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Enhancement of Distribution System Resilience Through the Application of Volt-Var Regulation Devices

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Idaho National Laboratory

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Enhancement of Distribution System Resilience Through the Application of Volt-Var Regulation Devices

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***Abstract*—This paper discusses a practical implementation of locating and sizing dynamic reactive compensation using** an **impedance matrix (Z_{bus}) approach to improve distribution system resilience in scenarios with high penetration of distributed resources. The modeled system is a 14.2 kV radial residential system modified to be fed by a combination of traditional sources and solar resources. Time-varying loads and PV sources are connected along the feeder to simulate the challenging operational voltage regulation scenarios faced by Modern Distribution Systems. Additionally, enhancement of the resilience of the electrical system is demonstrated through analyzing the effect of a topology change to the system. This study uses the GridLAB-D software.**

***Index Terms*— Volt-Var Regulation, Modern Distribution Systems, D-STATCOM, smart inverters, Resilience.**

I. Introduction

Most of electrical analysis performed on power systems focused on the transmission levels. In the last 20 years, distribution system analysis has gained more importance with the increase in distributed energy resources designed to operate on distribution levels. At the same time, the expectations for high levels of power quality for distribution customers have increased. Therefore, more detailed understanding of the distribution equipment modeling and distributed energy resources (DER) is needed to obtain a better control during the real-time operation of these modern distribution systems (MDS). Unlike transmission models, distribution modeling tools like GridLAB-D contain more detail on distributed end-user load behavior, operation with single-phase loads and single-phase lines, radial feeders, and higher resistance to reactance ratios (R/X) on lines, resulting in higher power losses [1]. Anticipated growth of renewables, storage, and flexible loads have led researchers to study the resilience of distribution systems [3]. The high penetration of solar generation in the distribution networks, has resulted in voltage, thermal and/or protection criteria violations. Due to the highly variable output of the solar generation, a less familiar challenge is being faced by the distribution engineers nowadays [2]. The authors of [3] mention that modern distribution system (MDS) resilience metrics should consider all these challenges by evaluating the distribution systems' assets and defining the "margin to maneuver" (M2M) that contributes to overcome any disturbance. In addition to the M2M for each asset, the concept of an economic unit (EcU) as an aggregation of uncontrollable and controllable elements which belongs to a specific physical topology is introduced to evaluate the degree of flexibility that is present on those groups. The authors of [4] give one example of evaluating resilience related to a MDS where the pinch points were defined as those points in the system where the generation takes an opposite direction of the load demand. By identifying these points, corrective actions could be applied such as the variation of power flow between those nodes or the connection of energy storage devices into the system. By applying the dispatchable generation actions, the minimum normalcy of the system will be maintained.

Unlike traditional distribution analysis, which comprises the focus on few significant time points (e.g., heaviest load), the introduction of DER introduces complexity to the analysis and there are suggestions for using time-series or time domain analysis to study the interaction between the different assets (load, generation, control equipment) during operational scenarios that are not made clear by using one single time point analysis [2].

The time-series analysis is key to assess the reliability and resilience of the MDS. Traditional distribution power system analysis is based on reliability metrics such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) that are computed based on the loss of service to assess the severity of past system failures and suggest areas for improvement [3]. The reliability metrics are not intended to holistically consider all the assets of the distribution system such as the power, control, and communication agents. The interaction of these agents creates an inherent resilience for MDS to natural or manmade disturbances. By using resilience metrics that include these interactions, an estimation of the future difficulty of maintaining minimum normalcy in real time is provided by providing situational awareness [4].

As mentioned above, voltage regulation is one of the main challenges that must be met in a MDS [5]. These days, utility companies regulate the distribution network's voltages by implementing the national standard ANSI C84.1-2016. This standard establishes the nominal voltage ratings and operating tolerances for 60 Hz electric power systems above 100 volts [6].

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The integration of DERs potentially makes the distribution power flow bi-directional and the voltage profile will depend on DERs location, injection of active power and power factor and R/X ratio of the feeder conductors. Therefore, the overall situation over the feeder becomes unpredictable and may not be sufficiently regulated by under-load tap changers (ULTC) and mechanically switched capacitors. Additionally, due to the intermittent output nature of renewable DERs and the varying dynamic behavior of loads, the voltage variations occur so rapidly that traditional ULTCs or shunt capacitors cannot regulate as fast as required [5]. Therefore, new devices are required to overcome this challenging problem. The device used in this research is the distribution static synchronous compensator (D-STATCOM). The D-STATCOM is a shunt connected voltage source converter with the ability of providing a very fast dynamic volt-ampere reactive (VAR) injection to overcome the voltage fluctuations due the MDS dynamic behavior. The authors note that VAR compensation is also available from smart inverters for solar or storage [7]. However, this paper currently considers the need to support a distribution system with legacy solar inverters without VAR control.

In this paper a methodology to improve the voltage regulation and ultimately resilience in a Residential EcU is proposed and validated by the placement of one or more D-STATCOMs in the system with location and rated determined following an impedance matrix (Z_{bus}) approach. Simulations are performed that consider time-varying loads and DER outputs during a whole year to represent seasonal behavior. GridLAB-D, a distribution system simulation tool has been used to obtain the results of this study.

The main contribution of this paper is to demonstrate the resilience improvement of the MDS by applying additional reactive power assets such as the D-STATCOM, which improves the ability to maintain an acceptable voltage profile for the EcU under study when the topology of the system is changed since external events. GridLAB-D was used to simulate time-varying loads and solar generation in addition to conventional generation and topology changes from circuit switching.

This paper is organized as follows. Section II presents an overview of the standards used as a reference for Voltage Regulation in MDS. Section III introduces the volt-var (VV) control devices implemented in this study. Section IV discusses concepts of resilience in MDS. Section V discuss the location and sizing criteria for the D-STATCOM using the Z_{bus} approach. Section VI presents the study system. Section VII explains the software tool used to simulate the power flow in the system. Section VII shows the simulation results and discussion, and Section VIII presents the conclusion for this study.

II. Voltage Regulation Standards Overview

Any solutions to improve voltage regulation on distribution systems need to comply with the relevant standards.

A. ANSI C84.1

The most applied steady-state voltage standard in the United States is ANSI C84.1-2016 [6]. Within the standard, steady-state service voltage requirements are defined in two categories, Range A, with a small tolerance for voltage error, is for normal conditions and Range B, with looser voltage tolerance, is for abnormal conditions and it is intended for events limited in quantity and duration.

B. IEEE 1547

The Institute of Electrical and Electronics Engineers (IEEE) developed Recommended Practice Standard 1547 [7] as a foundational document for the interconnection of distributed energy resources (DER) with the electric power system or the grid. This standard is the only US national recommended practice addressing systems-level DER interconnected with the distribution grid. IEEE 1547 is a recommended practice, and each jurisdiction can choose to apply it. If a utility chooses to apply IEEE 1547, all types of DER connected into the grid must meet the outlined requirements at their point of common coupling.

Under IEEE 1547-2018 [7] the operators of the distribution grid and DER owners are required to coordinate and approve when the DER can actively participate in voltage regulation by changes to the DER real and reactive power. Similarly, under mutual agreement between the operators of the grid and the DERs, the DER is permitted much wider latitude in how it responds to abnormal voltage and frequency conditions, including that DER are now clearly allowed to provide voltage and frequency ride through. The required voltage and frequency equipment functionalities are greatly expanded in the 1547-2018 [7], and the operational flexibility is enhanced.

III. Volt-Var Control Devices

A. D-STATCOM

A D-STATCOM is a shunt connected voltage source converter with no dc source or load on the dc link [8]. The control of reactive power in the D-STATCOM is done by controlling its terminal voltage through the switching modulation of the power electronic devices. Fig. 1 shows a simplified circuit in which the ac grid is represented by a voltage source, V_S, behind an impedance, X_L, and the D-STATCOM can represented by its fundamental frequency voltage, V_1. The impedance X_L is often the reactance of a transformer, although some installations add an additional reactance. A voltage source converter can control the magnitude and angle of V_1. In this case since there is no source or load on the dc link, the D-STATCOM does not inject and real power, and only draws sufficient power from the point of interconnect to meet resistive losses in the converter and coupling reactor [9].

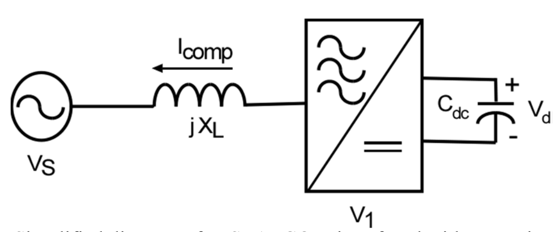

Fig. 1. Simplified diagram of D-STATCOM interfaced with an equivalent ac system

The D-STATCOM reactive power injection is controlled by varying the magnitude of V_1 [9]. A D-STATCOM can be fabricated using a three-phase voltage source converter, although some use single phase converters to better operate with unbalanced system conditions.

If the resistance of X_L is negligible the reactor power injection of the D-STATCOM can be described as follows.

• If $|V_S|$ is equal to $|V_1|$, there is no reactive power exchange between the power grid and the D-STATCOM.
• If $|V_S|$ is larger than $|V_1|$, the D-STATCOM will appear "inductive" and will absorb reactive power from the power grid. Therefore, the D-STATCOM controlled to reduce $|V_S|$.
• If $|V_S|$ is smaller than $|V_1|$, the D-STATCOM will appear "capacitive" which means it will supply reactive power to the power grid in order to increase $|V_S|$.

The operational characteristic of the D-STATCOM is shown in Fig. 2. D-STATCOM operation allows continuous control of reactive power over its regulation range from supplying to absorbing reactive power, but at a far higher speed than would be the case with a combination switched capacitors and reactors, due to the self-commutated converter using insulated-gate bipolar transistors (IGBTs) [8].

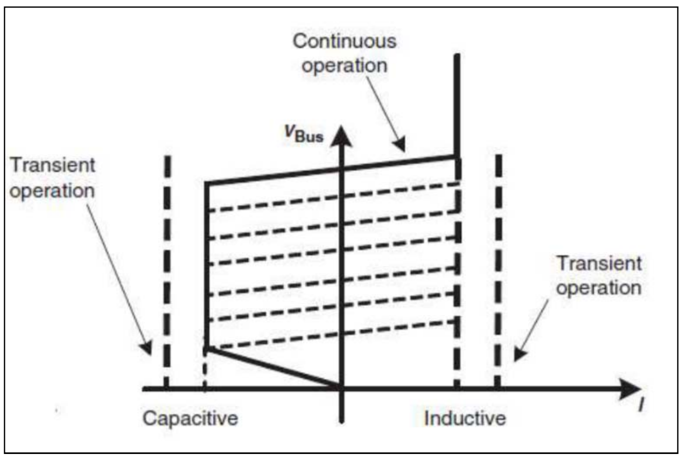

Fig. 2. Operational characteristic for a STATCOM [9]

B. Smart Inverters

Newer generations of inverters used for photovoltaic applications are sometimes referred to as smart inverters [8]. Smart inverters still use voltage source converters to connect the DC output produced by the PV systems to ac distribution systems. However, the converter controls are modified to allow the installation to provide ancillary services to the power system, most commonly being used to provide voltage support in addition to the primary function of providing the maximum available power transfer from the PV panels. The primary operative function of the smart inverters is fixed power factor function, but also include systems support functions such as VV functions, volt-watt functions and others [8], [10].

In the fixed power factor mode, as its name suggests it, the power factor at the inverter terminal is kept constant, often at unity. For power factors equal to unity the reactive power will be zero. A positive or leading power factor will indicate supply of VARs to the grid, and a negative or lagging power factor it will result on VARs absorbed from the grid [10].

In the volt-var mode the inverter generates or absorbs VARs based on the system voltage measured at the inverter terminals. By setting the parameters V1, V2, V3, V4, Q1, Q2, Q3, and Q4 shown at Fig. 3, the inverter will determine the generation or absorption of VARs in the point of the interconnection with the distribution network [11].

GridLAB-D provides a smart inverter element that can be controlled in volt-var control mode. This paper uses the smart inverter, with real power set to zero to represent the operational characteristics of a of the D-STATCOM. For systems with sufficient penetration of smart inverters, the method developed here could also be applied to produce voltage determine setpoint for smart inverters provide the reactive support without the need for D-STATCOM

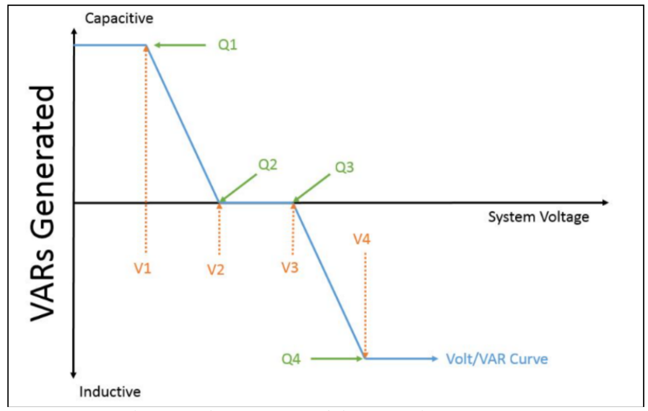

Fig. 3. Volt-var curve of the smart inverter [11]

IV. Resilience

Resilience defines the ability of a system to respond to unexpected disturbances while maintaining an acceptable operating state [3]. In [4] the term resilience is used to describe the ability of the distribution system to adapt depending on the assets available in the system.

The Disturbance and Impact Resilience Evaluation Curve (DIREC) shown in Fig. 4, describes the ability of a system to maintain minimal normalcy and the temporal measures of recovery to disturbances. The most relevant terms pointed out in the figure are as follow.

a) Agility: the ability of the system to resist disturbances as well as the rate of recovery toward acceptable operational conditions.

b) Robustness: a positive or negative number associated with the area between the disturbance curve and the resilience threshold that could indicate either capacity or insufficiency in ability to respond.

c) Adaptive Capacity: A value between 0 and 1 which represents the ability of the system to adapt to or transform from an impact and maintain minimum normalcy.

d) Adaptive Insufficiency: A value between 0 and -1 which represents the inability of the system to adapt or transform from impact, indicating unacceptable operation in the system in response to disturbances.

e) Brittleness: The area under the disturbance curve as intersected by the resilience threshold. This indicates the impact from the loss of operational normalcy.

f) Resiliency: The converse of brittleness, which for a resilience system is "zero" loss of minimum normalcy.

In this paper, voltage variance from the nominal level is considered as one measure of performance. Better voltage control improves the predictability of loads, reduces losses and can increase customer satisfaction in their electrical service. Additionally, better control of the voltage on a localized economic unit basis can allow for less frequent switching of SCs and ULTCs leading to less stress on these assets. This can improve the reliability of these elements allowing them to stay in service longer and minimize maintenance.

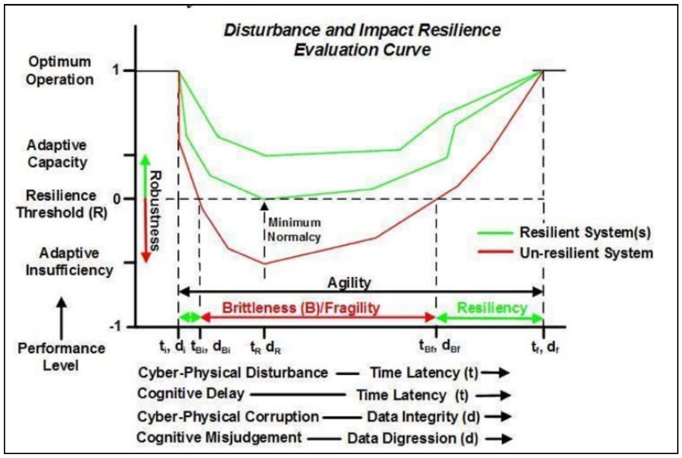

Fig. 4. Disturbance and Impact Resilient Evaluation Curve (DIREC) [4]

V. Location and Sizing of D-STATCOM Using Z_{BUS} Approach

The candidate buses for D-STATCOMs are determined by injecting a capacitive current at each bus in a simulation model of the system. The buses showing the higher incremental voltage, here referred to as delta voltage (ΔV), determines the candidate bus. The D-STATCOM is rated to find an approximate MVA rating to provide reactive support and make possible to keep nearby bus near acceptable voltage ranges under different system conditions.

The D-STATCOM placement will be determined by computing the voltage sensitivities due to current injections using the positive-sequence bus impedance matrix of the system (Z_{bus}). The Z_{bus} can be obtained from the inverse of the bus admittance matrix (Y_{bus}) modified for fault analysis [12].

$$\boldsymbol{Z}_{bus} = \boldsymbol{Y}^{-1}_{bus} \quad (1)$$

For circuit analysis the use of Y_{bus} allows efficient calculation the voltages and currents of the system by using the following matrix notation [12]:

$$\boldsymbol{YV} = \boldsymbol{I} \quad (2)$$

Where, $\boldsymbol{V}$ is the column vector of N bus voltages, and $\boldsymbol{I}$ the column vector of N current injections.

By using the Z_{bus} matrix and injecting capacitive currents into the different buses as shown in (3), two significant pieces information might be obtained about the system. The first item is the most effective locations for D-STATCOM placement by identifying which buses produce a higher ΔV on the largest number of buses in the system when a capacitive current is injected in one or more buses system, and the second point is the ability to compute the MVARs required by the system to obtain the desired voltages in each of the buses to meet the Range A or B levels established by the ANSI C84.1 [6].

$$\begin{bmatrix} Z_{11} & \cdots & Z_{1N} \\ \vdots & \ddots & \vdots \\ Z_{N1} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ -I_{cap} \\ 0 \end{bmatrix} = \begin{bmatrix} V_1 \\ \vdots \\ V_N \end{bmatrix} \quad (3)$$

Where I_{cap} is the capacitive current to be injected in the bus.

To test this approach, the Y_{bus} with positive sequence elements was created in Mathcad to calculate the incremental voltages (ΔV) by varying the capacitive currents to compensate the system. At the same time, the system was simulated with GridLAB-D under two conditions. The first condition was the power flow case without any compensation (base case) and the second condition was the power flow with reactive power compensation.

The proposed methodology to compensate reactive power in the system is comprised of the following steps:

Step 1: Read the distribution data (lines, buses, loads, generators).

Step 2: Perform the load flow by using the GridLAB-D program to compute the voltages for all the buses. Extract the Y_{bus} matrix from GridLAB-D or build it manually based on the configuration of the system.

Step 3: Inject capacitive currents into each bus to evaluate which buses produce a higher incremental voltage (ΔV) in the system. These buses will be the potential candidates to locate the D-STATCOM in the power grid.

Step 4: Identify the critical voltage point (or points) in the system. Once the weakest point in the system is identified, evaluate the voltage levels for the other buses for that condition.

Step 5: Calculate the incremental voltage (ΔV) required to increase all the voltage magnitudes to the desired values (Range A or B ANSI C84.1 [6]).

Step 6: Try different capacitive currents until the desired ΔV is reached for all the buses. Once the value of the D-STATCOM current to achieve this condition is determined; calculate the MVARs required.

Step 7: Run the power flow considering the reactive power compensation to calculate the new voltages in the system.

The Z_{bus} approach will be more accurate to determine the most effective candidate location for the D-STATCOM in the system. However, the D-STATCOM sizing will be more an iterative process considering that the Z_{bus} used in the computation is based in positive sequence impedances, which implies a balanced system. Using GridLAB-D allowed refinement considering the unbalance in the distribution lines and loads.

VI. System Model

The system under study corresponds to an EcU proposed in [3]. For an EcU, the power will be delivered for a distribution substation which will step down the voltage from 132.79 kV to 14.2 kV. From this substation, a 14.2 kV feeder will run through the residential area, which has radial branches, time-varying loads, and solar generation capabilities. For feeding the loads, residential transformers will step the voltage down from 14.2 kV to 240 V or 480 V. Additionally, the nodes with prosumers capable of injecting generated power to the grid (PS1R-PS8R) will generate solar energy at 480 V. Fig. 5 illustrates the model used for this study. The switches highlighted in green are normally open and those in red are normally closed. This topology will be referred to as configuration 1, which has normal operation conditions. In configuration 1, the system is divided into two branches, one connected from bus 2 to bus 9, and another from bus 2 to bus 10. From the point of view of voltage regulation, certain abnormal conditions cause the highest voltage drops in the system; therefore, these conditions will demand the highest reactive power compensation and they will be appropriate to size the D-STATCOMs that will be place strategically in the MDS. Configuration 2, shown in Fig. 6, will simulate the worst conditions for reactive power compensation since all the loads are fed by using a single distribution feeder that goes from bus 2 to bus 16.

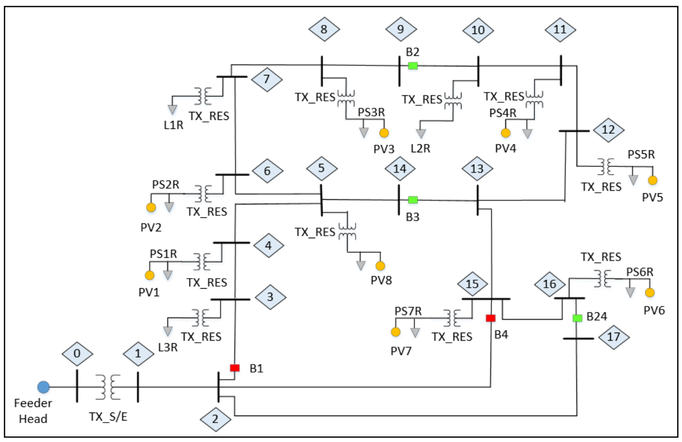

Fig. 5. Residential EcU during normal operation (configuration 1)

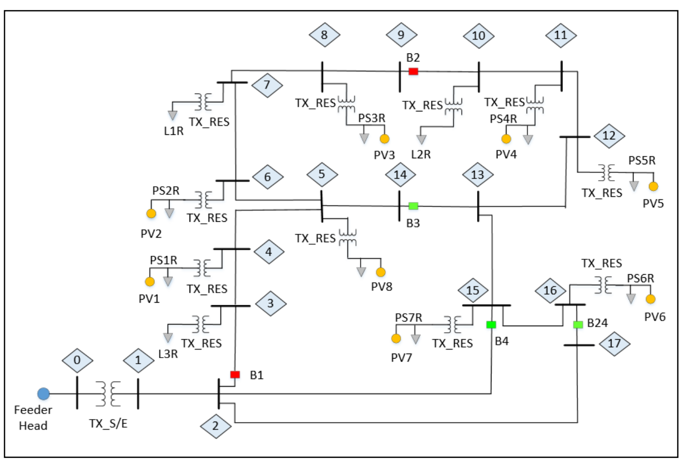

Fig. 6 Residential EcU during abnormal operation (configuration 2)

A. *Generation Capabilities*

The generation of electricity for the residential area will be provided largely by the electrical power coming from the bulk transmission system, which could be from traditional or non-traditional sources. In addition, some power will come from DER at prosumers.

The prosumer's generation is mainly solar generation for this study system. The climate module in the GridLAB-D processes hourly weather data conditions which are commonly available from input files known as TMY2 and TMY3. TMY stands for "typical meteorological year."

The solar generation output depends mainly on the TMY files, array size and solar cell efficiency [3]. Fig. 7 shows the generation profile from solar energy for prosumer PS1R during a sample 24-hour period for a summer day. In the EcU model there are additional prosumers (PS2R, PS3R, PS4R, PS5R, PSR6, PSR7 and PSR8) connected in the distribution system during the four seasons of the year.

The PV systems were modeled using the solar object and inverter object in GridLAB-D. For this project, the inverters related to solar generation were set to operate in the constant power factor mode. The power factor was set to 1 for each solar generation source. Therefore, the complex power obtained from the prosumers is only active power, expressed in kW.

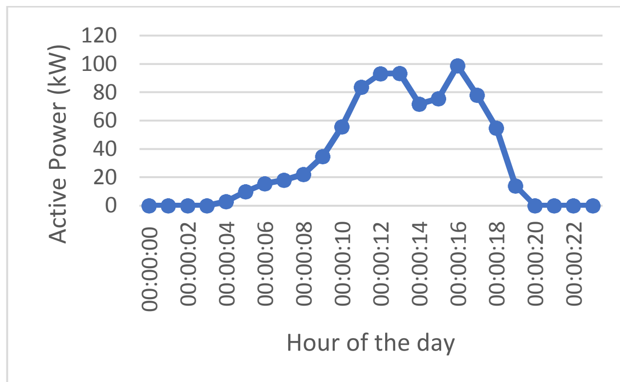

Fig. 7. Solar Generation PS1R on July 12 (Summer day)

B. *Time-varying Load*

Realistic model interactions between DERs and loads, time-varying load model with seasonal behavior were used. Load data was available in the NREL download site "Commercial and Residential Hourly Load Profiles for al TMY3 Locations in the United States" dataset [13]. Since only active power was included in this dataset, reactive power was calculated by assigning typical power factors according to the load type [3]. Once the load information was defined, a residential load player was created in GridLAB-D to simulate the annual load variation at the nodes with connected loads in the residential area topology.

In GridLAB-D, static load models can also be represented as ZIP loads, which mean portions of the load exhibit the following characteristics as the voltage magnitude changes: constant impedance (Z), constant current (I), and constant power (P) portions. In this paper, the load was simulated as constant power. Therefore, a voltage reduction condition in the node where the load is connected will increase the current linearly with the voltage change [11].

VII. POWER-FLOW WITH GRIDLAB-D

GridLAB-D is a time series power distribution system simulation and analysis tool that provides information to users who design and operate distribution systems and can be used to evaluate the energy technologies. GridLAB-D was developed by Pacific Northwest National Laboratory (PNNL) in collaboration with industry and academia through funding from the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability (DOE/OE).

There are two modules in GridLAB-D to run power flow computations. The first is the power flow module designed to work with distribution systems and the second is called network module which works with transmission systems. The initial release of GridLAB-D implemented the well-established Forward Backward Sweep (FBS) algorithm. However, this algorithm does not readily permit analysis of systems that are meshed. Therefore, the incorporation of a networked solver was needed. A Newton-Raphson (NR) based current injection method (TCIM) [12] was implemented into the GridLAB-D to solve meshed systems [1]. This method computes the real and imaginary part of the voltages at every node instead of voltage magnitude and angle [1] and was used in this project.

VIII. Simulation Results and Discussion

Load flow analysis is performed on the model proposed in Section IV of this paper to determine the voltages on each bus. Simulations are performed using 1-hour step size during one entire year. For evaluating the impact of the D-STATCOM in the voltage regulation and resilience of the systems the following cases were analyzed:

Case 1: System operating in normal conditions (configuration 1) without D-STATCOM (baseline).

Case 2: System operating in normal conditions (configuration 1) with D-STATCOM in Bus 9.

Case 3: Contingency scenario, transition from configuration 1 to configuration 2 (switch B2 closed, switch B4 open) with D-STATCOM in Bus 9.

A. Voltage Regulation

By injecting a unique capacitive current at each bus in the configuration 1, the ΔV were calculated, and the higher values resulted at Bus 9 (ΔV_{bus9} = 0.0567) and at Bus 10 (ΔV_{bus10}= 0.0564). For this study, the selected candidate bus was the Bus 9. This study is limited to the connection of one single D-STATCOM for the voltage compensation since volt-var control limitations in the GridLAB-D resulting from connecting a second D-STACOM, which reduced the voltages in the system rather to increase them.

The results for Case 1 and Case 2 are shown in Fig. 8 and Fig. 9. From these figures it can be observed the improvement in the voltage profile. Although, not shown here, the minimum and maximum voltages are met during every hour during the four seasons that are covered in the simulation.

The y axis, Voltage (p.u) represents the normalized, per unit value for a voltage base of 14.2 kV, as shown in (4). Per unit analysis is more commonly used in transmission analysis, but it used hear to provide a simpler indication of voltage regulation performance.

$$Voltage\ (p.u) = \frac{actual\ voltage\ measured\ in\ the\ bus}{14.2\ kV} \quad (4)$$

The estimated rating for the D-STATCOM connected at Bus 9 is 2.1 MVAR. The standard ANSI C84.1-2016 establishes two ranges, Range A for optimal voltage range and Range B for acceptable, but not optimal voltage range [6]. In this paper the minimum and maximum voltage acceptable were defined as 0.95 p.u. and 1.05 p.u., respectively based on the Range B in the standard [6] since the main focus of this study is to evaluate a contingency scenario for the EcU.

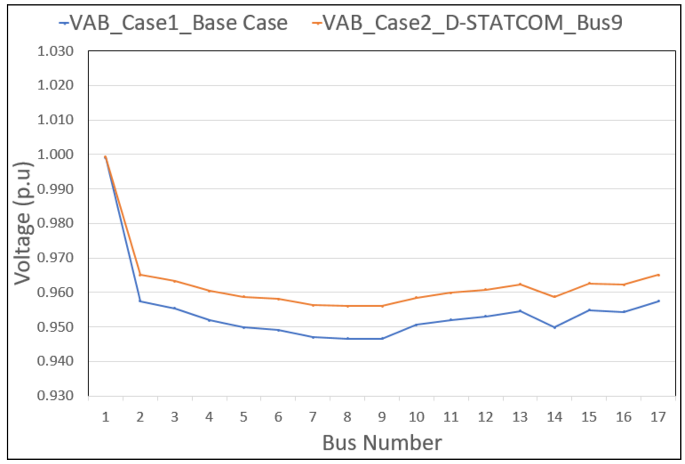

Fig. 8. Minimum voltages profile without and with D-STATCOM at Bus 9

B. Resilience

Configuration 2 was simulated by changing the status of the switch B2 from open to closed, and from closed to open for the switch B4 to simulate a change of the topology of the system from Configuration 1 to Configuration 2 (emergency condition). The event was scheduled in the simulation to happen on July 12th at 18:00 hours due to system reconfiguration in response to storm damage. Fig. 10 shows the differences in the per unit voltages from the event happening with and without the D-STATCOM at Bus 9.

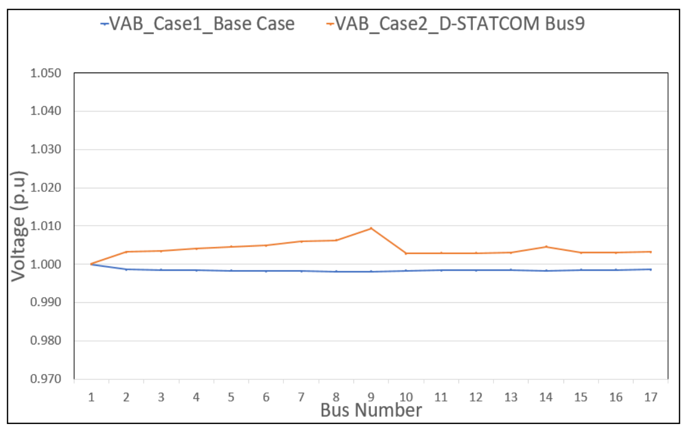

Fig. 9. Maximum voltages profile without and with D-STATCOM at Bus 9

From Fig. 10 is observed how the voltage in Bus 9 reaches values less than 0.95 p.u. close to the time that the change of topology is occurring for when the system does not have a D-STATCOM connected. By incorporating the D-STATCOM in the system, the response in the voltage magnitudes is better and the voltages magnitudes are kept above the 0.95 p.u. value, which is considered the minimum normalcy value related to Fig. 7. This response demonstrates the ability of the system to adapt to the new topology since the VV support provided by the D-STATCOM.

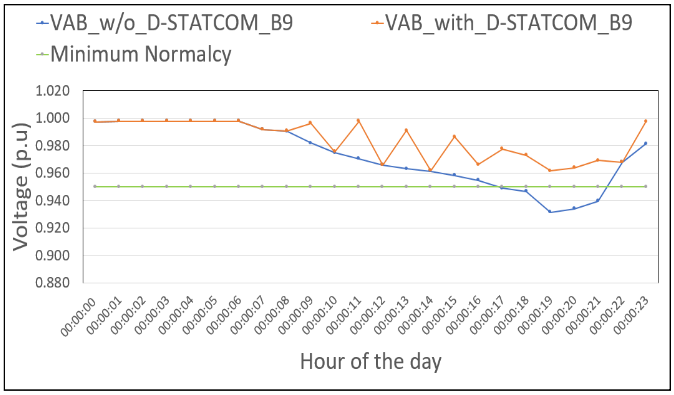

Fig. 10. Voltages profile without and with D-STATCOM at Bus 9 during the contingency (Case 3)

IX. CONCLUSIONS

The use of D-STATCOM in the MDS offers a good solution to improve the dynamic voltage regulation response and reduce the switching frequency of switched capacitors and ULTC components of the distribution system.

The Z_{bus} matrix approach was used to determine voltages exhibiting the higher ΔV potential in response to injecting capacitive currents in each bus, produced in each bus. Based on this information, the candidate bus to place the D-STATCOM was chosen in the model.

The simulation results demonstrate the positive impact of the D-STATCOM in the voltage regulation of the model presented in this paper. During the contingency scenario, it was clear the improvement in the system capability to adapt when a change of topology has taken place. This behavior demonstrates that the D-STATCOM makes the MDS more resilient under unexpected operational conditions.

The approach presented here can be extended to correct for overvoltage conditions in feeders with very high levels of PV generation. The approach can be extended to include larger numbers of reactive compensation devices, whether they are additional D-STATCOMs, smart inverters, or grid edge compensators.

Further research is needed to incorporate the unbalanced behavior of the impedances in the MDS in the Z_{bus} approach to determine more accurate results, especially in the sizing calculation of the D-STATCOM. Additional studies can examine different control models for smart inverters attached to the solar resources provided by the prosumers to develop financial incentives for providing such support.

X. ACKNOWLEDGEMENT

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XI. REFERENCES

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