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Drop In-Place Control Enclosure (DICE)
Rolling the DICE on IEC 61850

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SUMMARY

The increasing load and generation interconnections in Dominion Energy Virginia's service territory are creating demand for new substations. While digital substations are not new, Dominion is partnering with industry leaders to design and produce a standardized, mass-producible, IEC 61850-based, Drop-in-Place Control Enclosure (DICE) that will save time, money, and labor. The enclosure was designed to be modular, and it will be fabricated, assembled, and tested offsite, which will make the onsite installation and commissioning more efficient. The first operational DICE will be installed in a local training facility for two key purposes: 1.) to allow field personnel, operators, and engineers to engage in hands-on training and testing, and 2.) to allow everyone involved to provide feedback to further refine the design and procedures. This paper provides Dominion's framework for designing an IEC 61850 Drop-in-Place Control Enclosure.

KEYWORDS
DICE, IEC 61850, HMI, Standards, Sampled Values

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I. Company Overview

Headquartered in Richmond, Virginia, Dominion Energy Virginia currently serves approximately 2.7 million electric customers in Virginia and North Carolina. The company owns approximately 6,800 miles of transmission lines at voltages ranging from 69 kV to 500 kV in Virginia, North Carolina, and West Virginia; and approximately 60,000 miles of distribution lines at voltages ranging from 4 kV to 46 kV in Virginia and North Carolina.

II. The Need

Two main factors drive the need for new substations in Dominion's service area. PJM's 2023 load forecast for the company's service territory increased significantly compared to last year's forecast; rising energy and peak growth from data centers in Virginia were key drivers. In addition, the Virginia Clean Economy Act (VCEA), which requires 100% clean energy by 2045, mandates a significant increase in the integration of renewable energy facilities [1].

The forecasted increase in data-center load growth and generation interconnections required an innovative way to streamline the engineering, fabrication, integration, and testing of new substations. Historically, Dominion constructs 15-20 substations per year. The number of substations per year over the next five years is projected to double.

In order to manage this increased need, Dominion is looking at all avenues to build substations quickly, while streamlining design and engineering. One way to reduce substation construction time is to have the fabrication, component integration, and testing of the Control Enclosure (CE) completed off-site. This will reduce the amount of construction and commissioning time needed on-site. To facilitate transportation of the completed CE to the installation site, the enclosure must be no more than 15 feet wide to avoid special permits or the need to assemble two wider halves on-site. This space limitation required a rethink of the CE's design.

One way to reduce the CE footprint is by using IEC 61850. A fully digital substation removes the need for physical controls, lockout relays, and test switches on the panels. This means traditional wiring can be replaced with fiber wire. Connections can be accompanied by network engineering and relay programming to ensure that all binary and analog data is correctly mapped. More functions can be consolidated into fewer relays because the limits placed by relay binary inputs and outputs, test blades, lockout contacts, panel space and other physical constraints would be removed. For the same reasons, more relays can be placed on each panel. In addition to saving physical space, Dominion estimates that one standardized IEC 61850 DICE substation will save 4 weeks of panel fabrication and installation time.

A first-pass analysis suggested that the number of protection panels could be reduced by approximately 75%. Savings on the panel-to-panel wiring would be approximately 60%. A fully IEC 61850 substation will have increased costs for additional cabinets in the switchyard and additional merging units (MUs), which are dedicated I/O devices connected through a fiber-optic network. At this stage in the project, the additional costs are unknown.

III. The Vision

Dominion's goal was to create a new philosophy for a fully digital control enclosure that could be created quickly and installed efficiently to meet escalating demand. The project would be done in close collaboration with vendor partners. The CE's design would be simplified, reducing the number of components needed. That design would then become a template for mass-producing the unit. Fabrication also needed to be streamlined, to allow the enclosures to be built and tested offsite. The end goal was to save time, money and labor.

Developing the DICE requires input from many operating and engineering groups throughout the company. Their help will continue to be needed as we go through the rest of the project phases—developmental testing, panel and enclosure fabrication, CE construction and assembly, product testing, implementation, transportation, installation commissioning, maintenance and diagnostics at the substation site. Our vendors provided the bulk of their help during the design and development phases. They helped develop the DICE's philosophy and focused on diagnostics and testing, setting configuration, HMI and network development, and engineering workflow.

A pilot DICE, installed at Dominion's Training Center, will emulate a transmission four-breaker ring bus substation. This platform will allow field personnel, operators, and engineers to engage in hands-on training and testing. User feedback will be used to further refine the enclosure design. Having the DICE at the Training Center will allow a full review from various perspectives: human performance, safety, operations, maintenance, cybersecurity, commissioning, testing, training, and compliance. After standards are developed and personnel are trained, the DICE will be released to the project design teams to start deploying on generation interconnections or 3-4 breaker ring switching stations. After successfully implementing our first design, we will expand the DICE application to other substation configurations.

To facilitate mass production, Dominion is building a new relay panel shop that will have a DICE Integration Bay to streamline the process of integrating panels into the enclosures. The shop will be capable of integrating four CEs at a time and will also allow Dominion to control the fabrication process, the materials, and the quality of each DICE.

IV. The Team

Developing the DICE involves input from many internal departments including, but not limited to, Standards (Protection, Control, and Physical), Operating Centers, the Training Center, Work Methods, Data Communications, Compliance, Cybersecurity, and various field craft from Substation, Distribution, and Metering. This internal multi-disciplinary team allows comprehensive conversations to ensure objectives are achieved.

To help in engineering development, Dominion is working with three major partners:

- **POWER Engineers, Inc.** is familiar with Dominion's substation standards and application guidelines. POWER is assisting with the protection and control drawing package (elementary, wiring diagram, functional diagram, data-stream flow, etc.), protection relay settings, data concentrator settings, and IEC 61850 configurations.
- **Quanta Technology** is providing overall guidance and direction in scope, application and integration of IEC 61850.
- **SEL** is assisting with the development of the human machine interface (HMI) and network configuration, IEC 61850 testing, and merging-unit cabinets.

V. The Approach

Conventional substations were originally designed over a hundred years ago. While those designs have been updated as new technology was introduced, most substations today are engineered by applying long-established standards and making incremental improvements. By contrast, designing a digital substation is more like designing from scratch. A digital substation requires the team to think about large portions of the system with fresh eyes and re-evaluate how a substation should be engineered. The degree of change is similar to the industry's transition from electromechanical to microprocessor relays.

Use-Case Meetings

As the DICE's physical systems were developed, the goal was to figure out how the protection and control scheme should be designed and how it would operate under various conditions. To refine the scheme, the teams held "use-case" meetings with internal and external stakeholders multiple times a week for six months. Often, illustrations of the use-case scenarios needed to be drawn up to fully understand the application. The use cases developed included manual breaker operations, reclosing on/off, carrier on/off, local/remote, protection trip, protection reclose, testing, and failure modes. The outcomes of the use-case meetings were then used to develop the DICE engineering package including drawings, relay settings, network and HMI configuration.

Lab Setup

After a full P&C drawing package was created for the first DICE, the Lab group modified the drawings as needed. As testing progressed, mock-ups were created, and the drawings were updated accordingly.

The team introduced a new type of drawing called the Signal Flow Diagram, which showed the signals being published, the inputs connected to each device, and which device published signals landed on. One signal flow diagram was created for each IED that was publishing and/or subscribing to GOOSE or SV messages.

The IEC 61850 configuration, as well as the setting files for each IED (including protection and logic settings), were based on the use cases and the P&C drawings. The team used the IED's ability to customize the IEC 61850 data model to create custom data object names. Based on the abbreviations defined in the standard, the team took advantage of industry-standard naming and reduced reliance on vendor-specific and utility-specific names. The team then created specific IED Configuration Description (ICD) files for the project.

A system configuration tool (SCT), as defined in IEC 61850-6, was used to generate the IEC 61850 configuration file. An SCT was used for several reasons, but a major factor was its ability to replace ICD files without manually rebuilding the configuration. The custom ICD files will save countless hours throughout the project's lifetime.

The final HMI design consisted of a single-line diagram, line protection detail screens, breaker control detail screens, alarm screens, and islanding control screens. Additional screens, designed for maintenance and troubleshooting, showed diagnostic details for the relay network cards and the SDN switches, as well as diagnostic information for GOOSE, SV, and the Precision Time Protocol (PTP).

Lab Testing

Laboratory testing of an IEC 61850 substation must go beyond the level of testing for a normal protection scheme. Selection, design, and application settings of the communication equipment, specifically the network and satellite clocks, are now part of the protection scheme and influence the performance and reliability of the system. Using distributed functions in an IEC 61850 substation introduces multiple dependencies between the devices and the network, resulting in multiple possible operating contingencies. For this reason, the final design of a digital substation must be tested as a complete system to understand the substation's performance.

In the lab environment, we tested protection schemes and the communication network, which allowed us to detect issues with device configurations. Over the course of the testing, we made innumerable improvements to the original design. We used a third-party IEC 61850 test set to develop and run test plans for our protection schemes, including breaker failure and reclosing. A third-party network analyzer device was used to verify GOOSE and SV communications between relays on the process bus, in addition to MMS reports from the relays to the data concentrators on the station bus. After many weeks of functional testing, and many iterations of relay configurations and communication settings, the lab setup was ready for system testing.

We used an in-house real-time digital simulator (RTDS) in the lab to test the DICE protection scheme as a whole against various operating conditions. Since an RTDS models parts of the power system, it easily allows testing of numerous system contingencies, including faults at various locations with different fault resistance values, and breaker failure conditions.

The RTDS is connected through amplifiers both to the DICE system in the lab and to traditional (non-IEC 61850) microprocessor relays for the remote line terminals. This Hardware-In-The-Loop (HIL) test was designed to identify latent issues in the system configuration, carrier blocking coordination, line differential network time delay compensation, and interaction among devices, including the system performance during different operating contingencies and modeled device failures.

VI.DICE's Architecture

The DICE architecture is based on modularity, ease of construction and good utility practice while maintaining all applicable physical and cybersecurity, compliance and environmental requirements. The components are listed below:

Merging Unit Cabinet

An MU cabinet will be installed adjacent to each circuit breaker and will act as the interface between the primary equipment and the control enclosure. Each cabinet includes:

- **A merging unit.** Converts analog signals from the CTs and PTs to sampled values for the network. Two merging units have been installed for full redundancy.
- **An equipment annunciator.** A standard device that collects equipment-specific alarms and data and displays them on the enclosure's HMI and transmits them to the system operating center.
- **Test and control switches.** These are to provide airgaps for safety and isolation while testing, similar to their application on current relay panels.
- **Fiber management equipment.**

Control Enclosure Design

The DICE will contain relay, communication and network panels as well as AC and DC distribution equipment. For redundancy, two communication panels with touchscreen HMIs will be installed. Because the enclosure is only 12 feet wide, the original design called for batteries to be placed behind the panel row. Field and operations personnel objected, due to safety considerations. The revised design calls for the batteries to be installed in a separate room with outside access, adjacent to the main enclosure.

Protection Panels in the Control Enclosure

Early in DICE's development, the team decided to utilize the fewest relays possible while maintaining all the protection and control features currently used for standard applications. Fig. 1 shows the present, traditional standard: two breakers feeding a line which splits line protection and breaker controls into two panels. Two relays handle line protection, and two relays handle breaker failure and reclosing.

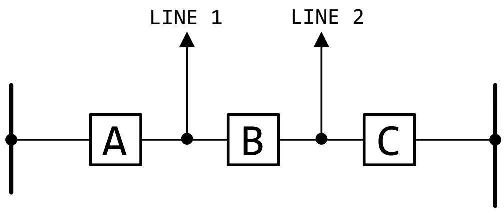

Fig., 1: Breaker-and-a-Half Configuration

This common breaker-and-a-half configuration has a total of five panels (two panels for Lines 1 and 2 and three panels for Circuit Breakers A, B, and C). In the DICE design, the breaker controls, breaker failure, and reclosing are all integrated into the line relays. This design eliminates three breaker panels, thus reducing the relay panel footprint by 60%.

To reduce both engineering and testing time, the panel design was based on an existing standard that already incorporated line protection and breaker controls in one panel. The standard was modified so that two breakers could reclose using Dominion's custom lead/lag scheme. This would allow reclosing and breaker failure to be initiated in a specific line relay, depending on the location of the fault. For example, in Fig. 1, if Breaker B trips for a fault on Line 1, reclosing and breaker failure would be initiated in a Line 1 relay. Similarly, if Breaker B trips for a fault on Line 2, reclosing and breaker failure would be initiated in a Line 2 relay.

Network

The DICE include various IEC 61850 protocols. Generic object-oriented substation event (GOOSE), sampled values (SV), and manufacturing message specification (MMS) are used to perform protection and control. IEEE 1588 Precision Time Protocol is used to provide high-accuracy time synchronization to all IEDs. Protection, controls, and time-sync are transmitted across an Ethernet network that is required to meet the same stringent physical and operational requirements as protective relays.

In 2019, Dominion partnered with a third-party contractor to perform an evaluation of the available networking technologies for IEC 61850 communications. After evaluating multiple options, representatives from the Data Communications group unanimously decided to pursue operation technology (OT), software-defined networking (SDN) as the IEC 61850 networking solution.

OT SDN is a deny-by-default networking solution, so it is inherently cyber-secure and provides a centralized configuration and monitoring of all SDN switches in the network. Since the networking data plane and control plane are parts of the software controller, network configuration can be fully automated from design documents. These documents include an architectural drawing that describes all the physical characteristics of the network (hosts, IP addresses, physical connections, etc.), a data-flow diagram that describes all the logical characteristics of the network (conversations/protocols between devices), and the IEC 61850 substation configuration descriptions (SCD) file that contains all the IEC 61850 configuration details.

The network architecture for the DICE consists of six OT SDN switches configured into three networks (see Fig. 2). Four switches connected in a ring are used for the station bus failover network. The station bus network consists of the MMS operational and control data used for the HMI and SCADA as well as time synchronization for all non-process bus devices. The failover network provides high-speed recovery for any network element failure (device, port, cable) as well as simplifies the device connections and management. This also minimizes the need for redundancy boxes for devices with single network ports, as most of these devices only need to connect to the station bus failover network.

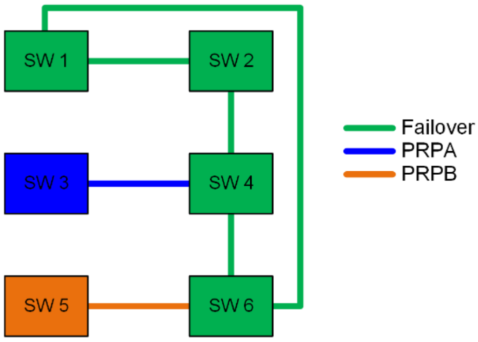

Fig. 2: DICE SDN Simplified Switch Architecture

Two switches are used for a parallel redundancy protocol (PRP) network for the process bus, listed as PRPA and PRPB in Fig. 2. The process bus is the network interface that carries sampled values between the CE and the MU cabinets, PTP time synchronization for the process bus devices, and protection controls using GOOSE. PRP uses duplicate networks between devices, so the recovery time for a network element failure is essentially zero. PRP also requires that devices are dually connected to each PRP network and devices that do not have dual ethernet ports (singly attached nodes (SAN)) require a redundancy box. OT SDN allows the normally isolated PRP switches to connect to the failover network so that the data concentrator can monitor switch port status, port packet counts, and alarms without interfering with any of the standard PRP communications or requiring additional network ports on the data concentrator.

VII. Expected Outcome

The DICE is a work in progress. While the design is complete and has been lab tested, much work remains. Dominion plans to start to fabricate the Training Center DICE at the end of 2023, and the teams are striving to produce deliverables to support the target date: developing standards, crafting engineering work practices, testing/commissioning work practices, documenting HMI, developing engineering and field training, and standardizing maintenance practices.

Dominion anticipates that getting the DICE to the stage where it can be mass produced will be a multi-year project. We will continue to work closely with our vendor partners and internal teams to create this new standard in digital enclosures.

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