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CReST-VCT System Integration Framework

February 2020

JP Ogle
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U.S. DEPARTMENT OF ENERGY

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Summary

In this paper, we propose a system integration framework for deploying the Coordinated Real-time Sub-Transmission Volt-var Control Tool (CReST-VCT) functionality between the transmission system, the distribution system, and DERs. This represents one possible set of design choices to implement the coordinated optimization capabilities in an operating environment. The framework provides the following:

- an architectural reference model that describes how the CReST-VCT solution maps into a broader grid architecture that accommodates and enables higher levels of DER penetration and utilization
- a system integration reference model that defines a possible allocation of CReST-VCT functionality within a utility's operational environment. This includes one possible system design approach for allocation of functionality within software and protocol selections across the various interfaces
- A list of potential performance and security issues that should be considered during an implementation.

This framework does not represent a specific implementation of the CReST-VCT algorithm or integration into a specific utility environment. It is intended to serve as a reference for those who plan to implement such a solution into their environment. The general model provided by the framework can be tailored to a specific environment based on its specific constraints and requirements.

Acronyms and Abbreviations

API	application program interface
CReST-VCT	Coordinated Real-time Sub-Transmission Volt-Var Control Tool
DER	distributed energy resource
DERMS	distributed energy resource management system
DMS	distribution management system
DNP3	Distributed Network Protocol 3
EMS	energy management system
GW	gigawatts
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
OPF	optimal power flow
PV	photovoltaic
SCADA	supervisory control and data acquisition
T&D	transmission and distribution
TLS	Transport Layer Security
UML	Unified Modeling Language

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1.0 Introduction

Incorporation of decentralized generation or distributed energy resources (DERs) such as solar, wind, and demand response, combined with increasing storage, is transforming the electricity grid. Developers, consumers, and energy providers are turning to renewable DER sources to supplement or supplant traditional sources. Driven by reductions in costs, increases in electricity prices, and requirements for sustainability, renewable generation has been steadily increasing as shown in Figure 1. From 2008 to 2018, electricity generation from renewable sources doubled. Utility-scale photovoltaic (PV) capacity in 2018 was 30 gigawatts (GW), while small-scale PV was 20 GW (EIA 2019). This trend will have a dramatic effect on the industry.

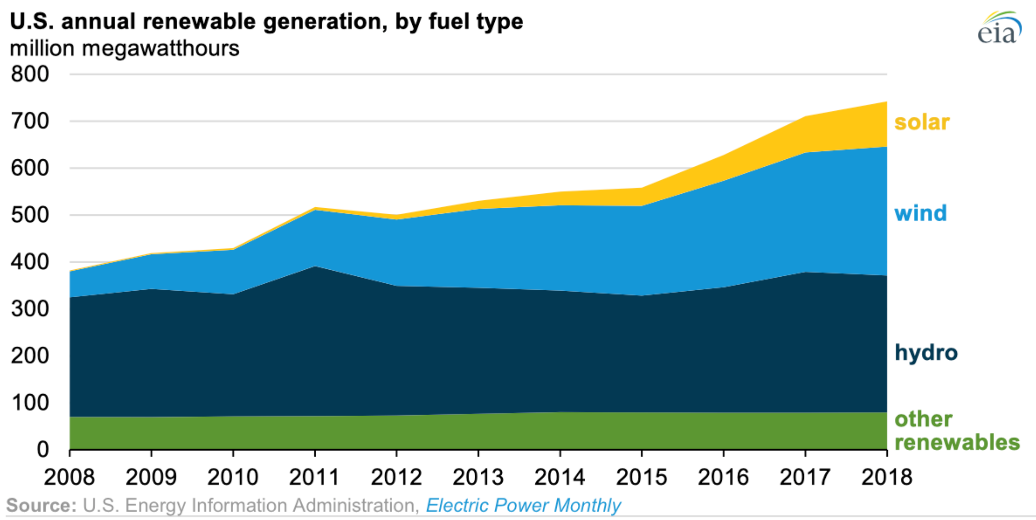

Figure 1. U.S. Annual Renewable Generation by Fuel Type (EIA 2019)

While the increasing numbers of DERs being integrated into the energy grid are creating new opportunities and challenges for grid operators, they must continue to fulfill the traditional expectations of safe, reliable, and affordable delivery of energy. To this end, industry, government organizations, and researchers have been developing tools that can increase system operational efficiency and reliability: substation automation, automated fault location identification, volt/var control, etc. Recently, Eaton developed the CYME Volt/var Optimization analysis module that helps find the optimal distribution network operation (Eaton 2019). In addition, Eaton developed the Yukon volt/var management solution that integrates with power quality distribution hardware control devices and optimizes the system further by managing the power factor (Eaton 2018). Recently, ETAP introduced a volt/var optimization tool that optimally manages system-wide voltage levels and reactive power flow to achieve efficient distribution grid operation (ETAP 2019). ABB, Siemens, Schweitzer Engineering Laboratory (SEL), and Dominion Energy also developed volt/var optimization solutions to increase distribution system operational efficiency (ABB 2018), (SEL 2018).

As described above, volt-var optimization is widely implemented in distribution systems. Increasing DER penetration in distribution systems make them more and more dynamic, with different volt-var profiles from traditional centralized supply models. With sufficient DER penetration, DERs can have both positive and negative effects on the upstream transmission system. By controlling the power injected into or absorbed by the distribution systems, which act as virtual power plants, transmission system operators in the energy management system

(EMS) control center can take advantage of the distributed DERs and also mitigate their negative effects on planning and operation of the transmission system. To achieve an optimal coordinative transmission and distribution (T&D) operation, T&D operators need to establish bidirectional communication and efficiently handle the computational effort required by the operation framework on each side. Because these capabilities have yet to be implemented, very limited information exchange and coordination exist between current EMS and distribution management system (DMS) T&D control centers. Co-optimization between transmission and distribution systems has thus not been implemented in practice yet.

Research focusing on closing the gap between transmission and distribution systems has recently been emerging. Sun et al. (2015) and Nguyen et al. (2019) present power system models and solutions of combined T&D systems. Singhal et al. (2017) discuss the benefits of improving long-term transmission voltage stability by incorporating a distribution model. The work in Singhal et al. (2017) proposes a framework to utilize distributed volt-var resources to support the transmission system by assuming that the distribution system is balanced. In Li et al. (2016, 2018) coordinated T&D optimization frameworks are developed for optimal power flow and economic dispatch. Ding et al. (2017) present hierarchical modeling for reactive power optimization with joint T&D networks by curve fitting . Zhao et al. (2019) propose coordinated restoration of a T&D system using a decentralized scheme. None of these works, however, address the communication challenges in such an integrated T&D system. In addition, most of the algorithms presented in the aforementioned research require multiple rounds of information exchange between EMS and DMS to achieve optimal system performance. This requirement poses a challenging computational problem for real-time applications.

As an extension of the existing works on co-optimization for integrated T&D systems, the Coordinated Real-time Sub-Transmission Volt-var Control Tool (CReST-VCT) is proposed to balance system performance, computational burden, and communication issues. Details of the performance and computation of CReST-VCT are shown in Ke et al. (2018), Sun et al. (2015), and Nguyen et al. (2019). This solution co-optimizes T&D control systems. The transmission control system requests grid services, such as reactive power support, from the distribution control system. The distribution control system evaluates its resources, including DERs, and determines the extent to which it can meet the request of the transmission system controller. It then reports the limits of its operations to the transmission control system for consideration at the next coordination interval.

Operation of systems such as CReST-VCT depends on the communication network between the various elements. Successful integration of the solution into a real-time operational environment will depend on the ability of the algorithm to complete necessary analysis and the ability of the communication system to transfer data reliably within necessary time constraints.

In this paper, we propose a system integration framework for deploying the CReST-VCT co-optimization functionality between the transmission system, the distribution system, and DERs. This represents one possible set of design choices to implement the coordinated optimization capabilities in an operating environment. The framework provides the following:

- an architectural reference model that describes how the CReST-VCT solution maps into a broader grid architecture that accommodates and enables higher levels of DER penetration and utilization

- a system integration reference model that defines a possible allocation of CReST-VCT functionality within a utility's operational environment. This includes one possible system design approach for allocation of functionality within software and protocol selections across the various interfaces
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This framework does not represent a specific implementation of the CReST-VCT algorithm or integration into a specific utility environment. It is intended to serve as a reference for those who plan to implement such a solution into their environment. The general model provided by the framework can be tailored to a specific environment based on its specific constraints and requirements.

2.0 System Architecture for Implementation of CReST-VCT

2.1 Grid Architecture Context

As highlighted in the introduction of this report, the number of DERs is increasing every year. This shift from a purely centralized model for supply of energy to a hybrid between centralized and distributed supply results in tighter coupling between transmission and distribution operations. To manage the complexity that this coupling can introduce, Taft et al. specified a grid architecture with a clear interface and responsibilities divided between the transmission system operator and the distribution system operator (Taft et al. 2015). In this model, the distribution operator takes responsibility for monitoring and control of DER assets. The transmission system operator makes requests for grid services from the distribution system operator. This allows the transmission system operator to benefit from DERs for resilience or supply flexibility while it allows the distribution operator to provide distribution system reliability. The structure simplifies the information flows between the distribution system operator and transmission system operator. The transmission system operator does not need detailed state information for the DERs because the distribution system operators are managing those interfaces (Taft 2017). This decoupling provides additional options to decompose the system into subsystems, aiming to increase scalability and ability of the system as a whole to manage more DERs. This structure is depicted in Figure 2

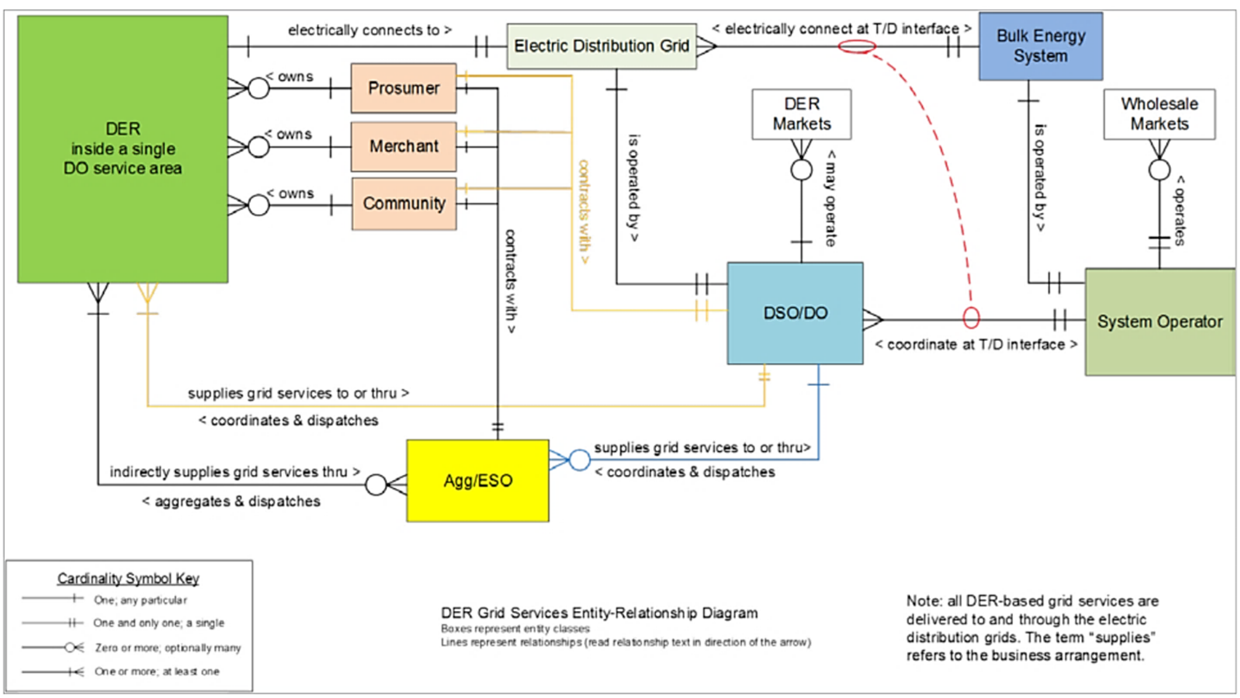

Figure 2. Transmission System Operator-Distribution System Operator–Based Model for DER Coordination (Taft 2017)

2.2 CReST-VCT Control System Architecture

The CReST-VCT control system architecture follows the principles of the grid architecture described above. As shown in Figure 3, CReST-VCT operates with a clear, logical interface between the transmission system and distribution system operations. At the beginning of an optimization interval, the transmission operation's EMS solves the volt-var optimization problem at the transmission level and sends a specific request for real and reactive power consumption/support to each downstream distribution system. Then each distribution operation's DMS solves its own optimization problem to determine the operating point for the local resources, including DERs, so that the transmission request is satisfied. The DMS then informs the EMS how much of the request it could satisfy.

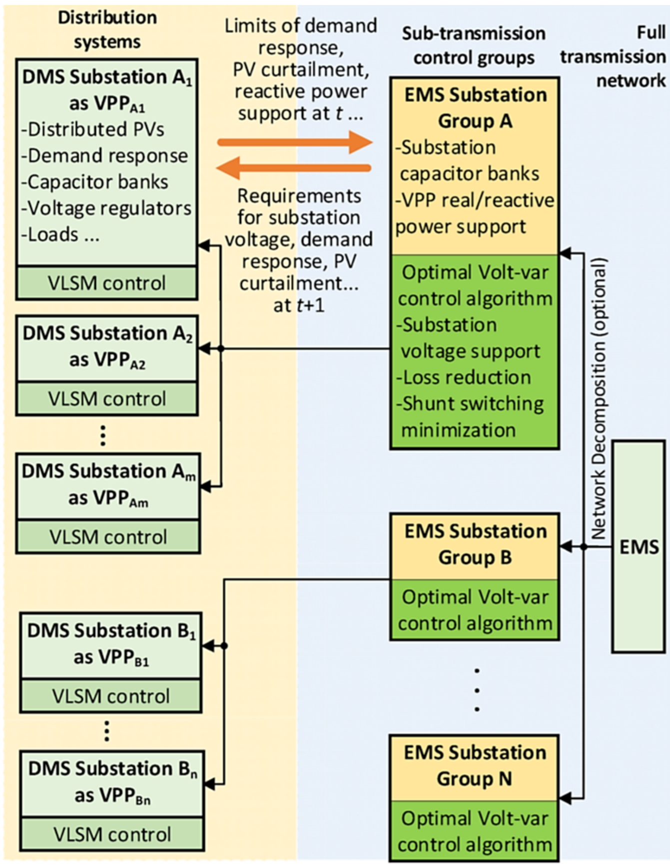

Figure 3. CReST-VCT Coordination Between Transmission and Distribution. VPP is virtual power plant; VLSM is voltage-load sensitivity matrix. (Ogle 2019)

The simplified information flow in this architecture approach is apparent, as the interface between the EMS and DMS is limited to just the request for real and reactive power support and the limits of the distribution system's response. The scalability of the approach can also be seen, as depicted in Figure 3, where the transmission side can decompose the system into different substation groups to manage processing or communication load. Similarly, the details of the types of DERs, controllable loads, or shunt devices on the distribution side are transparent to the EMS. The DMS can decompose these systems and their interfaces to manage its processing or communication load.

The CReST-VCT algorithm performs coordinated optimizations between the EMS and DMS at regular intervals. The frequency of operation for the algorithm is flexible, however, to actively control the reactive power in the system, re-running the algorithm every 5 minutes with updated measurements is optimal. The sequence of data flow is from measurement collection to EMS, to DMS, and then out to PV inverters. The control algorithms in the advanced applications at EMS and DMS are described in detail in Ke et al. (2018) and Zhu et al. (2018). Outside of the EMS and DMS, the collection of measurement and the communication flow of control signals are depicted in Figure 4. The expected duration for each of the stages, such that the entire operation is completed within 5 minutes, is also depicted. Preliminary tests indicate that solution of the CReST-VCT algorithm at the EMS takes about 45 seconds. The test was run at a research-scale facility, and performance might be faster in utility-scale computational infrastructure. About 15 seconds are expected for sending the newly calculated reactive power compensation request from EMS to DMS. The request can also include PV curtailment. Because an EMS might communicate with multiple DMSs, the communication may be staggered within those 15 seconds. At the DMS, solving the voltage-load sensitivity matrix-based volt-var control algorithm takes about 30 seconds, using the operating points from the EMS, to set real and reactive power dispatch set points for DERs and flexible resources. The DMS will also obtain the reactive power capacity from the DERs and aggregate the information.

The messaging to and from the DERs, and aggregation at the DMS, may take up to 120 seconds over various elements of communication infrastructure. An additional ~30 seconds will be required if re-optimization is required at the DMS. Dispatch of new set points, reaggregation of limits, if required, and sending the DER flexibility limits to the EMS may take about 60 seconds. The cycle is repeated every five minutes.

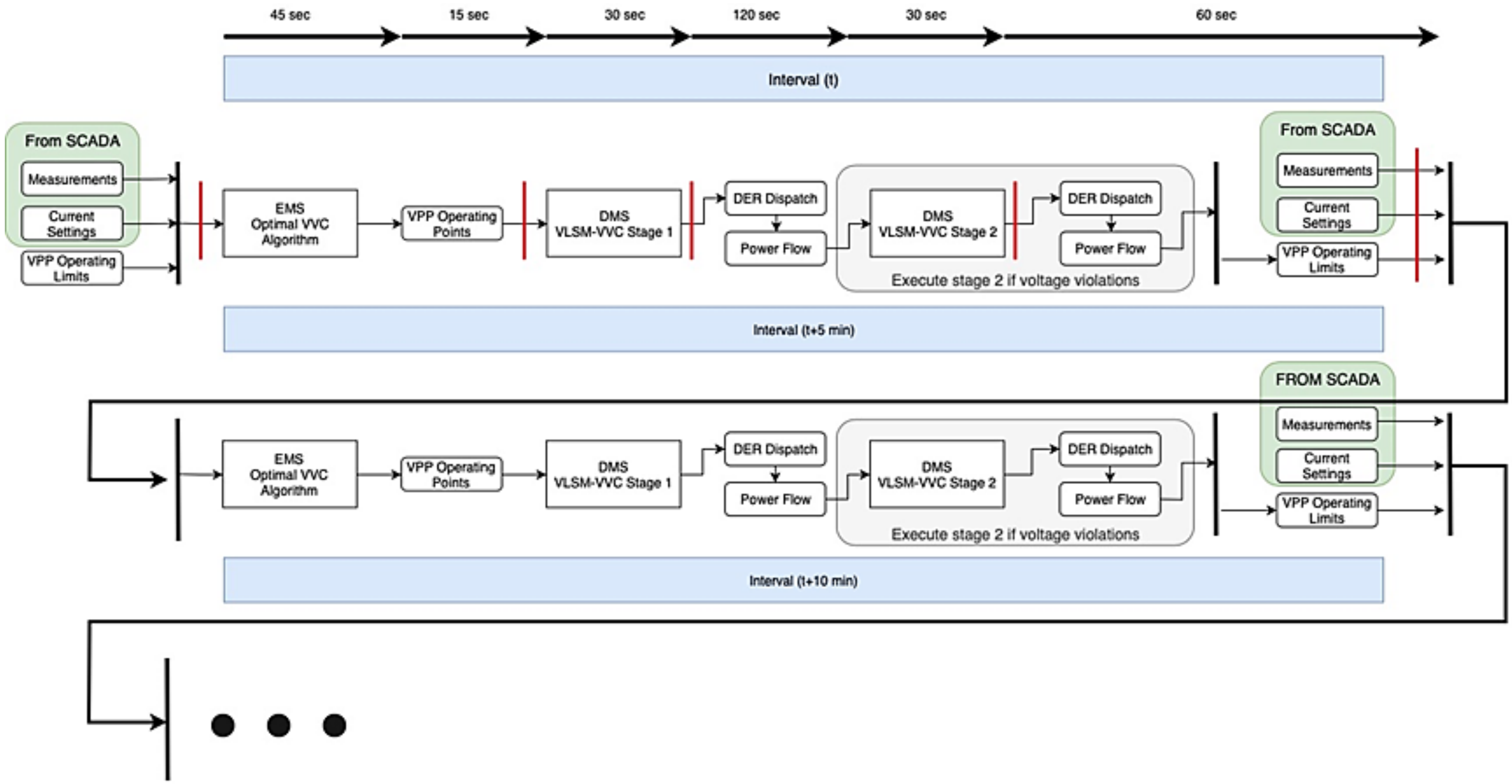

Figure 4. Operational Flow of CReST-VCT

3.0 CReST-VCT System Design Framework

In this section, a framework for implementation of CReST-VCT in an operational system is presented. The framework outlines one possible system design approach that defines the architecture structure, functional allocation to components, and resulting interfaces. Because electrical systems operate in many different physical and business environments, many variations of possible implementations can exist. While this represents only one approach, key considerations that may drive design choices are presented throughout to help tailor it to a particular operational environment.

3.1 CReST-VCT System Structure

The component diagram in Figure 5 shows the overall context for the operational environment in which CReST-VCT must be integrated. The Unified Modeling Language (UML) component diagram shows the relationship between the different components in a system. For this report, only the components interfaces that are relevant to CReST-VCT function are shown.

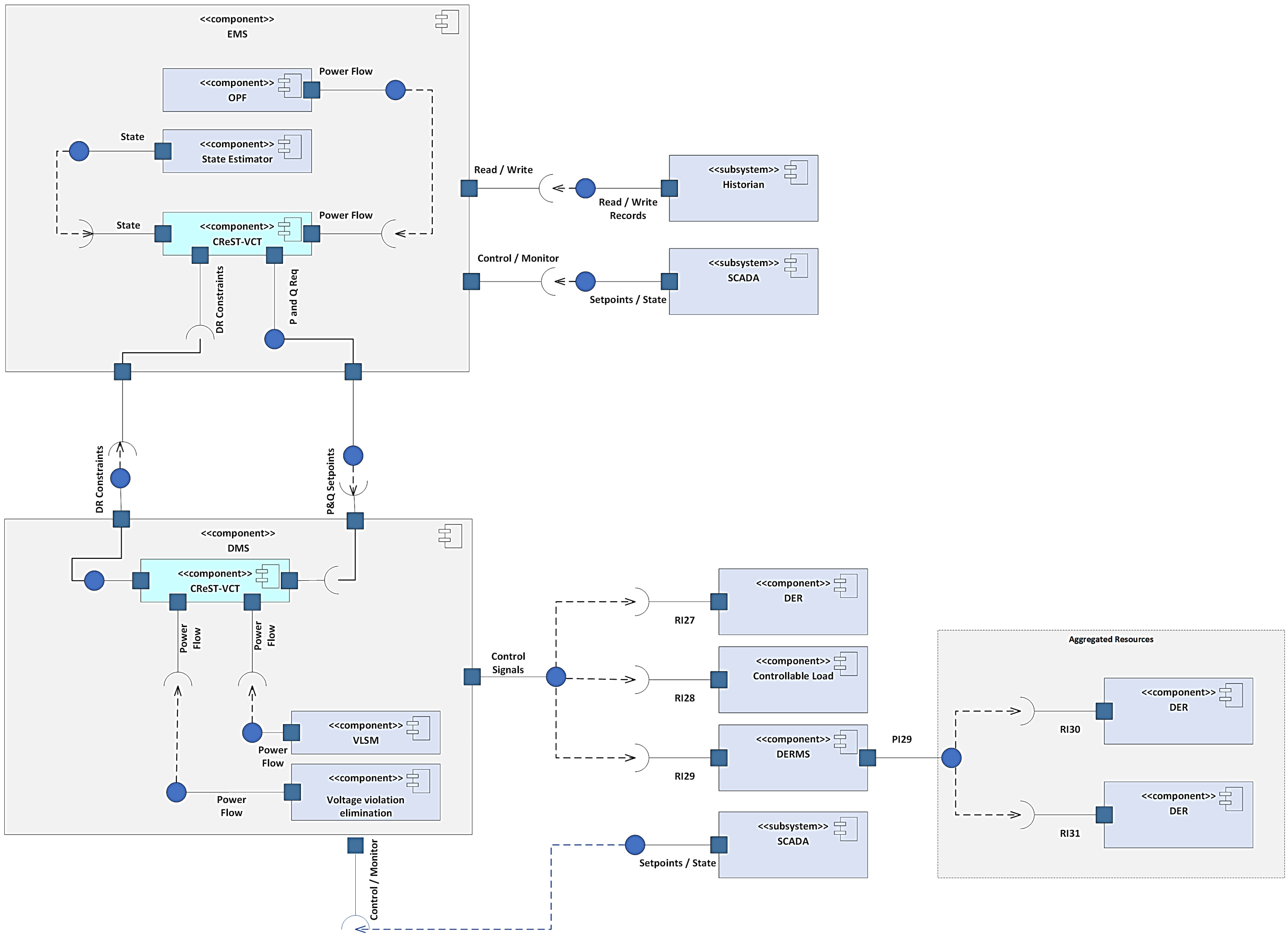

Figure 5. Component Diagram of CReST VCT in Operational Environment

3.1.1 EMS Subsystem

CReST-VCT would reside as one of the advanced applications in an EMS. It would have access to the data monitored by supervisory control and data acquisition (SCADA) and be able to store data in a historian or database. CReST-VCT would also require the state of the system from the state estimator application.

The current implementation of CReST-VCT acts as a solver for optimal power flow (OPF) using the General Algebraic Modeling System (GAMS) modeling language and commercial solver Knitro. Many EMS systems are also equipped with OPF tools. CReST-VCT can either leverage this or maintain stand-alone functionalities, so as to easily port between various vendors. In the component diagram, interfaces to an OPF system are indicated.

It is not feasible to specify the application program interfaces (APIs) for the CReST-VCT advanced application to be included within the EMS system, because this is usually proprietary information of the EMS system providers. An option to minimize API issues is to containerize the CReST-VCT advanced application using a platform like Docker. This would provide a common implementation that could be ported to a variety of different EMS systems. However, the EMS integration would still require translation from the EMS's unique APIs to those established by the container. Though CReST-VCT is not available as a container at this writing, that can be implemented if desired.

3.1.2 DMS Subsystem

Just as in an EMS, CReST-VCT will have an advanced application that resides in the DMS. As shown in Figure 4, this application takes into account requirements from CReST-VCT and allocates these requirements to its distributed resources so that the demand-response cost and the overall voltage deviation are minimized.

In the first stage, the requests for real and reactive power from the transmission system are optimally disaggregated to corresponding nodes such that the demand-response cost and the overall voltage deviation are minimized in the voltage-load sensitivity matrix, volt-var control algorithm. In the second stage, the objective is also to minimize the demand-response cost and eliminate voltage violations in the distribution system. The second-stage optimization is triggered only when voltage violations are detected in power flow results after the demand-response requirements have been executed in the first stage. Only controllable loads and smart inverters provide demand response in the second stage. Shunt capacitors and voltage regulators are disabled because their operation significantly affects the voltage along the feeder.

The DMS may have other advanced applications for distribution system optimization, such as integrated volt/var control. These applications can be dependent on control of the same assets that CReST-VCT uses. The DMS will need to make sure these applications are either not run at the same time over the same control area or that logic determines a nonconflicting set of operating points from multiple sets of advanced applications.

The CReST-VCT component will require telemetry data for DER and distribution assets through the SCADA system.. It is assumed the telemetry data is available within the DMS and the CReST-VCT component will interface using an appropriate data access API. To issue new operating points to the distribution assets in accordance with the CReST-VCT output, the DMS may communicate directly to DERs or may interface through a distributed energy resource management system (DERMS). The protocols used for these interfaces to these devices are discussed in a later section of this document.

Similar to the EMS integration, the details of the internal interfaces between the CReST-VCT and the DMS system are expected to be dependent on the vendor-specific DMS software and are not specified here. It is assumed that the CReST-VCT software will need to conform to the appropriate vendor-specific API. Again, this does not preclude the existing CReST-VCT software implementation from being implemented in a container as a stand-alone element or the DMS from implementing appropriate interfaces to the container.

3.2 CReST-VCT System Interfaces

In this section, the communication interfaces between the components used by the CReST-VCT solution are identified. These communication flows cross several different communication network domains in the utility operational environment and use several different protocols. The diverse communication network landscape was discussed in our previous work (Ogle et al. 2019). For reference, the high-level network diagram is shown in Figure 6.

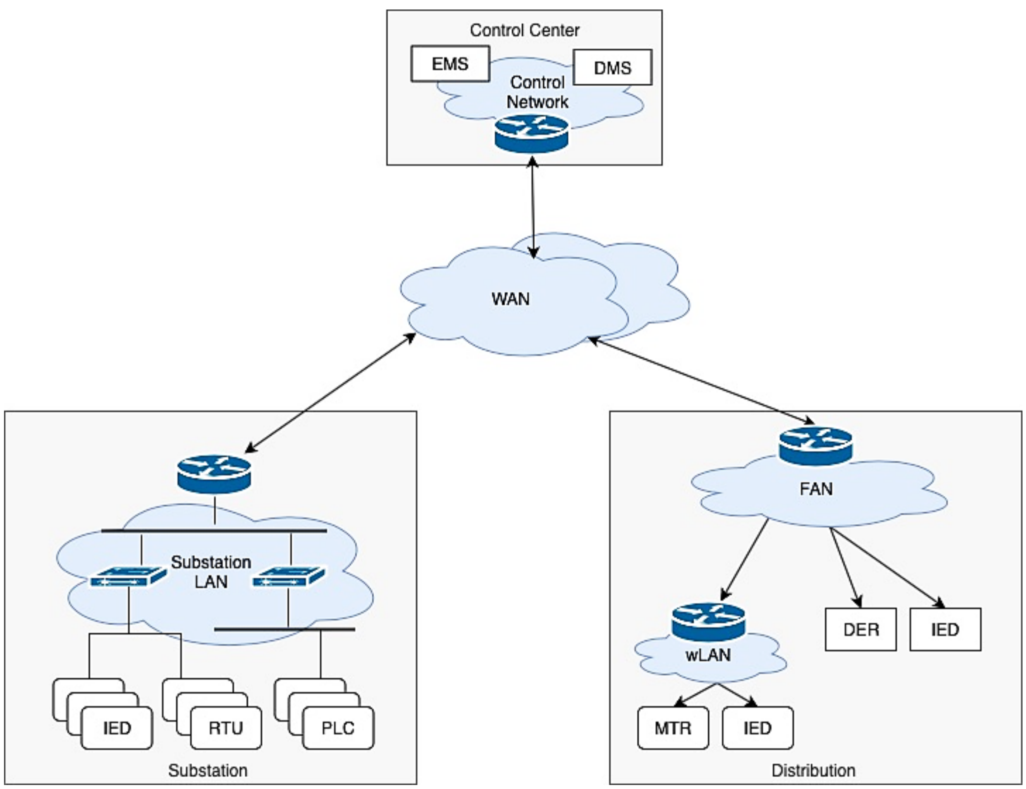

Figure 6. Communication Networks Supporting CReST-VCT

The UML sequence chart in Figure 7 depicts the communication flow and information exchange between the system components used in the CReST-VCT solution.

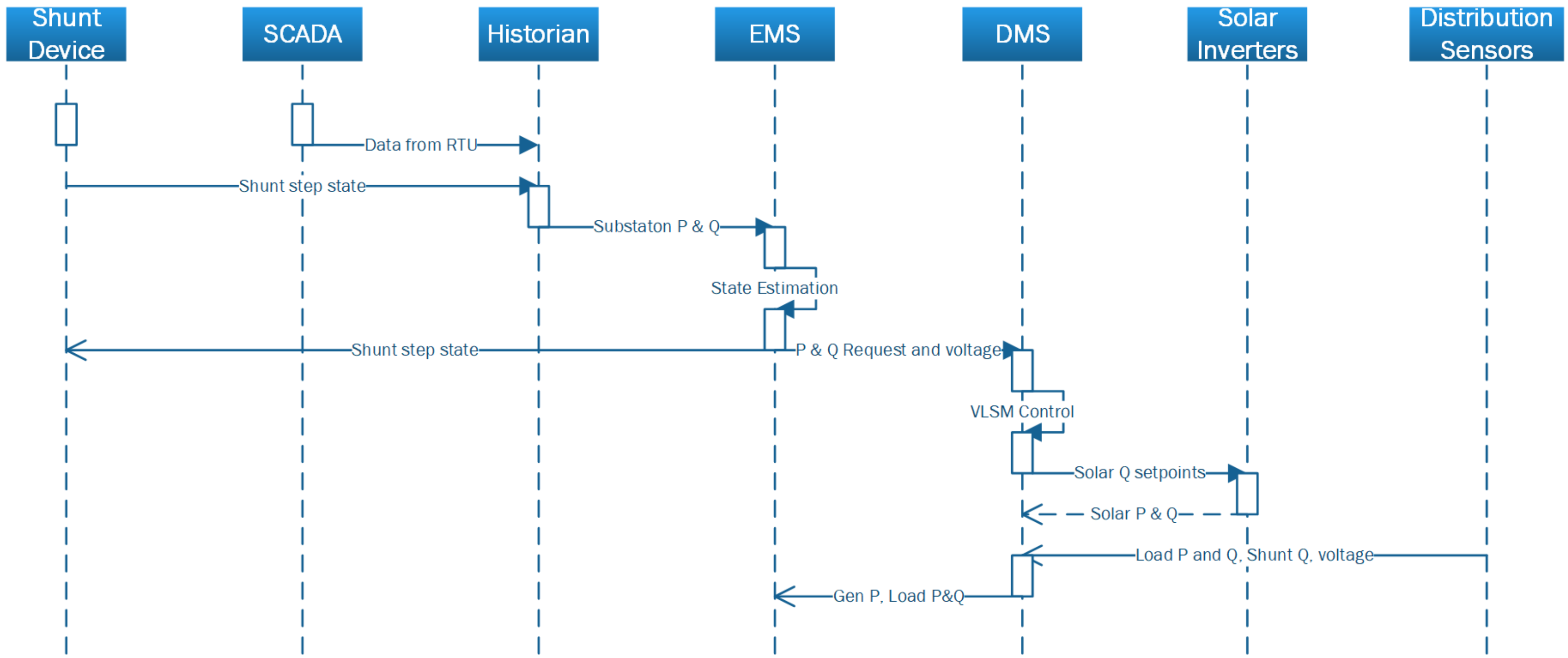

Figure 7. Data Exchange of CReST-VCT Across Subtransmission, Distribution, and DERs

3.2.1 EMS-DMS Interface

Connection from EMS to DMS is often point-to-point, dedicated connection. The messages that would be passed through this channel include the reactive power required to maintain voltage stability in the subtransmission network, substation voltage, aggregated PV curtailment, and demand-response requirement. No generally accepted standard protocol was identified for this interface in our research. This may be a sign of the relatively new nature of coordination between EMS and DMS. Because both EMS and DMS systems use Distributed Network Protocol 3 (DNP3) to communicate with power system components, our assumption for this paper is that the EMS-to-DMS interface to support CReST-VCT would be implemented in DNP3.

3.2.2 DMS to Inverters

Connection from DMS to DERs is an area of rapid evolution. Standards are being updated or developed to take into consideration the variability in the many DERs systems from different vendors. California Rule 21 (CPUC 2019) and Hawaii Rule 14 (PG&E 2018) have mandated communication capabilities and availability of advanced functions in solar inverters with remote controllability. These developments are timely, as the penetration of PVs has been increasing, especially in the states of California and Hawaii. The Institute of Electrical and Electronics Engineers (IEEE) Standard 2030.5, Smart Energy Profile 2, (SEP2, IEEE 2018b) defines open standards for communications and data format for DERs (Power Line Communications Committee 2013). IEEE Standard 1547-2018 specifies standard choices for communication at the DER as well as mandatory advanced capabilities (IEEE 2018a). Such standards support realization of requirements such as those specified by California Rule 21. However, a variety of different protocol options are still in use today.

Utilities have often had to face interoperability challenges for communication networks. Each utility standardizes internally, adopting the collection of standards that best suits their particular environment, and uses it to dictate procurement decisions. Therefore, the protocols used to integrate CReST-VCT into a utility’s operations may differ according to the network architecture and technology of that given utility. It is expected that the chosen set of protocols and the communication networks used will need to be able to handle various configurations of DERs such as individual, aggregated, and utility-scaled DERs (IEEE 2018c). An example of a utility’s communication systems and DER interface using different communication protocols is shown in Figure 8.

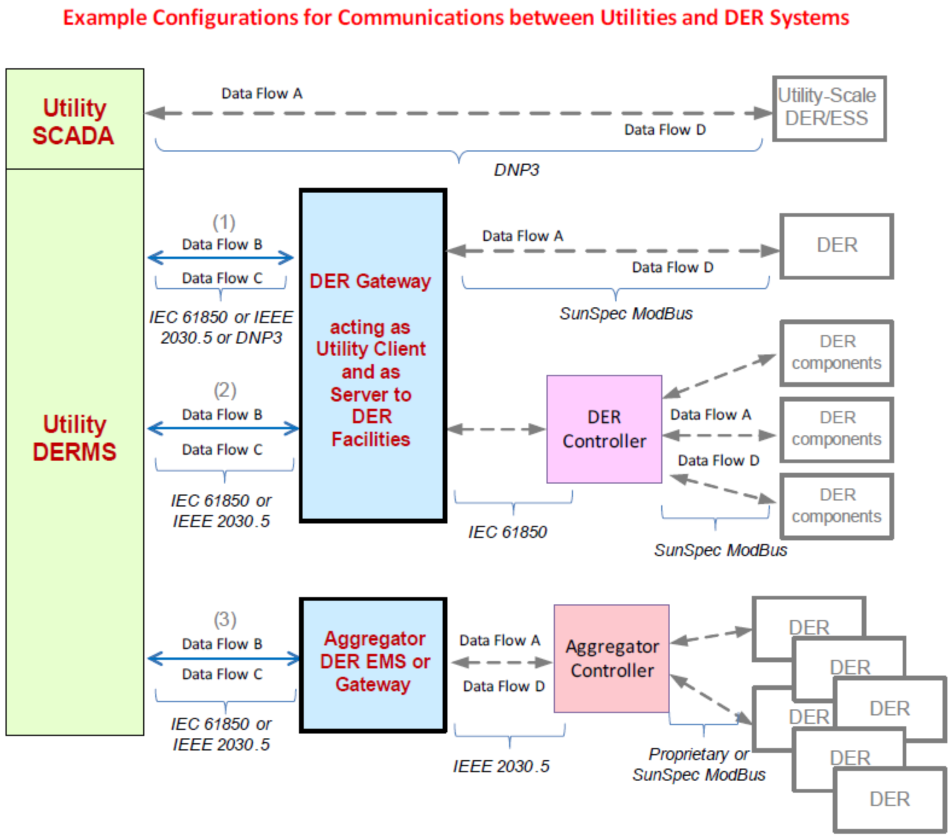

Figure 8. Communication Protocol Configurations for Interface to DER Components (IEEE 2018c)

The protocols in this sample configuration include IEEE Std 2030.5 (SEP2), IEEE Std 1815 (DNP3), and SunSpec Modbus. Although International Electrotechnical Commission (IEC) Standard 61850 is not directly indicated as one of the mandatory protocols in IEEE Standard 1547-2018, it is expected to be used globally for DER interactions with utilities (IEEE 2018c). The main properties, operation, and interoperability of these protocols can be summarized as follows:

- Modbus is a protocol widely used with most DERs to exchange local data rapidly between the DER controller and the inverter, the PV panels, the battery, and internal meters, as well as to local plant energy management systems. However, because each DER manufacturer defines its own proprietary version of Modbus, these implementations are not consistent or interoperable. Therefore, SunSpec and other groups, such as the Modular Energy Storage Architecture (MESA) Standards Alliance, have developed “standardized” profiles of Modbus data points that are specified by the new IEEE 1457. This standard Modbus protocol can be used interoperably by different DER manufacturers.
- IEEE 1815 (DNP3) is a SCADA protocol that is used by most North American utilities for rapid monitoring and control of utility equipment such as bulk power plants and now utility-scale DERs. Compared to Modbus, DNP3 is more reliable for long-distance communication. Since each utility has specified DNP3 uniquely for their own SCADA systems, there have not been any standard or interoperable DNP3 profiles. This design was not a problem in the past, because utilities only communicated with their own equipment. However, since current DER systems from different manufacturers need to communicate with different utilities, the

MESA Standards Alliance and the Electric Power Research Institute have developed a standardized DNP3 profile that was updated in parallel with the revision process of IEEE 1547. Therefore, this DNP3 protocol supports all the IEEE 1547 interoperability requirements.

- IEEE 2030.5 (SEP2) is a web-based protocol with its own DER information model, based originally on the IEC 61850-7-420 DER information model. This protocol was selected as the default protocol for California's Rule 21 implementations for those interactions between utilities and aggregators or DERs that are have response times of 5–15 minutes or longer. This protocol is used primarily to establish the settings for autonomous functions, send schedules of actions, and monitor periodic information from aggregators and groups of DERs.
- IEC 61850 has both the DER information model in IEC 61850-7-420 and two IEC 61850 standard protocols, IEC 61850-8-1 and IEC 61850-8-2. IEC 61850-7-420 has updated its information model to cover all the IEEE 1547 (and European) grid code requirements. IEC 61850-8-1 was designed for the extremely rapid (microsecond) interactions needed for protection and other functions in substation automation. IEC 61850-8-2 is web-based for "Internet of Things" implementations, and it uses the well-established Internet Engineering Task Force Extensible Messaging and Presence Protocol "chat" technology to provide rapid (seconds) interactions with individual DERs as well as with aggregators, facilities, and groups of DERs.

For this CReST-VCT system implementation, we assume that the interface for utility-owned DERs will use the DNP3 protocol. This protocol is widely used for existing SCADA interfaces with EMS and DMS. It is assumed the EMS and DMS would define appropriate data points for DER controllers, consistent with their existing operational practices.

For larger non-utility owned DERs, the DMS will interface via a DERMS systems or directly using IEEE 2030.5 SEP2 application protocol. For smaller DERs, the assumption is that an aggregator will manage the individual DERs and the utility will interface with the aggregator using IEEE 2030.5.

Other protocols, such as IEC 61850 and SunSpec Modbus, may be deployed at intermediate stages in the communication path or at the local interface. However, the use of these protocols as intermediaries is not visible to the utility's DMS or DERMS and is not discussed in detail in the CReST-VCT integration scope. Note that IEEE 2030.5 does leverage some data model elements of IEEE 61850, which is described below. IEEE 1547-2018 provides key information relevant to capabilities of DER for grid services and ultimately informs the data to be exchanged, and is therefore relevant.

Key considerations of the protocols relevant to this assumed CReST-VCT implementation are discussed below.

3.2.2.1 IEEE 2030.5 Considerations

Basic IEEE 2030.5 implementation requires DERs connected to the grid to be able to provide certification, discovery, secured Hypertext Transfer Protocol Secure (HTTPS), time synchronization, DER data collection, and controls. The IEEE 2030.5 protocol is based on the client/server model that uses representational state transfer (REST) architecture by using the core HTTP methods of GET, HEAD, PUT, POST, and DELETE. HTTP uses Transmission Control Protocol (TCP) as its transport protocol. In this IEEE 2030.5 protocol, the server should be implemented at the utility communications gateway, and the client is implemented at the aggregator system or DER clients. CreST-VCT also requires a design based on a client/server model to initiate control command through IEEE 2030.5, where the server is in the DMS and EMS and the client is located on the inverter.

In the IEEE 2030.5 protocol, servers expose some information (e.g., volt-var curve) of physical assets, and those pieces of information are called resources. Resources are defined in the IEEE 2030.5 XML schema, and the access method is written in Web Application Description Language (WADL). To use IEEE 2030.5 protocol, CReST-VCT should have should have an XML schema provided and capability to access resources information by reading WADL.

To implement IEEE 2030.5 functionality at the DMS and EMS level, the utility server must have the capabilities of time, device capability, end device, function set assignment, log event, subscription/notification, and a security function set.

To control the DER inverter, IEEE 2030.5 uses two types of control command:

- *DERControl* – An IEEE 2030.5 control event signal that contains a start time, a duration, and a control parameter value. *DERControl* events can be scheduled, superseded, canceled, etc. If configured, the utility DER server can receive the event status responses (e.g., received, started, completed, superseded, etc.) from each DER.
- *DefaultDERControl* – An IEEE 2030.5 control resource that is in effect if there are no active *DERControl*s for that resource.

For example, if used to modify a setting with start time “now” and end time “infinite,” *DefaultDERControl* can be created or updated. A limitation with *DefaultDERControl* is that there are no status responses. If status responses for modification of settings are needed, the utility server can use *DERControl* events. To accomplish this, the start time of the *DERControl* is “now.” And the duration is set to a very large, effectively infinite, number. To change the *DERControl* setting, a new *DERControl* is issued to supersede or cancel the existing DERControl. Hence, setting *DERControl* with start time “now” and end time effectively infinite would be appropriate for CReST-VCT.

Should there be a loss of communications, DERs SHALL complete any scheduled event and then revert to default settings or other settings, as determined by the site host or tariffs/contracts.

For direct DER communication scenarios, CReST-VCT should always initiate communication from the client side to the utility by maintaining predefined polling and posting intervals to make sure the DER has up-to-date settings.

The application layer of IEEE 2030.5 supports RESTful HTTP/1.1 as the application data exchange semantics. HTTP supports a variety of header types based on different applications. The accepted header length for IEEE 20303.5 varies from 35 octets to 106 octets. Some HTTP headers categorized as mandatory by the IEEE 2030.5 standard are Accept, Content Type, Allow, Date, Host, and Location.

Many different inverter models exist from different manufacturers. This diversity makes it very complex to build an intelligent grid that leverages solar resources using Modbus.
IEC 61850-7-420 standard is being improved to address this large-scale integration need by implementing an engineering process based on Substation Configuration Language. This

language eliminates manual mapping, automates configuration, and develops logical nodes for DER. The IEC 61850 abstract information model has been selected to provide the basis of the communication requirements in IEEE 2030.5. IEC 61850-90-7 provides specific object models for IEEE 2030.5 functions while IEC 61850-7-420 provides abstract information models for general data exchanges with DER systems. Hence, the CReST-VCT system will conform to IEC 61850 in order to incorporate the DER data exchange.

DER data that are being exchanged in each message have been modeled using the IEC 61850 data information model. This information model provides standardized names and structures to the data. In this information model, there are logical nodes that serve specific functions of a logical device. For example, a PV system is a device and comes with a wide range of capabilities, and each of the capabilities has its own logical node. Some logical nodes that are include in the PV system logical device are described below:

- DPVM: PV module ratings
- DPVA: PV array characteristics
- DPVC: PV array controller
- CSWI: Controller for operation of the various PV switches
- XSWI: DC switch between the PV system and the inverter.

3.2.2.2 IEEE 1547 Considerations

According to IEEE Standard 1547-2018 (IEEE 2018a), all DERs are required to have provisions for a local DER interface. This interface is for information exchange requirements that are specified in this standard to help DERs achieve voltage and frequency ride-through as well as voltage and frequency regulation. These functionalities are not within the scope of CReST-VCT. Other communication capabilities are allowed under mutual agreement between the DMS system operator and DER operator. The decision to whether use the local DER communication interface or a communication network is determined by the DMS system operator. Because CReST-VCT is based on a centralized operation that starts from an EMS subtransmission control center and proceeds to DMS distribution control centers and to each individual DER, a communication network needs to be established. Therefore, based on IEEE Std. 1547-2018, the DMS system operator needs to establish a communication network in addition to the local DER communication interface. In case of a communication failure, DERs can either switch to the local control mode through the local DER communication interface or keep using the centralized control with the reference set points from the previous time steps until the connection to the control center is reestablished.

For information interoperability, IEEE 1547 defines a unified information model. The information exchanged in this model is classified into the following four categories:

- Nameplate information – This information is the as-built characteristics of DERs. In CReST-VCT, the information used includes maximum apparent and active power ratings and AC nominal, maximum, and minimum voltage ratings. These parameters are required for the OPF algorithm at the DMS control center.
- Configuration information – This information is available through the local DER communication interface to provide an alternative for nameplate information, which cannot be changed. If the configuration information is different from the nameplate information, the former will be used. However, changes to the configuration information must be agreed

upon by both the DER system operator and the distribution operator. CreST-VCT does not include any configuration information in the OPF algorithm.

- Monitoring information – This information indicates the present operating conditions of the DER. This information is only used for situational awareness at the DMS control center.
- Management information – This information is extremely important for the operation of CReST-VCT, because the output of the OPF algorithm will be used to update the operating parameters for each DER, given the variations of load and PVs. The management information varies with the operation modes of a DER, such as constant-power-factor mode, voltage–reactive-power mode, constant-reactive-power mode, and real-power–reactive power mode. For CReST-VCT, however, only the real-power–reactive-power mode is deployed. Therefore, only active-power- and reactive-power-mode parameters are needed for the designed operation of CReST-VCT.

IEEE 1547 only specifies the local communication protocols. Regarding communication protocols, only protocols applied at the local DER communication interface are specified by IEEE Standard 1547-2018, as shown in Figure 9.

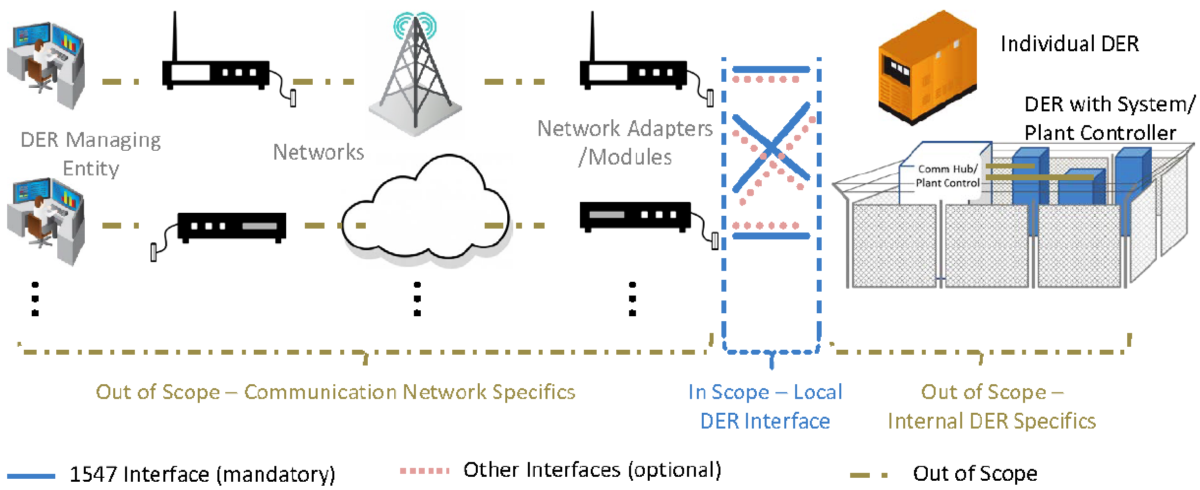

Figure 9. IEEE 1547 Standard Scope (IEEE 2018a)

4.0 Performance Analysis

4.1 Potential Communication Variation

CreST-VCT operation relies on a bidirectional flow of operational parameters and constraints between the transmission and distribution sides. The performance of the system depends greatly on the latency of the communication process. The faster a message flows between the two sides, the better performance system achieves.

However, there is a significant potential variation in the performance of communication networks that can be adopted for CReST-VCT applications. First, the communication latency and bandwidth vary with the chosen protocol and the layer of the network where the control resources of CReST-VCT, such as an inverter-based PV, are connected. For example, a DER connected at the neighborhood area network layer will have significantly more latency than a device connected at the substation local area network, as shown in Table 1. Feeder devices such as regulators, capacitor banks, or DERs connected at the field area network layer or the neighborhood area network layer are subject to the widest range of possible communication network performance. Advanced metering infrastructure networks also contribute to the variation, because their data rates can range from 10 kbps to 1.2 Mbps. Also, the specific geographic location with reference to network infrastructure, the surrounding topology, and network utilization also introduce variations in performance in a communication network such as a wireless network. (Gember et al. 2012). Congestion in cellular networks might introduce significant variations over the course of a day, with business hours being having the highest latencies.

Table 1. Typical Required Network Characteristics for Smart Grid Applications

Network Tier	Bandwidth	Latency	Availability
Wide area network	>1 Gbps	<50 ms	Very High
Secured local area network	>10 Mbps	<10 ms	Very High
Field area network	>1.2 Mbps	<1 s	High
Neighborhood area network	>100 kbps	<30 s	Medium

To obtain the potential benefits of the CReST-VCT, the communications must meet minimum response times. The timing requirements were discussed in a previous report (Ogle et. al. 2019). Timing requirements are defined independent of CReST-VCT as well. According to Hawaii Rule 14H, an advanced inverter shall actively control its reactive power output and provide dynamic reactive power compensation within a certain response time. The default values for the volt-var function according to Hawaii Rule 14H are indicated in Table 2.

Table 2. Volt-var Settings of Smart Inverters Defined in Hawaii Rule 14

Parameters	Default value
V_{ref}	Nominal Voltage (V_N) (e.g., 120 volts)
V_2	V_{ref} − 0.03 of V_N
Q_2	0
V_3	V_{ref} + 0.03 of V_N
Q_3	0
V_1	V_{ref} − 0.06 of V_N
Q_1	44% of nameplate apparent power
V_4	V_{ref} + 0.06 of V_N
Q_4	44% of nameplate apparent power
Response time	10 Seconds

Hawaiian Electric Companies states the following requirements for DER and storage management applications:

- Latency: 20 milliseconds – 14 seconds
- Bandwidth: 9.6–56 kilobits per second
- Coverage: 90%–100%
- Reliability: 99%–99.99%
- Backup: 1 hour backup (HECO 2018)

Given the variability in performance of candidate communication networks, their structure, technology, and external environment factors make it possible for the selected communication network to introduce enough latency or unreliability to negatively affect CReST-VCT operation and fail to meet requirements such as those highlighted above. During the system model analysis, a system planning engineer must carefully analyze, and probably optimize, the designed communication network and protocol so that at least the minimum requirements of the communication network characteristics are guaranteed for successful electrical operation of CReST-VCT. The final decision is likely to be a compromise between the operational benefits, i.e., loss reduction and voltage stabilization, and investment cost.

4.2 Effects of Communication Delays

As described above, CReST-VCT operation spans multiple tiers of a typical utility's communication network. Different communication system technologies may be used in each, with its own performance and reliability characteristics, as outlined in Table 2. The CReST-VCT algorithm runs on a repeating interval of nominally 5 minutes, as shown in Figure 9 in Section 3.2.2.2. At the beginning of each five-minute interval, optimization problems are solved sequentially from the subtransmission side to the distribution side, and a subset of the output of the former is sent to the latter as input data. The remaining output of the optimization problem at the subtransmission side is directly sent to its shunt capacitors and generators. On the distribution side, the output of its optimization problem, which includes real power curtailment and reactive power setpoints of inverter-based PVs, is sent to these PVs. Until that moment, the theoretical objective and operational constraints specified in CReST-VCT can be realized in the system. In other words, if solving optimization problems and sending data through the communication network takes *x* minutes, the system is only expected to achieve the minimum losses while keeping all load voltages within a prespecified desired range during the remaining (5 – *x*) minutes.

As a result, the CreST-VCT solution will be more meaningful in minimizing losses and satisfying all the operational constraints over a longer period if *x* is small compared to five minutes. On the other hand, if *x* is approximately 5 minutes, because of either communication delays or optimization solving time, the solution from CReST-VCT will not realize its expected advantages. In that case, the optimal dispatch from CReST-VCT to field devices actually applies to a new set of input data in the next five-minute interval, which includes demand and PV generation capability. The performance of the system now depends on such load and PV data. Theoretically, CReST-VCT is unlikely to achieve the same level of loss reduction or voltage regulation. There might be marginal voltage violation, since the solution of the previous step is unlikely to exactly match the solution of the subsequent step. The more similar the input of the next interval is to the previous one, the better performance we can achieve. From Figure 9, notice that solving the EMS OPF problem, sending a message from EMS to DMS, and solving the OPF problem at the DMS takes about 1.5 minutes. The remaining 3.5 minutes in the interval are for the message from the DMS to reach each DER. Messages to shunts or generators in the subtransmission system are sent directly from the EMS, so they will take less time.

The above discussion is true not only for the signals from the EMS to the DMS, but also for signals in the reverse direction. Notice that within each nominal five-minute interval, DMS distribution has to provide to the EMS its possible range of reactive power support, demand response, and PV curtailment in the next five-minute interval as parts of the input that EMS uses for solving its optimization problem in that subsequent interval. In this direction, communication delay fortunately affects system performance less. It results from the fact that DMS calculates all the possible ranges for interval (*t* + 1) within its interval *t*, and it is very likely that the message containing these ranges from the DMS will reach the EMS before the start of the interval (*t* + 1).

In case of a communication failure or an unacceptable delay while the EMS and DMS are waiting and trying to collect data from each other, both optimization algorithms in EMS and DMS centers will use the input data from the previous step to solve for the optimal dispatch of the next five-minute interval. At the same time, both EMS and DMS will keep checking whether the connection is reestablished so that new, updated data for the subsequent time steps can be used to regain the optimal performance as expected with CReST-VCT.

4.3 Scalability

At the subtransmission level, it is practical to achieve full communication capability from the EMS and control devices such as generators and switched shunts. At the distribution level, however, it is much more difficult to have 100% communication capability between the DMS and PV resources. Because a distribution system has a low *X*/*R* (reactance/resistance) ratio, voltages can be affected by both real and reactive power injected into or absorbed from inverter-based PV. Therefore, large-scale inverter-based PVs with a large amount of centralized real-power generation are prone to violate the strict American National Standards Institute voltage constraints (ANSI 2016). This property makes smaller rooftop PV a better candidate for expanding PV generation in distribution systems. Because their lower generation capability is smaller, the number of rooftop PVs can be very high. However, CReST-VCT assumes that the

DMS is fully capable of establishing two-way communication with all its control resources. Therefore, centralized control in a distribution system will reach a scalability limit, because the computational effort and communicational message flow are constrained by the five-minute interval in CReST-VCT input to guarantee a desired level of system performance. To make up for this insufficient communication, the distribution side might devise decentralized and distributed approaches to control DERs locally with significantly less stringent or no communication requirements, respectively. However, these approaches only consider local state measurements rather than comprehensive system network constraints. Therefore, it cannot match the CReST-VCT solution in terms of minimizing losses and guaranteeing all operational constraints, such as voltage stabilization. Another possible solution that is worth to considering is to make a compromise between the nominal 5 minutes specified in CReST-VCT design and the scale of hosted inverter-based PVs. With an extended interval such as 10 minutes or 15 minutes instead of 5 minutes, fewer limitations are put on communication and the number of DERs.

The CReST-VCT tool also provides a mechanism to parallelize the algorithm computation by dividing the system into substation groups. However, each of these groups is expected to be synchronized to the same five-minute operational interval to make sure the DER dispatch and supporting field measurements are coordinated across the grid. This means that the DER dispatch and field measurements will be executed in parallel. This could pose scalability issues for the communication network infrastructure.

SCADA systems at the substation level operate at the typical poll cycle of one to several seconds for all points. Because these points are maintained continuously, it is assumed that communication networks will be scaled appropriately for normal operations, independently of CReST-VCT. Connection to devices outside the substation to take advantage of CReST-VCT optimization capabilities may drive new connections to the SCADA system. Further, CReST-VCT increases the potential hosting capacity of DERs that might otherwise be curtailed, increasing the possible number of DERs a given feeder can support. The potential optimizations with a five-minute interval could again provide incentive to connect more devices and interact with those devices more often.

The system design model will need to analyze the communication load based on the number of controlled devices to assess the communication capacity. This analysis will need to be conducted across the target protocol and communication technologies that may be used to determine the overall scalability of the tool.

4.4 Security Considerations

CReST-VCT has features such as remote control and remote access to DERs, and those DERs are equipped with digital communication and control interfaces that pose as cyberattack surfaces. Also, larger numbers of third-party devices associated with DER deployment can also increase cybersecurity risk if the devices are not sufficiently secure. Communication protocols used for CReST-VCT are vulnerable to attacks by attempts to intercept, modify, and/or corrupt the control signal packets. The U.S. National Electric Sector Cybersecurity Organization Resource (NESCOR) Technical Working Group 1 describes some realistic cyber threats that concerning the DER domain (NESCOR 2014). Each of the Open Systems Interconnection (OSI) communication layers in the DER domain is vulnerable to potential cyberattacks. Cybersecurity should be considered with any type of EMS/DMS applications that are related to DER devices and their respective communication channels. The current cybersecurity postures of IEEE 2030.5, IEC 61850, and IEEE 1815 are discussed below.

4.4.1 IEEE 2030.5

IEEE 2030.5 standard uses public key infrastructure as the security framework (CSIP 2018). All aggregators and DER clients should be able to support this framework. This framework uses HTTPS in all direct and aggregated communication scenarios. Note that this standard uses Transport Layer Security (TLS) version 1.2 for their HTTPS transactions, and this TLS handshake provides a certificate to authenticate and authorize the HTTPS transactions. This TLS also provides encryption using the AES-CCM (Advanced Encryption Standard–Counter Mode with Cipher Block Chaining Message Authentication) mode. A recent Sandia National Laboratories report identifies some potential security gaps in the IEEE 2030.5 standard (Obert et al. 2019):

- weakly implemented TLS interception technique
- no certificate policy for security procedure
- no certification revocation method
- no method for updating the cryptographic algorithm for DER.

As TLS protocol provides communication security over DER networks, but care must be taken to make sure that gaps are not introduced though improper certificate authentication or unencrypted interfaces with older protocols.

4.4.2 IEC 61850-7-420

Currently, the IEC 61850 standard does not include any security framework. The main function of this standard is to describe the information model used to communicate with the DER devices. IEC 62351 series of standards provide the security feature for DER communication that mapped with IEC 61850. The IEC 62351 standards that secure IEC 61850 DER traffic (IEC Technical Committee 57 2016) include the following:

- IEC 62351-3 — Security for profiles that include TCP/IP
- IEC 62351-4 — Security for Manufacturing Message Specification (MMS) protocols
- IEC 62351-6 — Security for peer-to-peer profiles (e.g., Generic Object Oriented Substation Events [GOOSE])
- IEC 62351-7 — Security for network and system management
- IEC 62351-8 — Role-based access control
- IEC 62351-9 — Key management
- IEC 62351-10 — Security architecture
- IEC 62351-11 — Security for XML files

4.4.3 IEEE 1815

IEEE 1815 uses TLS to secure DER communication. IEEE 1815 provides cybersecurity features such as application layer encryption and secure authentication. This standard also addresses unauthorized spoofing. Devices that use DNP3 communications should be checked to make sure that mandatory security features have been implemented, and include TLS whenever the device hardware and network infrastructure are available to support it.

Table 3 summarizes different types of communication standards used for DER interconnection and their current security postures along with the associated information model.

Table 3. Cybersecurity Features of DER Communication Standards, Information Models, and Security Standards (Lai et al. 2017)

DER Protocol Cyber Security Features	Protocol: IEC 61850 Information Model: IEC 61850-90-7 Security Requirements: IEC 62351 Series	Protocol: IEEE 2030.5 Information Model: CSIP Security Requirements: IEEE 2030.5 + CSIP	Protocol: IEEE 1815 Information Model: DNP3 Application Note Security Requirements: IEEE 1815	Protocol: Modbus Information Model: SunSpec or MESA Models Security Requirements: None
Devices Support	DER, Power Systems Devices	DER, Smart Grid devices	Utility, Grid Devices	Utility, Grid, ICS devices
Encryption Capability	Non-Native	Yes	BITW	BITW
Encryption Required	No	Yes	No	No
Supported Transport Protocols	N/A	TCP or UDP	Serial or TCP	Serial or TCP
Supported Networks	N/A	IPv4, IPv6	IPv4	IPv4, IPv6
Authentication Support	Non-Native	Yes	Optional	Non-Native
Type of Communication Protocol	IEC 61850-90-7 contains functions for power converter-based DER systems	Communication protocol for device integration with the Smart Grid	Communication protocol for real-time monitoring and control	Communication protocol for real-time monitoring and control
Type of Information Model	IEC 61850-90-7	CSIP	DNP3 Application Note	SunSpec and MESA are information models for Modbus
Type of Security Requirements	IEC 62351 Series	IEEE 2030.5 + CSIP	IEEE 1815	There are no security requirements for Modbus communications
Type of Data Transmitted	DER settings, control modes, and measurements	DER measurement and control data	Data objects with defined attributes and priority levels	DER measurement and control data
Aggregation Support	Utility or aggregators can collect data	Yes	Yes	Yes

It will be important for CReST-VCT to be able to respond appropriately to a DER communication network failure. A resilient implementation would let the system react to the specific failure scenario and adjust to continue performing, but with reduced function or benefit. The effect of a communication network performance issue or disruption in service would depend on the location of the failure. Any disruption in service at the content-concentric network (CCN) would have a significant effect on the CReST-VCT tool, since algorithms run and coordination is initiated at this level. If a specific field area network segment is disrupted, though, the CReST-VCT tool could disable consideration of that area's assets and run the optimization for the remaining connected system. The system design model should include a mechanism to notify CReST-VCT of a dependent communication system failure so that it can adjust its operation.

5.0 Conclusions

The CReST-VCT solution coordinates transmission and distribution controllers to support use of DER devices to provide voltage support at the subtransmission level while maintaining operational requirements at the distribution level. This level of optimization coordination between EMS and DMS systems is not widely employed today. Coordination of DER assets, both utility-owned and non-utility owned, at the time intervals and scale that would achieve maximum optimization benefits of CReST-VCT is also not widely done today. The leading edge of these innovations combined with an evolving and diverse DER communication protocol landscape make integration of a CReST-VCT solution or similar tool into a production grid at a utility nontrivial.

In this paper, a potential approach to deploy this functionality into the real-time operational environment of a utility was presented in the form of a system integration framework. The framework provides an architectural basis to serve as a guideline for implementing CReST-VCT as well as other algorithms or systems that seek to co-optimize use of distributed energy or assets between transmission and distribution operations. Also included is a system integration model that identifies one set of protocols that may be used, while describing key considerations that may guide tailoring an implementation to other protocols that may be better suited to a particular environment. Finally, performance and security issues were discussed to highlight considerations that should be evaluated when applying the solution to a specific deployment. Some of the key points illustrated in the framework include the following:

- It is proposed that the CReST-VCT integration follow a grid architecture where the distribution operator takes responsibility for monitoring and control of DER assets. The transmission system operator makes requests for grid services from the distribution system operator. This allows the transmission system operator to benefit from DERs for resilience or flexibility while allowing the distribution operator to provide distribution system reliability.
- A reference system design for two-way data exchange between subtransmission EMS, distribution DMS, and DERs for co-optimization is identified. A suite of standard protocols at different interfaces is proposed as one possible communication protocol configuration. The protocols include DNP3, IEEE 2030.5, IEC61850, and IEEE 1547-2018.
- CReST-VCT requires remote control of and remote access to DERs, and those DERs are equipped with digital communication and control interfaces that can be cyberattack surfaces. Also, larger numbers of third-party devices associated with DER deployment can also increase cybersecurity risk if the devices are not sufficiently secure. The protocols used to communicate with these devices have varying levels of potential vulnerability that specific implementations need to consider to provide proper risk mitigation.
- Requirements for communication time (response time) are identified to maximize benefits of the CReST-VCT optimization. There is a significant potential variation in the performance of communication networks that can be adopted for CReST-VCT applications. More importantly, the communication delay, which is unavoidable, can negatively affect the performance of CReST-VCT. The physical communication networks vary widely across utilities. The specific deployment must evaluate any limitations in response time from trade-off between the operational benefits of CReST-VCT, loss reduction and voltage stabilization, and the investment cost of improving the communication network.

Through presentation of this CReST-VCT system integration framework, we hope to provide a starting point deploying CReST-VCT and more speedily receiving the benefits such a solution can bring.

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