Simulating Integrated Volt/Var Control and Distributed Demand Response Using GridSpice

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Abstract*—This paper proposes VVCDDR, an integrated volt/var control scheme which also uses distributed demand response capacity on distribution networks to improve the reliability and efficiency of the distribution network. The paper uses a new simulation platform, GridSpice, to show that demand response resources can be used to maintain a flat and stable voltage profile over the feeder without increasing the allocation of voltage regulators and capacitor banks. The improved voltage profile allows for a safe reduction of voltage while ensuring that all loads remain within the standard acceptable voltage range. Previous studies have shown that a reduction of the load voltage translates into lower power consumption, a technique known as conservation voltage reduction (CVR). The simulation platform, GridSpice, built on top of Gridlab-D [11], is the first distribution simulator to consider volt/var control, demand response, and distribution automation in a single simulation.

Keywords: Demand Response; Volt/Var Control; Distribution Automation; Power factor correction

I. Introduction

Utilities are responsible for voltage control, ensuring voltage levels on the distribution network remain within an acceptable voltage range, and 'var' control, ensuring that the power factor remains above a prescribed level. If the voltage levels on the network begin to rise or fall due to changes in load, the utility must adjust voltage regulators to compensate. If the amount of reactive load on the grid changes, the utility must respond by switching in or switching out capacitor banks. However, these capacitor banks affect the voltage level on the network. Therefore, voltage control and var control are interdependent. Over the last 30 years, utilities have developed integrated schemes for voltage control and var control. Studies [1][2][7] have shown that these integrated schemes allow for tighter control of the voltage and power factor.

Tighter control over voltage and power factor levels allows utilities to reduce the voltage at the head of the feeder and operate the system within a tight range. This tactic is known as conservation voltage reduction (CVR), and is believed to reduce power consumption [3]. One study showed that the ability to operate a distribution system within tight voltage levels in the lower half of the acceptable range could yield a 1 to 3 percent total energy reduction, a 2 to 4 percent reduction in kW demand, and a 4 to 10 percent reduction in kVAR demand without any negative effect on the customer [8].

Demand response (DR) is the ability to trim load when necessary or convenient. These loads can be trimmed either through a direct control or by sending price signals to the customers who respond to benefit from the economic incentives provided by the utilities for such response.

Today, demand response is used as a tool to reduce load at a specific time such as during peak demand hours or during an emergency event. Typically, demand response is viewed as a reduction in aggregate load at the head of the feeder without regard to the specific location of the load reduction within the distribution network. Demand Response is triggered independently of any volt/var optimization that might be available on the distribution feeder.

In this paper, we study the benefits of integrating demand response with distribution volt/var control. We show that utilities can improve volt/var control by sub-selecting eligible demand response events which would have been called by the original demand response controller. Conveniently, most volt/var operations occur during periods of heavy loading when demand response events are eligible. Voltage reduction has been studied as a method of demand response [12], and demand response has been recognized as a powerful tool to for emergency stabilization [4]. This paper takes a different approach using a new simulation framework to show that demand response can tighten voltage profiles and enable more effective conservation voltage reduction.

II. GridSpice Simulation Engine

The simulations in this study were performed using GridSpice, a web-based and open-source simulation platform that is being developed to study the interaction of power flows and power markets in distribution and transmission networks. GridSpice uses a modified version of Gridlab-D [11], developed by Pacific Northwest National Labs, for power distribution system simulation.

A. Powerflow

The Newton Raphson solver is used to solve the non-linear equations for determining the nodal voltages at each time step within the simulation. GridSpice uses the unmodified agent-based solution provided in Gridlab-D for this purpose. The Gridlab-D core coordinates the state of each agent involved in the simulation. The simulation clock advances without calculation as long as all agents are stable. As soon as an agent updates, Gridlab-D will allow dependent agents to update if necessary. This operation will rerun the NR solver for the new time if powerflow inputs have changed.

B. Volt/Var Controller

A base implementation of the volt/var controller was provided in the original Gridlab-D software. This implementation is based on the Integrated Volt/Var Controller (IVVC) [1][2], and does not use demand response. We modified IVVC to implement our control scheme, VVCDDR, which is described in the next section. Although IVVC does not represent the current state of the art, it does contain the fundamental elements that are used in commercial CVR schemes. We have used results from the IVVC scheme as a reference for evaluating the performance of our VVCDDR scheme.

C. Demand Response Controller

GridSpice extends the functionality of Gridlab-D to add a demand response controller that keeps track of contracts types and enumerates eligible DR loads. All DR loads are registered with the DR Controller, and all DR events are processed through the DR Controller. The VVC controller queries the DR Controller to determine which loads are eligible. DR loads become ineligible due to factors such as customer override, network outage, and overuse. See Appendix A for more detail.

D. Load Models

We modified the HVAC models provided in Gridlab-D to simulate a HVAC-based DR contract. During a DR event, the HVAC system operates in a new mode. (See Section IV). When simulating volt/var control and DR, it is imperative to accurately model the load because the properties of the load shed impact the volt/var of the network. It is common practice to classify loads as constant voltage, constant current, constant impedance, or some linear combination of the three (ZIP loads). HVAC is a classic example of a load which cannot be represented this way because it is thermostatically controlled. In order to accurately represent this in our simulation, we have changed the HVAC model to run in a new "DR mode" which cycles between cooling and circulation cycles during an event. We have also added a check which restores the HVAC system to normal operation if the temperature is more than four degrees from the thermostat setting.

III. VOLT/VAR CONTROL WITH DEMAND RESPONSE

The main goal of VVCDDR is improvement in the voltage profile. The control scheme is an improvement over standard volt-var control schemes because it can eliminate "hot spots". A "hot spot" is a temporary increase in load in a particular region of a distribution feeder, resulting in a decrease in the voltage level in that region. Any acceptable volt-var control schemes must guarantee that all loads remain within the standard acceptable voltage range at all times. In most distribution systems, a single voltage regulator serves a large number of loads. The number of loads served by the regulator can be much larger than the number of loads in the hotspot. Therefore, using a standard volt-var scheme such as IVVC, the operating voltage for all loads must be set at a higher level which can comfortably accommodate these "hot spots". This can lead to additional power losses in the entire distribution network in order to accommodate the hot spots.

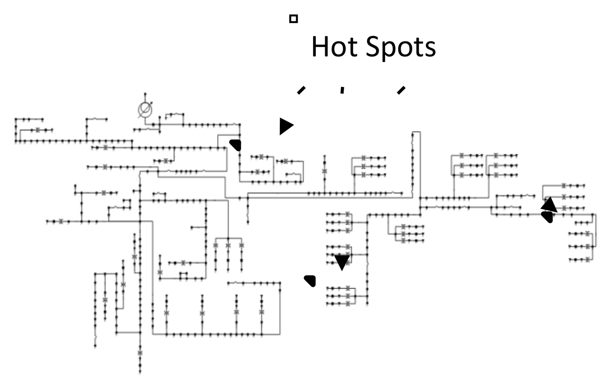

Figure 1. Distribution Network with Voltage Hot Spots

VVCDR proposes a new way of handling the hotspots. Instead of increasing the voltage for the entire network, decrease the load at the hotspots. This can be accomplished using demand response. The control scheme for the voltage regulator, including communication channels, is detailed in Figure 2.

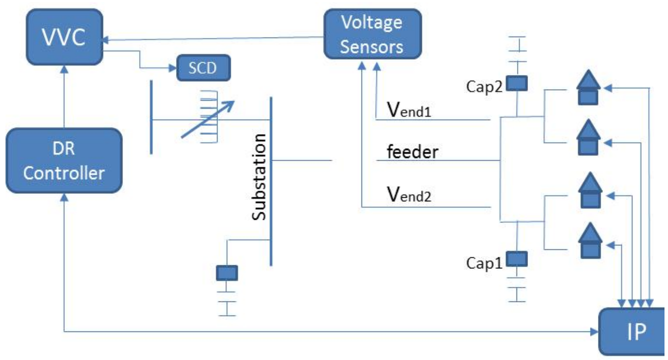

Figure 2. Integrated VVCDDR Control Scheme

The control scheme has the following steps:

1. The voltage measurements for each phase at each remote node are aggregated and transmitted to the VVC.

$$\{V_{end1\_a}, V_{end1\_b}, V_{end1\_c}, V_{end2\_a}, \dots\} \quad (1)$$

2. The VVC calculates the feeder voltage drop, VD, for each of the remote nodes, along with the average voltage drop:

$$V_0 = \text{voltage at head of feeder} \quad (2)$$

$$VD_{end\{node\#)\_\{phase\}} = V0 - V_{end\{node\#)\_\{phase\}} \quad (3)$$

$$\mu_{VD} = AVG\ \{VD_{end1\_a}, VD_{end1\_b}, \dots\} \quad (4)$$

3. If the VD for any (node,phase) is more than V_{hs} above the mean, all demand response events for the associated (node,phase) will be released (if any exist). Return to Step 1

If: $VD_{end\{node\#)\_\{phase\}} > \mu_{VD}$ for any (node,phase)

then: release any active demand response events

4. The VVC calculates V_{set} based on μ_{VD}. V_{set} is the voltage required at the head of the feeder to set μ_{VD} at the desired voltage, V_{des}. For CVR, V_{des} will be at the lower end of the acceptable voltage range (126V-114V).

$$V_{set} = V_{des} + \mu_{VD} \quad (5)$$

5. If V_{set} is outside a certain bandwidth, V_{bw}, around V_0, then the voltage regulator adjustment is calculated. V_{bw}, is calculated dynamically based on the load. If V_{set} does not violate the maximum standard voltage (V_{max} = 126V), enact the calculated tap movement. If V_{set} does violate the maximum standard voltage, set all capacitors to voltage control mode until $V_{set} < 0.98 * V_{max}$. Capacitor voltage control mode is left unchanged from the IVVC scheme presented by Borozan et al.

if: ($V_{set} < V_0 - V_{bw}$ or $V_{set} > V_0 + V_{bw}$)

if: ($V_{set} < V_{max}$ and $V_{set} > V_{min}$)

then: adjust voltage regulator

else: set capacitors to volt control mode

6. If the VD for any (node,phase) is more than V_{hs} below the mean, the associated (node,phase) is considered to be a hot spot. V_{hs} is a configurable parameter optimized experimentally.

if: $VD_{end\{node\#)\_\{phase\}} < \mu_{VD} - V_{hs}$ for any (node,phase)

then: (node,phase) is a hotspot

7. For each hot spot, rank each connected DR eligible load based the time it was last called. The eligibility of a load is determined by the DR controller which checks criteria such as number of recent calls and the time-of-day. Ignore hot spots which have been modified within the last 1-minute (latency for DR-call).

8. If any hot spots do not have at least a specified minimum of DR eligible load, P_{dr_min}, in their list, do not call DR events for any of the hot spots. Otherwise, call the DR events in the list until enough events have been called to satisfy P_{dr_min}. Begin the calling sequence starting with the least recently called event. Update the last timestamps for each hot spot and DR load.

IV. Simulation Details

A. Feeder Description

All simulations were run on a 13-node residential feeder. We assume there is a voltage sensor at each of the nodes, and that the latency on the sensor is negligible compared to the 1-minute latency for dispatching a DR event. There are approximately 650 homes on the feeder distributed amongst the 13 nodes. Some random loads were attached to each house in order to capture the hot spot phenomena.

B. Demand Response Contracts

In this study, we restricted ourselves to the use of a single form of Demand Response implemented on top of the residential HVAC model provided in Gridlab-D. During a demand response event, each AC system involved in the event is assigned a token which is either even or odd. All even AC systems enter the cooling cycle during first 15-

minutes of each half hour. All odd AC systems enter the cooling cycle during the second 15-minutes of each half hour. If the temperature in any house reaches more than 4 degrees above the thermostat setting, they return to normal operation. Additionally, after a maximum of 6 hours, the AC systems return to normal operation. This contract is based on the SmartAC program offered by PG&E, and is similar to HVAC-based demand response programs provided by other providers.

C. Communication Latency

The simulation assumes a 1-minute latency between the point where the volt-var controller decides to dispatch a particular DR event, and the time at which the AC unit enters the appropriate cycle.

V. RESULTS

A large number of simulations were performed using the parameters described above. One interesting metric of this scheme is the impact on the number of adjustments to the voltage regulator as shown in Figure 3. Over a 1-month simulation, we observed a significant reduction in the number of regulator tap operations as the DR penetration increased. However, it is clear that as the DR penetration increases, the DR dispatch is able to address voltage hot spots before fall outside the bandwidth which forces a regulator tap adjustment.

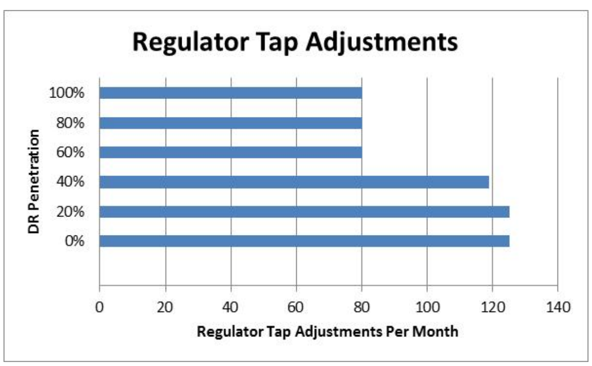

Figure 3. Total Regulator Tap Adjustments / Month

The VVCDR scheme helps stabilize voltage levels throughout the day. Figure 4 depicts the voltage profile for a particular node on a selected hot summer day using the IVVC scheme, and using the VVCDR scheme with 100% penetration. Using the IVVC scheme, the voltage sags due to an increase in HVAC usage, followed by a voltage spike due to a regulator tap adjustment. The VVCDR scheme is able to stabilize the voltage profile using demand response rather than a regulator tap adjustment.

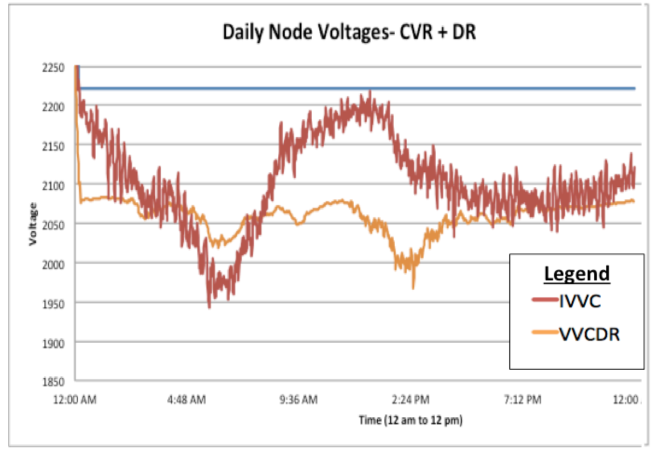

Figure 4. Node Voltge for Hot Summer Day

For each penetration level shown, we determined the minimum acceptable V_{des} which avoided all voltage violations over a 1-month simulation. From the results in Table 1, it is clear that the 60% penetration level allows for a more aggressive V_{des}, and subsequently a lower V_{set}.

TABLE I. VOLTAGE LEVELS BY DR PENETRATION

DR Penetration	V_{set} TWA	Minimum V_{des}
0%	122.1V	120V
20%	122.6V	120V
40%	123.1V	120V
60%	119.2V	118V
80%	118.8V	118V
100%	118.8V	118V
IVVC	122.1V	120V

VI. CONCLUSIONS

Demand response can be an important resource in volt/var control, and simulation provides an effective mechanism for evaluating the feasibility of integrated approaches to demand response, voltage control, and var control. We have shown that demand response can smooth the voltage profile and improve grid reliability. More importantly, we have created tool for researchers to test and validate new integrated control mechanisms.

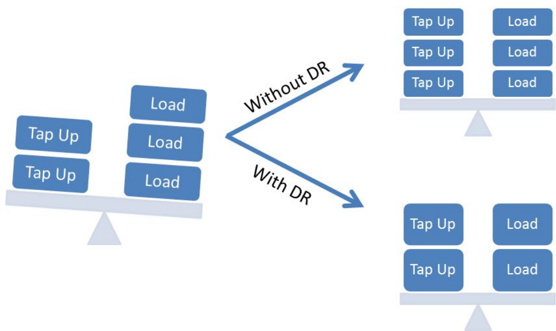

Figure 5. Balance System Using Demand Response

Intelligent control algorithms allow utilities to save energy by implementing conservation voltage reduction. This study estimates that VVCDR allows an additional 2V reduction beyond the CVR capable with IVVC. This paper does not address the extent to which voltage reduction translates directly to energy savings, but this can be added easily.

In addition to saving energy, our integrated simulation tool can help researchers determine the tradeoff between demand response and capital expense in such as voltage regulators, LTC transformers, static VAR compensators, and capacitor banks.

VII. Future Work

Although, in this paper we have focused on how DR can be used to augment Volt/Var optimization, the interaction between loads and distribution automation is fundamental and works both ways. In [5], authors show that the demand response, if done without taking grid conditions such as volt/var into account, provides up to 15% less reduction at the substation compared to the actual load shed. The authors in [5] use back of the envelope calculations but do not show any simulation results to calculate the impact. Our simulation framework can be used to simulate this scenario as well. Finally, even though we have discussed a direct load control type of DR in this paper, our simulation framework is able to take price-signals as a DR signal. We intend to use smart meter data from dynamic pricing studies to build a price responsive DR model and show the interaction of price-based DR with distribution automation techniques in our future work.

VIII. Appendix A

This appendix summarizes the functionality of the DR Controller. Each DR load registers with the DR controller when the simulation begins, as shown in Figure 6.

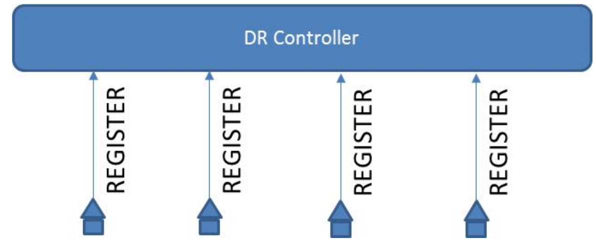

Figure 6. Step 1: DR Registration

When the VVC finds a hot spot, it queries the DR controller to find if any demand response is available near the hot spot, as shown in Figure 7. The location of the hot spot is indicated by the tuple (node, phase). The DR controller keeps track of loads which are ineligible due rate contract restrictions and loads which are already in DR mode. If there are no loads available based on these criteria, the DR controller will return an empty list to the VVC without querying any of the loads. If there are DR loads available based on contract and status, the DR controller will query the load to see if is online. In these simulations, we assume that all DR is online if it is within the restrictions of the contract which specifies a maximum number of events per month. However, this architecture is easily extensible to introduce randomly unavailable DR, customer overrides, or communication network outages. After these checks, the DR Controller returns an ordered list based on fairness to the VVC.

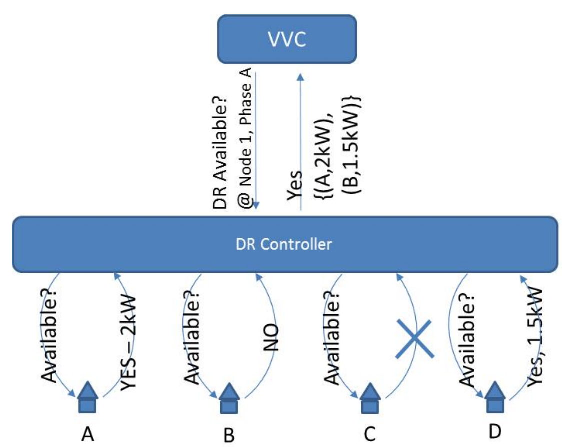

Figure 7. Step 2: VVC Query

Finally, the VVC will take the list and will call events on the loads as needed. The VVC should maintain the order provided in the list from the DR controller in order to ensure fairness. The VVC starts and stops events through the DR controller, as shown in Figure 8.

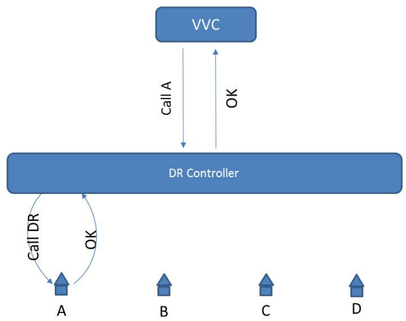

Figure 8. Demand Response Event Begins

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