Gridtec Solutions

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A dynamic solution to problems caused by high penetrations of Distributed Energy Resources (DER)

A white paper by AMSC

Executive Summary

As a result of state and federal incentives, greatly reduced equipment costs and a global awareness of the impacts of burning fossil fuels, there has been a large increase in the installation of Distributed Energy Resources (DER) including photo voltaic (PV) and small wind generation on the distribution systems of many North American utilities. As penetrations of DER increase, the problems caused by DER are also increasing and are in some cases causing utilities to limit the amount of DER that can be installed on their distribution grids.

The problems caused by high penetrations of DER have been well documented previously. They consist of voltage flicker due to rapidly varying wind speed or cloud cover, and the inability to regulate steady state voltage due to rapidly changing generation levels and reverse power flow. These changes in both voltage and generation also cause increased maintenance requirements for voltage regulators, transformer load tap chargers and capacitor bank switching devices.

All of these issues can be addressed with AMSC's new distribution solution called "D-VAR VVO." D-VAR VVO is a shunt-connected power electronics compensator that is directly connected to medium voltage systems up to 13.8kV at an optimal location and can provide transient and steady state voltage regulation, power factor correction, or a fixed amount of capacitive or inductive reactive capability. D-VAR VVO is a power electronic device with output that is continuously variable from full inductive to full capacitive.

D-VAR VVO is available with three-phase ratings of either +/-500 kVAR or +/-1000 kVAR. If higher ratings are needed, two systems can be installed at one site for a +/-2000 kVAR rating. It is also available in single-phase versions with ratings of +/-167 kVAR or +/-333 kVAR. D-VAR VVO also has short-term overload capability and can increase its output to 1.3 times its continuous rating for up to 1 minute. This overload capability is especially valuable when addressing short term or transient events like voltage swells or sags, or motor starting issues. In Figure 1 below, the typical connection of the D-VAR VVO to a three-phase distribution system is shown.

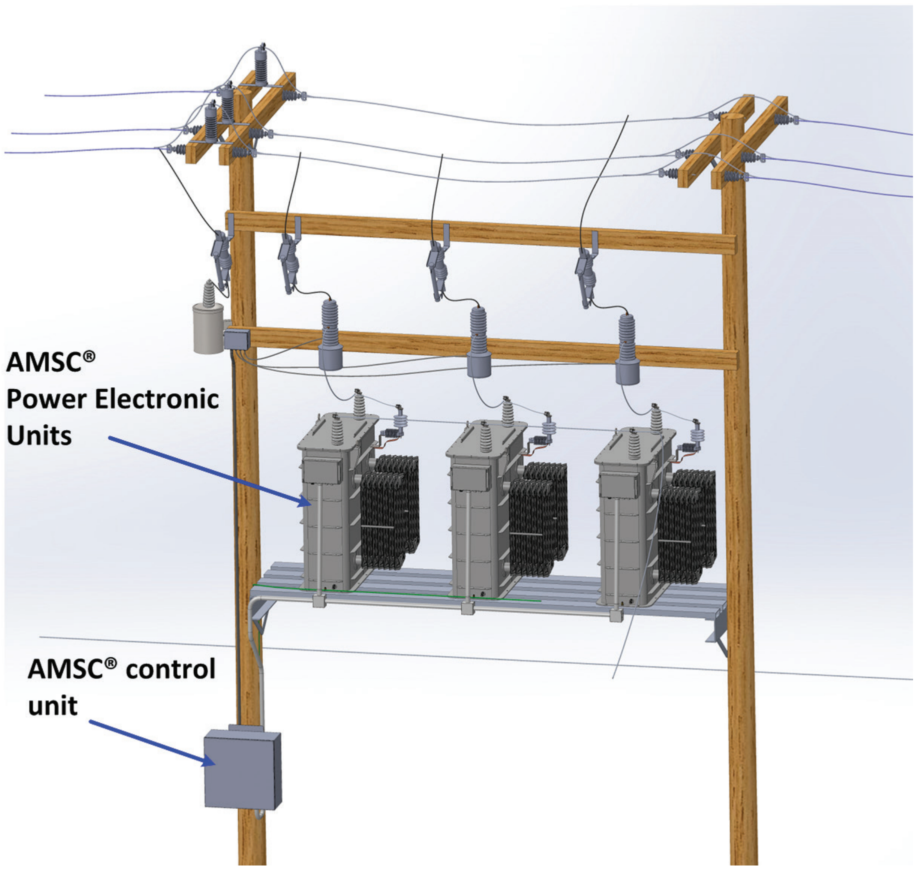
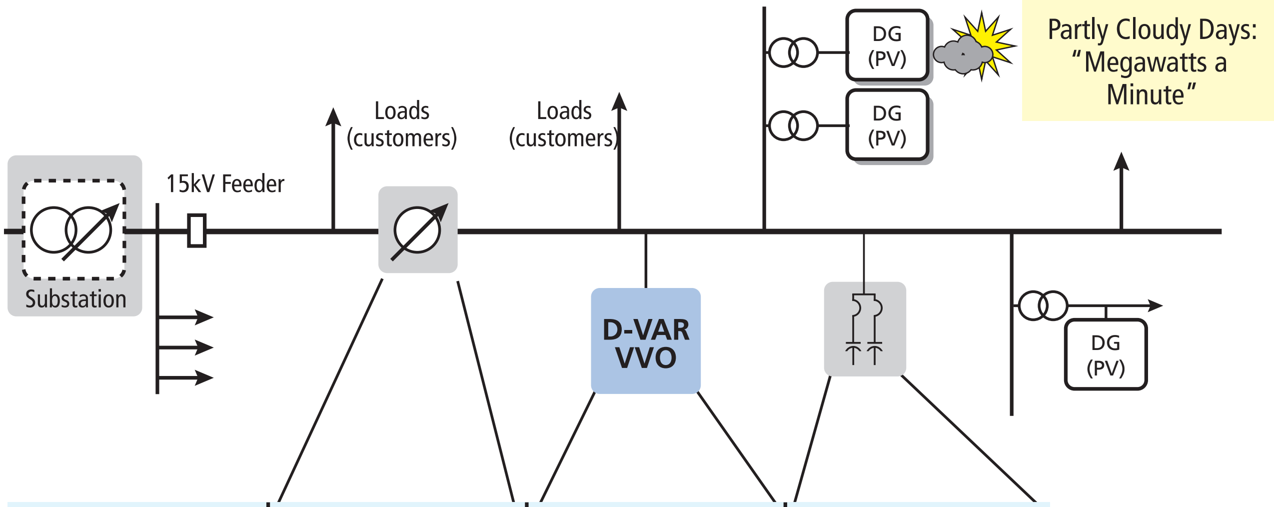


Fig. 1. D-VAR VVO connection to the distribution grid

Distributed Energy Resources – Future Prospects

In a May 2016 NREL publication called "Emerging Issues and Challenges in Integrating Solar with the Distribution System," the paper stated "From 2010 through the first half of 2015, the installed capacity of solar photovoltaics (PV) connected to the U.S. distribution system increased sixfold, from approximately 1.8 GW to more than 11 GW. This accounts for over half of the approximate total U.S. solar installations of 20 GW. Distributed generation from PV (DGPV) is expected to comprise 50%–60% of total U.S. PV capacity through at least 2020."

Similarly, small wind installations of 1-100 kW are being installed in record numbers throughout the USA. In an August 2016 paper written by Pacific Northwest Laboratory for the DOE, it was stated that "between 2003 and the end of 2015, over 75,000 wind turbines totaling 934 MW were deployed in distributed applications across all 50 states." With costs of wind installations falling by 60% over the past 5 years, it is anticipated that small wind generation will continue to be installed on



	Step VR		Switched caps
Corrects for load changes (time)	> 10 mins.		> 60 minutes
Daily operations limit (type)	< 30		< 4
Reverse power conditions	"Sensitive"		Can't reduce voltage

Fig. 2 Existing utility voltage regulation tools

utility distribution systems in ever greater numbers in the coming years.

Based upon historic trends and future forecasts, it is clear that there will be increasing levels of penetration of PV and small wind turbine generators (DER) installed on the North America's distribution systems. Utilities need to prepare for this future and develop a better understanding of the problems associated with DER. Understanding these unique problems caused by DER will allow utilities to investigate new system designs and look at advanced technology solutions that will enable greater penetrations of DER on their systems without jeopardizing the performance and operation of the distribution grid.

DER Impact on Power Quality and Voltage Flicker

The increase in DER penetration on utility distribution systems is causing several types of problems for utilities. One key problem is the inability of conventional voltage regulation equipment to prevent noticeable and objectionable changes in voltage due to rapid changes in DER generation output. The existing distribution system uses a combination of transformer load tap changers at the transmission source, one or more voltage regulators along the distribution line and switched capacitor banks to keep the steady-state voltage within an acceptable range along the distribution circuit from the source to the end use customer. As long as changes in either customer load or generation occurred gradually over several minutes, these slow mechanical devices did a reasonably good job of keeping the voltage within limits and preventing voltage flicker. Figure 2 above, shows a typical 15 kV class distribution feeder including the common voltage regulation equipment used by utilities to control steady-state voltages. Note that the changes in load that can be compensated with mechanically-actuated equipment are approximately 10 minutes or even longer in the case of switched capacitors. In addition, there are limits on the number of their daily operations and on their repeat intervals..

However, unlike the slow changing of most customer's loads, DER can change its output much more rapidly and many more times per hour and per day. The combined effect of the speed, magnitude and frequency of change in DER is more than the existing distribution system equipment can keep up with. The results are usually voltage flicker problems, reduced levels of power quality and higher maintenance on existing distribution system equipment.

The speed, magnitude and frequency of change in DER output are best seen by looking at an actual example of a PV generation site located in the upper Midwest. Figure 3 at right, contains generation data from a PV site in the upper Midwest and shows the daily variation in PV output due to the passing of clouds. Note that there are in excess of 30 cycles of PV generation changing by 50% or more. Also note the rapid rate of increase and decrease in PV output as a result of passing clouds. The 12-30 second timeframe for 50% PV generation changes is too fast for mechanical voltage regulation equipment (transformer LTC, voltage regulators, and capacitor banks) to react to and fix it in real time and therefore, voltage flicker will occur.

To demonstrate the voltage flicker problem, a typical 13.2 kV distribution system was modeled using DIgSILENT software. The three-phase system consisted of 8 busses, 6 loads, one set of three-phase voltage regulators, one 400 kW PV generation bus and one D-VAR VVO bus. The base case flows and voltages without the D-VAR VVO are shown in Figure 4 on right.

As seen in Figure 4, the voltages on all load serving busses from the source to the end of the feeder are in a very narrow range of 1.007-1.010 pu. The PV generation in the base case is 400 kW.

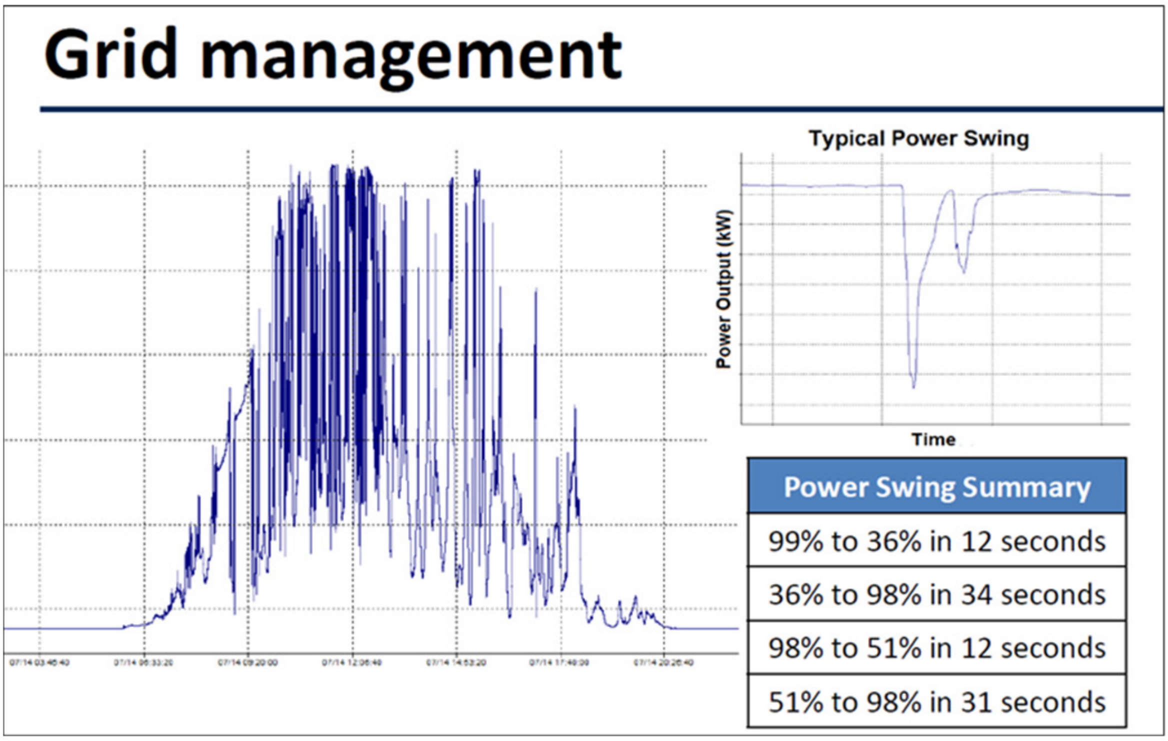


Fig. 3 PV generation variation due to passing clouds

When the loads and/or generation change very slowly, the regulators, LTCs and voltage controlled capacitor banks can do a reasonable job of maintaining an acceptable voltage profile from the source to all loads. However, when things change rapidly, voltage regulators, transformer LTCs and switched capacitor banks do not have the required speed of response, the repeatability or granularity needed to maintain voltages in the desired range.

Thus, when a cloud bank comes over the PV generation array and rapidly decreases its output from 400 kW to nearly 0 kW in 15-30 seconds, the voltage along the feeder will drop by 3.8-5.5%. The reason for the large voltage variation is because the LTCs, voltage regulators and capacitor banks are mechanical devices with control actions of 45-60 seconds or longer. Figure 5 at the bottom, shows the voltages that result from a 400 kW PV reduction prior to any corrective LTC, voltage regulator or capacitor bank operation.

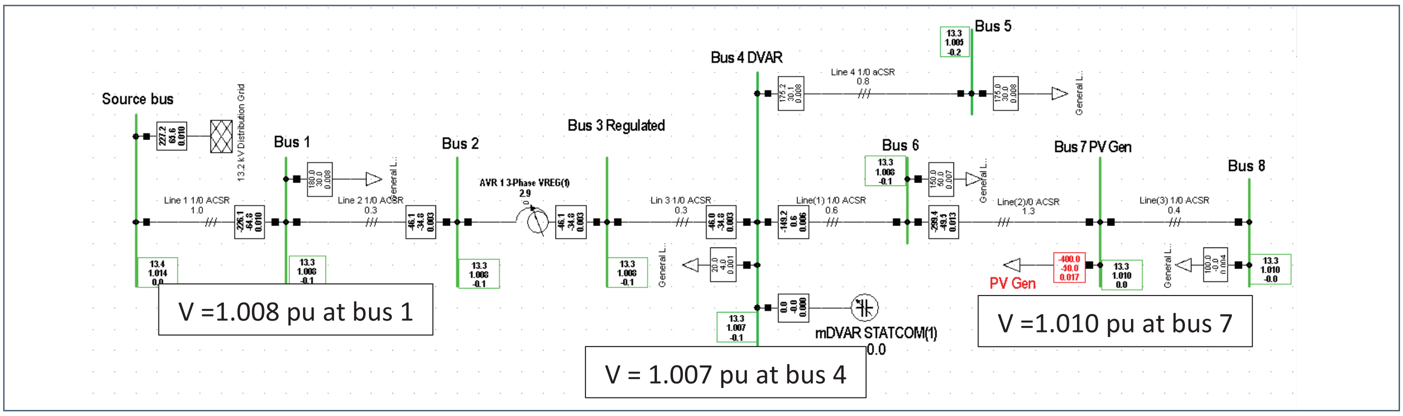


Fig. 4 DIgSILENT load flow base case without D-VAR VVO

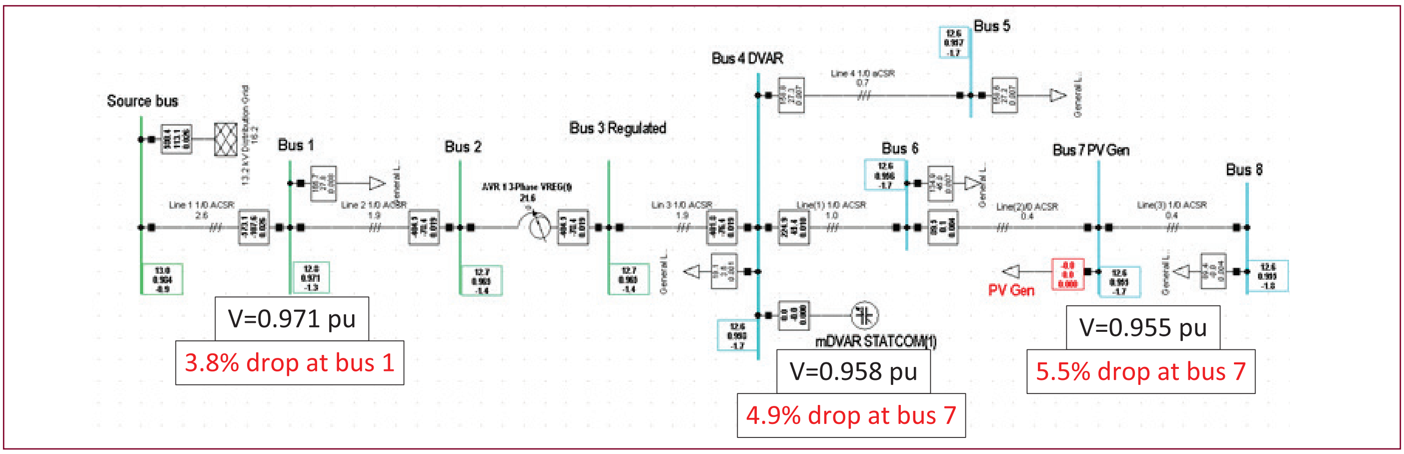


Fig. 5 Fast PV generation reduction 400 kW to 0 kW in 15 seconds - No D-VAR VVO

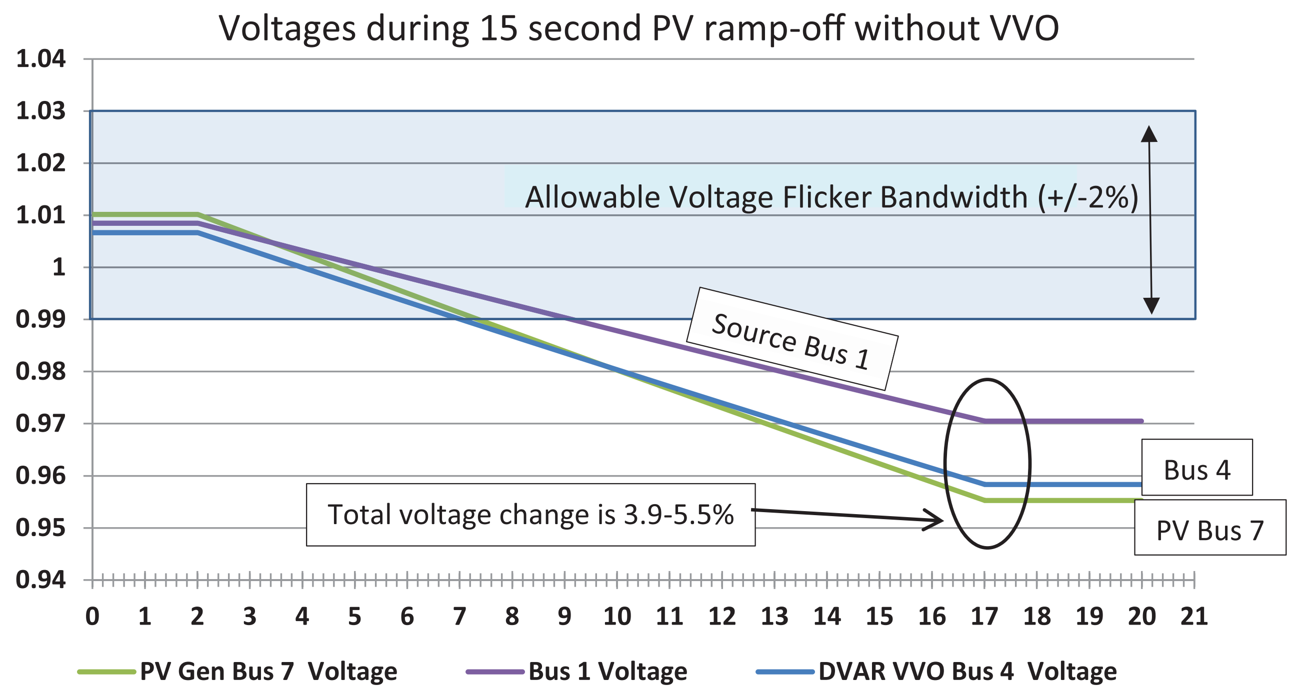


Fig. 6 Voltage vs. Time plot 400 kW PV reduction without D-VAR VVO Installed

Figure 6 above shows the voltage vs. time plot at three busses before, during and after the 400 kW PV generation reduction over 15 seconds. The simulation assumes no LTC or regulator tap position changes during the 20 second simulation period and no D-VAR VVO installed. Because the LTCs, regulators and capacitor banks are not fast enough to operate during this time, voltage flicker will occur because the voltage change exceeds flicker limits.

D-VAR VVO Dynamic Volt/VAR Compensator Added to Solve the Flicker Problem

To prevent voltage flicker, a fast dynamic, continuously variable device such as D-VAR VVO is needed. The D-VAR VVO varies its reactive current output on a sub-cycle basis to maintain voltage within a narrow range defined by the operator, owner, etc.

If a +/-1000 kVAR D-VAR VVO is added at Bus 4, the voltage change is limited to a narrow range of 0.5-1.3% during the same PV generation reduction scenario. The D-VAR VVO limits the voltage change to a value that does not result in voltage flicker. Figure 7 below, shows the voltage change at Bus 7 during a 400 kW PV generation ramp down over a 1 second period with and without the D-VAR VVO installed. Previously the voltage at bus 7 dropped by 5.5%, as seen in Figure 6 above. When D-VAR VVO was added, the voltage at Bus 7 only dropped by 1.3%. Voltage changes of this small magnitude are not considered to cause flicker or impact customer equipment.

As seen in Figure 7 below, the D-VAR VVO output at the completion of the 1 second PV ramp off is 543 kVAR capacitive or just over half of its continuous output rating. This indicates that the voltage could be held within a narrower range if desired by

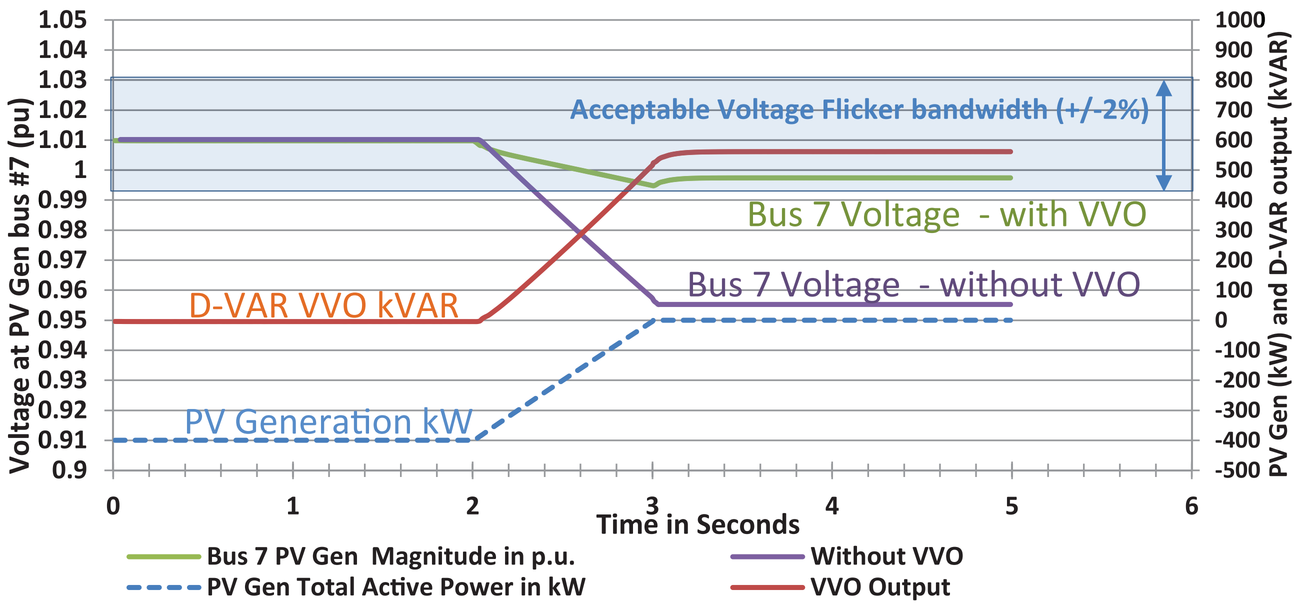


Fig. 7 Voltage vs. Time plot 400 kW PV reduction in 1 second with D-VAR VVO Installed

choosing a shallower droop setting instead of the 1% droop that was used in the simulation. It also suggests that a +/-500 kVAR D-VAR VVO would achieve nearly the same results for this particular situation

Off Peak Load issues

As customer load changes on a daily or hourly basis, the distribution system's LTCs, voltage regulators and capacitor banks all change their tap position or status according to a preset voltage control scheme. Load can vary from 30-100% of peak on a daily basis depending on the type of load being served and the time of year. This usually is not a critical issue for utilities unless the distribution circuit also includes a large penetration of PV or wind turbine generation. The issue stems from the change in direction of the power flow on certain sections of the distribution circuit. At light load levels, the DER generation can be greater than the total load on the circuit resulting in reverse power flow back to the transmission source. Reverse power flow may present problems such as limited stable tapping range for voltage regulators thus causing them to regulate improperly. Installation of the D-VAR VVO Dynamic Volt/VAR Compensator can prevent these regulator problems by continuously regulating the voltage and relieving the regulator of these responsibilities. .

Increased Equipment Maintenance Costs

On a typical distribution circuit, the load is low in early morning and begins to increase at daybreak. The load typically continues to grow through midday and then drops after sunset. Thus, capacitor banks typically turn on and off once per day while regulators and LTCs typically ratchet up slowly then down again slowly late in the day in response to these predictable load changes. However, with the introduction of DER on any distribution circuit, the total load will vary up and down many times per day. Figure 3 referenced earlier is a PV site in the upper Midwest and shows the daily variation in PV power output due to the passing of clouds. There are in excess of 30 cycles of PV generation changing by 50% or more during that day and there is a rapid rate of increase and decrease in PV output as a result of the passing clouds. The 12-30 second timeframe for a 50% PV generation change is too fast for mechanical voltage regulation schemes to react to and fix in real time and therefore, flicker will occur. However, all of these mechanical devices will still chase the voltage for several minutes after the change in output has occurred resulting in tens or hundreds of additional LTC and regulator tap position

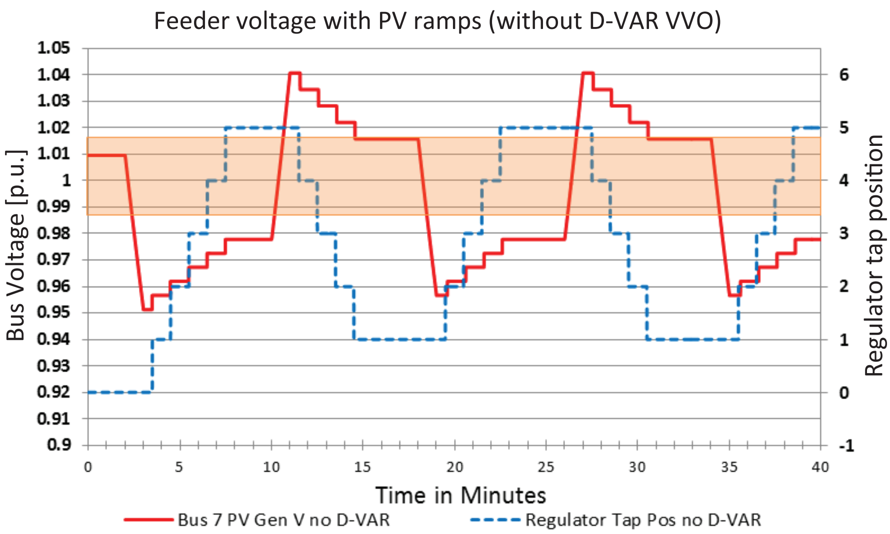


Fig. 8 Voltage and Regulator Tap Position during PV generation ramping on and off without D-VAR VVO

changes per day. Capacitor banks will also experience additional open/close operations if they are voltage controlled.

The following simulation shows how the D-VAR VVO prevents voltage flicker and can greatly reduce regulator tap changer operations. If mechanical voltage control devices are present on feeders with high DER penetration, the result will be a greatly increased maintenance requirement plus a premature need for replacement of equipment. Figure 8 above, provides a good example of the increased regulator tap changing required due to changes in PV generation level. The figure shows simulation results for a distribution grid including 400 kW of PV generation without D-VAR VVO installed. The figure shows the resulting voltages and the regulator tap position that would occur after each cycle of PV generation output change.

The dynamic simulation takes place over 40 minutes and assumes clouds move in to cover the PV site in 60 seconds causing the PV generation to decrease from 400 kW to 0 kW. Similarly, the clouds are assumed to move away in 60 seconds at the 10 minutes point which increased PV generation from 0 kW to 400 kW. This sequence repeats twice in 40 minutes.

The figure shows that when PV generation changes rapidly, regulators and transformer LTCs cannot react fast enough to keep voltage within the desired range. This causes voltage to fluctuate by 3-5% along the line and up to 9% near the end of the line. Clearly, this results in voltage flicker violations for customers due to the rapid PV generation changes.

In addition, after the PV generation changes its output, step voltage regulators react and change tap position to attempt to correct the voltage. The dynamic simulation above assumed a regulator target voltage of 1.000pu and a range of +/-0.015pu (shown in the orange shaded area). Several regulator tap position changes within a 40-minute period occur as the PV generation fluctuates due to cloud movement. Over the course of a month the regulator tap counter can register more than one thousand tap changes.

An excellent solution to avoid this added maintenance and/or premature equipment replacement is to install a fast-acting power electronics voltage control device, such as the D-VAR VVO. The D-VAR VVO is capable of varying output between the rated capacitive and inductive capability thousands of times a day. Because the device has no moving parts, this performance is accomplished without requiring additional maintenance or decrease of its useful life. Figure 9 below shows the same repeated PV ramp-on and ramp off sequence but with D-VAR VVO added.

As seen Figure 9 on the following page,, once D-VAR VVO is added to the simulation, voltage along the feeder remains within the orange shaded regulator voltage dead-band and requires only two regulator tap position changes over the same 40-minute period. Thus, there are 10 times fewer regulator tap position changes when the D-VAR VVO is operating. D-VAR VVO prevents voltage flicker and at the same time prevents the need for voltage regulators to change taps in response to large or small changes in PV output. This can save several hundreds of tap position changes on a monthly basis thereby reducing regulator maintenance while increasing the useful live of the equipment.

Coordination with Voltage Regulators

The addition of a D-VAR VVO on a distribution circuit with one or more sets of voltage regulators typically does not require changes in their controls. In some cases, the addition of a D-VAR VVO to the circuit allows an existing voltage regulator to be removed entirely. D-VAR VVO is a fast-acting power electronics device that operates to regulate voltage in a fraction of a second. Because the operational timeframes for D-VAR VVO and regulators (or transformer LTCs or capacitor banks) are so different, they will not interfere with or fight each other for control. The slow acting equipment will continue to perform a valuable function in reacting to slow, daily changes in voltage. In addition, because D-VAR VVO mitigates the shorter term voltage issues, existing regulation equipment will operate far less frequently.

Summary

Penetration levels of wind turbine and PV generation are growing in all areas of North America, and with this increased DER generation comes increased problems for utilities. These problems include reduced power quality, increased flicker voltage, inability to regulate feeder voltage and increased need for equipment maintenance and replacement. Fast acting power electronics based devices with no moving parts such as the D-VAR VVO Dynamic Volt/VAR Compensator can address and solve all of these problems. D-VAR VVO is a device that can be applied equally well on single-phase or three-phase distribution feeders to address both steady state voltage regulation and transient

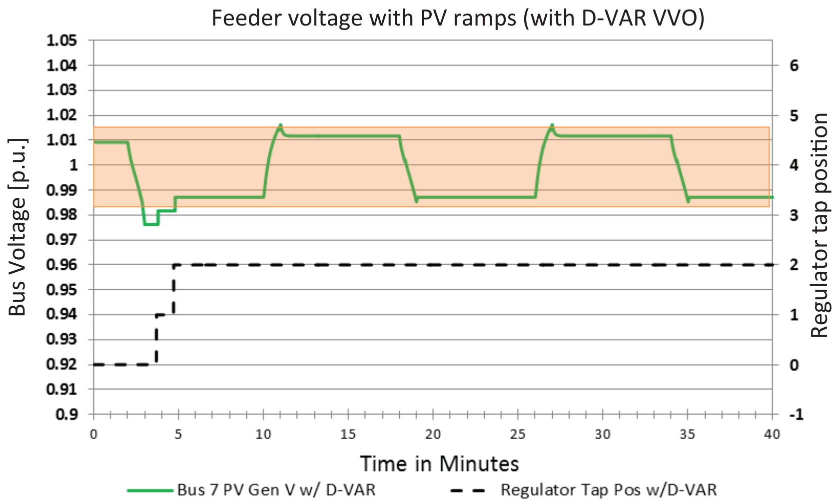


Fig. 9 - Voltage and Regulator Tap Position during PV generation ramping on and off with D-VAR VVO

voltage issues with its overload capability. It can also be remotely monitored and reprogrammed to change its control characteristics from straight voltage control to power factor or even a fixed level of capacitive or inductive output. Utilities that already have significant penetrations of DER or anticipate having DER added on their distribution systems should consider including D-VAR VVO Dynamic Volt/VAR Compensator technology as a solution to the voltage problems caused by DER.

Summary

Century-old techniques of managing utility load – in one direction – are unfit for the new age of distributed generation. The distribution system requires new innovations that are not only cost-effective and dynamic to adapt it to the ever-increasing penetration of DG, but also utility-controlled towards the greatest efficacy. Employing volt/VAR compensation equipment on-site could reduce voltage variations; however, this would require numerous (and growing) devices, which in turn would escalate installation, maintenance and operating costs. The best solution would have the flexibility and power to serve expansively – with one to a few installations required in a feeder. At the seamless meeting of utility industry needs and responsive solutions, AMSC's D-VAR VVO provides essential stability to the increasingly dynamic distribution grid, offering voltage and power factor control for DG outputs at the ideal location on 15kV feeders. ■

About AMSC

AMSC (NASDAQ: AMSC) generates the ideas, technologies and solutions that meet the world's demand for smarter, cleaner … better energy. Through its Windtec Solutions, AMSC enables manufacturers to launch best-in-class wind turbines quickly, effectively and profitably. Through its Gridtec Solutions, AMSC provides the engineering planning services and advanced grid systems that optimize network reliability, efficiency and performance. The company's solutions are now powering gigawatts of renewable energy globally and enhancing the performance and reliability of power networks in more than a dozen countries. Founded in 1987, AMSC is headquartered near Boston, Massachusetts with operations in Asia, Australia, Europe and North America.

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