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CIGRE US National Committee
2023 Grid of the Future Symposium

Modelling Dynamic CVR Schemes and DER Impacts

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SUMMARY

This paper presents a method for modelling a dynamic Conservation Voltage Reduction (CVR) scheme using Eaton's CYME power flow software. CVR is a method of reducing peak power demand and overall energy consumption by minimizing end-user voltage within jurisdictional limits. This operating principal leverages the fact that some load types, such as constant impedance and constant current, consume less power at lower voltages. Dynamic CVR utilizes meters to provide system information back to the CVR scheme for improved regulation capability. The modelling of dynamic CVR schemes within planning software is challenging due to the required feedback of sensors within the distribution system (DS) and the need for custom control logic. This paper proposes a method for modelling a dynamic CVR scheme, evaluates its efficacy, explores the impacts of adding Distributed Energy Resources (DER) with voltage regulation capabilities to a circuit with an existing CVR scheme, and introduces different methods that may improve CVR performance in the presence of large DER installations.

KEYWORDS

Renewable Integration, Voltage Optimization, Conservation Voltage Reduction (CVR), DER Integration and Control, Modelling

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Introduction

Conservation Voltage Reduction (CVR) is a common strategy in electric power distribution systems (DS) aimed at reducing energy consumption and improving overall system efficiency. By reducing DS operating voltages, CVR enables utilities to achieve energy savings while maintaining system voltage criteria and quality of service for consumers [1, 2, 3, 4, 5]. The ANSI C84.1 standard states that end-user voltage shall be kept between 114 V and 126 V. Due to significant voltage drop across long radial lines, it's typical for many distribution systems to be operated at the higher end of this range, e.g. 126 V or 105% of nominal, to ensure adequate customer service voltage is maintained. In the case of CVR, voltages on the DS are allowed to be held lower, assuming the service voltages are maintained within an acceptable range.

CVR has conventionally been implemented through open-loop static voltage reduction [2], where a fixed voltage set point is chosen and maintained throughout the system. However, this approach often fails to capture the dynamic nature of system conditions, leading to suboptimal energy savings and potentially compromising customer power quality [5]. Historically, daily loads on a substation exhibited a relatively smooth and predictable behavior and load growth was minimal. Now energy usage is expected to rise with the adoption of heat pumps, electric vehicles, and other modes of electrification. This coupled with the integration of distributed energy resources (DERs) is resulting in a more erratic load curve throughout the day. Closed-loop CVR schemes can improve system performance and ensure adequate customer power quality by monitoring system conditions in real-time. These schemes are particularly useful in the presence of dynamic load and generation sources [2]. However, it is important to note that due to inherent communication delays, CVR typically responds slower than inverter-based resources (IBRs) to fluctuations in load or generation [3].

Simulating the performance of closed-loop CVR poses a challenge as it is not typically a built-in function within commercial software packages, and requires custom control logic and feedback from multiple assets within the system. To address these challenges, the paper presents a closed-loop, or "dynamic", CVR modelling technique within Eaton's CYME software, designed to enhance the accuracy of system models equipped with CVR. The advantages of dynamic modelling relative to open-loop modelling are explored, as well as the methodologies involved in developing an effective dynamic CVR modelling technique. A combination of CVR and DER operations were modelled to observe the system's response to volatile conditions. The paper explores both peak and lightly loaded days to capture highly stressed DS scenarios.

The CYME distribution model used in the study was created to match current field configurations. The CVR system under consideration takes readings from a specific set of bellwether meters every 15 minutes. The meters are spread across all regulation zones in the system, which in this case denotes the sections between voltage regulators. The CVR scheme will change the regulator set points up to once per hour based on a CVR control algorithm and system meter readings. The algorithm utilizes an average of the lowest 10-meter readings to determine if an adjustment is needed. This method of operation is the basis for the CVR model that was developed for this work. Furthermore, Python control scripts were utilized to create custom controls for the regulators within the model. The model was validated through pre- to post-CVR simulations and results were analyzed to confirm the CVR scheme performed as expected.

This whitepaper provides an overview of the model validation and testing scenarios, the study outcomes, and system considerations as a result of the dynamic CVR modelling. The paper then concludes with a summary of the key findings and highlights future research directions in the field.

Model Overview

Versant Power provided a GIS based model for a distribution substation serving four (4) radial 12.47 kV distribution circuits, one of which feeds a switching station with three (3) additional feeders. The majority of the distribution substation load is made up of residential customers with a small amount of industrial and commercial loads. A constant power load model was replaced with a ZIP load representation to help facilitate the examination of CVR impacts to system power consumption. The provided model included distribution customer classifications for each load. A ZIP representation was developed for each customer type, i.e. residential, commercial, and industrial, using typical ZIP percentages based on RLC's experience with various electric utility systems. Table 2 summarizes the ZIP percentages, by customer type, that were used for this work.

Table 1: ZIP Representation by Customer Type

Customer Type	Z (%)	I (%)	P (%)
Residential	60	5	35
Commercial	20	10	70
Industrial	10	10	80

To properly scale the loads on the circuit within quasi-static time series (QSTS) simulations, a uniform customer type is required, i.e. all loads on Feeder A are assigned the "Feeder A" customer type, Feeder B loads are assigned the "Feeder B" customer type, and so on. Due to this, the ZIP breakdown was weighted based upon the percentage of each customer type being served on a given feeder. Table 2 provides both the ZIP breakdown that was used as well as the customer type percentages for each feeder.

Table 2: ZIP Load Percentages by Feeder

Feeder	% of Total				ZIP Modeling		
	Residential	Commercial	Industrial	Other	Z (%)	I (%)	P (%)
Feeder A	18.25%	58.47%	23.18%	0.09%	**25.02**	**9.08**	**65.90**
Feeder B	86.52%	13.26%	0.00%	0.22%	**54.70**	**5.66**	**39.64**
Feeder C	54.91%	35.64%	9.13%	0.32%	**41.18**	**7.24**	**51.58**
Feeder D	77.74%	22.15%	0.00%	0.12%	**51.14**	**6.11**	**42.75**

Note that Feeder B contained the greatest amount of residential customers and thus had the highest amount of constant impedance loads; therefore, it was expected that this circuit would benefit most from the introduction of the CVR scheme. Recall that constant impedance loads (Z) benefit most from CVR, followed by constant current loads (I), and constant power loads (P) are not impacted by the reduction in operating voltage. All distribution loads within the CYME model were modeled as spot loads connected to the medium voltage (MV) system.

Feeder B also had a 5 MW DER site seeking interconnection, making it an ideal choice as the focus of our testing. The 5 MW DER was modeled as two aggregate IBR collector systems below two separate grounded wye – grounded wye generator step up (GSU) transformers. The 5 MW DER also required a Volt/Var regulation scheme as part of its interconnection requirements. Figure 1 provides a circuit overview for Feeder B, which is regulated by the substation's transformer load tap changer (LTC), a midline voltage regulator (VR), and single-phase VR at the end of the three-phase backbone, creating three CVR regulation zones.

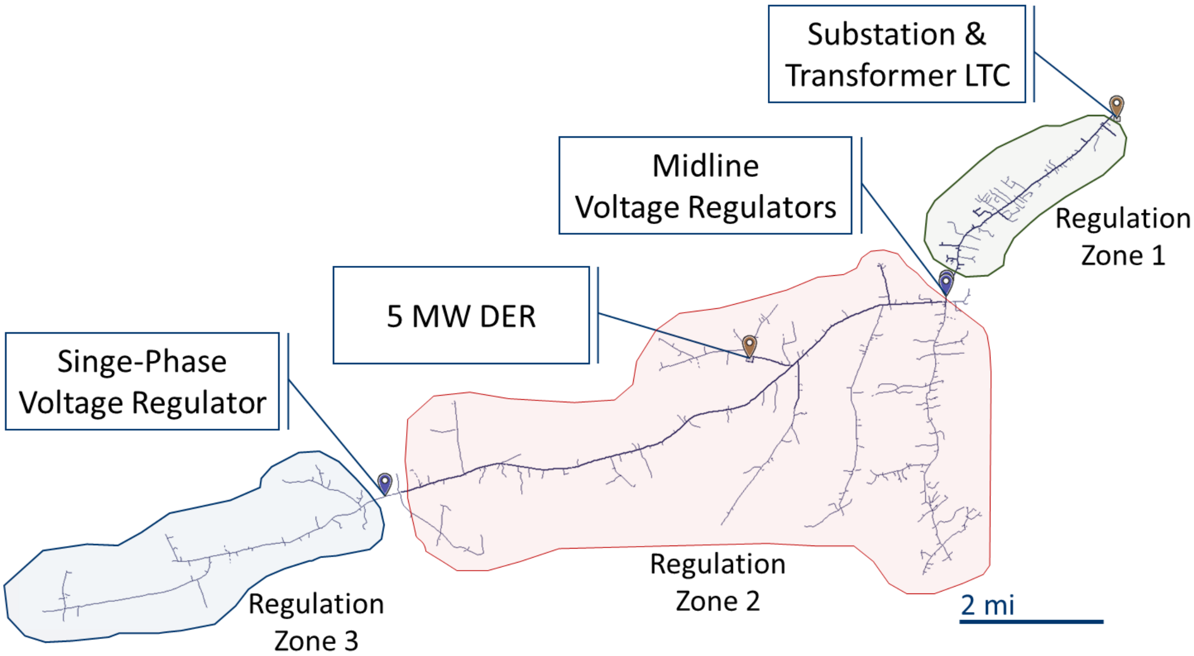

Figure 1: Feeder B Circuit Overview

Dynamic CVR Model Overview

The CVR scheme had a nominal voltage of 125 V on each regulation device, was allowed to adjust the transformer LTC or VR common mode voltage (CMV) by plus or minus one volt per hour (± 1 V / hour), and received telemetry from the customer meters every 15 minutes. The CVR scheme was implemented within CYME using the built-in VR Python device control script functionality. CYME's device control scripts allow users to add custom control logic to select devices, which offered a convenient method to create and model the CVR scheme. Because the provided distribution system model utilized MV connected spot loads, and in reality, the CVR scheme receives telemetry from secondary connected customer meters, one of the steps to creating the CVR model was calculating the secondary voltage at the customer meters. While the distribution system model did not include the secondary networks for each customer, this data was saved within Versant's GIS and exported to Excel. A Python script was created to read the secondary network information, i.e. the transformer impedance, the secondary cable impedance, etc., and the customer meter voltage was calculated using the model's spot load amount and 12.47 kV node voltage from the model. This method allowed for a more accurate representation of the CVR scheme and allowed for AC voltage drop calculations to be applied and the variable voltage drop across each customer's secondary network to be accounted for using the following equation:

$$V_{drop} = I * (R * \cos(\theta) + X * \sin(\theta))$$

In this equation, V_{drop} is the voltage drop being calculated, I is the current drawn from the load in question, R is the equivalent resistance from the given customer's MV tap to the meter, X is the equivalent reactance, and θ is the angle between voltage and current at the MV tap. Figure 2 provides an overview of the CVR scheme operation and logic.

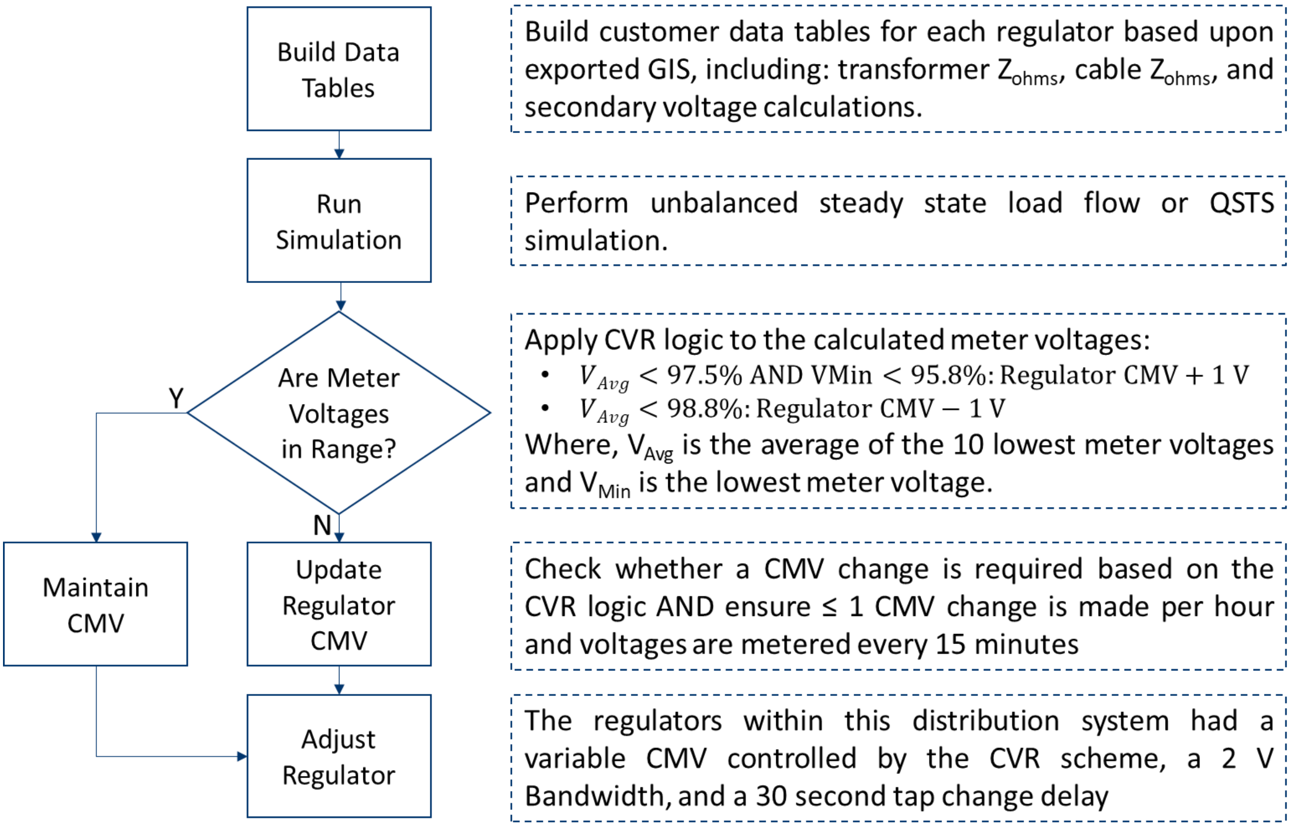

Figure 2: CVR Scheme Overview

To create the required QSTS load curves, historic hourly load data was obtained for the substation and data points were interpolated to achieve the required resolution for the simulation. Figure 3 and Figure 4 show Feeder B's peak and light load profiles, respectively.

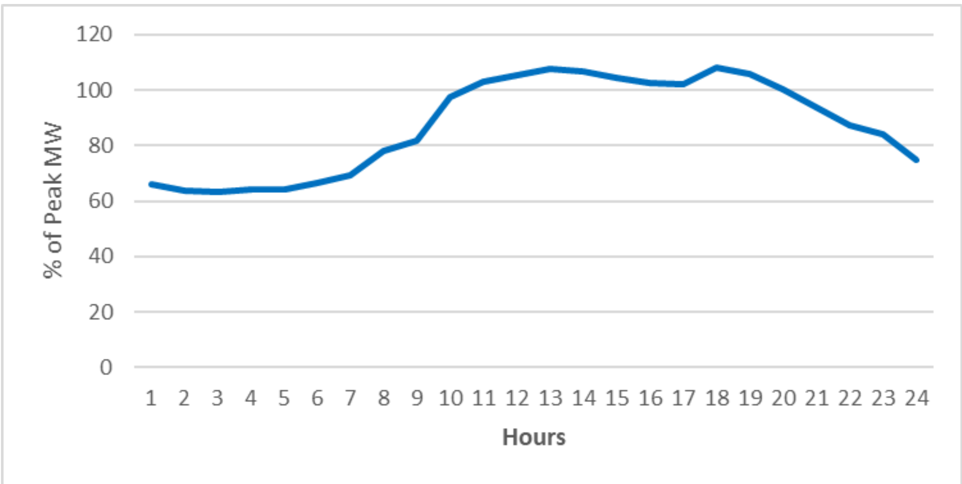

Figure 3: Feeder B Peak Load Profile

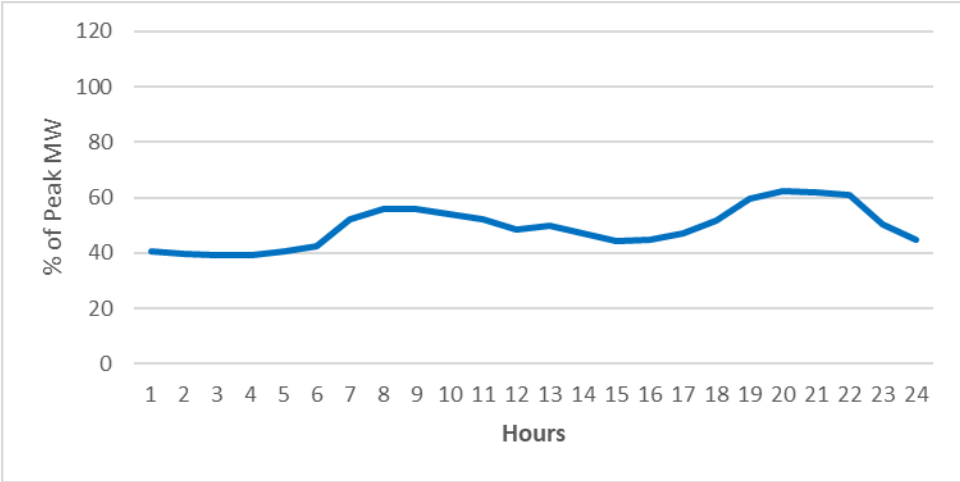

Figure 4: Feeder B Light Load Profile

Additionally, a volatile PV profile was developed and used to simulate a high generation output day with significant volatility to sufficiently stress the system and CMV scheme, which can be seen in Figure 5.

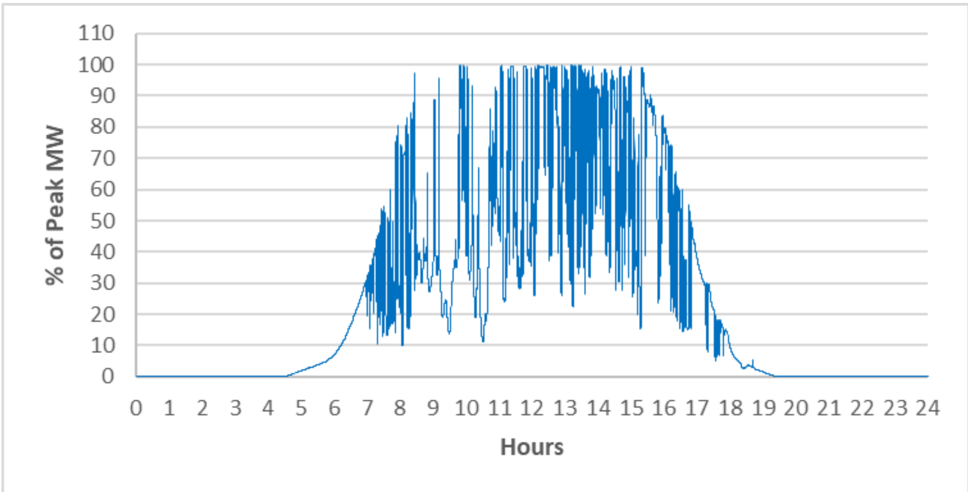

Figure 5: Volatile PV Profile

Dynamic CVR Model Validation

Benchmarking the CVR model performance was a challenge due to limited historical data points. In the absence of this data, a qualitative assessment was performed using steady state and QSTS simulations to confirm that the dynamic CVR scheme operated as expected based upon the control logic specified. In steady state, voltage profiles were examined to gauge CVR performance based on the lowest voltages within each regulation zone. Figure 6 displays the observed behavior of the CVR scheme on Feeder B during a light load period with the 5 MW DER offline. Note that the nominal voltage control settings for all circuit regulators is a CMV of 125 V with a bandwidth of 2 V; therefore, voltages held below 124 V reflect CMV operation.

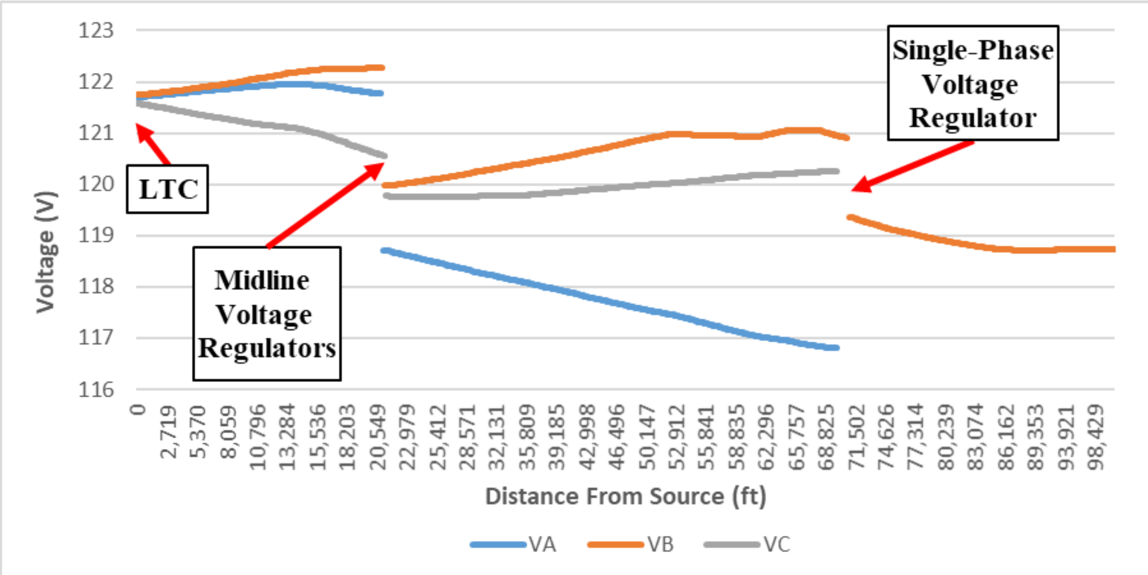

Figure 6: Feeder B, Light Load Voltage Profile: CVR Online, 5 MW DER Offline

As shown, voltage set points were lowered to account for the lightly loaded period, with the substation LTC set point being 122 V, the midline regulators being 119 V, and the single-phase regulator being 119 V. The impact of the CVR scheme is less pronounced under peak load conditions due to low meter readings forcing regulator set points near the nominal 125 V CMV.

Additionally, QSTS simulations were performed for several different scenarios. The substation LTC and feeder VRs operated as expected with the CVR scheme enabled. Figure 7 provides a comparison of the midline regulator terminal voltage both with and without the CVR scheme enabled.

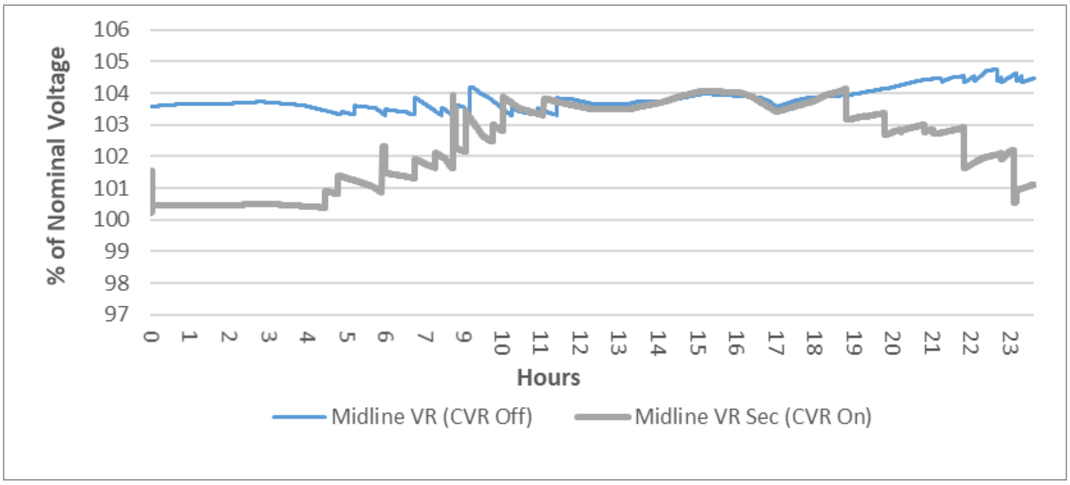

Figure 7: Feeder B, Light Load, QSTS CVR Performance Validation

The results show that voltages were maintained near the 125 V (104.2%) set point for the entire 24 hour simulation with the CVR disabled. Enabling the CVR scheme shows reduced voltages during the morning and night time hours, with the midday voltages held near 125 V (104.2%), which was the most heavily loaded part of the day. This operation affirmed the expectations of the CVR scheme. Future work could involve the installation of several power quality meters to facilitate a quantitative evaluation of CVR performance based on measured and simulated data. A quantitative evaluation would require a verification of both customer voltages as well as regulator terminal voltages on the MV system.

Dynamic CVR Simulations

Steady state and QSTS simulations were conducted for four (4) scenarios under peak and light load conditions:

1. CVR0 + DER0: CVR disabled and the 5 MW DER offline
2. CVR1 + DER0: CVR enabled and the 5 MW DER offline
3. CVR1 + DER1: CVR enabled and the 5 MW DER online
4. CVR2 + DER1: CVR enabled with faster communication times and the 5 MW DER online
    - Note that the CVR2 evaluation, with faster communications, is only applicable to QSTS simulations, as the steady state CVR evaluations assumed the system had reached its final state.

The objective of this testing was to evaluate CVR performance under existing system conditions, evaluate the impact of a 5 MW DER on CVR performance, and to identify whether faster communications, i.e. customer telemetry every minute and the ability to adjust regulator CMV every five minutes, would benefit CVR performance. Steady state analyses were used to evaluate the boundary conditions and assumed the CVR scheme had fully settled at the desired hold voltage and final tap position. QSTS simulations were used to evaluate transitory behavior and better understand the impacts of DER volatility on CVR performance.

Steady state analyses showed that enabling the CVR scheme resulted in an expected reduction in power demand, with the greatest reduction on Feeder B, which had the highest percentage of constant impedance loads as shown in Table 2. Table 3 summarizes the steady state simulation results.

Scenarios		Net kVA Flows				
Loading	**Label**	**Substation**	**Feeder A**	**Feeder B**	**Feeder C**	**Feeder D**
Peak	CVR0 + DER0	20,848	6,713	5,296	4,428	4,257
	CVR1 + DER0	20,813	6,713	5,266	4,428	4,253
	CVR1 + DER1	16,321	6,707	1,645	4,421	4,248
Light	CVR0 + DER0	5,590	1,977	1,437	1,066	1,323
	CVR1 + DER0	5,334	1,937	1,335	1,023	1,241
	CVR1 + DER1	717	1,928	3,388	1,013	1,231

Table 3: Steady State CVR Results

As shown, the CVR scheme reduced energy consumption in the scenarios with the 5 MW DER offline. The greatest reductions were observed under light loading scenarios. This may seem counterintuitive; however, the peak loading scenarios experienced lower voltages, and the CVR scheme had limited ability to reduce the regulator below the nominal 125 V set points without causing voltages criteria violations. This was not an issue under light loading scenarios and regulation set points were lowered such that energy consumption was reduced.

In scenarios with the DER online, it’s challenging to determine native loading and thus reduced energy consumption. Therefore, instead of using energy consumption as the metric for CVR performance, system voltages and regulator tapping frequency were compared and used as metrics to gauge CVR performance with the 5 MW DER online. QSTS simulations were conducted for each of the four scenarios under both peak and light loading conditions. The QSTS simulations were used to better capture the transitory behavior of the volatile PV output and CVR adjustments over time. Figure 8 shows six (6) locations where voltages were monitored within the QSTS simulations.

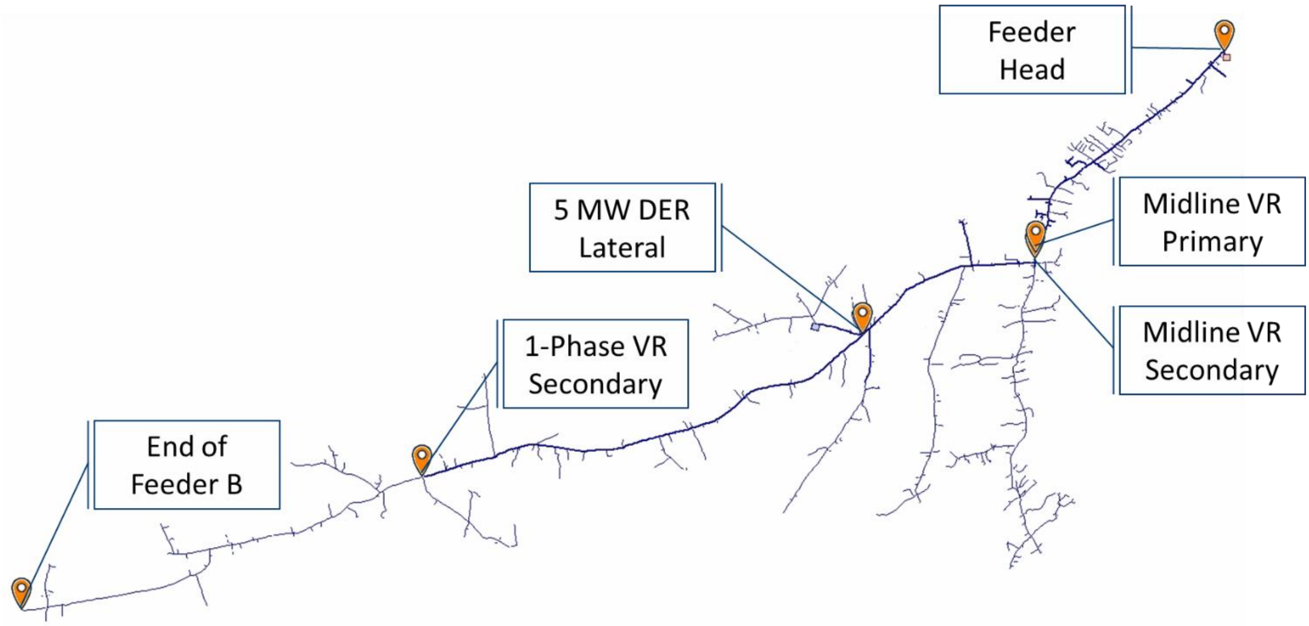

Figure 8: Feeder B, Voltage Capture Locations

Figure 9 shows the peak loading QSTS simulation voltage performance at the 5 MW DER lateral under all four (4) scenarios.

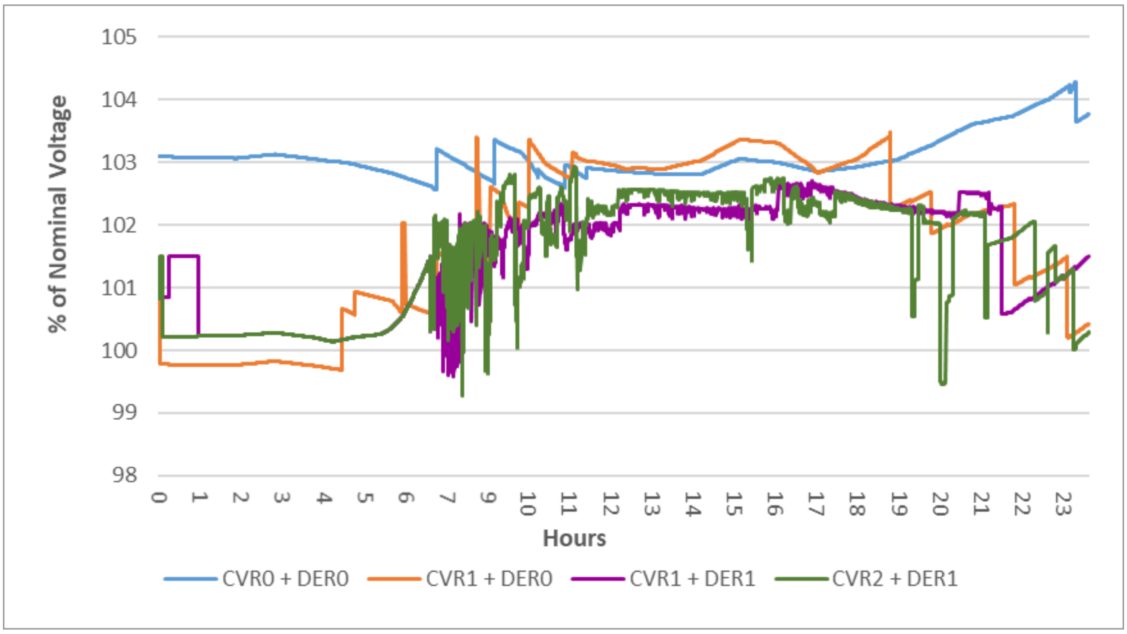

Figure 9: Feeder B, Peak Load, DER Tap QSTS Voltage Plot

The results showed that the CVR scheme lowered the system voltage in the presence of DER, which created headroom and reduced the burden on the 5 MW DER installation's Volt/Var regulation. The CVR scheme allowed the 5 MW DER site to operate within its Volt/Var deadband more often, which allowed for reduced real power curtailment as less reactive power absorption was required to regulate system voltages. Furthermore, the CVR2 scenario shows that DER volatility is tracked more closely than CVR1 due to the increased communication frequency.

While the CVR scheme seemed to benefit the DER site by creating headroom and reducing reactive burden, the DER operating within its voltage deadband increased the real power output fluctuations on the DS with reduced support from DER site's Volt/Var regulation. This increased exposure to voltage-related volatility and caused a significant increase in tap operations on Feeder B's circuit regulators, as shown in Table 4.

Scenarios		Tap Count		
Loading	**Label**	**LTC***	**Midline Regulators†**	**Single Phase Regulator**
Peak	CVR0 + DER0	1	25	14
	CVR1 + DER0	2	49	35
	CVR1 + DER1	2	36	35
	CVR2 + DER1	3	140	69
Light	CVR0 + DER0	0	10	8
	CVR1 + DER0	3	29	27
	CVR1 + DER1	2	117	149
	CVR2 + DER1	2	286	205

*The substation LTC is gang operated. Each tap count reflects a tap on all three phases.
†The midline regulators regulate individual phases. Tap counts across these phases are summed.

Table 4: QSTS Regulator Tapping Summary

As shown, CVR operation in general increased tap operations with significant increases observed under the CVR2 scenarios where faster communication times were implemented. Furthermore, the introduction of the DER site under light loading scenarios greatly increased operations, which was driven by the fact that this site's Volt/Var settings were optimized for the base regulation scenario with all devices at a 125 V CMV and a bandwidth of 2 V.

In summary, the CVR scheme achieved its objective of reducing power demand while maintaining system voltage within limits. Results showed that impacts of the scheme were generally positive; however, opportunities for optimization are present for both the baseline scenario and scenarios where large DERs are present. These are discussed further in the following section.

Future Research Opportunities

The study recommends further research to optimize the CVR scheme for traditional scenarios where the distribution system primarily serves customer load and also for emerging scenarios with high DER penetration that may result in reverse power flows at the feeder or substation level, which are becoming more and more common. While results showed that the CVR scheme was effective at reducing power demand, this paper presented evidence that there are opportunities for improvement.

The CVR scheme currently operates by polling metered voltages every fifteen (15) minutes and once a change has been made to a regulation device CMV, that device is blocked from implementing another CMV change for one (1) hour. CVR2 scenarios attempted to improve performance by reducing polling intervals to one (1) minute and CMV change blocks to five (5) minutes. As shown in Figure 9, regulation voltages are more closely tracked with DER volatility under this scenario; however, Table 4 indicates that this may have negative consequences associated with increased device tapping, thus leading to a shortened lifespan of system regulation devices. Both the meter polling rate and CMV adjustment rate should be explored in future work, whether they be static values or dynamic depending on system needs, and individual device tapping delays may be increased to reduce the potential for excessive operations while under the CVR scheme. Furthermore, alterations to the CVR algorithm may be beneficial in eliminating or reducing CMV determination based on periods of system volatility. Rather, an approach that utilizes a moving average or similar method for reducing impacts of outlier data points on CMV selection could prove useful to CVR scheme performance.

An additional consideration is the Volt/Var operation of the 5 MW DER. The Volt/Var set points had previously been optimized for system conditions not reflecting CVR operation; however, these settings were utilized for scenarios with the CVR scheme enabled. Future research should explore optimizing set points to coincide with CVR operation. Due to the dynamic nature of regulation set points resulting from CVR, it may be appropriate to implement a scheme where the Volt/Var reference voltage (V_{Ref}) is autonomously adjusted [6] rather than static. V_{Ref} may coincide with voltages local to the DER site or could potentially be coordinated with remote meters (similar to the CVR scheme).

Conclusion

This paper presents a comprehensive overview of a dynamic CVR modelling technique implemented within Eaton's CYME software. The paper covers the advantages of dynamic modelling over open-loop modelling and explores the impact of adding a large DER with voltage regulation capabilities to a circuit with an existing CVR scheme. The study demonstrated that the CVR model produced expected results and achieved its objective of reducing power demands while maintaining system voltages under DER offline conditions. The results also showed the potential to reduce DER curtailment and reactive power consumption of a 5 MW DER by lowering system voltages with the CVR scheme. However, an identified drawback was that the reduced voltages caused the DER Volt/Var scheme to operate within its deadband more often and significantly increased circuit regulator tapping.

The paper identifies opportunities for optimization of the CVR scheme, particularly in scenarios where the CVR scheme is used with a high penetration of DER. The study recommends further research to optimize the CVR algorithm and DER Volt/Var scheme to operate more effectively in unison. Future research opportunities could explore the optimal timing variables for CVR, investigate solutions to mitigate excessive device tapping, and delve into intelligent Volt/Var control to best fit system needs.

In conclusion, this paper offers a detailed methodology for effective dynamic CVR strategy implementation and provides insights into the modelling of dynamic CVR schemes within planning software. The paper highlights the need for accurate modelling and feedback from multiple assets within the system. By offering new methodologies for effective dynamic CVR strategy implementation, this paper contributes to the advancement of electric distribution system analyses and renewable integration.

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