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Original Research

Volt-Var Control for Utility-Scale Solar PV Plants to Downsize SVCs and Curtailment Effects

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Abstract

One way to increase solar photovoltaic penetration in the grid is the management of voltage fluctuations. This is because a photovoltaic plant cannot be interconnected to the grid if it causes voltage violations. Voltage violation is where voltage exceeds the acceptable range. Often, grid operators request photovoltaic plant owners to regulate voltage sufficiently with expensive and space-consuming static Var compensators. Unfortunately, this sometimes makes the project less feasible. This paper argues that there are better ways to regulate voltage. It also asserts that these ways must be sought before blindly procuring a static Var compensator or seeking battery storage. We simulated with a 70-MW photovoltaic plant as an addition to the grid. Without voltage regulation, voltage violations in Spring were found to be particularly significant. However, the proposed reactive power compensation removed all voltage violations smartly. Furthermore, the study results demonstrated that the operator-induced curtailment effectively reduced the necessary amount of reactive power compensation, leading to a smaller size of SVC, as it occurred specifically at certain overvoltage points. This paper argues that the economic and spatial efficiency of reactive power compensation devices is key to increasing photovoltaic penetration. It argues that one-sided bearing of the cost of reactive compensation devices is inefficient.

Keywords
Reactive power/Volt-Var control; reactive power absorption/injection; overvoltage; undervoltage; static var compensator; curtailment; solar photovoltaic penetration

1. Introduction

Among various types of solar photovoltaics (PV), megawatt-scale or utility-scale PV plants can significantly contribute to PV penetration in the main grid due to their scale. Increasing PV penetration in the grid is a common goal of many countries as it is one of the major decarbonization methods. To this end, much research has been conducted to mitigate voltage violations that PV plants can bring about, such as [1-3]. Voltage violation is a deviation from the allowed voltage range at the point where a PV plant is interconnected. If left unmitigated, voltage violations, are one of the major limitations of grid-tied PV plants [4]. Voltage fluctuations in PV plants are prominent because their generation amounts unavoidably vary according to the amounts of irradiation they get, and voltage at the interconnection point varies significantly. The amount of irradiation is something difficult to predict. The weather forecast can help predict rough amounts of irradiation, but small changes in its amounts due to causes such as cloud covering are almost impossible to predict. The varying voltage is also due to the variation of ever-changing power demand. Therefore, PV's interconnection point is subject to supply and demand side variations. These variations make voltage susceptible to abrupt changes, sometimes leading to voltage violations.

Much research aims to regulate voltage with hybrid PV-battery storage systems. If planned appropriately, this is an effective way to mitigate voltage fluctuations, as argued by [5, 6]. Chaudhary [7] found that storage systems and smart inverters are efficient in dealing with overvoltage caused by PV generation, and some papers, such as [8], focus on the optimization algorithm. Battery storage is an effective tool to regulate voltage in the network and is also effective in a high PV-penetrated grid. This is because voltage can be controlled both by injection/absorption of reactive power and supply/consumption of active power [9]. Battery storage can discharge/charge active power as its fundamental property, enabling voltage regulation with the active power flow. Smart inverters, on the other hand, inject/absorb reactive power. With these two in place, the voltage can be more effectively regulated.

Although the combination of battery storage and smart inverters significantly improves voltage regulation, there are two difficulties for battery storage deployment. Battery storage has economic and spatial downsides as well. The biggest challenge with battery storage is that procuring these batteries may still be uneconomical. When the installation cost of the batteries is too high, the PV system installation needs to proceed without them. The battery storage also requires some space. This may hamper the installation of batteries. For utility-scale PV plants, available lands may be limited. Proceeding with the smart inverter's reactive power control alone may free up the space batteries would require and help install more PV panels. Battery storage takes up more space, and land constraints may make the project less feasible. Although the role of active power flow is an important discussion for the ever-evolving PV markets, battery storage's spatial requirement can hamper PV penetration in the grid. With adequate reactive power controls mitigating voltage violations, we can increase PV penetration without incurring additional costs of batteries and occupying extra space for battery storage. For these reasons, reactive power control is a critical control system that needs to be thoroughly explored and exploited. As an additional point to note, lithium iron phosphate batteries that may be most compatible with PV plants are at an early stage of adoption. Using batteries could make PV generation less green, depending on the source of energy used to produce the batteries. Greater benefits can be obtained when we consider manufacturing and installing places of batteries and PV panels, and greener manufacturing processes of both batteries and PV panels are practiced [10].

Utility-scale PV plants struggling with voltage regulation must have literature examining their problem. However, not much research focuses on voltage regulation for utility-scale PV plants. Large utility-scale PV plants interconnect to higher voltage lines due to their scale [11], e.g., greater than 60 kV. Gush [8] also focused on lower voltage distribution systems. Although there are an incredible number of PV installations on the distribution network, large utility-scale PV plants are interconnected to the transmission line. Utility-scale PV plant installers are often independent power producers (IPPs) that develop, build, operate, and maintain these plants by themselves. IPPs are another player in the power market besides the grid operators. IPPs have technical discussions with grid operators about interconnecting the PV plant to the power grid. During these discussions, voltage regulation is on the agenda, and the grid operator sets minimum reactive power compensation requirements. Traditionally they require a Static Var Compensator (SVC) of a certain capacity to be installed, as demonstrated in [12]. Upon this request, the IPP can either blindly follow the suggestion or propose another device that satisfies the requirements. The problem with an SVC is that it is an additional device, and installation and maintenance can be costly [13]. It also requires additional space. A static synchronous compensator (STATCOM) has similar functionalities to an SVC and requires less space but is even more expensive. An alternative approach with a reactive power control system on the PV inverter can be accepted by the grid operator as long as it fulfills the requirements. Interconnection to a higher voltage line involves bidirectional discussions. An IPP can propose even a control system with higher-than-ever efficiency and cheaper-than-ever cost, and it can be adopted. The IPPs need to be knowledgeable enough to know the most cost-effective and efficient control systems to grow as another significant player in the market. Few research papers have IPPs as one of the audiences. On the other hand, the interconnection to a lower voltage line has less room for the installer to engage in bidirectional discussions.

When choosing the best reactive power compensation device, we need to consider curtailment that reduces the output of a PV plant to an output level lower than the generation capacity [14]. There are different types of curtailment by actors and by reasons. This paper defines curtailment as a situation where grid operators instruct IPPs for local or system-wide reasons. Curtailment is necessary as more and more PV plants connect to constrained networks. The effect of curtailment on the voltage is fewer voltage violations; therefore, less reactive power compensation is needed. This gives a bigger role to reactive power control on the inverter.

We believe the best solution is first to exploit reactive power/volt-Var control on the inverter, as explored in [15, 16]. There are additional benefits of volt-Var control on the inverter, such as energy savings on the network. Some research has been conducted around advanced volt-Var controls that achieve this mitigation of energy loss, including [17]. Instead of pursuing advanced volt-Var controls to maximize energy savings, this paper will focus on more direct effects and how an IPP should propose the best reactive power compensation device, given the circumstances of each project. And this device can be a simpler volt-Var control because advanced volt-Var control can be costly. For IPPs, we recognize the importance of emphasizing that an SVC is costly and requires a large space. Therefore, IPPs should take full advantage of the bidirectional discussions and pursue the best solution to proceed with their PV project and not give up on it. In this paper, we added IPPs as one of the audiences and explained the theory and practical reasons for using the volt-Var control for PV plants in detail. Then we demonstrated the proper order of voltage regulation devices to be utilized, first without curtailment and then with curtailment, using real data from the most recent PV generation and load data in Kyushu, Japan. The expected result is to deploy the volt-Var control on the inverter first, consider oversizing the inverter next, and then deploy the SVC.

2. Materials and Methods

2.1 Voltage Control

2.1.1 Voltage Violations

Consider a simple feeder model, as shown in Figure 1. The voltage of particular interest is the one at the point where the PV plant is interconnected, as this location is most impacted by the PV plant. We will call this node the "point of common coupling (PCC)" and the voltage at the PCC "V_{pcc}." The sending-end voltage is expressed as V_s.

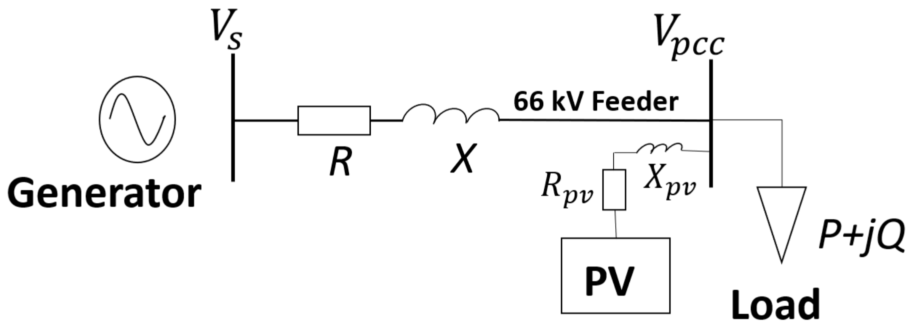

Figure 1 Simple two-bus system with an interconnected PV plant.

The voltage drop (ΔV) is approximated by Equation (1), with a slight error margin. In the equation, R and X represent the resistance and inductive reactance, respectively, between V_s and V_{pcc}. I denotes the 66 kV feeder current, and θ represents the power factor of the load:

$$\Delta V = \sqrt{3}I(Rcos\theta + Xsin\theta) \tag{1}$$

which is derived from Figure 2.

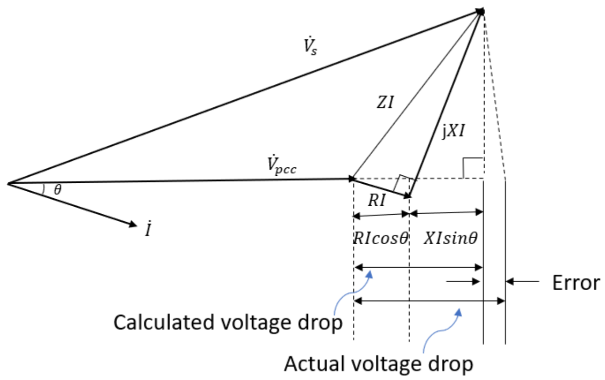

Figure 2 Single-phase voltage vectors of V_s and V_{pcc}.

Equation (1) can be rewritten as:

$$\Delta V = \frac{P_L R + Q_L X}{V_{pcc}} \tag{2}$$

where P_L is the load demand for active power, and Q_L is the load demand for reactive power. Using the per-unit method, by setting V_{pcc} to 1 p.u., Equation (2) can be further simplified to:

$$\Delta V_{pu} = P_L R + Q_L X \tag{3}$$

Equation (3) tells us that voltage drop is caused by the magnitude of impedance along the line between V_s and V_{pcc}, and the load's consumption of active power and reactive power. We define positive voltage drop (ΔV_{pu}) as the normal voltage drop, and negative voltage drop (ΔV_{pu}) as higher voltage than V_s.

ΔV_{pu} fluctuates depending on the load conditions. Equation (3) tells us that, as the load becomes lighter, ΔV_{pu} decreases; therefore, V_{pcc} increases. This is because the load consumes less, i.e., P_L and Q_L are smaller, then the voltage drop $P_L R + Q_L X$ is smaller. Conversely, as the load becomes heavier, ΔV_{pu} increases, and V_{pcc} goes down. This is because as the load consumes more, the voltage drop $P_L R + Q_L X$ becomes larger.

When a PV plant is interconnected, the PV inverter will adjust the output voltage phase angle to lead the V_{pcc} so that active power will flow. When active power flows from the PV plant, Equation (3) is no longer the only voltage drop impacting ΔV_{pu}. Equation (4) is added below:

$$\Delta V_{pu} = P_L R + Q_L X - (P_{pv} R_{pv} + Q_{pv} X_{pv}) \tag{4}$$

where P_{pv} is the PV plant's active power, Q_{pv} is the PV plant's reactive power.

When we place our viewpoint at Generator, we see R and X of the feeder before reaching the PCC, and P_L and Q_L consumed by the load at the PCC. If a PV plant suddenly interconnects to the PCC and sends P_{pv} and Q_{pv} to the PCC, then there are two power sources that send power in the opposite directions. This causes the negative sign in front of $(P_{pv} R_{pv} + Q_{pv} X_{pv})$. $P_L R + Q_L X$ is a measure of voltage drop, but $-(P_{pv} R_{pv} + Q_{pv} X_{pv})$ is a measure of voltage rise. This V_{pcc} increase is independent of the load, so if the load becomes lighter, it can lead to a further V_{pcc} increase. An overvoltage violation is where the V_{pcc} increases more than $+\%V_{max}$ of the nominal voltage, where $+\%V_{max}$ is the upper bound of the permitted voltage range set by grid operators. Conversely, an undervoltage violation is where the V_{pcc} decreases more than the lower bound $-\%V_{min}$ of the voltage range.

A power line or a node such as the PCC is designed to withstand a certain voltage level [18]. When the voltage becomes too high, the insulation can break down, which needs to be avoided at all costs. Also, the voltage level must not be outside of the allowed range, as that is the threshold of acceptable power quality for various devices being used. Therefore, grid operators set a specific range of permitted voltage. A stringent standard uses ±2% of the nominal voltage. The lower bound also matters to protect devices and defer equipment upgrades [19].

Now we will add the control of absorption/injection of reactive power on the inverter. Equation (4) says Q_{pv} also affects ΔV_{pu}. When the PV plant absorbs some amount of reactive power, Q_{pv} is a negative value, and ΔV_{pu} becomes larger, decreasing V_{pcc}. As the PV plant increases the absorption, the term $Q_{pv}X_{pv}$ counteracts the voltage rise caused by the other term, $P_{pv}R_{pv}$. There will be a point where the term $Q_{pv}X_{pv}$ cancels out the numerical value of $P_{pv}R_{pv}$. If the plant continues to increase the absorption, $Q_{pv}X_{pv}$ will more than compensate for the effect of the term $P_{pv}R_{pv}$. Therefore, absorbing reactive power is useful when dealing with overvoltage issues.

Conversely, when the PV plant does not generate active power, and if undervoltage is an issue, the plant can increase the voltage by injecting reactive power. This means that the reactive power control can provide the service of injecting reactive power to the grid operator. The load can become unusually heavy, and the control can prove helpful.

Voltage fluctuation is a nodal issue. It occurs on a local level. The dispatchable generators do not adjust reactive power to compensate for each nodal reactive power change because reactive power imbalance does not cause frequency instability like active power imbalance. However, considerable voltage violations will break the equipment being used. Reactive power control at a local level is, therefore, essential. Each node has different stressors by newly added loads or non-dispatchable power plants, including PV plants. Voltage instability is a ubiquitous problem as our power systems are becoming increasingly complex.

There is a reason why reactive power controls may be more effective than the role of active power flow. When we look at R and X in the power network, X can be larger than R. This is particularly true for a higher voltage line [20]. This means that Q has a more significant effect on the PCC voltage than P because the product $Q_{pv}X_{pv}$ will be more impactful than the product $P_{pv}R_{pv}$.

2.1.2 Volt-Var Control Characteristics and Limitations

Figure 3 shows characteristics of volt-Var control.

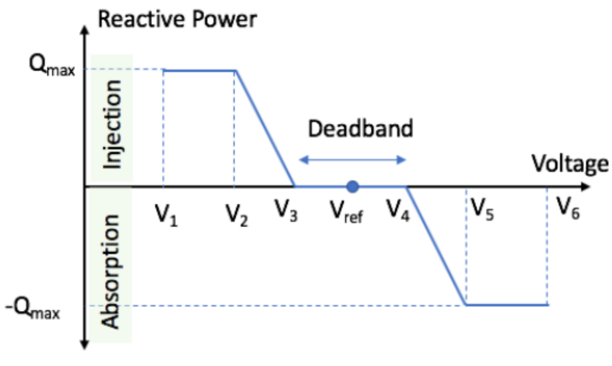

Figure 3 Droop curve of volt-Var control on inverter [21].

where V_{ref} is the reference voltage set to 1.0 p.u. for the volt-Var control. The slope m is calculated as:

$$m = (-Q_{max} - Q_0)/(V_5 - V_4) = (Q_0 - Q_{max})/(V_3 - V_2) \quad (5)$$

For example, in the case of a 70 MVA inverter equipped with volt-Var control, Q_{max} (70 MVar) and $-Q_{max}$ (–70 MVar) can be set as 1.0 p.u. and –1.0 p.u., respectively. This ensures the control cannot absorb or inject more than the inverter capacity. If we assume that V_3 and V_2 are 0.99 and 0.98 in p.u., we get $m = -100$. This means we can also work out the equation on the reactive power absorption side as follows:

$$(-Q_{max} - Q_0) = m(V_5 - V_4) \quad (6)$$

We assume that V_{ref} is in the middle of V_3 and V_4, so the slope is the same for both absorption and injection sides. In the deadband area, the control rests. If we solve in terms of V, the droop gain K is -0.01. That is, we have a relationship between V and Q in terms of V for reactive power injection as follows:

$$(V_3 - V_2) = K(Q_0 - Q_{max}) \quad (7)$$

The droop gain K and the slope m determine the amounts of reactive power compensation. When V_{pcc} is in the deadband area, Q_{inv} is 0. However, Q_{inv} is not 0 whenever V_{pcc} is outside the deadband area. The reactive power compensation equations are as follows:

$$Q_{inv} = \begin{cases} Q_{abs} = (V_{pcc} - V_4)/K = m(V_{pcc} - V_4) & ; \quad V_{pcc} \geq V_4 \\ 0 & ; \quad V_3 < V_{pcc} < V_4 \\ Q_{inj} = (V_{pcc} - V_3)/K = m(V_{pcc} - V_3) & ; \quad V_{pcc} \leq V_3 \end{cases} \quad (8)$$

The reactive power control on the inverter has another capacity limitation as well. The absorption/injection of reactive power is done only if the inverter has excess capacity. The capacity of an inverter is determined by the rated apparent power S and how much active power it generates. Equation (9) shows the limitation of reactive power.

$$Q_{max} = \pm\sqrt{S^2 - P^2} \quad (9)$$

Therefore, the absorption of reactive power is possible when the active power generation does not reach its peak and there is excess capacity. Nevertheless, the volt-Var control must be fully exploited, because it would be a waste if absorption of reactive power is necessary and the excess capacity sits idle.

A Static Var Compensator (SVC) is a device that can absorb/inject reactive power. SVCs are not limited by active power generation since the device is purely for reactive power compensation. As the maximum amount of absorption/injection is set as the rated capacity of the device, it simplifies the maximum reactive power it can compensate for. This is one of the reasons why an SVC may come up as a straightforward first line of defense. However, this device requires an additional purchase and also considerable space.

2.2 System Model

We collected the load demand and PV-generated power data in the Kyushu area, Japan (April 2021-March 2022) from the ISEP website [22]. This area is where PV penetration is relatively high in Japan. The PV-generated power can be approximately 5 GW at its peak, and the load can be two to three times that number. We simulated in our study an extreme variation in the PV-generated power and the load demand in this area. We conducted an 8760 yearly analysis with a time resolution of 1 hour. We ran a simulation using MATLAB/Simulink software to examine how V_{pcc} changes as the PV plant sends P_{pv} and compensates Q_{pv}. Figure 4 shows our test system model. Using the ISEP data, we plucked out a "study town" consuming a fraction of the entire load demand. We varied the load from 25-65 MW, with a power factor of 0.85 lagging. We assumed a 70-MW PV plant, interconnected to the PCC, exists in this town. As the PV plant is sizeable compared to the town's load, any extra PV power would flow out of this town to serve a portion of the neighboring town's load. Nevertheless, the voltage problem is often local and would occur near the sizeable PV plant in the "study town." We adopted the stringent voltage violation standard of ±2%. And all this gave us a study environment with many voltage violations. The volt-Var control looks at the PCC voltage and absorbs or injects reactive power with the result reflected in the next hour.

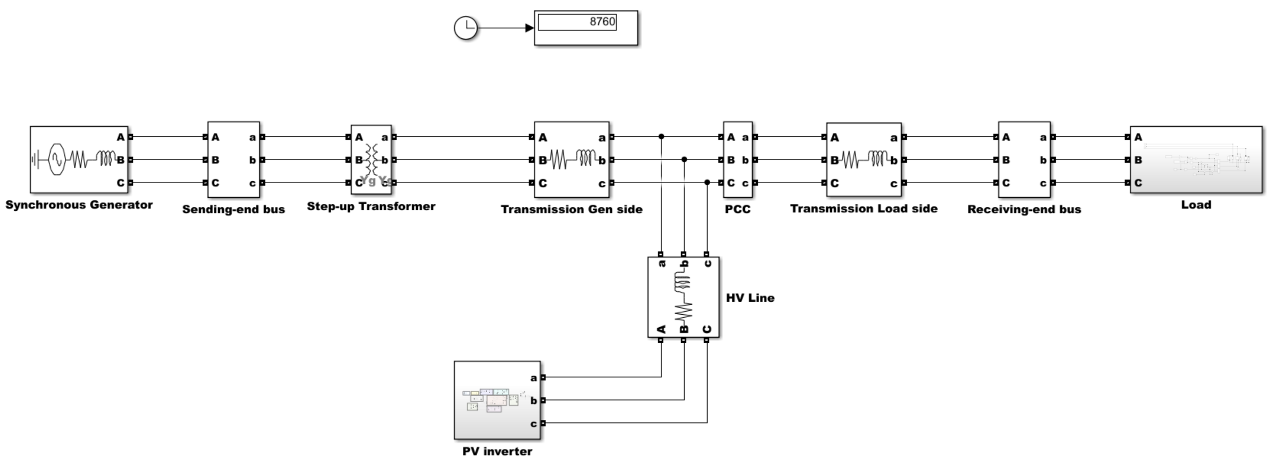

Figure 4 Test System Model.

Figure 5 shows the relationship between active power from the PV plant, load demand, and voltage fluctuations before adding volt-Var control. On the right side of the orange trend line are overvoltage points greater than +2%. On the left side of the green trend line are undervoltage points less than −2%.

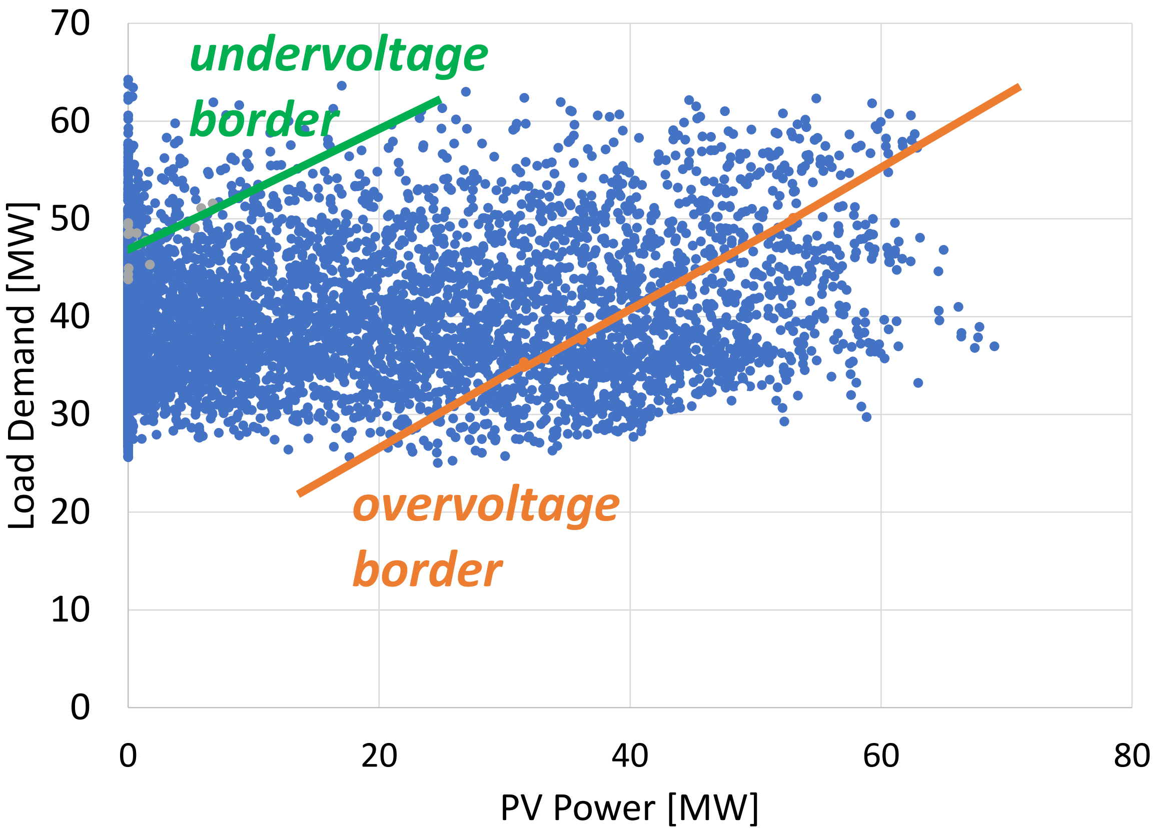

Figure 5 Relationship between PV active power, load demand, and voltage fluctuations.

We can see how the combination of high PV generation and low load demand tends to cause overvoltage and how the combination of low PV generation and high load demand tends to cause undervoltage. By activating the volt-Var control, we want to return the violated points to the acceptable voltage range of ±2%.

We first performed a study on volt-Var control on the inverter. As Equation (4) shows, the PV plant should increase V_{pcc}, as it generates active power. The generated power from the PV plant is highly variable, and V_{pcc} will fluctuate accordingly. This means that at the peak of PV's active power transmitted and the trough of load demand, V_{pcc} should peak, assuming reactive power absorption does not occur. PV-generated active power will be zero when the photovoltaic activity does not occur. This means that the PV plant will vary its active power output from 0-70 MW, and at the trough of PV's active power and the peak of load demand, V_{pcc} should sag. We put a volt-Var control to observe the injection/absorption of reactive power, which mitigates these voltage fluctuations. We used a droop coefficient of -0.01, as described in the volt-Var control characteristics in Equation (7). $V_2, V_3, V_4, and\ V_5$ were set as 0.98, 0.99, 1.01, and 1.02, respectively. We then estimated the capacity of an SVC required to take care of the voltage violations that remain after the compensation by the volt-Var control.

Then we added a final component to the study: curtailment. Curtailment is where grid operators curtail some amounts of the active power generated from non-dispatchable sources to improve power quality and avoid congestion [14]. Curtailment happens to PV plants especially around midday with light load. When the curtailment occurs, voltage rise is decreased, as shown in Equation (4).

A cautionary note needs to be discussed. If the nominal voltage is set assuming the PV plant generates a specific amount of active power, say 35 MW, V_{pcc} can get higher or lower than the nominal voltage depending on the generated amount. However, if the PV plant is considered a pure addition to the feeder disrupting the nominal voltage, any amount of active power generated by the PV plant would hike V_{pcc}, and it will cause V_{pcc} to always be higher than the nominal voltage. This is a matter of perception, but it seems reasonable to clarify, as depending on how this nominal voltage is set, the PV plant can either only hike the V_{pcc} or both hike and sag the V_{pcc}. As shown in Figure 4, volt-Var control can generally compensate for reactive power in both directions. If the PV plant is a pure addition to the existing feeder, the volt-Var control may only be responsible for lowering the V_{pcc} to the nominal voltage range. However, this leads to reactive power absorbing operation of the control only, and the other half of the control capacity is not utilized. In any case, it seems neither technically nor economically reasonable to have two controls, one of which only functions to lower the V_{pcc} and the other installed by the grid operator to increase the V_{pcc}. Therefore, setting the nominal voltage assuming the large-scale PV plant generates 35 MW or somewhere in between seems reasonable.

3. Results

We observed voltage fluctuations at V_{pcc} under different conditions. First, we assumed curtailment does not occur, studied the effects of volt-Var control, and checked if the necessary capacity of SVC can be reduced. Next, we assumed curtailment does occur, studied the effects of volt-Var control, and checked if the necessary capacity of SVC can be further reduced.

3.1 Simulation Results

Figure 6 and Figure 7 show voltage fluctuations at V_{pcc} with and without volt-Var control, assuming curtailment does not occur. We observed considerably fewer voltage violations when we put volt-Var control on the inverter. Overall, the voltage fluctuations in Figure 7 are more toward the allowed voltage range. Table 1 shows a distinct difference between the two scenarios with numbers. With no volt-Var control in place, there were 993 overvoltage hours out of 8,761 hours. The volt-Var control on the inverter reduced the overvoltage hours to 595. The undervoltage hours were 364 without the control, which decreased to 91. The volt-Var control absorbed/injected reactive power to reduce these voltage violation hours.

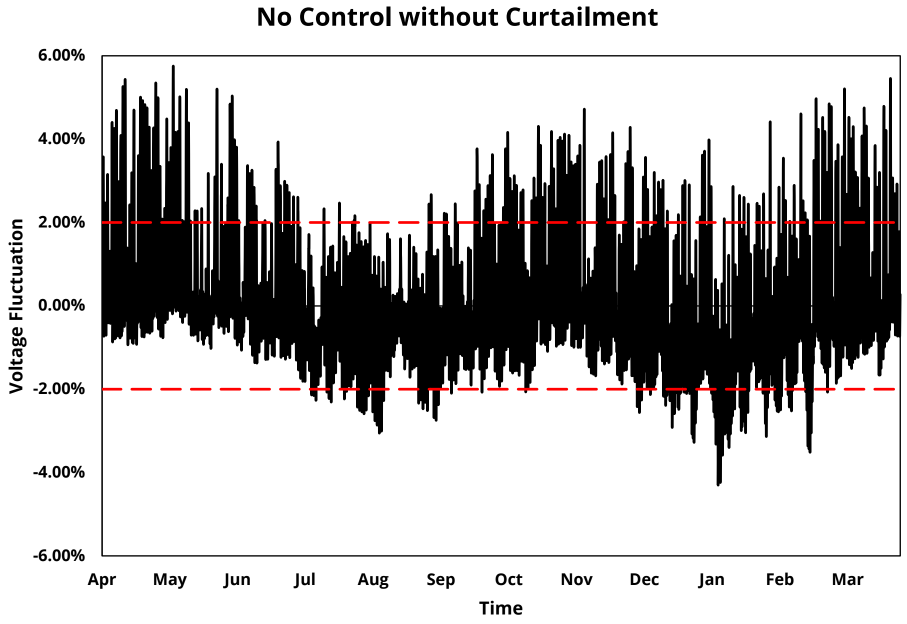

Figure 6 Voltage fluctuations at V_{pcc} without volt-Var control.

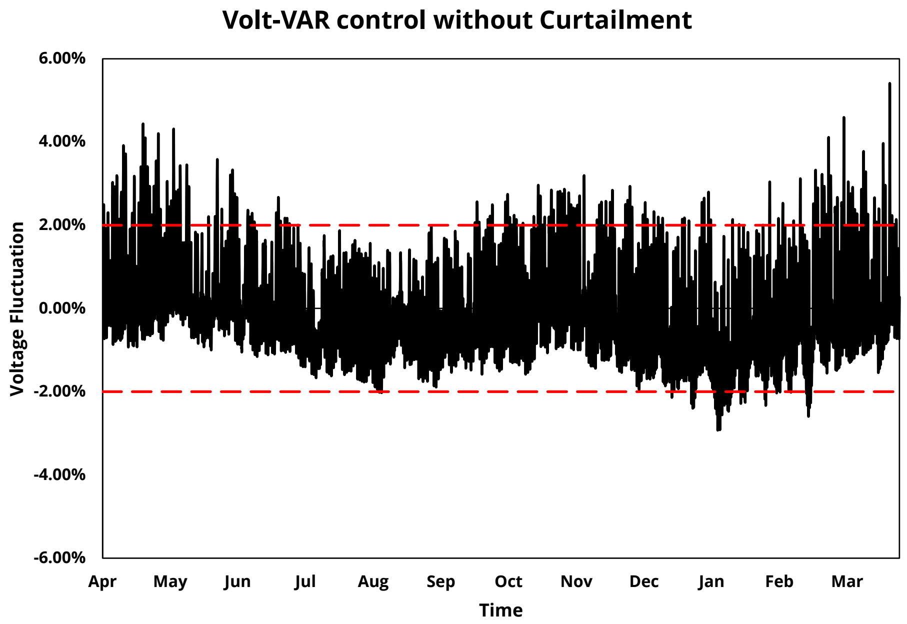

Figure 7 Voltage fluctuations at V_{pcc} with volt-Var control.

Table 1 Summary of simulation results.

		Qinv (MVAR)		Qsvc (MVAR)		Over (h)	Under (h)	Safe (h)
		min	max	min	max			
Without Curtailment	No Control	-0.004	0.004	-20.623	32.268	993	364	7404
	Volt-VAR Control	-26.123	19.130	-10.818	2.942	595	91	8075
With Curtailment	No Control	-0.006	0.004	-12.657	25.017	971	363	7426
	Volt-VAR Control	-22.712	19.130	-4.798	2.282	498	90	8172

We then checked the result of our SVC study to remove 595 overvoltage hours and 91 undervoltage hours to investigate the maximum capacity of the device required. The result was −10.8 MVar for overvoltage and 2.9 MVar for undervoltage, which means we need a 10.8 MVar SVC.

Figure 8 shows injected/absorbed reactive power by the inverter. The maximum reactive power absorption is more than 26 MVar. Table 1 shows –26 MVar, which means injecting −26 MVar or absorbing 26 MVar. On the other hand, the maximum reactive power injection is about 19 MVar. As these numbers represent only the maximum absorption and injection, we can look at Figure 8 to learn the frequency of reactive power absorption and injection. Figure 8 shows the control absorbed much more reactive power than it injected. As shown in Table 1, the number of overvoltage incidents is 993, almost three times more than the number of undervoltage incidents of 364. The number of overvoltage hours that decreased to fit within +2% of the nominal voltage was 398, representing 40%. The number of undervoltage hours put back in the accepted voltage range was 273, representing 75%.

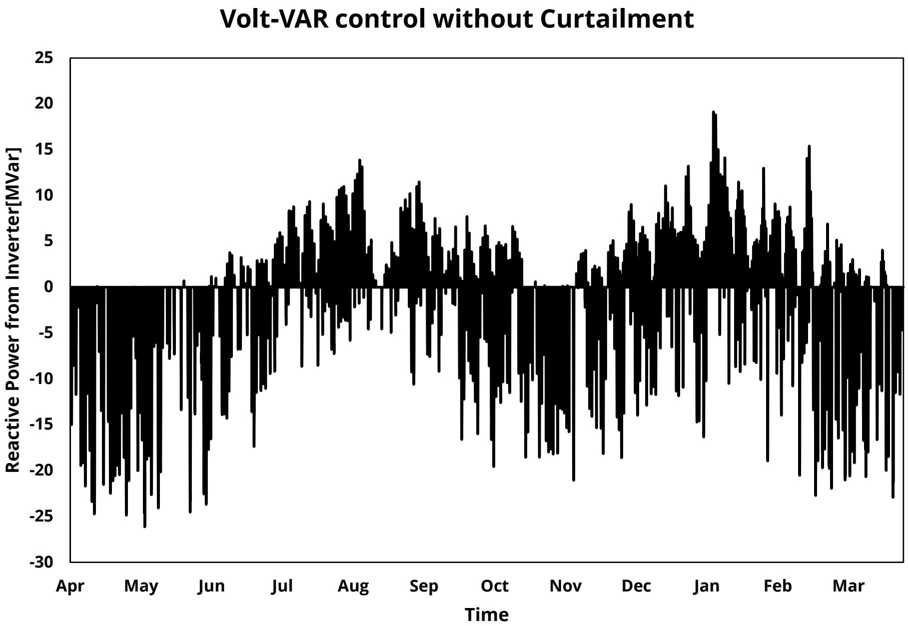

Figure 8 Reactive power absorption/injection from inverter.

Although the control absorbed much more reactive power than injected, only 40% was mitigated sufficiently. This contrasts with the 75% success rate for undervoltage mitigation. One of the reasons for the contrast is the magnitude of voltage deviations depicted in Figure 6. Overvoltage hours deviate much more from the upper bound on average. In contrast, the magnitude of undervoltage hours' deviation is less on average. This means the injected reactive power by the control can more easily return the undervoltage hours to the allowable voltage range.

The other reason for the contrast is the ceiling of reactive power absorption by active power generation. Equation (9) states the remaining capacity of the inverter limits the reactive power compensation amounts . For example, when the inverter generated as much as 69.664 MW, the absorption amount was 6.85 MVar. This amount of absorption seems to have been truncated because, according to Equation (9), the maximum Var absorption is also 6.85 MVar.

Figure 9 and Figure 10 show voltage fluctuations at V_{pcc} with and without volt-Var control, assuming curtailment occurs. We again observed considerably fewer voltage violations when we put volt-Var control on the inverter. Overall, the voltage fluctuations in Figure 10 are more toward the allowed voltage range, and we can see how curtailment truncated a significant number of overvoltage bar lengths compared to the no curtailment scenario depicted in Figure 7.

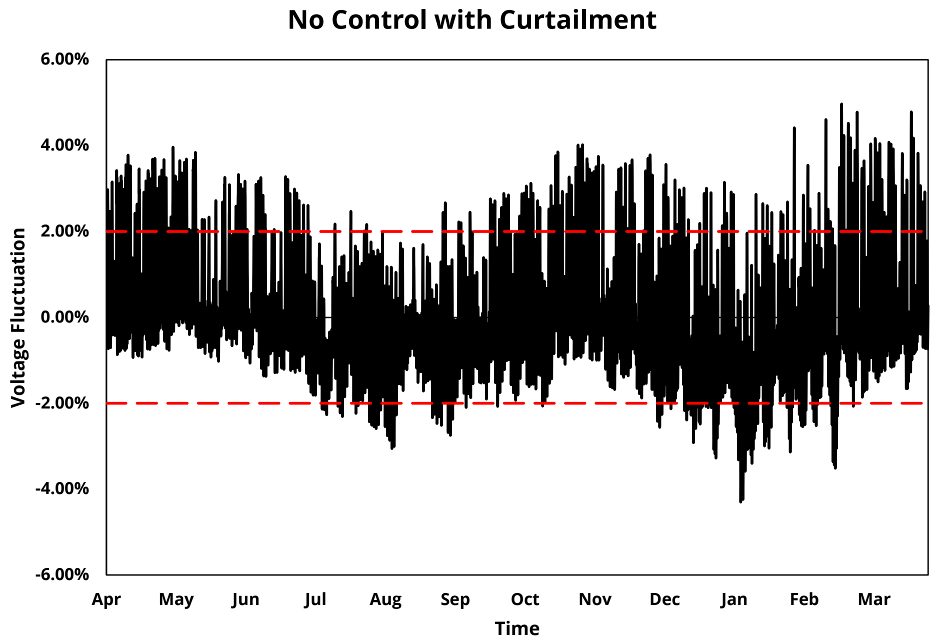

Figure 9 Voltage fluctuations at V_{pcc} without volt-Var control under curtailment.

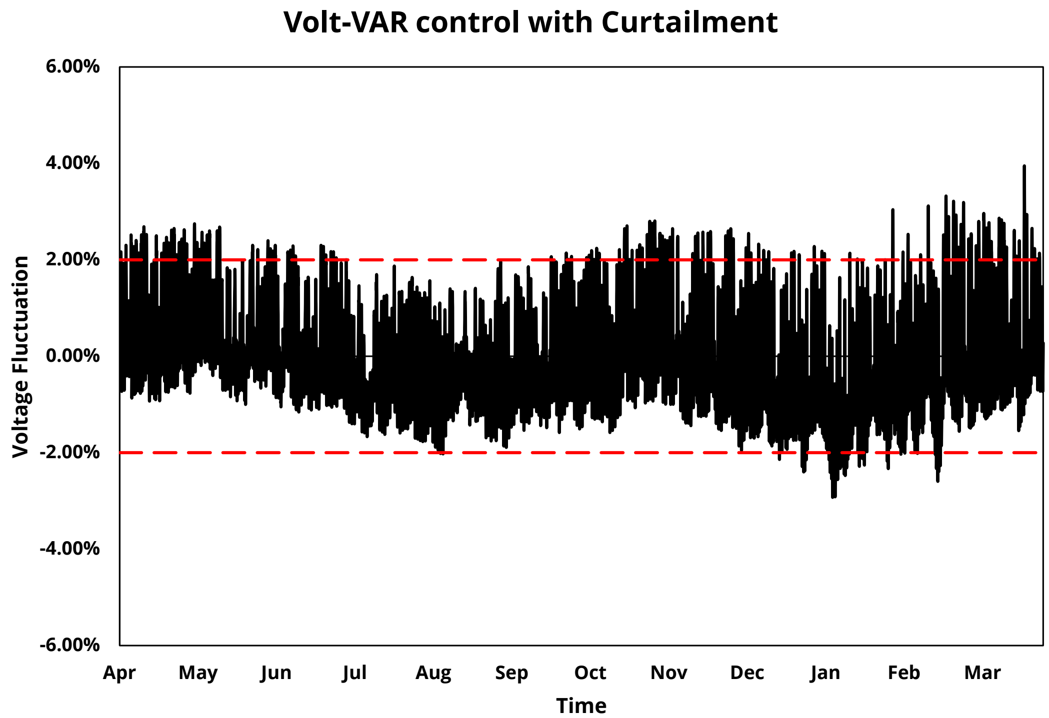

Figure 10 Voltage fluctuations at V_{pcc} with volt-Var control under curtailment.

Subsequently, we investigated the SVC capacity required to remove 498 overvoltage hours and 90 undervoltage hours. Figure 10 shows that the bar length of the maximum Var absorption is longer than that of the maximum Var injection. This means the absorption side will determine the SVC capacity. As shown in Table 1, the result was 4.8 MVar for overvoltage correction, which means we need a 4.8 MVar SVC. For the non-curtailment scenario, the capacity of the SVC required was 10.8 MVar, demonstrating how the curtailment contributes to reducing the required capacity of the SVC. The operator-induced curtailment was happening specifically at certain overvoltage points and mitigating overvoltage.

When we compare the injected amounts of reactive power from the inverter in Figure 8 and Figure 11, there is no difference. This is because curtailment does not occur when reactive power injection is necessary, which is necessitated by undervoltage. Undervoltage at the PCC generally occurs when there is an insufficient supply of PV active power and excess power demand through the node.

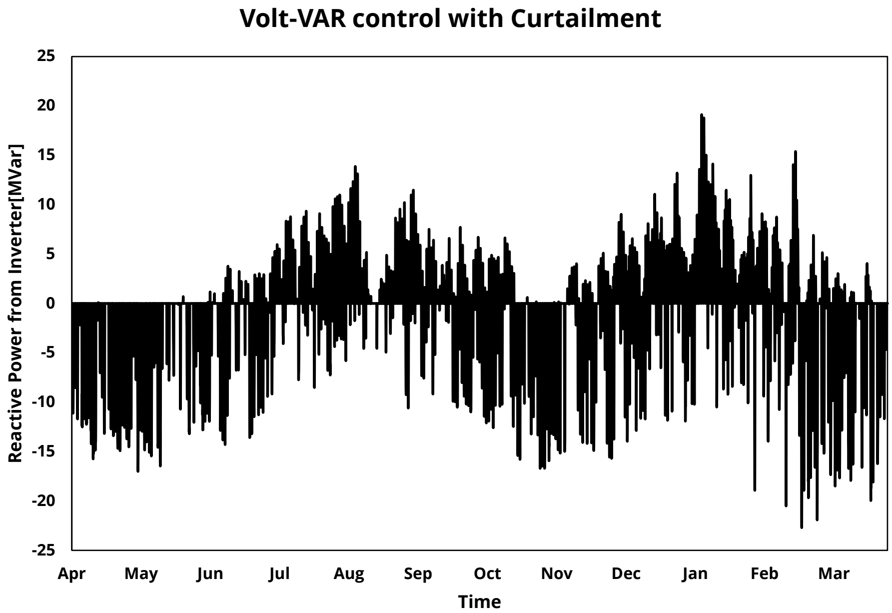

Figure 11 Reactive power absorption/injection from inverter under curtailment.

However, there is a drastic difference when we compare the absorbed amounts of reactive power. Without the curtailment, the maximum reactive power absorption is more than 26 MVar. The maximum reactive power absorption in the curtailment scenario is reduced to 22.7 MVar. In April and May, we can observe that significant curtailment occurs as the bar lengths of the reactive power are significantly shorter. On the other hand, in February, the bar lengths of the reactive power were mostly unchanged, indicating that the curtailment did not occur to the same extent as in April and May; it only occurred to a limited degree. The curtailment occurs when there is an oversupply of PV power and low demand for power, which tends to cause overvoltage. When the curtailment curtails high PV power output, Equation (4) tells us that the truncated PV active power decreases the magnitude of voltage rise. When active power is reduced, it also makes more room for reactive power absorption, according to Equation (9). Thus, the interplay of droop curve and curtailment determines the reactive power compensation amounts. When the curtailment occurs, there is more room for reactive power absorption according to Equation (9), but the droop gain also sets the ceiling for the maximum absorption. Overall, the overvoltage points are reduced in magnitude. When curtailment mitigates the overvoltage hours, the volt-Var control does not have to absorb as much reactive power. This is why the maximum absorption by the inverter was reduced from 26.1 MVar to 22.7 MVar, and the size of SVC was reduced from 10.8 MVar to 4.8 MVar.

4. Discussion

We will discuss some of the implications of the study results here. For volt-Var control analysis, we have seen that the control mitigated voltage fluctuations to a large extent. If we utilize the volt-Var control on the inverter, we may be able to downsize the SVC significantly. In our study, we downsized the SVC from 32.3 MVar to 10.8 MVar, with no curtailment assumed. If we oversize the inverter by 3% to 72.1 MVA, when the active power generation is 69.8 MW, the maximum reactive power absorption jumps from 5.3 MVar to 18.1 MVar, according to Equation (9). This is a significant jump in the reactive power compensation capability. This would reduce the necessary capacity of SVC and could even eliminate it.

It is an IPP's choice to rely on an SVC for all the reactive power compensation. However, this may not be wise. At times the land available may not be large enough to accommodate the SVC, and some PV panels may be forgone. The road to carry the SVC to the place to install it may be too narrow. The SVC itself is costly. Thus, the associated cost of the SVC may be too high.

In the curtailment analysis, we have seen that the curtailment significantly reduced the number of voltage violations above the upper bound. Curtailment is usually done when the PV plant generates high output because high active power raises the voltage at PCC. By curtailing active power at these hours to some extent, the V_{pcc} does not rise as much, as shown in Equation (4). If the curtailment reduces active power to one-half, the overvoltage will also be one-half if there is no reactive power. If the inverter injects/absorbs reactive power, V_{pcc} will be affected by the amount of reactive power.

Curtailment is currently imposed on the PV plant, and the plant owner has no control over it. This is understandable because very few PV plants are currently ready to control the voltage sufficiently. It is also understandable because of other grid issues, such as power supply and demand's geographical and temporal imbalances [23]. As more and more renewable energies penetrate the grid, these imbalances are expected to become larger in extent. Therefore, curtailment is necessary and imperative, and the grid needs more fast-response controls. What this means for the volt-Var control is that we may use it less often than we would if there were no curtailment. Grid operators need to consider that curtailment will reduce many overvoltage points and then calculate the required capacity of the reactive power compensation device. IPPs need to recognize the role of smart inverters adequately. With the curtailment in place, the amount of reactive power absorption decreases. A smart inverter may play a bigger role than an SVC. It also means removing the SVC altogether may be possible by oversizing the smart inverter appropriately.

Who should bear the cost of the SVC? This is not an easy question to answer. For PV plants, the output can vary from zero to the peak wattage of the PV plant. It may not be realistic to expect IPPs to be entirely responsible for undervoltage, which normally happens when there are little PV output and heavy loads. Overvoltage, which arises from high output and light loads, IPPs may be expected to be responsible. On the other hand, a smart inverter can inject and absorb reactive power, and so can an SVC. The challenge is that if IPPs bear 100% of an SVC's cost and are not compensated for its operation, they may choose not to utilize the SVC when the plant does not generate power. In this case, the SVC may mainly absorb reactive power, and the injection capability may be underutilized. As a result, the SVC does not run to its full capacity, and we are not taking full advantage of the device. One idea is to split the cost and have a contract stipulating each party's responsibilities. A policy that facilitates this type of structure should exist.

Our study defined the accepted voltage range as ±2% of the nominal voltage. This is a rather stringent threshold. Less reactive power absorption/injection will be necessary if we relax the range. Depending on the grid infrastructure, the allowed range may differ. However, grid operators need to announce the accepted voltage range with a proper justification.

Regarding the ultimate goal of increasing PV penetration, voltage violation is not the only obstacle to increasing PV penetration. Other obstacles do exist. One such obstacle is power supply and demand's geographical imbalance [23]. This occurs when the load center is located at a significant distance from the PV plant, and the power line is insufficient to transport the supplied power to the center without causing congestion. Another obstacle is power supply and demand's temporal imbalance, which can lead to congestion and frequency instability. The advent of battery storage and load flexibility can address these obstacles to a large extent [23]. They also necessitate some grid enforcement. In this paper, these matters are unresolved. Instead, this paper focuses on voltage stability in higher-voltage systems. This is because there is a risk of PV projects becoming unfeasible due to voltage violations. After all, voltage violations may remain unresolved for economic or spatial reasons. Without proper knowledge of reactive power controls, PV plant development can be hindered.

Voltage instability is a ubiquitous nodal problem observed in much of every network. This is because the power flow is no longer unidirectional, and more and more non-dispatchable power sources are penetrating the network. A volt-Var control on the inverter is an autonomous distributed control and does not require communication lines. Utilizing this type of inverter first seems appropriate.

5. Conclusions

This paper addresses the voltage violation problem, which is one of the major obstacles to increasing PV penetration. The study's main findings were that volt-Var control was very effective in mitigating voltage fluctuations. Additionally, the study found that the curtailment occurred at overvoltage points, significantly reducing SVC size. To understand efficient control systems, voltage control methods and parameters may need further investigation. While much research focuses on battery storage as a solution to this problem, IPPs may confront practical issues such as spatial and/or financial issues. When voltage violations are a problem of PV plant interconnection, grid operators tend to request IPPs to install an SVC. The problem with SVCs is that they are also expensive and space-consuming. This can cripple IPPs with significant financial burden and additional land acquisition or removing some PV panels. We studied a 70-MW PV plant with volt-Var control on its inverter. The result demonstrated that utilizing excess inverter rating to absorb/inject reactive power removed many voltage violation points. The study further investigated the effect of curtailment on voltage violations. The curtailment was occurring at overvoltage points. Therefore, it decreased the magnitude of reactive power absorption, and significantly reduced the necessary capacity of SVC. The findings suggest that oversizing the inverter would remove many more voltage violations. As a result, the study indicated that the required capacity of the SVC can be reduced further, and the SVC can be eliminated depending on the magnitude of oversizing. Thus, IPPs should seek the most economical and space-efficient device that fulfills the technical requirements of reactive power compensation. This paper also points out a responsibility issue of these devices and supports a policy that facilitates reasonable demarcation of responsibilities. In future research, the voltage control methods and parameters may be examined in detail to aid in selecting the most efficient control parameters.

Author Contributions

Ken Shimomukai – conceptualization, simulation formation, simulation output analysis, writing/editing; Haruka Maeda – simulation formation, conducting the simulation, simulation output analysis; Zahirah binti Muhammad Azman – simulation formation; Sandro Sitompul – simulation model building, advising on the story flow; Goro Fujita – providing guidance on the direction of the study.

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Competing Interests

The authors have declared that no competing interests exist.

References

1. Varma RK, Siavashi E, Mohan S, McMichael-Dennis J. Grid support benefits of solar PV systems as STATCOM (PV-STATCOM) through converter control: Grid integration challenges of solar PV power systems. IEEE Electrif Mag. 2021; 9: 50-61.
2. Carvalho PM, Correia PF, Ferreira LA. Distributed reactive power generation control for voltage rise mitigation in distribution networks. IEEE Trans Power Syst. 2008; 23: 766-772.
3. Jahangiri P, Aliprantis DC. Distributed Volt/VAr control by PV inverters. IEEE Trans Power Syst. 2013; 28: 3429-3439.
4. Aziz T, Ketjoy N. PV penetration limits in low voltage networks and voltage variations. IEEE Access. 2017; 5: 16784-16792.
5. Mak D, Choi DH. Optimization framework for coordinated operation of home energy management system and Volt-VAR optimization in unbalanced active distribution networks considering uncertainties. Appl Energy. 2020; 276: 115495.
6. Prabpal P, Kongjeen Y, Bhumkittipich K. Optimal battery energy storage system based on var control strategies using particle swarm optimization for power distribution system. Symmetry. 2021; 13: 1692.
7. Chaudhary P, Rizwan M. Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. Renew Sust Energy Rev. 2018; 82: 3279-3287.

8. Gush T, Kim CH, Admasie S, Kim JS, Song JS. Optimal smart inverter control for PV and BESS to improve PV hosting capacity of distribution networks using slime mould algorithm. IEEE Access. 2021; 9: 52164-52176.
9. Zimann FJ, Batschauer AL, Mezaroba M, Neves FA. Energy storage system control algorithm for voltage regulation with active and reactive power injection in low-voltage distribution network. Electr Power Syst Res. 2019; 174: 105825.
10. Tsafack P, Ngwashi D, Ducharne B, Tanyi E. Greenness percentage of the said green renewable energy: A case study. Energy Rep. 2019; 5: 979-986.
11. Cabrera-Tobar A, Bullich-Massagué E, Aragüés-Peñalba M, Gomis-Bellmunt O. Topologies for large scale photovoltaic power plants. Renew Sust Energ Rev. 2016; 59: 309-319.
12. Iioka D, Sakakibara K, Yokomizu Y, Matsumura T, Izuhara N. Distribution voltage rise at dense photovoltaic power generation area and its suppression by SVC. IEEJ Trans Power Energy. 2006; 126: 153-158.
13. Howlader AM, Sadoyama S, Roose LR, Sepasi S. Distributed voltage control method using Volt-Var control curve of photovoltaic inverter for a smart power grid system. Proceedings of 2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS); 2017 December 12-15; Honolulu, HI, USA. Piscatwe: IEEE.
14. Kane L, Ault G. A review and analysis of renewable energy curtailment schemes and principles of access: Transitioning towards business as usual. Energy Policy. 2014; 72: 67-77.
15. Jabr RA. Robust Volt/VAr control with photovoltaics. IEEE Trans Power Syst. 2019; 34: 2401-2408.
16. Xu R, Zhang C, Xu Y, Dong Z, Zhang R. Multi-objective hierarchically-coordinated Volt/VAr control for active distribution networks with droop-controlled PV inverters. IEEE Trans Smart Grid. 2021; 13: 998-1011.
17. Satsangi S, Kumbhar GB. Energy savings estimation of a distribution system in presence of intelligent Volt-VAr control based on IEEE Std. 1547-2018. CSEE J Power Energy Syst. 2022; 8: 1477-1486.
18. Erickson JC, Gilligan SR. The effects of voltage reduction on distribution circuit loads. IEEE Trans Power Appar Sys. 1982; PAS-101: 2014-2018.
19. Delgado AV, Latif MK, Ahmed-Zaid S. Mitigation of distribution voltage violations using single-phase residential static var compensators. Proceedings of 2019 IEEE 62nd International Midwest Symposium on Circuits and Systems (MWSCAS); 2019 August 04-07; Dallas, TX, USA. Piscatwe: IEEE.
20. Yang G, Marra F, Juamperez M, Kjær SB, Hashemi S, Østergaard J, et al. Voltage rise mitigation for solar PV integration at LV grids Studies from PVNET. dk. J Mod Power Syst Clean Energy. 2015; 3: 411-421.
21. Horowitz KA, Peterson Z, Coddington MH, Ding F, Sigrin BO, Saleem D, et al. An overview of distributed energy resource (DER) interconnection: Current practices and emerging solutions. Oak Ridge: U.S. Department of Energy Office of Scientific and Technical Information; 2019; NREL/TP-6A20-72102.
22. ISEP. Electricity Generation and Demand | ISEP Energy Chart [Internet]. Arlington: ISEP; 2017 [cited date 2022 December 16]. Available from: https://isep-energychart.com/en/graphics/electricityproduction/.

23. O'Shaughnessy E, Cruce JR, Xu K. Too much of a good thing? Global trends in the curtailment of solar PV. Sol Energy. 2020; 208: 1068-1077.