, the reactive power of the unit has changed from zero to a negative value, i.e., consumption. Hence, for the same active power output, the rms current increases. In this way, the terminal voltage of the unit is affected. How-

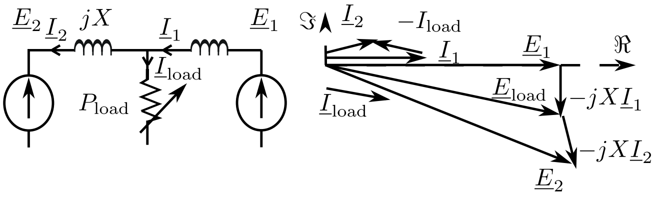

Fig. 8. Phasor voltages in inductive network

ever, the influence of Q on V is limited and here, still an over-voltage condition is present. The value of $I_{\rm rms}$ should be limited for protection of the converter and eventually, this requires to lower the output active power.

Fourth, the VBD control can be implemented in its fully dispatchable form (constant-power band with a zero width), in its undispatchable form (infinite constant-power band) or inbetween. An effective voltage-limiting is obtained. When comparing the dispatchable unit ($b = 0$ %) with the less dispatchable unit ($b = 5$ %), it is concluded that there is a trade-off between maximum injected power and voltage control. This trade-off can be set by adjusting b according to the characteristic of the unit, e.g., the renewable DG unit operates closer to its maximum power point, but induces a higher voltage.

Inductive microgrid lines

The same network as Fig. 3, but with inductive lines $X_{\rm line} = 3\ \Omega$ is studied. If the considered microgrid is inductive (which is generally not the case), no over-voltage problems arise. The reason is the Q/V linkage in this network. This is clarified using Fig. 8, showing that $E_1 < E_2 = 230$ V. For the undispatchable grid-following DG unit, $\underline{E}_1$ and $\underline{I}_1$ are in phase because of the zero power-factor. The same is valid for $\underline{E}_{\rm load}$ and $\underline{I}_{\rm load}$. Here, $P_{\rm load} < P_1$, hence $I_1 > I_2$. The figure shows that $E_1 < E_2$. However, the voltage can become too low. This can be solved by the droops as well. As shown in Table 2, the Q/V droops enable to augment the terminal voltage. Note that for a same ΔV significantly less Q is required compared to the case with resistive lines. This is clearly because of the Q/V linkage in inductive networks. The VBD controller now also injects some reactive power in the networks because the reactive power consumption is not zero any more in the inductive lines. Like the Q/V control, the VBD controller enables to obtain a terminal voltage close to the nominal value.

In conclusion, in the considered resistive networks, the VBD and P/V controllers are effective to avoid voltage limit violation. The Q/V droop controller has a limited effect on the terminal voltage of the DG units.

3.2. Utility network with Q/V dependence

Practically, opposed to the previous case, the utility network $\underline{E}_2$ in Fig. 3 is not a perfectly strong network. A Q/V linkage is present, mainly through the Q/V droops in the central generators that are connected to the transmission network. In the previous case, it was shown that the Q/V droop-controlled grid-following units did not significantly affect the terminal voltage in the resistive microgrid, opposed to the VBD and P/V controllers. This does however not mean that Q/V droops are ineffective, hence, the Q dependence in the utility network is considered as well. Here, the utility network is again represented as a voltage source, but now with a droop K_Q that is equal to that of the DG unit. Practically, the Q/V droop of the network is highly dependent on the local network state.

Table 2. Study of influence of control strategy: inductive lines

Case	P (kW)	Q (kVAr)	$V_{\rm DG}$ (V)
Gr-foll, undispatchable	3	0	216.7
Gr-foll, Q/V	3	0.3	226.0
Gr-form, VBD	2.6	0.5	235.1

Table. 3 shows that Q/V droops become more efficient because of the network's Q/V dependence. The P/V droops and VBD controller are able to limit the voltage, analogously as in the previous case with resistive network lines.

However, still, the effect of the DG units' reactive power on the local utility network is limited; even more so as often, the voltage deviation of the PCC from its nominal value is further restricted by designated devices such as on-load tap changers. Hence, the Q influence on the PCC voltage and, thus, on the local terminal voltage is limited when compared to the active power droops.

Table 3. Study of influence of control strategy: utility with Q-V dependence

Case	P (kW)	Q (kVAr)	$V_{\rm DG}$ (V)
Gr-foll, undispatchable	3	0	271.0
Gr-foll, P/V	1.9	0	248.7
Gr-foll, Q/V	3	-1.2	250.7
Gr-form, VBD	1.7	0	245.7

3.3. Constant-power bands

In order to study the effect of the usage of constant-power bands, an analogous network as in the previous cases is considered. In Fig. 3, $\underline{E}_2$ remains the utility voltage and $\underline{E}_1$ represents DG 1. An additional DG unit (DG 2) is connected to DG 1 through a line resistance. Both units have a nominal power $P_{\rm nom}$ of 1500 W and $K_P = P_{\rm nom}/25{\rm V}$.

First, the grid-following P/V controller is studied. Second, the VBD controller is studied. In order to make a distinction between the renewable source DG 1 and the controllable unit DG 2 in the VBD control, the first DG unit has a constant-power band of 8 % while DG 2 operates without constant-power band. The results are summarized in Table 4. Both controllers lead to effective voltage limiting. Because of the usage of constant-power bands, the VBD controller clearly enables to capture the renewable energy potential.

Table 4. Influence of constant-power bands (P in kW)

Case	P_1	P_2	$V_{\mathrm{DG},1}$ (V)	$V_{\mathrm{DG},2}$ (V)
Gr-foll, P/V	0.9	0.7	239.7	245.9
Gr-form, VBD	1.5	0.2	243.9	245.8

4. CONCLUSIONS

In order to prevent voltage problems in low-voltage networks, the DG units should be equipped with an additional control strategy to change the injected power dependent on the local state of the network.

For this, analogous as in the high voltage networks, Q/V droops can be implemented. The lines in the considered networks are predominantly resistive. Therefore, the voltage magnitude is mainly linked with the active power, not reactive power like in the transmission network. Hence, the impact of Q/V droops on the terminal voltage is limited. The effect is dependent on the Q/V linkage of the PCC voltage and the low, but non-zero value of X/R in the lines. This is often counteracted by (often expensive) designated devices such as tap changers that control V_{PCC}.

The P/V droops on the other hand affect the voltage in a direct manner. In this paper, it is shown that V can more easily be controlled through P changes.

The VBD control also effectively affects V through P changes. This control strategy enables to delay changing the output power of the renewables to more extreme voltages compared to those of the dispatchable DG units, thanks to the usage of constant-power bands. The same approach can be implemented in the grid-following P/V controllers. Also, a combination of the three control strategies can be beneficial, as:

- Q/V droops: only reactive power changes are required. However, Q also changes the rms current of the DG unit, thus, indirectly the maximum P that can be injected
- P/V droops: are more effective for voltage control
- VBD control: effective for voltage control and delayed response of renewables

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