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Transactive Approach for Engaging Distribution Network Assets for Voltage Management in Southern California Edison Distribution Feeders

June 2018

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U.S. DEPARTMENT OF ENERGY

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Acronyms and Abbreviations

ANSI	American National Standards Institute
CPUC	California Public Utilities Commission
CVR	conservation voltage reduction
DER	distributed energy resources
EPIC	Electric Program Investment Charge
ESS	energy storage system
FMM	fifteen-minute market
IGP	Integrated Grid Project
ISGD	Irvine Smart Grid Demonstration
LMP	locational marginal price
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
SCE	Southern California Edison
UQ	University of Queensland
WTA	willingness to accept
WTP	willingness to pay
VVC	Volt-Var Control

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1.0 Introduction

This report documents an effort by Pacific Northwest National Laboratory (PNNL) investigating the utility of using incentive signals to elicit useful responses from smart inverters associated with customer-owned distributed energy resources (DERs). This project was an element of the Southern California Edison (SCE) Integrated Grid Project (IGP) funded by the California Public Utilities Commission's (CPUC's) Electric Program Investment Charge (EPIC) program (CPUC 2018) to support applied research and development, technology demonstration and deployment, and the market facilitation of clean energy technologies and approaches.

1.1 Background

Under the IGP project, SCE intended to demonstrate next-generation grid infrastructure to manage, operate, and optimize the use of preferred resources (DERs) and to develop a framework to determine the value of DERs as grid assets. In line with these high-level objectives, SCE began discussions with PNNL in 2015 regarding PNNL's work on transactive energy systems. In those discussions, PNNL and SCE identified the use of incentive signals to usefully engage smart inverters associated with customer-owned DERs as a topic of mutual interest. This led to the creation of this project in October 5, 2015, and initial discussions to specifically scope the investigation. These discussions took place over a 15-month time period, culminating in a workshop in March 2017, during which the specific problem of voltage management was identified as a test case around which to assess the use of incentive signals. The discussion also recognized that the source of the incentive signals would be a transactive mechanism, the specifics of which would depend on the economic basis of the incentive signals. With this specific focus for the work determined, a rough outline of the work plan was developed for further refinement by PNNL after the workshop. The remainder of this report describes the specifics of the work and the results of the effort.

1.2 Summary of Key Findings

- A double-auction based transactive approach could be used to engage assets in a distribution feeder for voltage management services.
- Supply curves for assets to participate in the transactive market process can be constructed using their capability curves (P-Q curve, where P and Q are active and reactive power, respectively) and efficiency curves.
- The approach for construction of a demand curve depends on the use case. In this work, demand curves for SCE to participate in the transactive process are constructed based on the conservation voltage reduction (CVR) benefits.
- Transactive simulation and a series of cost-benefit analyses suggests that CVR alone is not adequate for engaging the assets. Additional benefits, such as avoided cost of capacitor bank switching, must be included.
- Cost and benefit estimation of engaging customer-owned assets for different voltage management use cases is required to assess the feasibility of deploying a transactive mechanism for implementing those use cases. A tool with capabilities to estimate these cost and benefit values would be useful in this regard.

1.3 Organization of the Report

Section 2 provides background and preliminary ideas on transactive systems that are required to understand the approach used in this work. Section 3 describes the bulk of the work performed in this project, including its approach for constructing supply and demand curves (for a proof-of-concept system and the SCE feeder), a market-clearing simulation mechanism, and results of the market-clearing simulation. At the end of Section 3, limitation of CVR-only use case for acquiring enough var is analyzed and the necessity for including additional benefits is discussed. Section 4 describes a voltage management planning and assessment tool that originated from the modeling and simulation approach developed in Section 3.

2.0 Transactive Approach Primer

This section provides a basic understanding of transactive approaches and their applications in power distribution systems.

2.1 Basics of Transactive Systems

Transactive energy systems are a class of systems in which economics and controls converge to address problems requiring control or coordination of a variety of assets in an electric power system. The GridWise® Architecture Council (GWAC 2018) formally defines transactive energy systems as follows:

> A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.

Practically speaking, one can consider transactive energy systems as a means of engaging flexibility to offset variability. They are particularly useful in considering how to monetize the value propositions associated with DER integration. The challenge is to identify the specific basis for each value stream, the relationships between value streams, and the spatial and temporal dimensions of the problem. These considerations lead to both the basis for monetization – for example, avoided cost – and the identification of a specific transactive mechanism suited to the specific control and coordination problem being addressed. For this project, we identified a double-auction market as a transactive mechanism well suited to the problem of creating incentive signals to engage smart inverters.

2.1.1 Double-Auction Based Transactive Systems

A *double auction* refers to a market clearing process in which the buyers and sellers simultaneously submit their bids to buy and sell a commodity. The bids and offers typically constitute price–quantity pairs, specifying the amount of a commodity to be bought (or sold) at a desired price. The bids and offers may consist of a single price–quantity pair, or multiple such pairs, which form the supply and demand curves. Buyers' price–quantity pairs contain information on their *willingness to pay* (WTP), which is the maximum amount of money they are willing to pay for the corresponding amount of commodity. Hence, the price–quantity pair, and by extension the demand curve, contain information on buyers' preferences to consume the commodity. A buyer's demand curve is also referred to as the *marginal benefit* curve, because WTP for an incremental unit of a commodity represents the additional *utility* (and hence, marginal benefit) from consuming it. Similarly, sellers' price–quantity pairs contain information on their *willingness to accept* (WTA), which is the minimum amount of money they are willing to accept for the corresponding amount of the commodity. Hence, the price–quantity pairs contain information on sellers' implied costs to produce the commodity.[1] The market clearing transaction occurs at the intersection of the demand and supply curves, revealing the market clearing price and the amount of commodity to be transacted (Figure 2.1). At the market clearing point, the buyers' WTP equals the sellers' WTA.

[1] It is reasonable to assume that most sellers operate with a profit motive, and hence, their WTA for a given amount of commodity must be greater than the production cost. In case of a *purely competitive* marketplace, and auction designs such as *uniform price* auctions, the sellers have no incentive to report anything but their true marginal production costs, and hence, the supply curve is the same as the *marginal cost curve*.

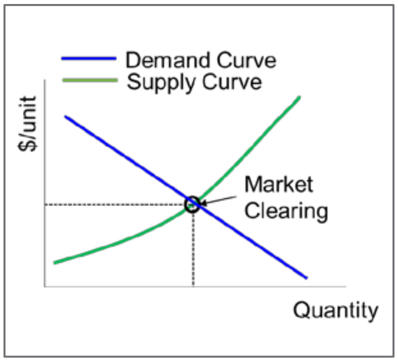


Figure 2.1. Notional demand and supply curves to demonstrate the idea of market clearing

2.2 Application of Transactive Approach in Distribution Network Management

Double-auction transactive energy systems have been used in both distribution and bulk-power systems to engage resources to help achieve various operational requirements of the power system. The specification of a transactive system begins with the identification of a desired operational objective (use case) to be achieved, such as management of voltage within the American National Standards Institute (ANSI) bounds on a distribution feeder. Once a use case has been identified, the next step involves specification of the *commodity* to be transacted along with its units of measurement and transaction, as well as identification of the *counterparties*—buyers and sellers. For instance, a distribution utility could transact with customer or third-party owned assets, such as inverters, to source or sink *reactive* power to manage the voltage on a distribution feeder. In this case, the commodity to be transacted is reactive power, and the buyer is a distribution utility. The next step involves translation of the desired operational objective into a *transactive incentive signal*, which is expressed using the same financial units as the seller's reported offer. In the context of a double-auction market, a transactive incentive signal represents the maximum price a distribution utility is willing to pay for the commodity, i.e., its demand or marginal benefit curve. The seller's cost for providing the commodity could be either the direct cost associated with production, or a cost based on implied or assumed trade-offs with other monetizable commodities. For instance, customers' WTA for providing flexibility with air-conditioning load (to manage line thermal constraints) can be derived from their *temperature elasticities*, i.e., the level of comfort they are willing to forego in return for a monetary compensation.

2.2.1 Transactive Mechanism to Engage Inverters for Reactive Power Support

In this project, a double-auction based transactive mechanism was designed and developed to engage inverters to provide reactive power support. The use case initially identified for proof-of-concept of the transactive mechanism was *conservation voltage reduction* (CVR), which is essentially a form of Volt-Var control (VVC) scheme exercised by distribution utilities to maintain voltage across the network, preferably within the lower half of the allowable ANSI range (±5%, or 114-120 V on a 120 V scale). This allows reduction in power and energy consumption of voltage dependent loads. More details on CVR are provided in the sub-section below, including information on SCE's initiatives on this topic.

For the CVR use case, the monetized benefits of reduced energy consumption and procurement in the wholesale market were identified as the initial value drivers from the utility's perspective (*buyer* of reactive power). Hence, the time-varying *demand curve* was constructed to represent the utility's WTP for reactive power based on knowledge of energy savings, and the monetary value achieved thereby. The sources of reactive power constituted of customer- and utility-owned inverters, attached to rooftop photovoltaic (PV) and battery systems. In providing reactive power, the resources incur *opportunity* cost, associated with lost revenue from real power, as well as power losses. Given that reactive power does not have a direct production cost, a *supply curve* from resources' perspective was constructed using the costs associated with lost opportunity of producing real power and the power losses due to inverter inefficiencies. The trade-off between real and reactive power was modeled using an inverter's *P-Q* capability curve. The details of the mechanisms to determine time-varying demand and supply curves are provided in Section 3.0. The concept of *benefits stacking* was also explored by identifying additional value streams that could be accessed by the utility, such as reduced/avoided capacitor bank switching operations. Other use cases were also identified, such as enabling feeder reconfiguration and switching operations by managing system voltage. The monetized value of these use cases can be used to determine the associated demand curve for reactive power using the same approach.

2.3 CVR at SCE

CVR is typically implemented as an area-wide scheme consisting of multiple feeders (or, a single feeder at the minimum) and engages the feeders' voltage control resources, including tap changing transformers, voltage regulators, capacitor banks, and sometimes more sophisticated power electronic devices (e.g., a D-STATCOM). Smart inverters may also be brought into the pool of CVR resources. These resources are directed by distribution automation systems or dedicated VVC systems at the substation for controlling var as required to create space and time-varying voltage profiles necessary for CVR. In the past, several U.S. utilities have performed field demonstrations of CVR and assessed its benefits. Table 2.1 lists a few of those projects.

In SCE, one of the earliest CVR demonstrations was the Distribution Capacitor Automation Project (DCAP) project, run between 1992 and 1994, where operations of 72 capacitor banks in 12 distribution circuits were coordinated to achieve the lowest acceptable voltage. The approach developed in DCAP was essentially used again in the Irvine Smart Grid Demonstration (ISGD) project in 2014. SCE's Distribution Volt-Var Control (DVVC) scheme was used in the ISGD project to demonstrate CVR benefits on seven distribution circuits. The demonstration was conducted for sixteen 2-week periods. Each 2-week period consisted of a week with DVVC on and the next week with DVVC off.

In its most recent VVC initiative under IGP, funded by CPUC's EPIC program, SCE explored the possibility of engaging inverter-based Distributed Energy Resources (DERs) for VVC. A VVC use case narrative of IGP said that the centralized volt-var system being deployed at SCE works well with "light penetrations of variable generation resources, but falls short in high penetration cases". The VVC use case in IGP aimed to investigate the performance of DERs integrated into SCE's Grid Management System (GMS) and its Optimization System (OS) to make VVC algorithms more responsive to high penetrations of DERs. Moreover, SCE explored the use of incentive signals to engage the resources for various VVC use cases, such as CVR. The transactive approach is an incentive-signal-based mechanism to facilitate DER participation in the VVC scheme.

Table 2.1: Previous field studies on CVR in different U.S. utilities

Year	Study Location/ Details/ Methodology	Benefit Metrics
1987 (Pinney et al. 2014)	Snohomish Public Utility District, Washington.	2.1% Voltage reduction resulted approximately same reduction in energy consumption. Customer bill reduction 6.28 $/customer/yr
1992 (Southern California Edison 2016)	Southern California Edison. CVR demonstration using capacitor bank automation in 12 circuits.	CVR Factor (CVRf): 1%
2007 (Anderson 2016)	Northwest Energy Efficiency Alliance. 3% voltage reduction at Boise substation. End-of-line voltage feedback. 24 hours on/24 hours off.	1.5% - 2.5% Energy reduction (kWh); 1.8% - 2.6% demand reduction (kW)
2008 (Wilson 2012)	Plum Creek Timber. 40 MW load. Project sponsored by BPA and Flathead Electric Cooperative.	Overall demand reduction –3.72%.
2009 (Dominion Voltage Inc 2012)	Midlothian Virginia. 2x34.5 kV urban circuits. Voltage regulation in the lower 5% band (114 to 120 V).	2.8% reduction in energy consumption.
2010 (Wilson 2012)	Ripley Power and Light. Demand reduction VVO. three substations and nine feeders.	Energy reduction range of 1.3% to 5.4% across all feeders; demand reduction up to 3.4%, or 1.64 MW
2010 (Wilson 2012)	AEP Ohio GridSmart project in Gahanna. 13.2 kV feeder regulators and capacitor banks.	Average energy reduction over 3%; Station peak demand reduction over 3% (higher than energy reduction percentage); Approximately 1/3 reduction in tap operations.
2011 (Wilson 2012)	Murray State University. Program sponsored by TVA. Two on-load tap changers, 4 feeders.	4.38% peak reduction; 4.82% energy conservation; 27.5% mean reactive reduction.
2012 (Pinney et al. 2014)	Four substations in Iowa Lakes Electric Cooperative set up for 2.5% (3 V) reduction.	CVRf: 1.04-1.05. Verification of CVR benefit is challenging because load changes due to CVR only is difficult to isolate.
2012 (Sergici et al. 2016)	Dominion Virginia Power. Compared pre-CVR period with CVR period using day-pairing approach.	CVRf: 0.92
2012 (Sergici et al. 2016)	Indianapolis Power and Light Company. CVR turned on for a few short periods in 2012 and 2013.	CVRf: 0.7-0.8
2012 (Sergici et al. 2016)	West Penn Power Company.	1.5% reduction in voltage resulted a range of CVRf with an average value of 0.86
2014 (Solar City Grid Engineering 2016)	Sothern California Edison. Application of smart inverters at low-voltage feeders to enhance CVR benefit in the overall feeder. Voltage at certain customer services were shifted up using smart PV inverter so that CVR voltage for the overall system could be reduced further to increase savings.	0.38% additional reduction in energy consumption and 0.41% additional reduction in peak demand.
2016 (Pacific Gas and Electric Company 2016)	Pacific Gas and Electric pilot project, day on/day off benefit measurement approach, 14 circuits, 1-year demonstration period with seasonal variations.	Weighted average CVRf: 0.7

3.0 Transactive Approach to Engage Assets for Voltage Management

This section describes how a transactive approach for engaging inverter assets in the SCE feeder is designed for voltage management. In this case, voltage management will be performed by acquiring reactive power (var) from customer-, third-party, or utility-owned inverters. The approach to construct the basic elements of a transactive market process, such as the supply curve, demand curve, and market clearing mechanism are described. A proof-of-concept study is performed first, using a simple but real distribution test system to develop the basic approach, which is then expanded for the SCE feeder.

3.1 Proof-of-Concept Study

Aim of the proof-of-concept study was to develop an understanding of the applicability of transactive approach for acquiring Var from customer owned assets, and to design and validate methods for developing the basic elements of transactive system (e.g., supply curve, demand curve, market simulation mechanism). The proof-of-concept test system is a model of a distribution feeder (Alam et al. 2016) that connects The University of Queensland (UQ) Gatton campus substation and the Gatton zone substation of Energy Queensland supplying the Gatton campus, as shown in Figure 3.1. It is an approximately 8 km long, 11 kV line with a step voltage regulator (SVR) in the middle, which was deactivated for our simulation since the SCE feeder under consideration does not have an SVR. The UQ Gatton campus has a 3 MW PV plant and a 0.6 MW/0.76 MWh lithium-ion energy storage system. For the simulation, only the PV inverters are used for reactive power capacity (3.5 MVA).

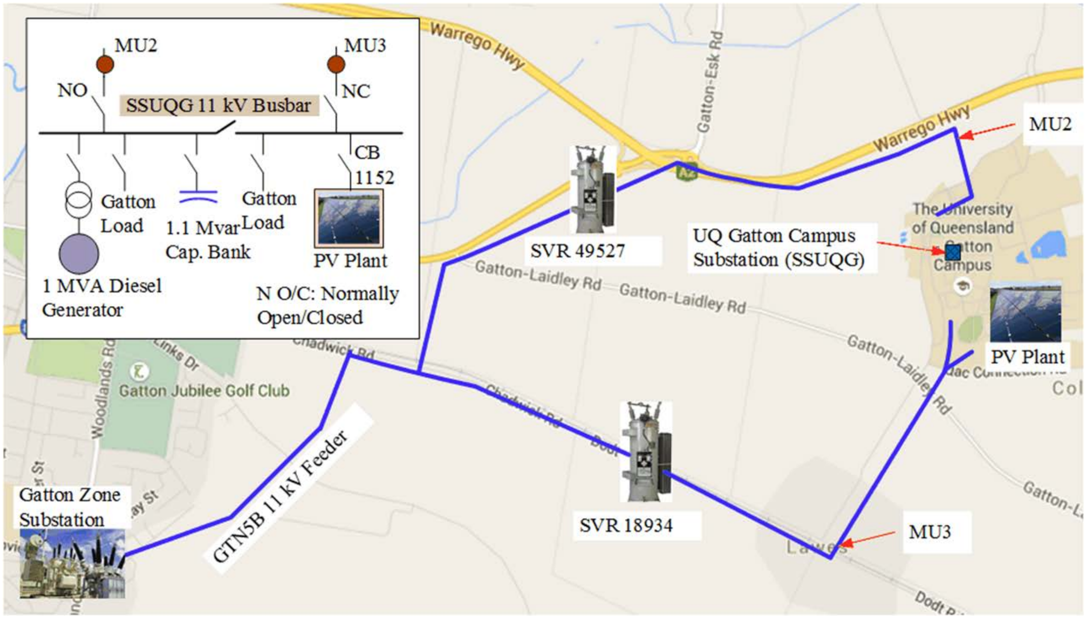


Figure 3.1. Simple distribution system used for proof-of-concept study

Elements of the transactive simulation platform are described below with respect to the UQ test feeder. Additional considerations are needed for the SCE feeder, and will be described later in this section of the report.

3.1.1 Supply Curve for Reactive Power

A supply curve in a transactive system describes the relationship between the quantity and the marginal price of a commodity being offered by a supplier. In this case, the commodity being transacted is reactive power and the supply curve needs to provide the marginal price of reactive power against the amount of reactive power offered by an asset (e.g., inverter). An approach is developed to determine the cost of reactive power considering two aspects of inverter operation: one is the portion of inverter apparent capacity (kVA) used for real power production, and the other is the amount of additional power loss incurred for producing reactive power. A marginal price curve is obtained by taking the first derivative of the reactive power cost curve. The approach used for constructing a reactive power supply curve is described below.

If an inverter is fully loaded to its rated apparent power capacity to convert real power from a solar PV array or an energy storage system (ESS), as shown in Figure 3.2(a), it does not have any capacity left for sinking/sourcing reactive power. Therefore, the inverter will need to curtail real power production if reactive power (var) needs to be produced. Curtailment of the real power has two possible effects: (1) if the PV production is higher than the customer's own demand, it reduces the economic benefit to the inverter owner obtained from net energy delivered to the grid; or (2) if the PV production is less than or equal to the customer's own demand it incurs additional energy cost. Therefore, depending on the case, the reduction in economic benefit from net energy metering or additional energy charges to meet the customer's own demand could be considered as the cost of reactive power for a fully loaded inverter.

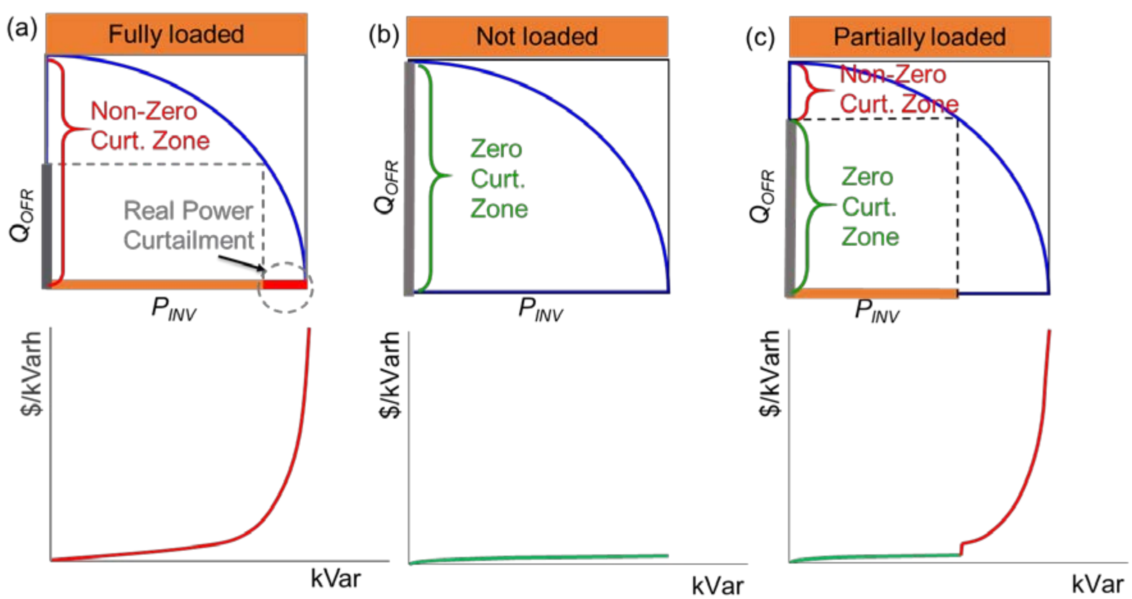


Figure 3.2. Supply curve for a fully loaded inverter: (a) fully loaded inverter; (b) non-loaded inverter; (c) partially loaded inverter

If the inverter is not producing any real power, then the entire apparent power capacity is available for reactive power production, as shown in Figure 3.2(b). In this case, there is no equivalent loss of real power production due to curtailment; therefore, the cost of curtailment is zero. However, due to the current flow through the inverter circuit, real power loss is incurred, which is monetizable using the price of electricity set by SCE (e.g., a time-of-use tariff). The cost of real power loss is used to construct the reactive power cost curve of an unloaded inverter, as shown in Figure 3.2(b). Inverter wear and tear, increased life cycle costs, etc., could also be considered for this case, if they are properly monetized.

When the inverter is partially loaded to produce real power, the cost curve will contain two portions, as shown in Figure 3.2(c). One portion corresponds to the unused apparent power capacity, where the curtailment cost is zero, and the cost of reactive power is determined using the real power loss in the circuit. The other portion corresponds to the loaded part of the apparent capacity for real power production, where the cost of curtailment is nonzero. The real power curtailment cost is used as the reactive power cost for this portion of the reactive power cost curve.

An expression for the nonzero curtailment portion of the reactive power cost is given in Equation (1), and the corresponding marginal cost (MC_{curt}) is obtained using Equation (2).

$$C_{curt} = ET \times \left[\left(\sqrt{S_{INV}^2 - Q_{INV}^2} - P_{INV} \right) - \left\{ \sqrt{S_{INV}^2 - (Q_{INV} + Q_{OFR})^2} - P_{INV} \right\} \right] \tag{1}$$

$$MC_{curt} = \frac{dC_{curt}}{dQ_{OFR}} \tag{2}$$

where C_{curt} is the reactive power cost calculated as the cost of curtailed real power; ET is the electricity tariff (Net Energy Metering tariff, SCE tariff etc.); S_{INV}, P_{INV}, and Q_{INV} are rated apparent power, real power, and reactive power (if any, not including the reactive power for transactive process), respectively, at a given instant; and, Q_{OFR} is the reactive power offered by the inverter asset. Although P_{INV} in the first and second terms of the right-hand side of Equation (1) cancel out each other, these are kept to show the general form of the equation.

To assign cost to the zero-curtailment portion of the cost curve, additional real power loss for reactive power production is determined using the inverter efficiency curve provided by the manufacturer (SMA 2018). The expression in Equation (3) describes the relationship between reactive power and real power loss on the inverter circuit, which is then used for the corresponding marginal cost, MC_{loss}, by applying Equation (4).

$$C_{loss} = ET \times \left\{ \left(\frac{S_2}{\eta_{INV2}} - S_2 \right) - \left(\frac{S_1}{\eta_{INV1}} - S_1 \right) \right\} \tag{3}$$

$$MC_{loss} = \frac{dC_{loss}}{dQ_{OFR}} \tag{4}$$

where, C_{loss} is reactive power cost calculated as the cost of real power loss to produce reactive power; ET is the electricity tariff (SCE tariff); S_1 and S_2 are inverter outputs without and with reactive power supplied, respectively, for the transactive process; and, η_{INV1} and $\eta_{INV2}$are the inverter efficiency at the apparent power output S_1 and S_2, respectively, which can be determined from a manufacturer-supplied curve or a test report.

While this work considered only real power loss in the construction of the zero-curtailment portion of the cost curve, inverter wear and tear, lifetime, etc., could also be considered if they are monetizable. Technically the nonzero curtailment portion of the cost curve should also include a real-power loss component, but it is much lower than the curtailment cost.

3.1.2 Demand Curve for Reactive Power

A demand curve in a transactive system describes the relationship between the quantity and marginal price of a commodity being demanded by an entity. With the commodity being reactive power, the demand curve needs to provide the marginal price of reactive power that the buyer (e.g., the utility) is willing to pay for a given amount of reactive power. Marginal price from the buyer’s perspective can be estimated from on the benefit to the buyer of generating/consuming reactive power. Monetization of reactive power benefit is a rather complex task that requires comprehensive understanding of the financial impact of not receiving reactive power, the cost of alternative approaches to acquire reactive power, etc. Instead of considering a specific use case (e.g., CVR), a conceptual demand curve is constructed for the proof-of-concept study as a function of feeder voltage deviation from an arbitrary reference value (e.g., 1.0). The goal is to understand how change in the demand curve as a result of voltage deviation in the feeder drives the market interaction in a transactive process. Voltage deviation is incorporated in the construction of the demand curve in such a manner that it simulates a tendency to pay a higher price if the voltage deviation increases, with a goal to achieve a target voltage. Figure 3.3 shows sample demand curves for increasing voltage deviation from a reference value.

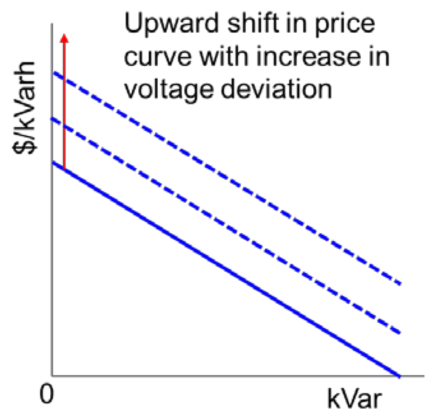


Figure 3.3. Demand curve used for the proof-of-concept study

3.1.3 Market Clearing Simulation

Among different transactive market clearing processes, double-auction market clearing is selected for this work. In this process, a seller will submit their reactive power supply curve and a buyer will submit their reactive power demand curve. Market clearing is achieved if the supply and demand curves intersect. Since voltage-rise during a lightly loaded condition was reported as one of the major technical challenges that SCE intended to address, the proof-of-concept study was set up to vary the loading of the circuit in Figure 3.1 according to the pattern shown in Figure 3.4(a) to create a gradual increase in voltage. As the voltage at SSUQG bus in Figure 3.1 increases, so does its deviation from the reference value (of 1.0). Noteworthy, distribution network voltage unbalance is not considered in this work and the reported voltage values represent equivalent positive-sequence voltage magnitudes only. Intersection points of the supply and demand curves constructed using the approach described in Sections 3.1.1 and 3.1.2 were tracked to obtain market clearing. The *x*-axis intercept of the market clearing point is the amount of reactive power that is dispatched by the inverter at the cleared price, which is the *y*-axis intercept of the clearing point, as shown in Figure 3.4(b). Following this approach, reactive power dispatch for all the points in the loading factor profile is obtained, and the amount of reactive power procured using the transactive approach is shown in Figure 3.4(c), with the resulting voltage profile in Figure 3.4(d).

For comparison purposes, optimal power flow analysis of the circuit is conducted to determine the reactive power required to achieve the reference voltage (1.0), which is overlaid in Figure 3.4(c) with the reactive power obtained using the transactive process. The significance of the amount of reactive power obtained using the transactive approach is that it is “the amount” for which the marginal economic benefit is equal to the marginal cost, even if it is not the same as the amount obtained using optimal power flow. While the particular case presented here shows that the amount of reactive power determined using the transactive approach is lower than the amount of reactive power obtained by running optimal power flow, varying the demand curve parameters to increase sensitivity of price with voltage deviation could produce different results.

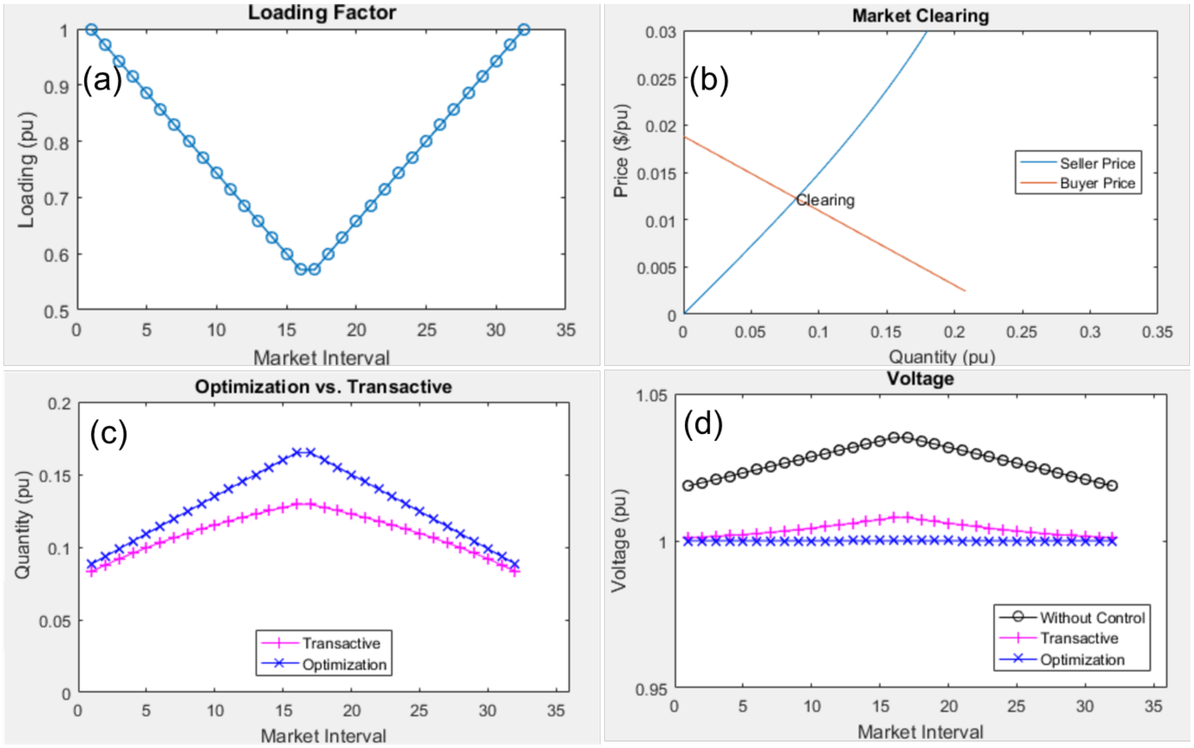


Figure 3.4. Market clearing simulation for the proof-of-concept system: (a) loading factor; (b) market clearing; (c) reactive power quantity; (d) voltage

While the simulations in Figure 3.4 were conducted using a conceptual demand curve, a CVR-benefit-based demand curve for the proof-of-concept system is presented in Figure 3.5 for illustrative purposes. The demand curve is based on the marginal reduction in energy cost due to a reduced operating voltage, created by consuming var by the Gatton solar farm inverters. Australian Energy Market Operator's (AEMO[2]) spot price data for Queensland is used to calculate the bulk energy costs. Supply curves constructed using Equations (1)-(4) and Energy Queensland's tariff data are overlaid on the demand curve. The dashed and solid supply curves correspond to fully loaded and partially loaded inverter, respectively. Overlaying supply and demand curves clearly reveals the economic value that CVR could achieve against the cost of var to accomplish the voltage needed for CVR. For a fully loaded inverter, the marginal cost of acquiring var increases very steeply in comparison to the marginal CVR benefit, and hence, only a fraction of the available var capacity is cleared in the market (<100 kVar, as indicated by the left green circle in the zoomed portion of Figure 3.5). On the other hand, the marginal cost of acquiring Var from a partially loaded inverter, when the inverter does not require curtailment of real power, is much lower than that from the fully loaded inverter. Therefore, the amount of Var acquired by market clearing is relatively high (approximately 800 kVar) as indicated by the right green circle in the zoomed figure. It must be noted that the quantity of var cleared in the market depends on the marginal benefit of CVR, which is a function of different factors (e.g., reduction in operating voltage by consuming var, amount of voltage dependent load in the network, and variation of line loss with change in voltage).

[2] https://www.aemo.com.au/

These benefits, and hence the resulting demand curves, will be situationally unique. The next subsections explore CVR use case for SCE and apply the transactive approach described above for accomplishing it.

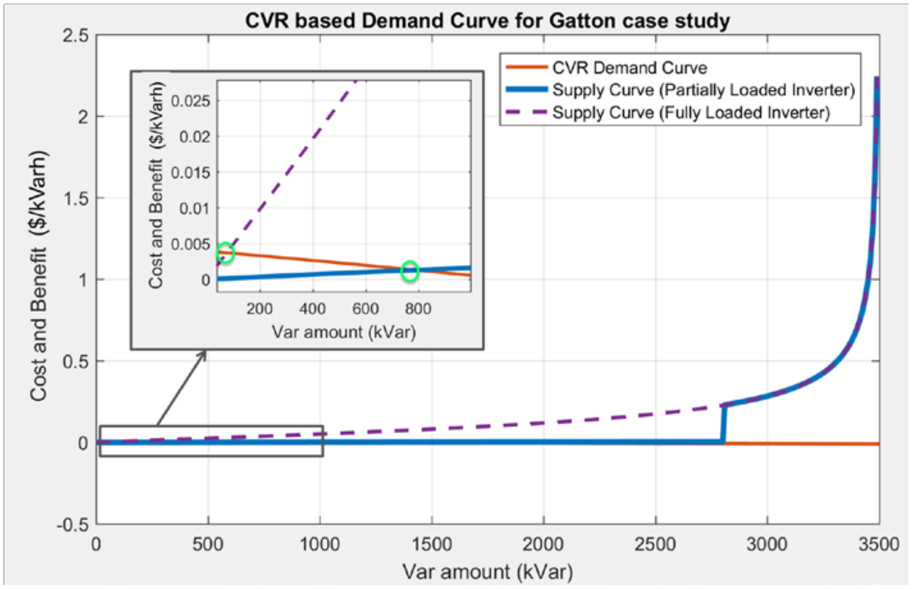


Figure 3.5. CVR demand curve for the proof-of-concept network

3.2 SCE Feeder Study

SCE selected a feeder for this study which contains inverter assets that could potentially be engaged for different applications related to the IGP. The project being described in this report is related to a use case for voltage optimization with DER. In a workshop at the beginning of this project, PNNL and SCE decided to adopt CVR as a use case for engaging assets through the transactive mechanism. The subsections below describe the approach used for constructing supply and demand curves CVR use case for the selected feeder, and an illustration of market clearing simulation.

3.2.1 Aggregate Supply Curve

As in the proof-of-concept test system, supply curves for individual inverter assets are available. However, using individual supply curves, and hence performing separate market clearing, would require the decoupling of the CVR benefit. Reactive power absorbed/provided by a given inverter can change voltage in the whole feeder to varying degrees. While power flow Jacobian matrices could theoretically estimate the change in voltage at all of the feeder nodes for a given level of reactive power by a given inverter, using the Jacobian will increase the complexity and hence the computational burden of the process. To start with a rather simple approach, an aggregate supply curve is constructed by sorting the pairs of reactive power quantity and marginal price for individual supply curves in ascending order of marginal price. The process is illustrated in Figure 3.6 using individual supply curves (left side of the figure) from four assets, each offering up to 3 kVar with different marginal costs. The aggregate offer of the four assets would be 12 kVar (right side of the figure). The first 2 kVar of the aggregate supply curve constitutes offers from the first asset (QC1) because they have the lowest marginal cost (1 and 3 $/kVarh, respectively). The next unit of kVar is taken from the supply curve of the fourth asset (QC4), which offers the next lowest marginal price (5 $/kVarh). This process is repeated until the maximum of 12 kVar is reached.

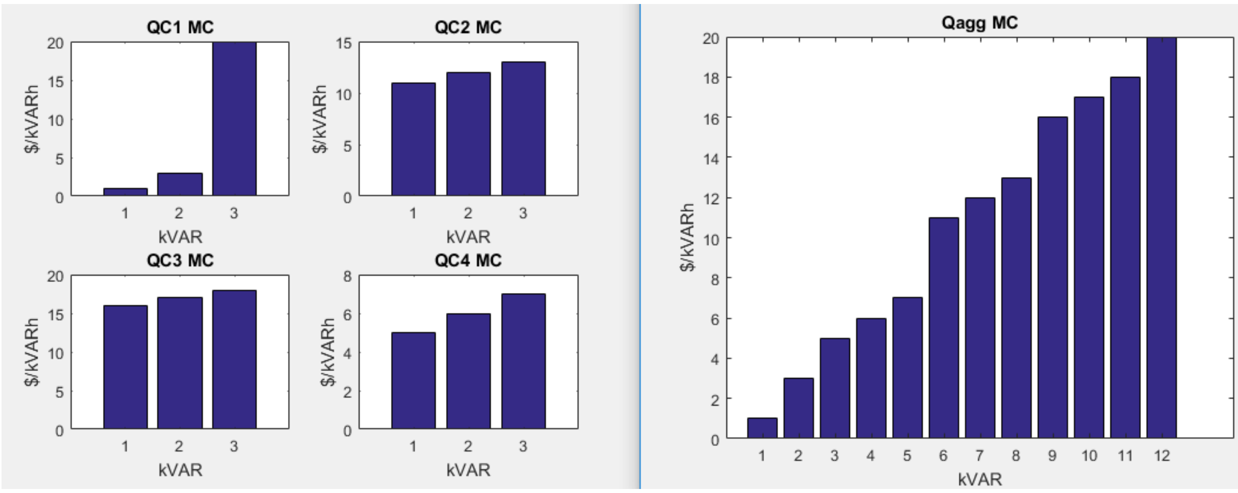


Figure 3.6. Constructing aggregate supply curve

3.2.2 CVR-Based Demand Curve

A CVR-benefit based demand curve is constructed using the marginal hourly savings of electricity cost from performing CVR. To obtain a CVR benefit curve, GridLAB-D simulations are performed by setting all inverter assets in the feeder to simultaneously sink reactive power from 0% to 100% of their available reactive power capacity (applied in suitable steps, e.g., 10%). The resulting energy savings are plotted against the amount of reactive power in Figure 3.7. A demand curve is then obtained by taking the first derivative of the CVR benefit curve with respect to the kVar. The term “available reactive power capacity” refers to the zero-curtailment portion of the inverters’ apparent power capacity, where the marginal cost of reactive power is determined using the real power loss in the inverter circuit. The nonzero curtailment portion is excluded from the current version of the work because of the much higher marginal cost of reactive power relative to the marginal benefit. It can be incorporated with the analysis, if desired.

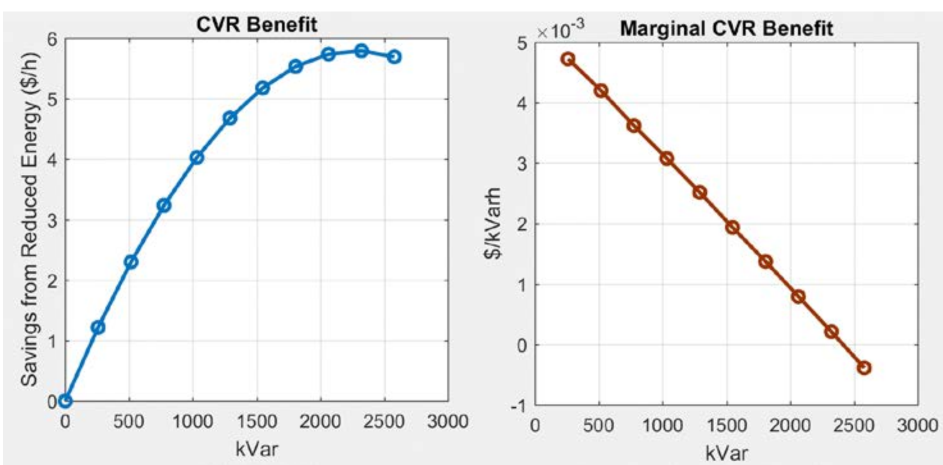


Figure 3.7. Constructing a CVR-based demand curve

3.2.3 Market Clearing Simulation

Market clearing simulation is performed by determining the intersection point of the aggregate supply curve and the CVR-benefit based demand curve for each market instant under consideration. Individual asset supply curves are constructed considering real power outputs from PV arrays and ESSs, as applicable, using the approach described in Subsection 3.1.1. The amount of reactive power to be dispatched by each inverter asset is determined from its contribution to the amount of market-cleared reactive power obtained from the aggregate supply curve. An illustration of market clearing simulation is shown in Figure 3.8; this is one of the very few instances in which the CVR benefit is at such a level that at the cleared price, a reasonable amount of reactive power (e.g., 700 kVar) could be procured. In most of the instances, the CVR benefit is so low that the amount of reactive power acquired by the demand curve does not produce a significantly visible voltage reduction. This observation could be related to two aspects: one is the relatively small amount of voltage reduction achieved by reactive power consumption due to stiffness of the SCE feeder; the other is the portion of voltage-dependent loads in the feeder. During the time of this work, no reference study was found that characterized the feeder loads. Therefore, an assumption of 20% voltage dependency is considered (Lee Willis 2004), with 10% as constant current load and 10% as constant impedance load.

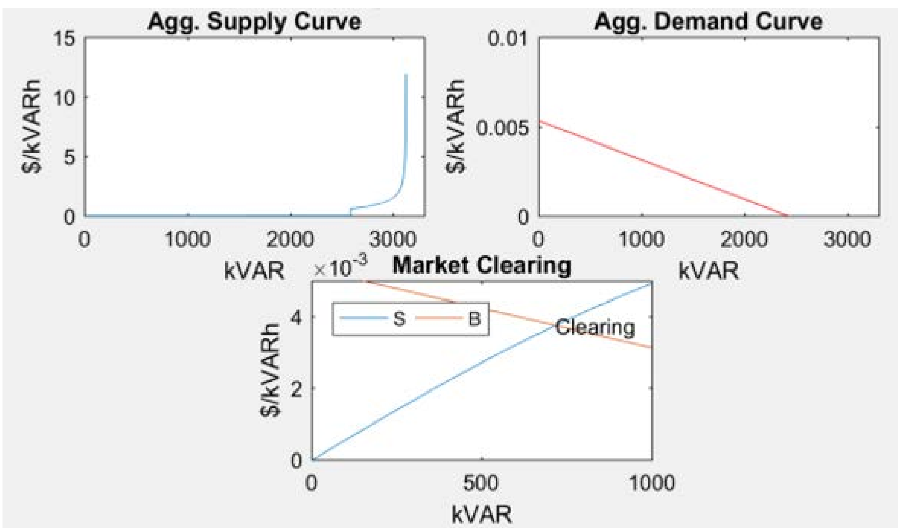


Figure 3.8. Market clearing simulation

The relatively low level of CVR-only benefit observed in a few instances of market clearing simulation using the data supplied by SCE indicated that monetization of other benefits would be necessary. The following subsection presents a CVR cost/benefit analysis using larger samples of SCE feeder load and PV data, and illustrates the need to stack use cases to enhance the amount of benefit.

3.3 CVR Cost/Benefit Analysis and Need for Benefit Stacking

To build an understanding of how CVR cost and benefit vary over the course of days, weeks, and months in a year, analysis is performed using fifteen minute market (FMM) locational marginal price (LMP) data from 2016. To limit the computational burden, one week from each month in 2016 is selected for the analysis. The week that contains the highest LMP of the month is selected for this analysis, because that is the time instant that would produce the highest CVR benefit.

Because CVR benefit is calculated using the savings produced by reducing feeder energy consumption, net positive benefit is obtained only when the wholesale electricity price is such that the cost of energy saved exceeds the cost of reactive power consumed by the inverter assets. Results from an illustrative day (September 26, 2016) with multiple occurrences of high LMP enabling positive net benefit are shown in Figure 3.9 and Figure 3.10. Total available reactive power capacity of the inverter assets throughout the day, as shown in Figure 3.9(a), makes it possible to reduce voltage for performing CVR. Using the amount of reactive power consumed SCE tariff profile shown in Figure 3.9(b) and the amount of reactive power consumed, the total reactive power cost heat map in the upper panel of Figure 3.10 is obtained. The costs are calculated using marginal cost curves of the assets derived using the approach shown in Section 3.1.1. Similarly, using the LMP values shown in Figure 3.9(b) and the reduction in energy consumption due to CVR, the heat map of CVR benefit in the lower part of Figure 3.10 is obtained. Hotspots in the CVR benefit heat map correspond to the time instances when high LMP occurred.

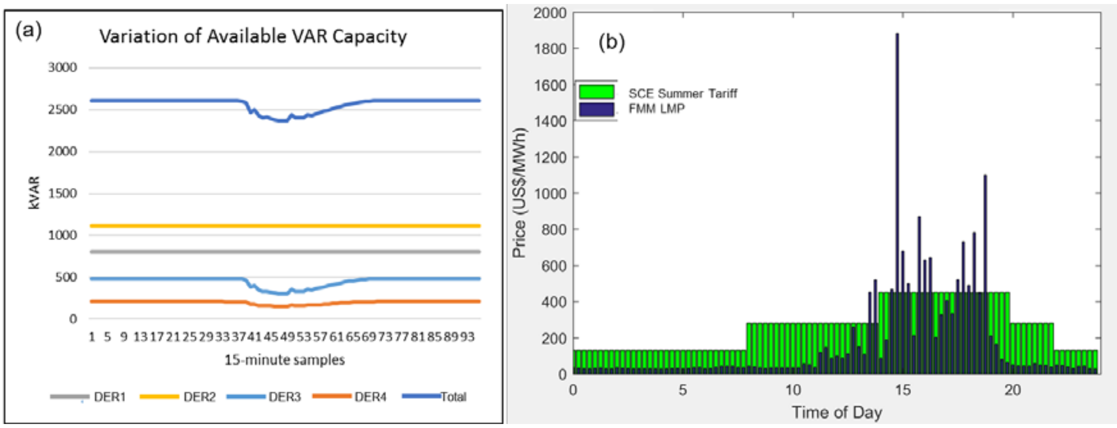


Figure 3.9. Calculating reactive power cost and CVR benefit: (a) variation of available reactive power capacity; (b) SCE Tariff and 15-minute market LMP

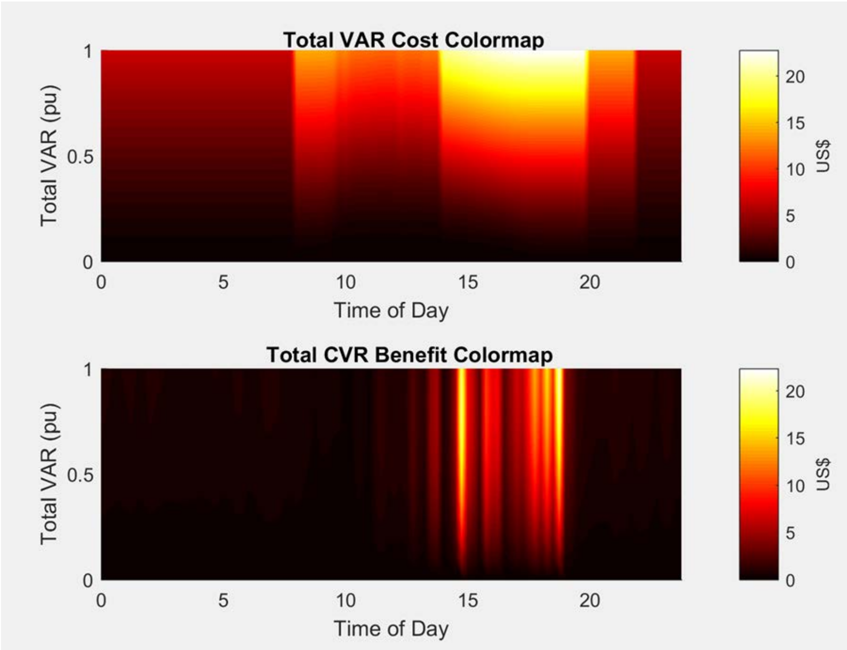


Figure 3.10. Heat maps of CVR cost/benefit for September 26, 2016

Values of net benefit obtained from CVR cost/benefit analysis performed using 12 weeks’ data are plotted in Figure 3.11, which shows there are only a few instances of positive net benefit in each week. Only 1.62% of the 15-minute time instances in the analysis horizon produced positive net benefit. Frequency of positive net benefit for each of the weeks is presented using a bar chart in Figure 3.12. The maximum number (26) of occurrences of positive net benefit is found in the week from September 23–29 that includes September 26, which is illustrated in Figure 3.10.

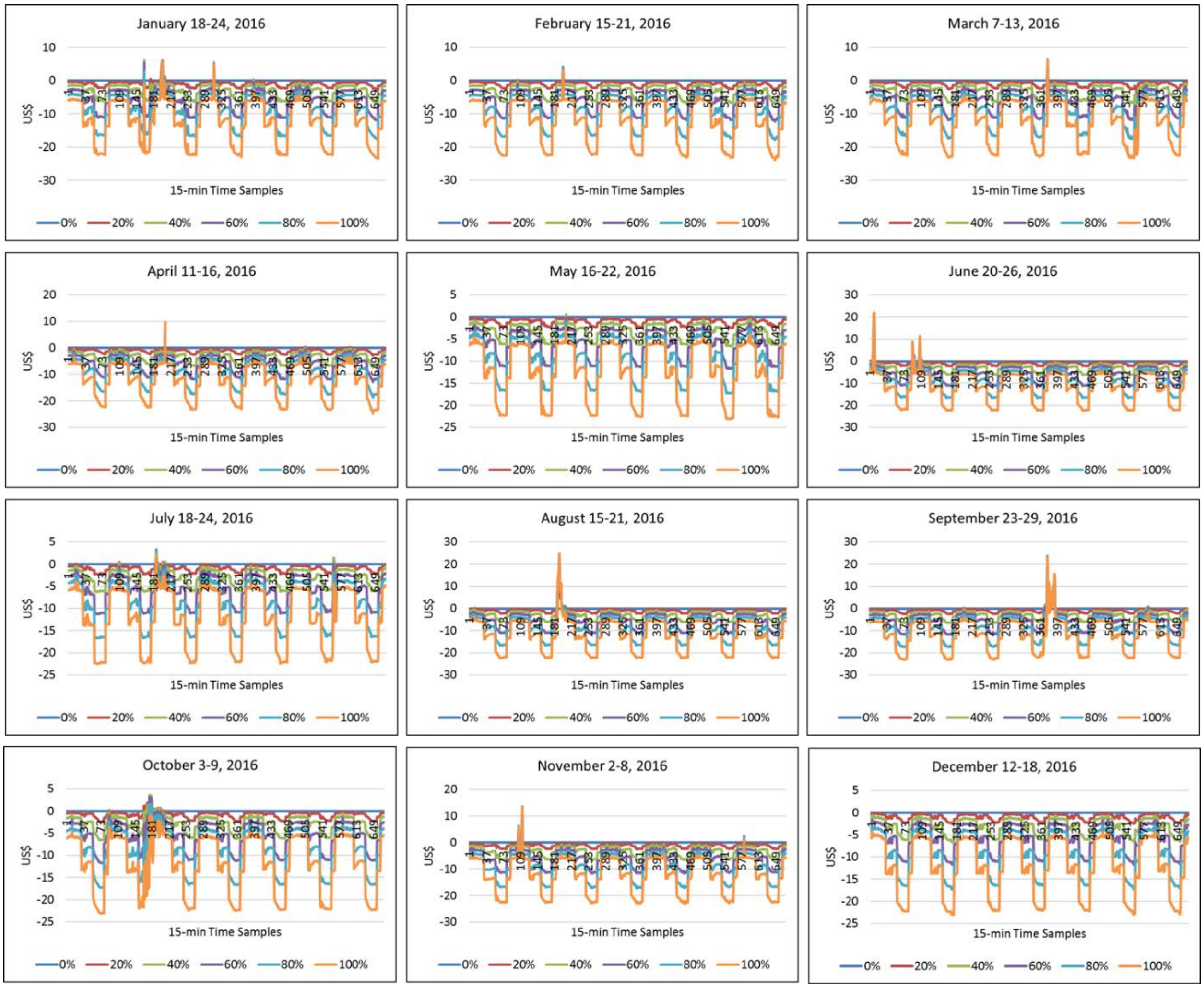


Figure 3.11. Net benefit in the selected weeks over 12 months

The lack of net benefit instances resulting from CVR alone suggests the need to explore additional benefits that could be stacked up to ensure acquiring the amount of VAR required for an intended purpose. An illustration of benefit stacking is presented below in relation to capacitor bank switching.

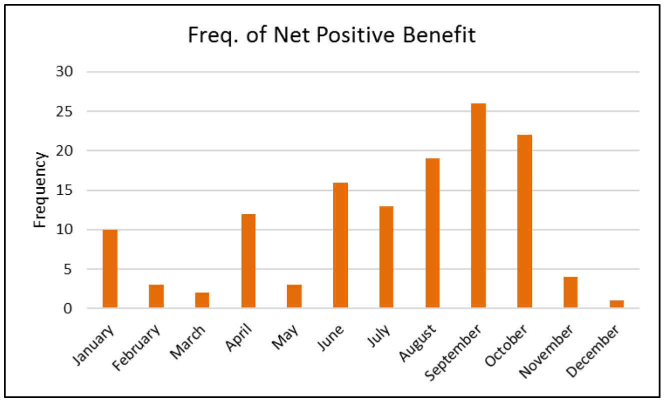
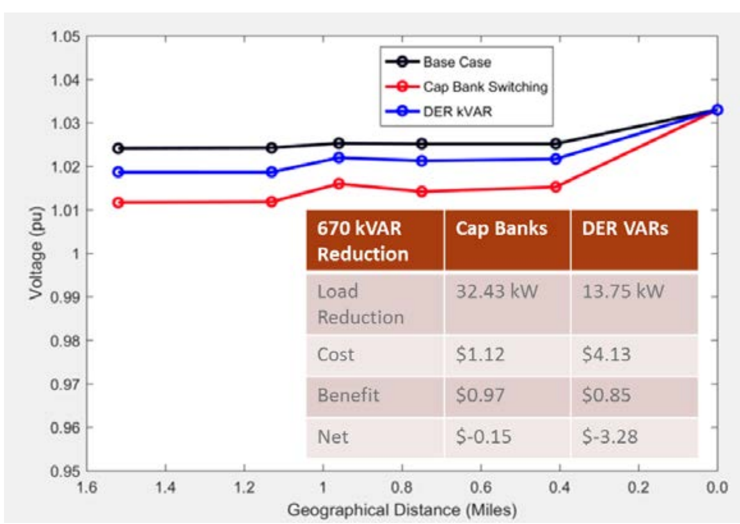


Figure 3.12. Frequency of net positive benefits in the selected weeks over 12 months

3.3.1 Benefit Stacking

To illustrate the concept of benefit stacking associated with use of inverters to source/sink reactive power, it is assumed that SCE intends to perform CVR by switching out a capacitor bank to reduce voltage. The switching operation, however, incurs a cost that can be determined from the rated number of switching events allowed over its lifetime. Therefore, when CVR is performed instead by absorbing reactive power through the smart inverters, it not only saves energy cost, but also avoids the cost of a switching operations. The red (bottom) line voltage profile in Figure 3.13 is created by switching out one third of the capacitance from the four banks in the feeder, which is equivalent to approximately 670 kVar. The blue line voltage profile in Figure 3.13 is created by absorbing the same amount of reactive power (670 kVar) using the inverters (only two of the DERs have been selected based on their locational similarity with the capacitor banks). The total benefit in this case is the CVR benefit plus the avoided cost of switching. Although in this occasion the benefit still does not exceed the cost, it illustrates a methodology to explore the possibility of stacking other benefits that could enhance the demand curve and acquire higher amount of reactive power when applied to a transactive process. The reason the CVR benefit produced by the inverters is lower than that of the capacitor banks is the locational effect of reactive power consumption on voltage reduction that is directly related to reduction of energy consumption.



670 kVAR Reduction	Cap Banks	DER VARs
Load Reduction	32.43 kW	13.75 kW
Cost	$1.12	$4.13
Benefit	$0.97	$0.85
Net	$-0.15	$-3.28

Figure 3.13. Illustration of benefit stacking

4.0 Voltage Management Planning and Assessment Tool

Results of the cost/benefit analysis of using inverters to produce or consume reactive power performed in Section 3 encourages the stacking of benefits from additional use cases. Since many use cases can be implicitly described in terms of voltage profiles (e.g., pushing a voltage profile down could create a CVR effect, while increasing voltage could provide voltage support during a peak load condition), one way to perform cost/benefit analysis of different reactive power related use cases would be to determine the cost of achieving a “desired” voltage profile by controlling reactive power that corresponds to the use case under consideration. This approach is implemented in the form of a planning and assessment tool in this work.

4.1 Tool Description

Different components of the tool and its operation are described below.

4.1.1 Tool Inputs

Network model (suitable for detailed power flow analysis), load profile, asset information (e.g., capability curve), the utility’s tariff, and wholesale electricity price at the relevant node are taken as inputs by the voltage management planning and assessment tool. User inputs, such as time instant, configuration of the assets as reactive power source or sink, and the percentage of reactive power capability to be used, are also needed, as shown in Figure 4.1.

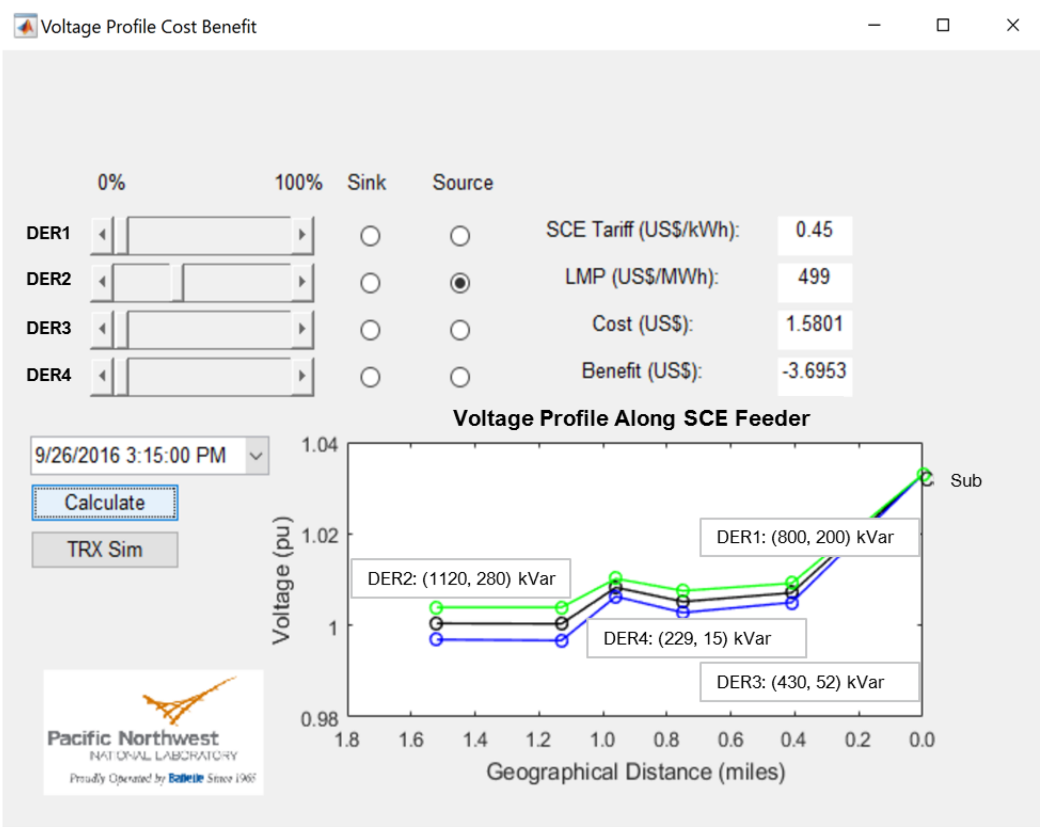


Figure 4.1. Screenshot of voltage management planning and assessment tool

4.1.2 Tool Outputs

The tool will perform power flow analysis and will provide voltage profiles resulting from the specified reactive power control configurations of the assets (e.g., operate as source or sink, percentage of reactive power) connected to the feeder. If the resources are not configured for reactive power control, then the voltage profile produced will be the base case voltage profile (black line in Figure 4.1). To illustrate the capability of the tool, both sink and source functions are considered. In Figure 4.1, the DER2 asset is configured as a reactive power sink and the reactive power percentage slider is set to 30%. With this configuration, the resulting voltage profile is the blue (bottom) line in the graph in Figure 4.1. This situation corresponds to CVR. The cost of reactive power consumption using DER4, calculated based on the marginal cost curve (supply curve), is also output by the tool, as indicated in the window adjacent to "Cost (US$)". To compare CVR benefit with its cost, the monetary value of energy saved, calculated using the wholesale electricity price, is also shown, in the window adjacent to "Benefit (US$)". The values in parentheses adjacent to the asset names (e.g., DER1, DER2) in the voltage profile window represent these assets' available reactive power capacity (without real power curtailment) and the total reactive power capacity for each asset. An illustration of configuring DER2 as a reactive power source is also given in Figure 4.1, and the resulting voltage profile is shown as the green (top) line.

Once the user performs cost/benefit analysis of a desired voltage profile and considers this instance worth exploring for transactive simulation, clicking the "TRX Sim" push button in Figure 4.1 launches the transactive simulation feature; outputs for the example described here are shown in Figure 4.2.

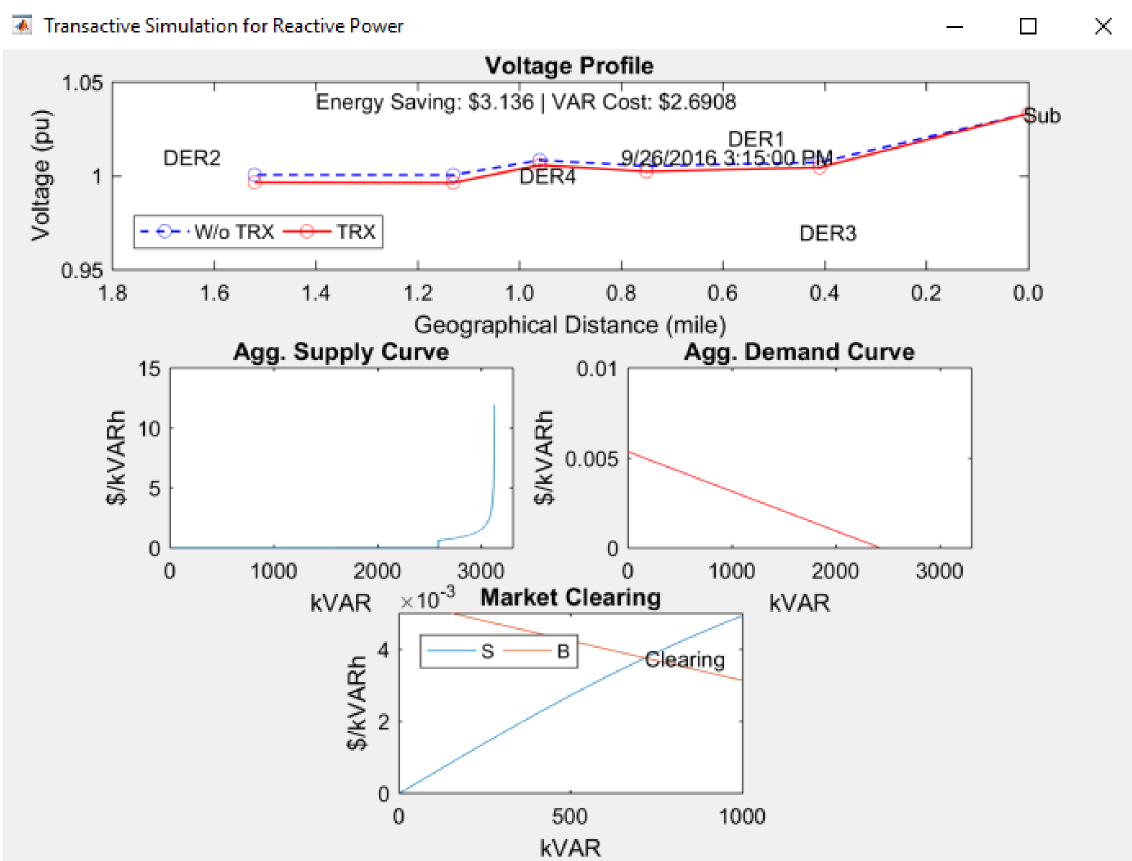


Figure 4.2. Screenshot of transactive simulation feature of the tool

4.1.3 Extension of the Tool for Other Use Cases

With the ability to assess the cost of achieving a desired voltage profile by engaging assets in a given distribution network, this tool would be able to model other relevant use cases for applying the transactive mechanism. The use case must be represented through a desired voltage profile to analyze cost and benefit. Two examples of additional use cases are briefly described below.

4.1.3.1 Dynamic Hosting Capacity for Renewable Energy Resources

Network impacts of high penetration of renewable energy resources into the distribution grid, and the necessity to limit penetration level due to the difficulties with managing those impacts, are well-known issues in the utility industry. Solar PV systems are the most common type of renewable energy resources integrated with distribution grids. Voltage rise and voltage fluctuations caused by solar PV are among the major impacts that could lead to limiting the PV penetration level in a given network. If distribution utilities could maintain a desired set of voltage profiles despite solar PV generation, they would be able to increase the solar PV hosting capacity limit. This limit can also be dynamic, to host different levels of PV penetration throughout the day with a varying set of desired voltage profiles. The tool being presented in this section can be extended to support this objective: (a) to determine the cost and benefit of a set of desired voltage profiles that enable higher PV penetration; (b) to create the elements (e.g., supply curves, demand curves) needed to assess the feasibility of creating those voltage profiles through a transactive process.

4.1.3.2 Network Switching for Reconfiguration

Distribution utilities often encounter situations that require reconfiguration of network topology by switching operations. Closing a normally open switch to supply a portion of the network from an alternative source is a common example of this situation. Depending on the topology and loading level of the network in the switched configuration, the voltage profiles may not always be within the utility's desired range. Inverters in a distribution network may be engaged to provide voltage management services to achieve the utility's desired voltage profiles. However, to assess the feasibility of implementing this use case with a transactive process, cost/benefit analysis of the desired voltage profiles needs to be performed, and the transactive process elements (e.g., supply and demand curve) need to be created. The tool can be extended to serve these purposes.

5.0 Conclusion

This project investigated the feasibility of applying a transactive mechanism for engaging inverters connected to SCE distribution feeders for voltage management purposes. The SCE feeder was chosen for the study due to the presence of multiple customer-owned solar PV and energy storage inverters. CVR was selected for the first use case to study. Lessons learned from this project could be applied to other distribution feeders in the SCE service territory to engage assets for additional use cases. Key outcomes from the project are listed below.

5.1 Key Outcomes

- A double-auction transactive approach to engage assets in a distribution feeder for voltage management services is designed, and successfully simulated for a simple but real proof-of-concept feeder and an SCE feeder.
- An approach for constructing supply curves for assets to participate in the transactive market process is developed incorporating their capability curve and efficiency curve.
- An approach for constructing demand curves for SCE to participate in the transactive process is developed based on the benefits of voltage management (e.g., CVR benefit)
- Analysis of the CVR benefit relative to the cost of engaging the assets is performed, including the need for benefit stacking, such as avoided cost of capacitor bank switching.
- A planning tool is developed to: (1) analyze the cost and benefit of voltage management for different use cases by engaging distribution network assets; and, (2) assess the feasibility of deploying a transactive mechanism to implement the use cases.

5.2 Future Directions

Within the current project scope:

- Identify and monetize benefits associated with desired voltage profiles corresponding to additional use cases.
- Set up a demonstration to engage the resources in the SCE feeder through a transactive process based on the project outcomes (e.g., cost/benefit analysis, supply curve, demand curve, market clearing tool).

Beyond the current project scope:

- Extend the planning tool to include additional functions, such as the ability to change the location, size, and penetration of inverter-based DERs.
- Extend the planning tool to include an optimal sizing and location function, based on a specified use case.

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Appendix A

CYME to GridLAB-D Conversion

SCE feeder models were provided in a self-contained study (SXST) file from CYMDIST. We converted this to GridLAB-D [1] using a process and tools, shown in Figure A1, that were developed in an on-going DOE project called GridAPPS-D. The overall steps are:

1. Convert the CYMDIST SXST file to OpenDSS format [2], using a PNNL-developed Python script called Cyme2DSS.py
2. Export the model from OpenDSS into the Common Information Model (CIM)
3. Load the CIM XML into a triple-store database [3]
4. Export the model from CIM XML into GridLAB-D format

This tool set supports other model formats not shown in Figure A1, and it is planned to publish all of these tools with documentation under an open source license on GitHub [4].

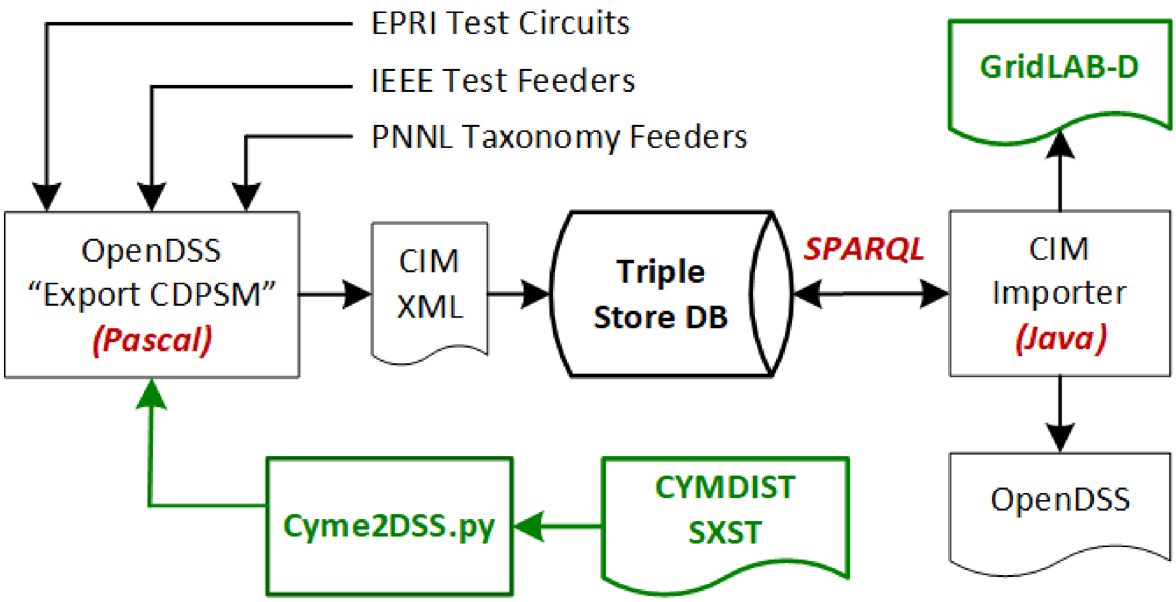

Figure A1: Model conversion process from CYMDIST through the Common Information Model to GridLAB-D

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