In Hawaii, smart inverters are privately owned assets, and utilities do not control where the next "PV or smart inverter" is installed on the grid. Even if the utility may be able to control those assets either directly or via a system aggregator, it will require numerous SCADA, ADMS, DERMS and IED (Intelligent Electronic Device) integration for each individual vendor with associated integration costs to be supported by all utility end-users. Another aspect that needs to be considered is the losses of smart inverters that are typically in the range of 2%-3% which could become a large factor limiting VVO/CVR objectives when the main purpose is to reduce technical losses and energy consumption at the utility end-users.

One of the promising methods to solve the aforementioned challenges of PV penetration is through the deployment of DVCs [1]. The DVCs are fast-acting power-electronics devices that are installed on the secondary side of a distribution grid, to autonomously sense and regulate voltage with a ± 0.5% within control range by injecting sub-cycle kVArs (between 0 to 10 kVArs in 1 kVAr increments). Since DVCs are utility owned devices, utility can install the device anywhere to manage voltage problems. Most importantly, unlike the smart inverter, DVCs can manage voltage without curtailing solar generation.

Hawaiian Electric Company and Sentient Energy, Inc. have a strategic partnership to validate the performance of DVCs for ensuring grid reliability and efficiency while allowing more private rooftop solar systems to be added to island grids. The first pilot project is completed in 2017 and the test result shows that the DVCs solution doubles the pilot substation's PV hosting capacity [2][3].

This paper shows the result of the second pilot project, where Sentient Energy and Hawaiian Electric address the voltage issues at a 12.47 kV distribution substation located in South East Oahu Island. This substation has more than 37% of PV penetration (1.03MW rooftop solar generation) and 30 DVC devices are deployed on one circuit. This paper will demonstrate how DVCs could help to reduce voltage fluctuation and control the secondary voltage of the system to within the ANSI compliance. The field results show that DVCs support and improve the voltage at low voltage nodes on the system and provide extra 1.54% of lower voltage margin which allows the LTC center band to reduce. This creates extra upper voltage margin for the entire feeder and allow more rooftop solar installation without causing overvoltage issues to the system.

The load and voltage profile of the circuit model is fine tuned to match the field result. Sentient Energy used their proprietary PV hosting module to simulate the circuit model with different worse case scenarios considering all possible load and solar conditions. The result of the simulation study shows that with the extra 1.54% voltage margin provided by DVCs, the solar hosting capacity of the substation can be increased from 37% (1.03MW) to 99% (2.70MW).

II. DYNAMIC VAR CONTROLLERS (DVC)

Smart inverters with Volt-VAr or Volt-Watt control may help resolve some the voltage issues caused by high PV penetration. However, smart inverter cannot address the impact of legacy inverter. In order to increase the hosting capacity of the circuit, a new solution on the distribution system is required. Deploying the grid-connected DVCs is one of the promising methods to extend the functionality of the smart inverters.

DVCs are utility-owned equipment that closely regulate the local voltage (on the secondary side) and system voltage (on the primary side). DVCs are shunt connected on the secondary side of the service transformer (208V – 240V – 277V) and are usually single-phase but can be designed to install on a three-phase transformer as well. The tight voltage control is achieved by injecting VArs when the sensed voltage falls beneath a configurable Set-Point and VArs is removed if the voltage exceeds the configurable Set-Point.

A swarm of these DVC devices can be operated with a single broadcast of voltage Set-Point via a supervisory control system, requiring no peer-to-peer communication to achieve multiple control objectives at feeder level. These DVCs devices act in unison through a local intelligent algorithm programmed into each device that prevents infighting. The collective action of the swarm of devices result in taming the grid into a well-behaved system to unlock a simple grid-edge VVO/CVR scheme that increase system efficiency, provides feeder level dynamic VAr control [4] and finally support the penetration of solar PV by tapping down the LTC Set-Point [5]. The DVCs can communicate through cellular or mesh radio and managed by a supervisory control system. This supervisory control system performs secure data collection and management, visualization and analytics, over-the air upgrade and control of the entire swarm of DVCs devices. The supervisory control system can be either deployed behind the utility firewall on utility premises to ensure cyber security or hosted in the cloud. This software control system can also communicate with enterprise system such as ADMS.

Despite having several benefits over conventional solutions, DVC technology has its constraints. While DVCs can be built to absorb VArs to reduce voltage directly, this is usually more costly, so most cost-effective DVC solutions can only inject VArs. Second, DVCs rely on system impedance (service transformer impedance, upstream line impedance, etc) to have impact the supported voltage. Finally, although it has been shown that DVCs provide 1%-3 feeder-wide voltage improvement, the voltage control it offers is system-dependent as a shunt-connected technology. However, cost-benefit analysis has shown that the technology's benefits are far outsmarting the limitations [4].

III. OAHU PILOT PROJECT RESULTS

Hawaiian Electric and Sentient Energy, Inc. carried out a pilot in South East O'ahu to confirm the performance of DVC technology in order to mitigate voltage problems, thus allowing the Hawaiian Electric distribution circuit to include more private rooftop solar systems.

A. Feeder Specifications

The pilot substation has one feeder whose nominal voltage is 12.47 kV (L-L) with eight single-phase step-down transformers (7.2 kV / 2.4 kV). The feeder at the substation is controlled by the LTC. The specification of the feeder is shown in TABLE I. The substation has 1.03 MW of PV installed. Figure 1. shows the location of the PV and DVC deployment on the feeder. 26 percent of the distribution transformers are connected to solar panels.

TABLE I. FEEDER SPECIFICATIONS

Type of Circuit	Length (Miles)	Peak MW	Installed PV (MW)
Residential	3.69	2.75	1.03

Based on engineering study, the DVC locations are determined to optimize the voltage profile of the circuit. The engineering study considers the deployment of one DVC (rated at 10 kVAr) in a transformer rated below 50 kVA, two DVCs in anything above 50 kVA and less than 100 kVA. In total, 30 DVCs are deployed according to the analysis (8 in Phase A, 17 in Phase B and 5 in Phase C).

Figure 1. Circuit Diagram of Substation location, PV Locations, DVC locations, PQ Meters and primary step-down transformers (7.2 kV / 2.4 kV)

Substation LTC uses a line drop compensator (LDC) to control the voltage levels for the feeder. The LTC control is gang operated and regulates voltage using phase A voltage. The LTC centerband Set-Point = 121V and the line drop compensation (LDC) settings are enabled (R=3 and X=3) to prevent overvoltage problems caused by high daytime PV penetration and under-voltage problems caused by nighttime peak load.

B. Evaluation Measurement and Validtaion (EM&V)

Depending on the loading and the PV power output on the feeder, the LTC voltage changes regularly with LDC enabled. In order to maximize benefits, it is important to coordinate or synchronize the LTC Set-Point with DVCs when operating with DVC devices on the system. The DVCs are programmed via the supervisory control system to have two different voltage Set Point (day time Set-Point = 120V, night time Set-Point = 122V) to match the change of LTC voltage.

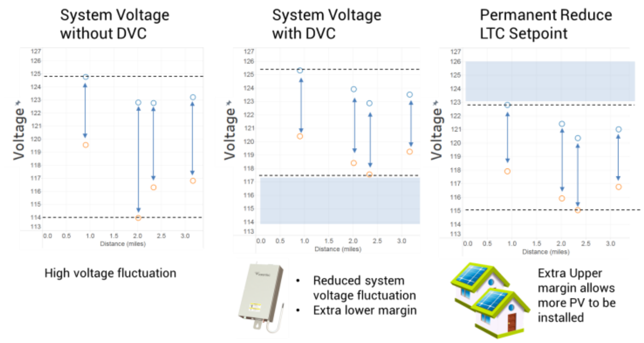


Figure 2. DVC Local Voltage Support (one node)

Figure 2. illustrates how the DVC solution reduces the voltage volatility and increases the solar hosting capacity of the system

1. System voltage without DVCs shows high voltage fluctuation
2. With DVCs enabled, it reduces the system voltage fluctuation and provide extra lower voltage margin
3. With the extra lower voltage margin provided by the DVC solution, it allows the system to permanently reduce its LTC Set-Point, which gives the system extra upper voltage headroom to install more solar PV

Figure 3. shows voltage measurement from all 30 DVC devices for a DAY ON / OFF test over 3 weeks. The minimum voltage improved from 114.1V to 115.95 V (1.85V improvement) when DVCs were engaged. Furthermore, DVCs not only improve the voltage at the DVC locations, but behave in unison to enhance the voltage of the entire circuit. This is proved through the transformer sensors installed at 8 transformer location for tracking the secondary voltage of service transformers where most of these locations do not have DVCs (7 out of 8 do not have DVCs). Even these locations see a voltage rise of 1.75V validating the swarm effect created by the DVCs, which helps to reduce the overall circuit voltage (see Figure 4.).

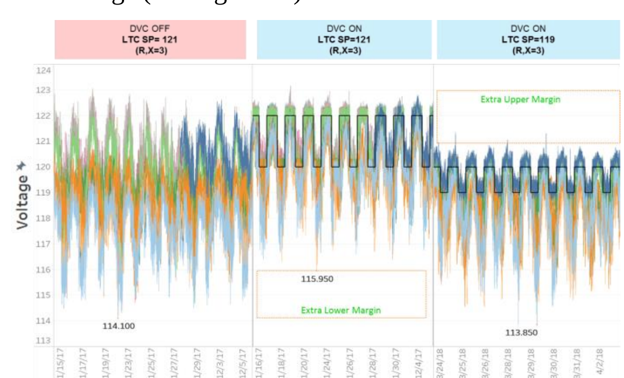


Figure 3. DVCs Voltage during ON/OFF Testing

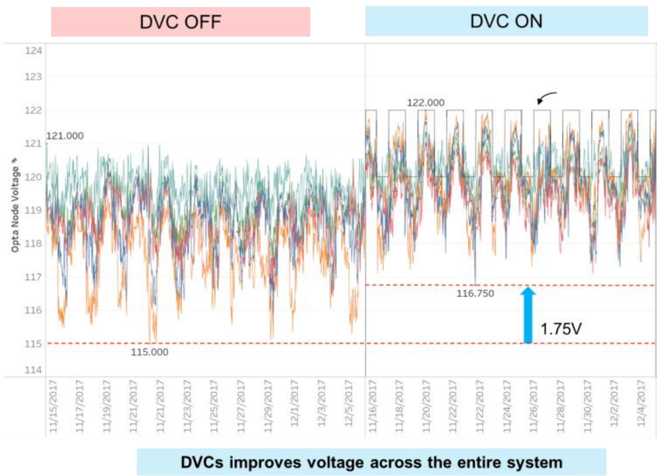


Figure 4. Voltage from other transformer sensors where DVCs are not deployed during ON/OFF Testing

Figure 4. validates the capability of DVCs supporting low voltage nodes and providing the system with an additional lower voltage margin. This allows the utility to decrease the LTC's Set-Point and provide additional upper voltage margin to host more rooftop PV.

C. *PV Hosting Simulation Results*

One of the primary objectives for this project was to compute the increase in PV hosting capacity that can be achieved with the DVCs solution. Further, another objective was to recommend the associated settings of both LTC and DVCs required to achieve this increase in hosting capacity. The field testing validates that the LTC center-band can be lowered in coordination with DVC without causing any low voltage violations, thus creating upper voltage headroom for hosting more PV. However, the estimation of the increase in PV hosting capacity needed to be performed with simulations in Synergi. Sentient Energy used their proprietary PV Hosting Module for performing this study. The load and voltage profile of the Synergi model is fine tuned to match the field measurement, where the substation PQ flow is within +/-3% error, the voltage at the DVC and PQ meter locations is within error of +/-1V, Figure 5. shows that the voltage profile of the tuned model matches very well with the voltage profile of the DVC field measurement.

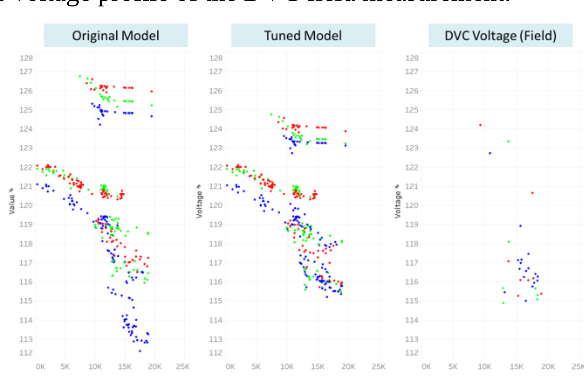


Figure 5. Voltage profile of the Original Model vs Tuned Model vs DVC Voltage Measurements

The simulation study calculates the system voltage volatility based on three worst case scenarios:

1. Day Time Min Load (max PV with day time minimum load)
2. Day Time Peak Load (max PV with day time peak load)
3. Night Time Peak Load (night time peak load with no PV)

Figure 6. shows the voltage volatility of the circuit without DVCs (9.1V) and Figure 7. shows the voltage volatility of the circuit with DVCs (7V), the simulation results matches up with the field results closely.

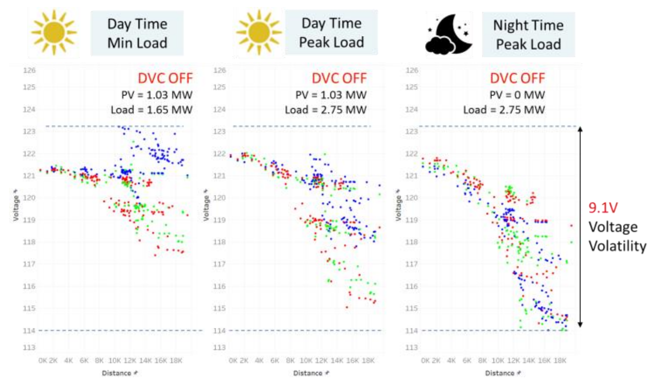


Figure 6. Synergi simulation: System Voltage Volatility with DVC disabled

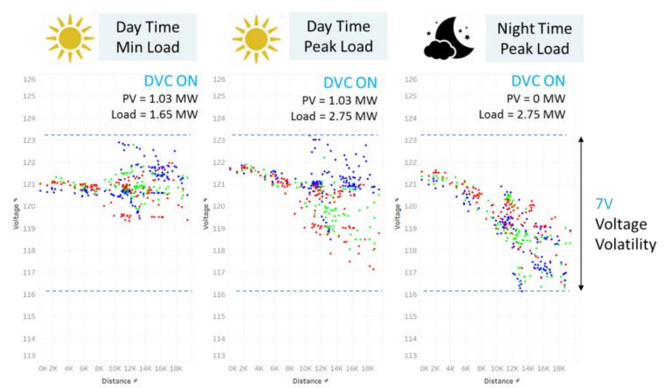
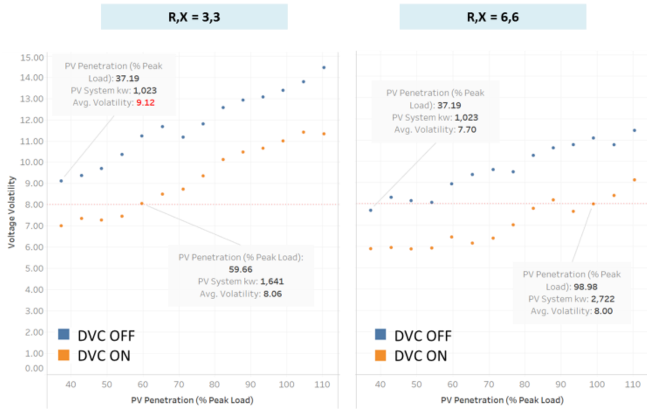


Figure 7. Synergi simulation: System Voltage Volatility with DVC enabled

The PV hosting simulation results for two different LTC settings are shown in Figure 8. As the result is estimated at the secondary of transformer terminals a threshold of 8V (assuming +/-2V drop/rise on secondary conductors) is taken as the limit. If the voltage volatility crosses this limit, the level of PV penetration is deemed the hosting capacity of the system. With an R, X setting of 6, 6, it is shown that without DVCs the PV hosting capacity is 37%, while with DVCs the PV hosting capacity is increased to 99% (increase in installed PV MW from 1.03MW to 2.70 MW).



LDC (R,X=3)	Max Hosting Capacity %	Max Hosting PV kW
DVC OFF	< 37.2 %	< 1023 kW
DVC ON	~ 59.6%	~1641 kW

LDC (R,X=6)	Max Hosting Capacity %	Max Hosting PV kW
DVC OFF	~37.2%	~1023 kW
DVC ON	~99%	~2722 kW

Figure 8. PV Hosting Simulation results for Waimanalo Beach

IV. Conclusions

A utility-owned DVC solution can allow greater solar penetration by reducing voltage volatility. The pilot project showed that this second pilot substation's hosting capability with DVCs increased from 1.03MW to 2.70MW and the system's voltage levels are maintained within ANSI-A limits (114V -126V)

Key pilot project results showed the DVC solution:

- Provides a minimum voltage improvement of 1.85V at DVC location and 1.75V at non-DVC location
- Regulates and maintains the secondary voltage within ANSI standard by coordinating LTC and DVC Set-Point to mitigate violations of the lower / upper voltage threshold,
- Reduces voltage variation to 5.83% from 7.58%,
- Increases PV hosting capacity from 1.03MW (37%) to 2.70MW (99%) with DVCs and by using LDC control with a lower band center and higher R, X setting,
- Provide voltage visibility of the circuit

Acknowledgment

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