Comparison of Voltage Control by Inverters for Improving the PV Penetration in Low Voltage Networks

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ABSTRACT Voltage rise caused by reverse power flows and intermittency in renewable power is the main limiting factor for integration of photovoltaic(PV) generation in low voltage networks. Inverter voltage control techniques have been developed to provide effective voltage control and support higher penetration integration of PV generation. In this paper, the common Volt-VAR control, PF(P) and Q(U) control of photovoltaic inverter methods are detailed compared. A set of simulation study-cases have been designed based on a generic LV grid model, which is considered as representative for the Bornholm network. Observations of the influence of different Volt-VAR control strategies upon different electrical parameters on hosting capacity increase potential have been performed. Results show that inverter controls can greatly contribute the integration of PV in LV networks in the perspective of avoiding overvoltage.

INDEX TERMS Low voltage network, PV inverter, voltage control, hosting capacity.

I. INTRODUCTION

Driven by the advancement of the generation technology and the ever decreasing technology cost, a steep deployment of solar PV has been seen in recent years. The installation capacity worldwide increased more than 10 times since 2010, and reached 580.1 GW at the end of 2019 [1], which is after hydro and wind power, the third most important renewable energy source in terms of installed capacity. In China, the total installation capacity of PV reached 204.3GW at the end of 2019, and 62.6GW is the distributed PV generation [2]. Most of them are connected in the distribution networks. Though a variety of benefits have been brought with the integration of PV, network issues in the low voltage networks are becoming significant as well, which in turn limits the scaling up of PV [3], [4].

One of the main limitations for further PV integration into existing low voltage networks is the voltage rise caused by the reverse power flow along the distribution feeders [5]–[7]. This phenomenon is bound to be exacerbated under higher penetration of PV sources. Several techniques to alleviate the voltage rise issue have been proposed.

One simple solution is to lower the set point of the on-load tap changer at the high-voltage/medium-voltage substation, or to use a voltage regulator [8]. However, this method cannot

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guarantee that the voltage profile will be within acceptable bounds throughout the feeder. In addition, other feeders that are connected to the same transformer may be adversely impacted by this action. Besides, the voltage regulation devices like On-Load Tap Changing transformer (OLTC), Switched Capacitor Bank (SCB), and Step Voltage Regulator (SVR) are slow to operate and usually are very sensitive to the number of operations [9], [10]. High shares of PV penetration combined with intermittency of PV systems on the feeder may cause excessive and unnecessary operations of these devices.

Alternatively, the utility can choose to reinforce the distribution grid, by increasing conductor sizes to reduce the resistance of medium- and low-voltage lines. While installed capacity of PV systems always increased at a much faster rate than the development of new controllers or the updating of grid codes, this practice has led to high costs [11]. Yet another solution is to curtail real power feed-in from PV units at times of low demand. For instance, in the Japanese grid code, when the voltage at the point of common coupling exceeds the upper limit, the PV system is required to reduce its active power output [12], [13]. The disadvantage of this technique is that it causes the curtailment of solar energy, which is not economically attractive to the PV panel owners.

Voltage control through reactive power generation from PV inverter, is one of the easiest to implement because of the

versatility of the inverter unit in providing a set of voltage control techniques [14]–[16]. Appropriate reactive power control can offset the voltage rise in distribution networks, while reducing or delaying the need for new assets or grid reinforcements. Furthermore, from an economic point of view, using reactive power contribution strategy to tackle the voltage problem lowers the costs of PV integration, as the alternatives through grid reinforcement, storage or active power curtailment come at a higher cost.

Various inverter voltage control methods have proposed to explore the capability of voltage rise mitigation and show the potential on improving PV penetration in LV networks. A new approach for reactive power management with volt–var control considering inverters' capacity and sensitivity to the critical bus is presented in [17]. In [18], the effects of autonomous voltage control strategies based on the active and reactive power control capabilities of PV systems as well as the on-load tap changer of transformers on the PV hosting capacity (HC) in LV distribution feeders are investigated. Hosting Capacity increase through the controls available in smart inverters and BESS is evaluated in [19], and result demonstrates that in relation to allowing a high HC and presenting a good cost-benefit, the most indicated solution would be the use of the Volt–VAR + Volt–Watt control. In [20], conventional and smart inverter voltage controls are compared to investigate their impact on the local voltage profile and findings show renewable energy share can be increased in networks with smart inverter deployments, without making substantial changes to rest of the network. In [21], it shows how PV inverter controls can regulate distribution network voltages, reduce network losses, increase the network hosting capacity and hence the uptake of distributed renewable energy. Though different voltage control methods are proposed, detailed comparison of those inverter voltage control methods and their different impact on HC due to different control parameters are little concerned.

The determination of the HC is subject to uncertainties like load consumption, PV production, distribution of PVs, and distribution transformer primary voltage. Thus stochastic frameworks are commonly used to address these uncertainties [19], [22]–[24]. However, integrating local voltage control strategies in a power flow-based HC assessment framework would be time-consuming and complex. For the comparison of influence of different control methods on HC improvement, it is sufficient and convenient to define a reference scenario for the abovementioned uncertainties instead of following the stochastic approach [25].

This paper provides an analysis on the voltage regulation techniques that can be applied in the LV network with photovoltaic inverter technology. The main purpose of the research is to systematically explore the influence of reactive power control strategies of PV inverter on increasing the hosting capacity in the perspective of avoiding overvoltage and the associated grid losses. A set of simulation study-cases are performed on the generic LV grid model to verify that inverter voltage control could be a potential option for improving the voltage profile.

The paper has been divided into sections: Section 2 introduces the definition of PV penetration and HC and the sensitive factors of HC. In Section 3 the different PV voltage control methods are discussed, with a special focus on $PF(P)$ control and $Q(U)$ control. In Section 4 several cases and scenarios are designed to compare the effectiveness of $PF(P)$ control and $Q(U)$ control, and their influence on improving the PV HC in LV networks. Conclusions will be drawn in Section 5.

II. HOSTING CAPACITY OF LV NETWORKS
A. PV PENETRATION AND HC
Due to the need to estimate the allowable PV penetration in a LV distribution network in order to avoid undesired effects, the concept of HC was established. So far, there is no exact definition of HC that is unanimously agreed upon. It varies widely among researchers. Some researchers have defined it as the ratio of the total installed PV capacity of network to the feeding transformer's capacity [23], while others have calculated it as the ratio of installed PV peak capacity to the feeder maximum load [26]. Some have even replaced the "feeder maximum load" with "feeder minimum load" in these ratios. Moreover, in some research, PV penetration at a certain point of time was considered as the ratio of the actual PV output to the actual active power load.

The PV peak capacity versus feeder maximum load has stronger relevance for both the power flows and the voltage profiles of the network. There are two different scenarios depending on the PV generation and load profiles. First, if the peak PV generation coincides with the maximum or peak load then relatively higher levels of PV penetrations will be achievable, however if that is not the case then the network hosting capacity for PV will be reduced significantly due to voltage violations. Therefore, the scenarios of PV generation and load should be carefully checked, in order to avoid the over- or -under estimation the HC.

The concept of PV peak capacity also needs to be noted, given that the actual PV production varies depending upon multiple factors like temperature and solar irradiance. In strong solar insolation areas temperature tends to be higher, which has the effect of reducing the efficiency of the PV, resulting in lower power output from the PV, further decreasing the PV peak capacity. Taking into account both the actual PV generation level and the actual feeder load would allow a more precise scenario for defining the PV penetration limits in LV distribution networks.

As the deterministic method is used, the definition of HC used here is the ratio of PV peak capacity installed to the peak load on the feeder, as shown in the following equation:

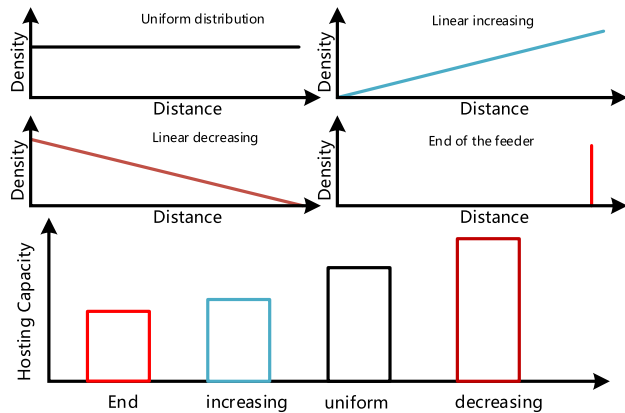$$HC = \frac{S_{pv}}{S_{\max}} \times 100\% \qquad (1)$$

FIGURE 1. The distribution of PV integration and the relative HC.

where S_{pv} is the PV peak capacity under the local circumstance, and S_{max} is the peak load on the feeder, depending on the number of customers.

B. SENSITIVE FACTORS INFLUENCING THE HC

LV networks usually present radial topologies, thus voltage amplitude reduction is observed along the circuit due to the voltage drop at radial conductors. As the PV system model resembles a current source, the power injection into the network increases the voltage level at the coupling point. Therefore, if the grid's voltage is below the nominal values, the PV can bring benefits to the distribution network. Conversely, if there is a large amount of PV, overvoltage above the limits can easily occur. Therefore, this behavior must be taken into account in determining the HC.

Besides, a high PV penetration can increase the network current, leading to violation of the permissible thermal limits and lifespan reduction of the assets. Therefore, the HC main limiting factors are the voltage level and thermal capacity, with the overvoltage being the most restrictive aspect for increasing penetration levels. This is mostly due to the fact that in a residential feeder the peak of PV generation usually occurs at the condition of lower load, causing overvoltage and thermal limit violation. In this paper, how to handle the voltage issues to increase HC will be the main point.

The voltage rise due to PV penetration in any LV network is very sensitive to the location, size and numbers of the PV system. A reasonably large number of PVs can be safely hosted by an LV network if they are distributed evenly over the network in relatively smaller units. If the PV is located far away from the substation, the permissible penetration level without violating the overvoltage limit will be lower. Conversely, the closer it is to the substation, the allowed amount of power injected into the network may be higher, thus increasing the HC.

Four PV distribution models along the LV feeder are shown in Figure 1. In the upper part, it refers to the PV integration density along the feeder. Uniform distribution means the PVs are integrated into the feeder in a uniform way. Linear increasing and decreasing means the PV integration density is increasing and decreasing along the feeder. End of the feeder means all the PVs are located at the end. As we can see
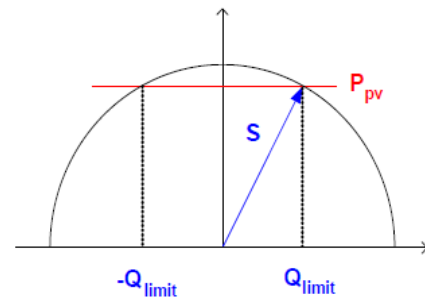

FIGURE 2. Determining the inverter's reactive power limits.

from the below part of the figure, the linear decreasing PV distribution model can host the most PVs, and PV located at the end of the feeder is the worst case, which illustrates that the PV distribution can influence the PV penetration level.

Although a perfectly homogenous PV distribution is a purely theoretical case, networks with high PV penetration are expected to tend to this case and it offers the possibility to better understand and compare different control concepts and generalized parameterization in the HC improvement.

In addition to the voltage variation, regulations vary from country to country which have a significant effect on estimating PV penetration limits by imposing different voltage variation limits on the network. For example, a 10% voltage variation limit will enable the network to host more PVs than 5%.

As mentioned in previous section, voltage control strategies by inverters also influence the HC, since it has the capability of mitigating the overvoltage phenomenon. Meantime, it should be noted that R/X ratio of the LV network is an important parameter that influence the performance of voltage control schemes.

III. VOLTAGE REGULATION TECHNIQUES FOR PV INVERTER

Many inverters have the capability of providing reactive power to the grid and regulate voltage on feeder in addition to the active power generated by their PV cell. This is illustrated in Figure 2. The inverter's ratings are represented by a vector with magnitude S; the semicircle with radius S denotes the boundary of the inverter's feasible operating range in PQ space. Assuming that the power produced by PV array is P_{PV}, reactive power (Q) limits are then found by projecting the end points of the segment down to the Q axis. The advantage of an inverter relative to a fixed capacitor is that it can vary the supplied reactive power continuously, and the regulation of inverter is extremely fast (3-5 cycles) compared to traditional voltage regulation devices.

With the capacity of providing reactive power for inverter, automatic voltage regulation techniques can be applied in PV inverter. This method operates based on a voltage range with a PID controller. If voltage at the point of measurement is out of range, PV inverter will inject or absorb reactive power to impact the local voltage until the voltage go back to the normal range. According to the rule of active power priority,
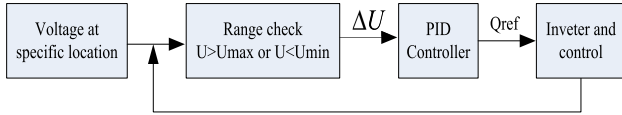
FIGURE 3. Block diagram of the automatic voltage regulation techniques.

TABLE 1. Common control methods.

Control	Attributes
Q(U)	Reactive power as a function of the voltage
PF(P)	Power factor as a function of the injected active power
P& Q(U)	Combination of P(U) and Q(U)
PF(P)&P(U)	Combination of PF(P)and P(U)
P(U)	Active power curtailment as a function of the voltage
Optimal Power Flow	Maximise the net PV power subjected to power flow constrains

the reactive power provided by inverter should be limited between $(-Q_{\text{limit}}, Q_{\text{limit}})$, which is determined by:

$$Q_{\text{limit}} = \sqrt{S^2 - P_{PV}^2} \qquad (2)$$

Figure 3 shows block diagram describing the automatic voltage regulation techniques of inverter. The close loop control basically aims to regulate the voltage profile within the existing limits rather than controlling it to a specific reference, such as set point voltage control mode, which needs the inverter to maintain the voltage to a fixed value. However, sometimes it is also difficult to control the local voltage in the normal range because of the reactive power limit by inverter and the strong interactions among the voltage of adjust buses. Thus, common methods of voltage regulation for inverter are to let the reactive power be a function of the local active power production $Q(P)$, local voltage $Q(U)$ or the combination of both. Table 1 summarizes the common voltage control methods in the LV networks.

In this study, in order to deeply give insight into the influence of voltage control methods by inverter and their parameters on HC improvement, two kinds of basic voltage regulation techniques instead of whole methods listed above are selected and studied, which are $Q(U)$-Reactive power by grid voltage and $PF(P)$-Power Factor by active power. These control strategies provoke distinct reactive power flows within the LV feeders. Figure 4 shows the load- and control-related reactive power flows for the these two control strategies.

Figure 4a shows them in the case of local $PF(P)$ control. All inverters absorb the same amount of control related-reactive power, if equal PV power production conditions (irradiance, temperature, tilt angle of PV-modules, etc.) along the LV feeder are assumed and all consumers have the same PV-module and inverter rating. If $Q(U)$ control is used, the distributed inverters absorb different amounts of control related-reactive power, depending on their local grid voltage, as shown in Figure 4b. Both of the two methods provoke inhomogeneous control-related reactive power flows through the line segments, leading to different voltage regulations.
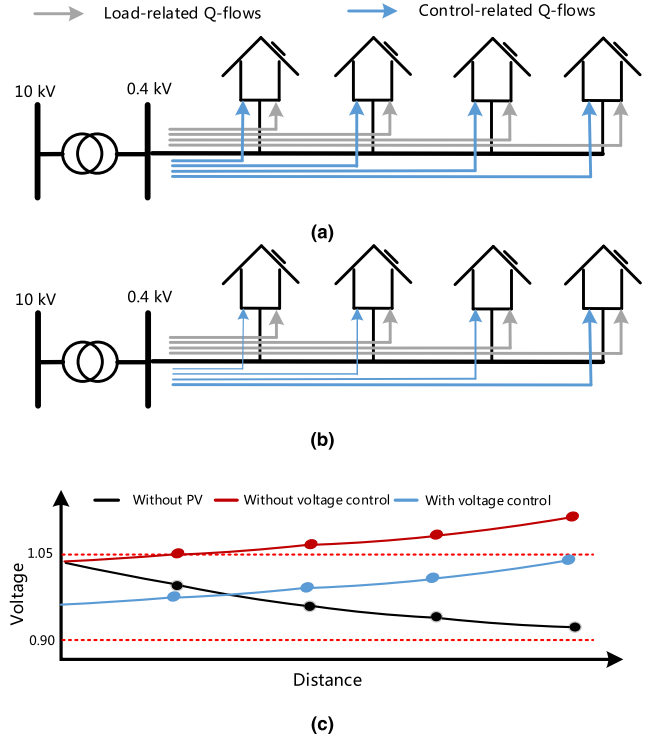

FIGURE 4. Load and control related power flows of different control methods and relative voltage along the feeder: (a) *PF(P)* control; (b) *Q(U)* control; (c) Voltage profile.
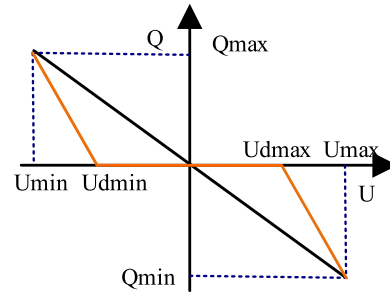

FIGURE 5. Generic *Q(U)* curve and defining parameters.

From the Figure 4c, it can be seen the corresponding voltage distribution along the feeder in three scenarios, which are LV network without PV, PV without voltage control and PV with voltage control.

A. REACTIVE POWER BY GRID VOLTAGE

The main purpose of applying a $Q(U)$ control algorithm is to use the reactive power of the inverter in such a way that in case of overvoltage conditions the control will decrease the voltage to a certain degree, and in case of under voltage situations the control will tend to increase the voltage towards a prescribed value.

The $Q(U)$ control is normally implemented as in Figure 5. The voltage at the inverter bus terminals can be used as an input value to the controller. The slope m of the $Q(U)$ characteristic represents the sensitivity of the reactive power controller versus voltage changes, shown in equation (3). Such as, if voltage at point of measurement is slightly above desired range of operation, capacitive reactive power based on
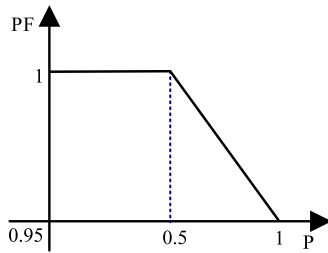
FIGURE 6. Generic *PF*(*P*) curve.

slope is supplied by the inverter to bring down the voltage. The maximum limits of inverter reactive power can be set based on sizing of inverter and inverter's capability.

$$m = \frac{\Delta Q}{\Delta U} = \left| \frac{Q_{max} - Q_{min}}{U_{max} - U_{min}} \right| \quad (3)$$

Parameters U_{dmin} and U_{dmax} are defining as the width of the voltage dead band in which the $Q(U)$ control should not generate any reactive power. This region should restrict the inverters injecting unnecessary reactive power. For the $Q(U)$ control method without deadband, the $Q(U)$ can be donated by:

$$Q(U) = m(U - 1) \quad (4)$$

For the $Q(U)$ control method with deadband, the $Q(U)$ can be donated by:

$$Q(U)$$
$$= \begin{cases} Q_{max}(U_{d\,min} - U)/(U_{d\,min} - U_{min}) & U < U_{d\,min} \\ 0 & U_{d\,min} \leq U \leq U_{max} \\ Q_{min}(U_{d\,max} - U)/(U_{d\,max} - U_{max}) & U > U_{d\,max} \end{cases} \quad (5)$$

A too broad dead band will also have negative effects since inverters closer to transformer station will not participate at all in regulating the voltage, while inverters at the remote ends will provide maximum reactive power.

B. POWER FACTOR BY ACTIVE POWER

PV systems are required to generate negative reactive power to account for rise in voltage due to injection of real power. One property of this type of control is that the inverters will inject reactive power independently of the location in the feeder in comparison with $Q(U)$ algorithm, in which the farthest inverter would inject always more reactive power than the ones closer to the transformer. Thus, overall better control of the voltage is assumed, since all inverters in the network are participating. The disadvantage is that the inverters might inject reactive power into the network even though it may not be required (no overvoltage situation).

The amount of reactive power required to be supplied is based on a curve shown in Figure 6. As long as the inverter real power output is less than 0.5 pu, power factor(PF) is to be maintained at 1 pu. If the PV real power exceeds 0.5 pu, a lagging power factor based on the slope is to be maintained. The maximum power factor setting can be either 0.90 or
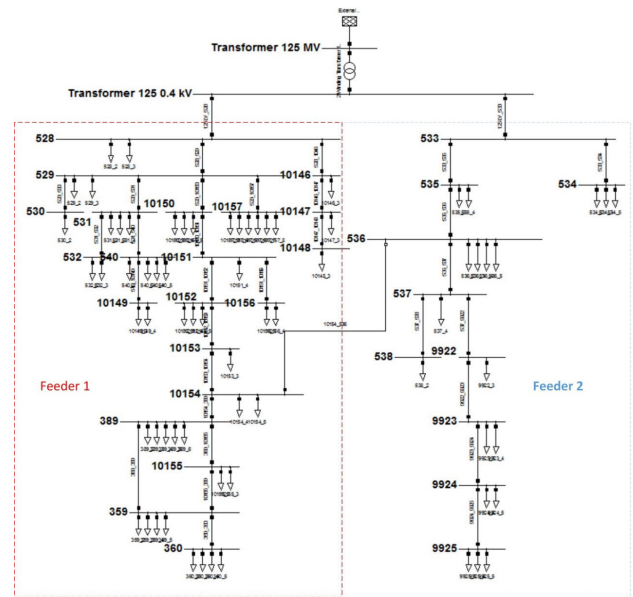

FIGURE 7. Testing system topology and load connections.

TABLE 2. Simulated study cases and chosen parameters for *Q*(*U*) control strategy.

Ca-se	Penetrat-ion(%)	U_{min} [pu]	U_{max} [pu]	Q_{min} [pu]	Q_{max} [pu]	m	U_{dmin} [pu]	U_{dmax} [pu]
1	0,10,60	1	1	0	0	0	1	1
2	0,10,60	0.9	1.1	-0.6	0.6	6	1	1
3	0,10,60	0.9	1.1	-0.6	0.6	7.5	0.98	1.02
4	0,10,60	0.9	1.1	-0.6	0.6	10	0.96	1.04
5	0,10,60	0.9	1.1	-0.48	0.48	4.8	1	1
6	0,10,60	0.9	1.1	-0.4	0.4	4	1	1

0.95 pu lagging. The *PF*(*P*) can be expressed by:

$$PF(P) = \begin{cases} 1 & P < 0.5 \\ (P - 0.5)/10 + 0.95 & P \geq 0.5 \end{cases} \quad (6)$$

IV. SIMULATIONS AND RESULTS

A. GENERIC LV NETWORK AND STUDY CASE

The study case is implemented on a generic LV network from Danish island Bornholm, as shown in Figure 7. The grid contains 71 households with two LV feeders supplied by one MV/LV 100 kVA transformer. The two feeders contain 52 and 19 consumers respectively. Consumer loads are with a power factor 0.95. PV inverters modelled as controlled current sources are placed near each load.

Here, we define PV peak capacity as the installed PV capacity for each customer, and the peak load equals to the maximum PV inverter capacity for each customer. Under the studied LV network, it is expected that an economical investment in a residential solar plant will result in an installed capacity of 5 kVA. Having all the consumers in a residential feeder installing a 5 kVA solar system would therefore be equivalent with 100% PV penetration in the respective network feeder. This method to estimate the amount of PV HC in the network has the advantage of creating a uniform distribution across the entire feeder of PV power.

TABLE 3. Simulated study cases and chosen parameters for *PF*(*P*) control strategy.

Case	PV penetration(%)	Min PF	Trafo(kVA)
7	0,10,60	0.92	100

TABLE 4. Different scenarios.

Scenario	PV[pu]	Load(kVA)
1	0.8	0.4
2	0	1.2

The simulated study cases are shown in Table 2 for $Q(U)$ and Table 3 for $PF(P)$. The transformer capacity is 100kVA. The base study case is case 1 which represents the situation that the PV inverters have no voltage control algorithm implemented. Case 2 represents the PV inverters with $Q(U)$ control algorithm, which has a high voltage sensitivity without deadband. Case 3 and case 4 represents $Q(U)$ control algorithm with different deadband. Case 5 and case 6 represents $Q(U)$ control algorithm without deadband, but with different voltage sensitivity compare to Case 2. Case 7 represents the PV inverters with $PF(P)$ control algorithm, and the minimum power factor is 0.92(lagging), which can make a better comparison with case 5 and 6, whose minimum power factor is 0.89 and 0.92 respectively.

Each study case includes two scenarios, shown in Table 4. Scenario 1 respects to peak PV power output (0.8 pu)and lowest load(0.4 kVA), and scenario 2 respects to the lowest PV power output (0 pu)and peak load(1.2 kVA). Thus maximum voltage for each bus can be obtained in scenario 1, and the minimum voltage for each bus can be obtained in scenario 2.

In this study, the upper limit of service voltage is defined as 1.05, and the lower limit of service voltage is defined as 0.90. All the scenarios are studied for variable PV penetration levels from 0 to 60% in steps of 10%, which provides numerous results to be analyzed, and a comparison between the study cases is of greater interest to see the impact of different voltage regulation techniques on the PV penetration in the LV network.

B. COMPARISON OF NO VOLTAGE REGULATION AND Q(U)

It is assumed that the voltage of low voltage side of the 60/10 kV transformer is 0.994pu in the lowest load condition, and 0.9727pu in the peak load condition, as depicted in Figure 8 and 9. The 10/0.4 kV transformer can change tap position resulting in a +2.5% voltage increase at the secondary side to compensate the voltage droop in the peak load period, but for this study a constant tap position for transformer is used. Figure 8 and 9 display the maximum and minimum voltage levels at each bus of feeder 1 for case 1 for variable PV penetration levels from 0 to 60% in steps of 10% as in Table 2.

It is obvious that for the farthest distances to the transformer the highest voltage variations will be observed (Bus 5 in Figure 8). The minimum voltage value for a specific bus is the same for all PV penetration levels, since at maximum load hours (during evening) no changes are performed by the PV inverters. Increasing the PV penetration to 60% will
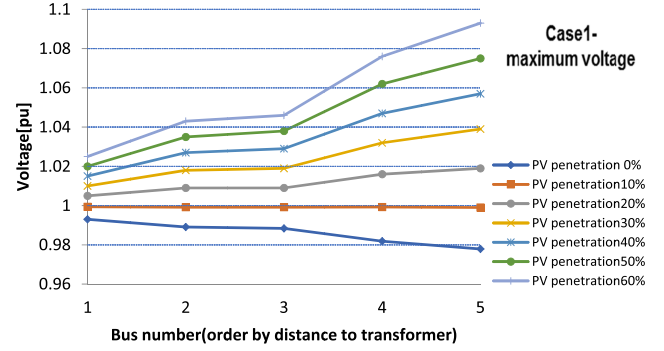
FIGURE 8. Study case1-Maximum voltage for each bus for variable PV penetration.
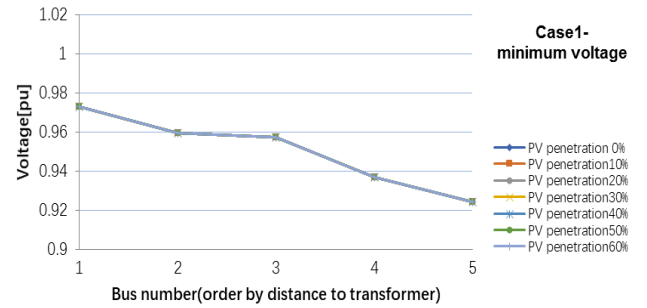
FIGURE 9. Study case1-Minimum voltage for each for variable PV penetration.
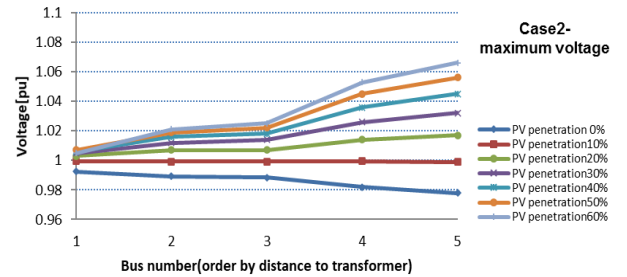
FIGURE 10. Study case2-Maximum voltage for each bus for variable PV penetration.
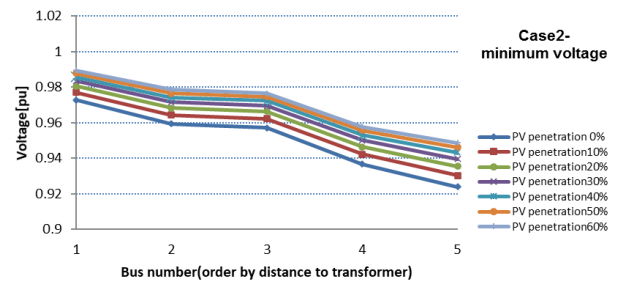
FIGURE 11. Study case2-Minimum voltage for each bus for variable PV penetration.

result in a high maximum voltage increase of approximately 1.095 per unit in Bus 5. It is 11.7% percent increase compared to the situation of 0% PV penetration, which is 0.98 pu.

Taking the case 2 as example, where $Q(U)$ control is adopted. It can be observed from Figure 10 that the voltage
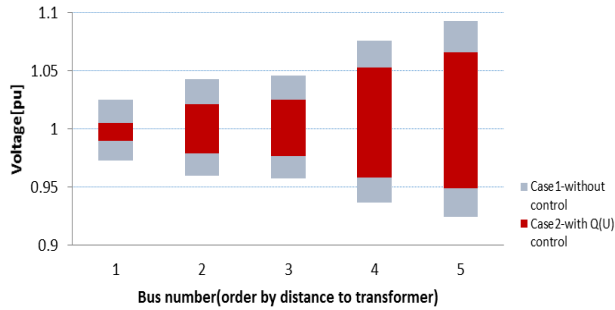
FIGURE 12. Comparison of maximum/minimum voltage for each bus for 60% PV penetration.
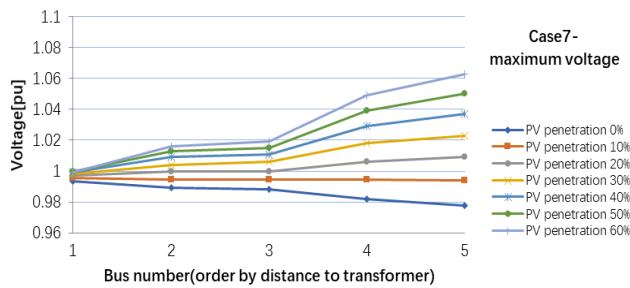

FIGURE 13. Study case7-Maximum voltage for each bus for variable PV penetration.
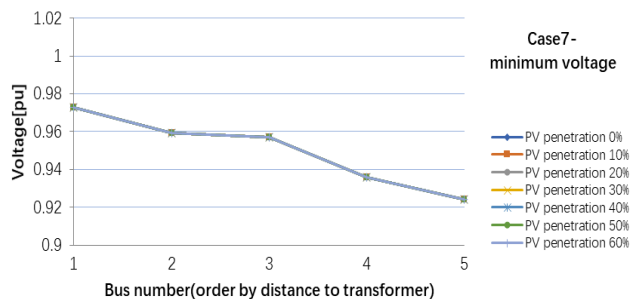

FIGURE 14. Study case7-Minimum voltage for each bus for variable PV penetration.

FIGURE 15. Comparison of maximum/minimum voltage of each bus for 60% PV penetration between $Q(P)$ and $PF(P)$.

FIGURE 16. Study case2-Reactive power for inverters for scenario1.

that without $Q(U)$ control, voltage of each bus varies greatly, especially for voltage of bus 5 at end of the feeder, which varies from 0.92 pu to 1.09 pu. With the $Q(U)$ control, voltage variations become smaller for each bus, and the impact of high penetration PV integration on the voltage profile decreases.

C. COMPARISON OF Q(U) AND PF(P)

For the case 7, $PF(P)$ control is adopted. Figure 13, 14 displays the maximum and minimum voltage for each bus for variable PV penetration with $PF(P)$ control. It can be observed that the maximum voltage for each bus is very low since all the inverter can inject the same maximum negative reactive power to the networks according to the slope of $PF(P)$ curve. By increasing the PV penetration, the more real power PV output, the small power factor will be, and more reactive power will be injected by PV inverter.

Besides, it also can be observed that the minimum voltage value for a specific bus is the same for all PV penetration levels, since for scenario 2 PV outputs no real power(at night), the PV inverter inject no reactive power.

A small comparison between the efficacy of $Q(U)$ and $PF(P)$ control algorithms is shown in Fig15. Case 2 and case 7 are selected, since case 2 corresponds to most effective $Q(U)$ voltage control method. It can be observed that $PF(P)$ control is more effective in lowering the maximum voltage in each bus due to the strong voltage control capacity, $Q(U)$ control can be contributing to lift the minimum voltage while $PF(P)$ has no influence.

D. IMPACT ON REACTIVE POWER AND LINE LOSSES

Figure 16, 17 display the reactive power injected to the grid by inverters in different PV penetration and scenarios under

variations of buses have the same trends with no voltage regulation in case 1. Increasing the PV penetration to 60% will result in a maximum voltage increase of approximately 1.065 per unit in bus 5, 8.7% percent increase compared to the situation of 0% PV penetration. Moreover, with the increase of the PV penetration, the minimum voltage value for each bus is lifted, which improve the voltage profile, as shown in Figure 11.

An interesting thing we can observe in Figure 10 is that the voltage for 60% PV penetration in bus1 is lower than 50% PV penetration, which is not the common trends as other buses. This is due to the strong reactive power output capability of all inverters in 60% PV penetration, which impact the whole system voltage profile, even near the transformer. In addition, for PV penetration levels higher than 45% (excluded) the allowed voltage variation is exceeded, so their hosting capacity is said to be 45%.

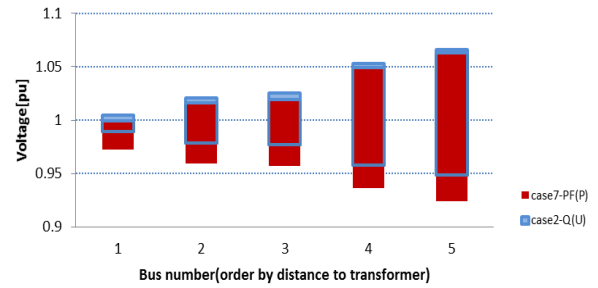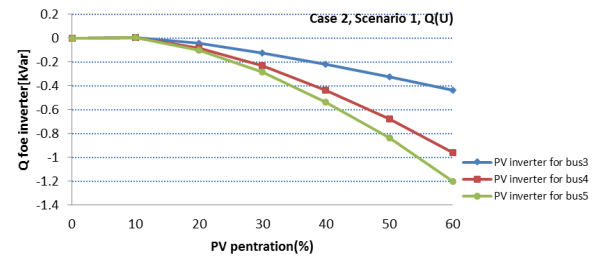Figure 12 displays the comparison of maximum/minimum voltage for each bus for 60% PV penetration. It is obvious
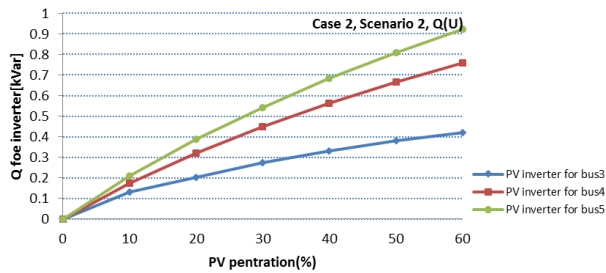
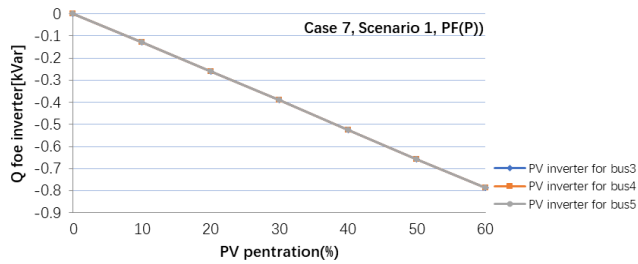**FIGURE 17.** Study case2-Reactive power for inverters for scenario2.

FIGURE 18. Study case7 -Comparison of reactive power injected by inverter with different bus.

$Q(U)$ control. It can be observed that PV inverters inject negative inductive reactive power in scenario 1 due to the voltage in each bus is higher than 1 pu, and inject positive inductive reactive power in scenario 2 due to the low voltage in each bus in peak load period.

For scenario 1 the reactive power injected by inverters varies according to the bus voltage, and inverter for bus 5 injects the most reactive power compared to the other two inverters closed to the transformer. Reactive power injected is limited by PV inverter capacity and $Q(U)$ control slop, as different PV penetration corresponds to different PV inverter capacity, the bigger PV penetration, the more reactive power will be injected.

For scenario 2, as the low voltage profile in LV networks, all inverters will inject positive reactive power into the grid to improve the voltage profile. PV inverter for bus 5 provides the maximum reactive power support due to the large voltage variation in bus 5, as shown in Figure 17.

With $Q(U)$ control, inverters near the transformer are less effective in providing reactive power support to lower the maximum voltage due to the small voltage fluctuation near the transformer, while $PF(P)$ can provide the same reactive power support no matter where it locates, as shown in Figure 18.

Figure 19 plots the power losses in lines for all simulated cases. The situation with no voltage control at all in the network would generate a total power loss of almost 4.3kW. For smaller PV penetration levels there are no significant differences among the simulated cases, since the reactive power flow is also at minimum. With the PV penetration level increasing, different power losses can be observed due to the different reactive power injection capability for different control methods. In all cases, a minimum power loss is reached
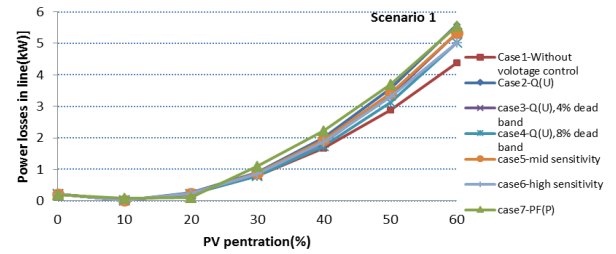

FIGURE 19. Total line losses for all simulated case.

TABLE 5. Comparisons of hosting capacity for the 7 cases.

HC (%)	Case	Note	Max Q for inverter (pu)	Min PF for inverter	Line losses (kW)
36	1	Base case	0.0	1	1,287
37	4	$Q(U)$ 8% dead band	-0.6	0.8	1,350
40	3	$Q(U)$ 4% dead band	-0.6	0.8	1,880
41.4	6	$Q(U)$ low sensitivity	-0.4	0.92	2,050
43	5	$Q(U)$ mid sensitivity	-0.48	0.88	2.260
45	2	$Q(U)$	-0.6	0.8	2,719
50	7	$PF(P)$	-0.26	0.92	3,367

for a 10% PV generation levels since the load demand is small in scenario 1, few PV power is required for minimizing the power transfer in LV networks.

If comparing $Q(U)$ with $PF(P)$, fewer power losses are achieved by using $Q(U)$ for the PV penetration 20%-50%. While for the 60% PV penetration the losses are almost the same, and if compare to case 1 without voltage control, the losses increase by 28% for both $Q(U)$ and $PF(P)$ control.

E. COMPARISON OF HOSTING CAPACITY FOR THE CASES
The comparison of hosting capacity for the 7 study cases are shown in Table 5. The cases are rearranged in order of hosting capacity, which refers to the maximum PV penetration levels within the allowed voltage variation. The first column shows the hosting capacity for the cases observed from an overvoltage perspective; the second is the case-number and the third is a short description of the case. The fourth column is the maximum amount of exchanged reactive power for the inverters and the fifth column is the corresponding PF.

Case 1 is the base case with a hosting capacity of 36 % (1.8 kW per residence) without taking any reactive power control measures into consideration and the Cable losses are minimal.

$Q(U)$ control with high sensitivity and 4% dead-band as in case 3 has a hosting capacity of 40% (2kW per residence) and can be further increased a few percent by removing the dead-bands as in case 2. If we enlarge the dead band as in case 4, the hosting capacity would decrease. By using $Q(U)$ with dead-band, the hosing capacity maybe not as high as that without dead-band, while the line losses are low and some unnecessary regulation can be avoided, which may bring

much economic benefits from the perspective of long time period.

The hosting capacity is increased further to 41.4% (2.07 kW per residence) and still keeping the power factor above 0.92 in case 6 by applying $Q(U)$ control with a low sensitivity. $Q(U)$ control with mid sensitivity would have a higher hosting capacity than the one with low sensitivity due to that it can inject more reactive power to the grid, as in study case 5. The penetration can be increased further to 45% if the highest sensitivity is applied. However, line losses are almost double compared with the base case with only 36% penetration.

The usage of the standard $PF(P)$ in case 7 increases the hosting capacity to 50% (2.5 kW per residence), and the line losses are the highest as well.

Thus, for $PF(P)$ overall better control of the voltage is assumed when compared with the $Q(U)$, since all inverters in the network are participating voltage control, independent of the actual grid voltage. While it seems that with the increase of hosing capacity, the line losses in the networks will increase as well.

V. DISCUSSION AND CONCLUSION

This paper provides an analysis on the main Volt-VAR regulation techniques that can be applied in the low voltage (LV) network with photovoltaic (PV) inverter technology. The results indicate that without any Volt-VAR control the overvoltage phenomena starts for PV generation levels at 36% in the Bornholm LV network, while deploying the $PF(P)$ and $Q(U)$ control method, the overvoltage issues are relieved, and the PV generation penetration level can be lifted to 50%, demonstrating that voltage control by the inverters can effectively improve the PV penetration level in LV networks.

From the perspective of overvoltage, $PF(P)$ is a good solution for voltage regulation by PV inverter, but the losses may also be high. Moreover, one reactive power control technique may be recommended for one network type while it would have negative impact on a different type. Another possibility may come from the need of applying different control strategies depending on seasonal, daily and hourly schedules.

For $Q(U)$ control method, determining parameters among several PV systems is a challenge due to that PV systems at the beginning of a radial PV feeder participate less in the voltage regulation compares to those at the end which experience the voltage rise. Thus, proper coordination parameters can make the control methods more effective, which plays an important role in the voltage regulation to the extent that its absence can cause poor voltage regulation as well as more losses.

Furthermore, new voltage and power control strategies and controllers for distribution networks with high shares of PV systems could be developed and validated in future, in order to improve the PV penetration further in the LV networks.

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