New Intelligent Direct Transfer Trip Over Cellular Communication

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Abstract— **The paper will discuss two installed system designs and methods used to transmit a DTT signal over cellular systems.**

This new approach solves the communication reliability problems and addresses application security.

This paper is a case study of 3 installed Direct Transfer Trip (DTT) systems that use cellular communication - one system at Central Virginia Electric Cooperative and two at Dominion Energy. In this paper the authors will report on the design, implementation, performance and issues encountered during and post project execution. These intelligent DTT systems have been designed to increase availability of the Distributed Generation (DG) by preventing the indiscriminate disconnection of the sites. Traditionally DTT Signals have been sent between substations and remote DG sites using leased telephone lines. If DTT communication is interrupted, the DTT system will disconnect the DG site. Leased copper lines are becoming less reliable, leading to unwanted disconnection of DG sites. Installation of fiber is not always feasible due to the cost. This paper will discuss an approach to provide DTT signals using wireless communications. The paper will address the security concerns that many Utilities might face. Two new innovations to increase the DG site's availability will be discussed.

1) **Automatic Direct Transfer Close**

If system conditions return to normal after a DTT event, the system will automatically close the DG site back in onto the feeder.

2) **Dynamic Feeder State change protection function**

It must be expected that using cellular or wireless communication systems will result in temporary communication interruptions during normal operation. During these times the DG site device activates a new protection function that will detect any anomalies that could constitute a change in the connected feeder systems (e.g. caused by a fault or the opening of a breaker) and then only disconnect the DG site.

I. INTRODUCTION

Traditionally Direct Transfer Trip Signals (DTT) were sent between substations and remote Distributed Generation (DG) sites using leased telephone lines. DTT systems are installed for critical high-speed tripping of circuit breakers on either side of a feeder interconnecting substations or between the substation breaker and a DG site's station equipment.

When a line fault occurs, the DTT disconnects DG quickly, protecting it from damage and ensuring that it will not feed into a faulted circuit.

Due to the highly specialized and critical nature of DTT, the equipment and communication medium must be extremely reliable. It is recommended that all the DTT equipment is substation class and DC powered.

The use of traditional leased lines is becoming more and more problematic as telecommunication companies are moving away from this technology or even not providing this as a service. Long distance fiber installation is very expensive and is not always feasible.

This paper discusses a novel new approach to provide DTT signals reliably between sites using wireless cellular communication systems. The solution can use modern communication infrastructures, including Cellular communications, that most major telecommunication companies are moving towards.

Two new innovations will be discussed that were developed to increase the DG site's availability.

- Automatic Direct Transfer Close

If system conditions return to normal after a DTT event, the system will automatically close the DG site back in onto the healthy feeder.

- Dynamic Feeder State Change protection function

It must be expected that using cellular or wireless communication systems will result in temporary communication interruptions during normal operation. During these times the DG site device activates a new protection function that will detect any anomalies that could constitute a change in the connected feeder systems (e.g. caused by a fault or the opening of a breaker) and then only disconnect the DG site. This new approach solves the major reliability problems and address security and speed of DTT signals using substation hardened equipment only at each site.

This paper is a case study of 3 installed DTT systems that use cellular communication. One system is operated by Central Virginia Electric Cooperative (CVEC) and the other two are operated by Dominion Energy. The design, implementation, performance and issues encountered during and post project execution will be detailed in the proceeding sections of this paper.

The systems differ in design but share a common goal. The resultant solution provided a cost-effective, reliable and intelligent DTT alternative. These new intelligent DTT systems are designed to increase the availability of DG sites by not indiscriminately disconnecting them on loss of communication links.

II. PROJECT DRIVERS

A. *Central Verginia Electrical Cooperation (CVEC)*

CVEC contracted with a solar energy company to connect two new Solar sites to their distribution grid. Dominion Energy deliver power to CVEC and required CVEC to implement a DTT system from the Dominion delivery point to the DG sites as these sites are in Dominion's operating territory. CVEC also needed to implement DTT from two Substations to the two DG sites. The remoteness and distances involved between the DTT points made the DTT system a very expensive proposition. CVEC investigated the cost for installing fiber and leased lines. In both instances the cost of the traditional DTT communication system was cost prohibitive. CVEC implemented a distribution automation and protection system on a remote distribution system that uses cellular communications for peer to peer communication (IEC61850 "GOOSE) between field devices for the very same reasons. CVEC decided to contract with Siemens to develop a DTT system using the same technologies to keep the cost down to acceptable levels for a reliable DTT system.

B. *Dominion Energy DTT Pilot Projects*

Dominion experienced DTT communication reliability issues at certain DG locations that caused unwanted disconnection of solar energy from their system. Dominion Energy is a leader in DTT technology and has implemented many systems on their power grid. The systems in question though, relied on leased copper telephone lines to transmit DTT signals from substations and recloser sites to the DG sites. This technology is for the most part being replaced with fiber or cellular communication links. Today very few people still rely on land lines, as cell or internet phones have become the norm. The old land lines are falling in disrepair and the reliability can get problematic as experienced by Dominion and other utilities.
Dominion investigated many different technologies to find an alternative for the transmission of DTT signals. In all instances these technologies could not offer an immediate deployable and cost-effective solution. Dominion decided to contract with Siemens to help them develop a DTT solution based on their experience using this technology to transmit IEC61850 "GOOSE" messages between field devices using cellular communication systems.

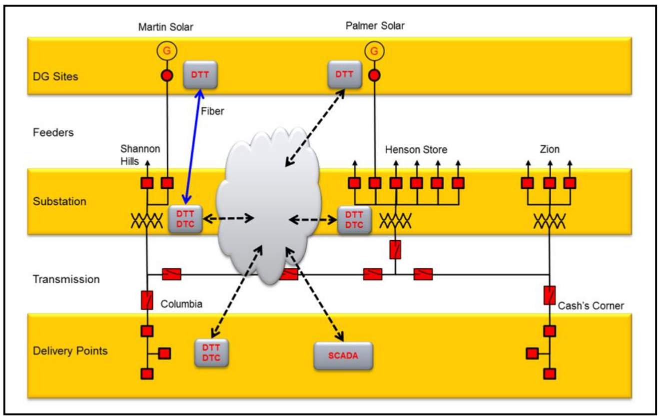
III. IEC61850 "GOOSE"

Using the IEC61850 "GOOSE" messages brought a new design element into the equation in the DTT application. This technology can communicate binary and analog information between the DTT field devices. In this paper we will show how it was possible to add intelligence to the DTT systems. This intelligence is mainly used to keep the DG sites connected to the grid and only disconnect when absolutely required. A simple communication interruption in an intelligent DTT system is not enough to disconnect a DG site from the grid.

IV. DTT SYSTEM TOPOLOGIES

A. *CVEC Project*

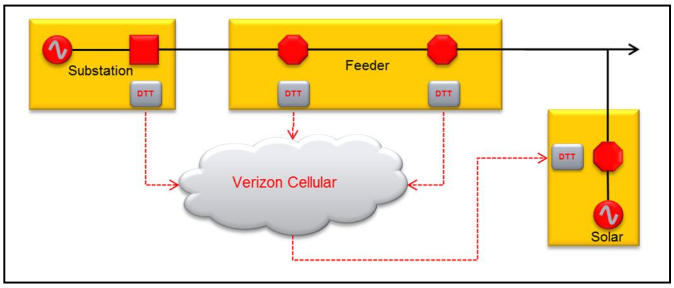
Fig. 1. *(CVEC DTT Project Topology)*



The topology as indicated in Fig.1 required a system to provide DTT signals from the delivery point at the Columbia transmission substation or delivery point to the Martin and Palmer DG sites. DTT signals were also required from each distribution substation to the connected solar site. The link between the Shannon Hill substation and the Martin solar site was just over 1000 feet and it was decided to pull fiber for this short link. The other communication links between the delivery point solar sites and the substations required approximately 27 miles of fiber or copper if used for this system.

B. *Dominion Energy Pilot Project*

Fig. 2. *(Dominion Energy DTT Pilot Project Topology)*



The topology as indicated in Fig.2 required a DTT system to provide trip signals from the Dominion Energy substation and two inline reclosers to the solar site. The total line length is approximately 14 miles. An existing leased line based DTT system provided the DTT functionality. This existing DTT systems' communication reliability caused unwanted disconnect of the solar site. The existing system is an analog based DTT system. The system is an energized hardwired circuit with series connected normally closed protection contacts at the substation and recloser sites, if the circuit is interrupted by the protection contacts or physically broken the DTT relay at DG site is deenergized closing the DTT contacts initiating trip at the DG site. The circuit should only be broken to initiate a DG site trip by the opening of the substation breaker, opening any one of the inline reclosers or a remote transfer trip signal. The system has no intelligence and every time—the communication system inline transformer or amplifiers or telephone wire fails, a DTT trip is initiated. It was decided on this project to have the two DTT systems run in series. The Solar site would only be disconnected if both systems initiate a DTT signal at the same time.

V. Functional Design

The system functional design for the DTT systems consisted of three different functional elements:

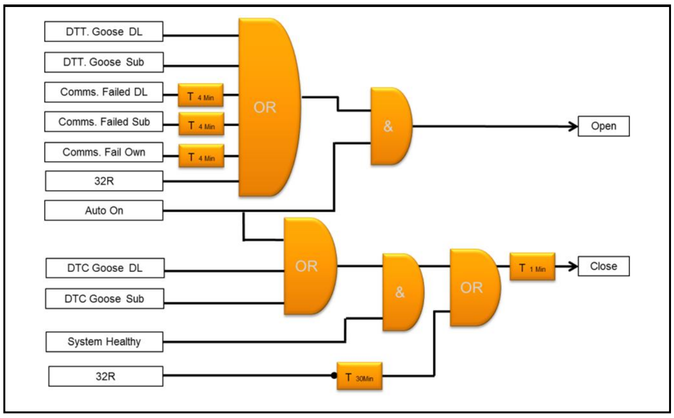
- Distributed Generation inter-tie DTT (PCC-DTT)
- In line feeder reclosers DTT (REC-DTT)
- Substation DTT (SUB-DTT) for both distribution and transmission substations.

The functional design at each of these locations is unique in its functional logic. The PCC-DTT is mainly responsible to receive DTT signals and disconnect the DG site. The recloser REC-DTT is responsible to receive protection trip and open status information form the primary switch and in turn send a DTT signal to the PCC-DTT. The substation SUB-DTT is responsible to receive protection trips from more protective devices, open status information from the primary feeder breaker and other required DTT signals to send a DTT signal to the PCC-DTT. The basic building blocks for the systems consisted of a DTT controller and a cellular modem. The DTT controller interfaced to the protection and primary gear though binary inputs and outputs or "GOOSE" where applicable. The DTT controller is connected to the cellular modem though an Ethernet link. The cellular modems are responsible to transmit the "GOOSE" messages between the DTT functional elements. The cellular modems and controllers were deployed in cabinets for the PCC-DTT and the REC-DTT. At the substation locations the designs included a mounting plate to house the DTT equipment. This design can typically vary from substation to substation.

A. CVEC Functional Design

1) DTT at Point of Circuit Connection Feeder (PCC)

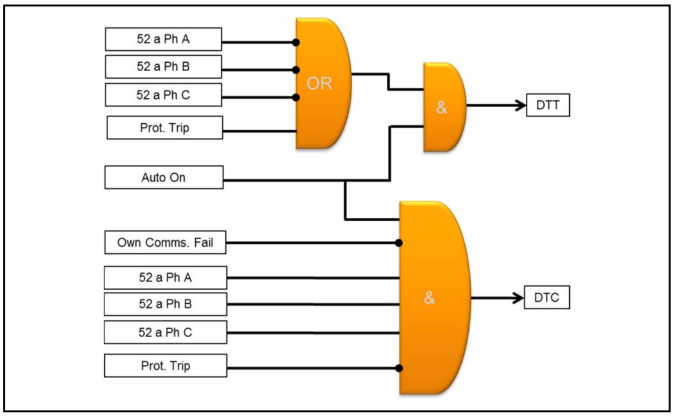
Fig. 3. (Point of Circuit Connection "PCC" Direct Transfer Trip logic)



From Fig. 3 the PCC-DTT initiate a DTT trip on the receipt of a DTT "GOOSE" from the either the delivery point substation or the distribution substation in addition if a communication failure is detected at any of the DTT devices. A reverse power function was implemented to disconnect the DG sites if a possible reverse power condition could occur at the substation delivery point. The system Auto Mode must be enabled to allow a DTT trip to occur. A new feature direct transfer close (DTC) function was implemented on this system to automatically close the DG site Inter-tie recloser switch subsequent to a DTT trip if the system returned to a normal healthy state for 1 minute with no reverse power detected for a sustained time. This new intelligent feature ensures the DG site is connected automatically, without having to wait for an operator to be available, maximizing the possible uptime DG site.

2) DTT at Distribution Substation

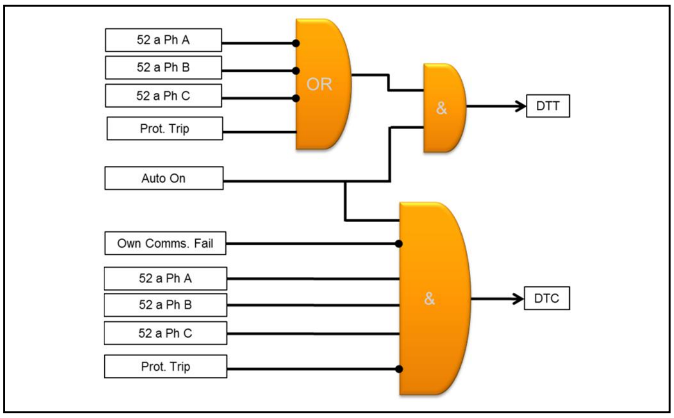
Fig. 4. (Distribution Substation Direct Transfer Trip logic)



The distribution substation functionality is depicted in Fig 4. The DTT must be in the auto mode for any DTT or DTC "GOOSE" to be generated. The DTT signal is generated by the opening of any one of the substation feeder recloser poles or a protection trip. The DTC is generated if the DTT controller detects no communication failure, the recloser poles are all closed and the there is no protection trip present.

1) DTT at Transmission Substation

Fig. 5. (Transmission Substation Direct Transfer Trip logic)

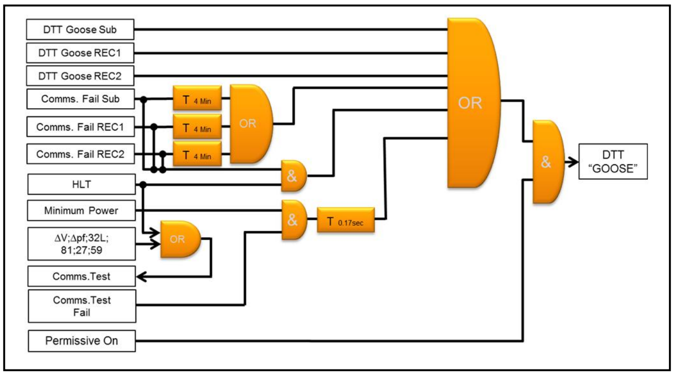


At the transmission substation or delivery point from Dominion Energy to CVEC the functionality is depicted in Fig. 5. The DTT must be in the Auto Mode for any DTT or DTC "GOOSE" to be generated. The DTT signal is generated by the opening the substation breaker, a protection trip or a DTT signal is received from Dominion Energy. In addition, there is reverse power function that will send a delayed DTT signal to the two DG sites to disconnect in succession if a possible reverse power condition persists. The DTC is generated if the DTT controller detects no communication failure, the circuit breaker is closed, there is no protection trip present and the bus voltage is present. Independent DTC "GOOSE" is generated if the reverse power condition clears.

B. *Dominion Energy Functional Design*

1) DTT at Point of Circuit Connection (PCC)

Fig. 6. (Point of Circuit Connection "PCC" Direct Transfer Trip logic)



From Fig. 6. the PCC-DTT initiate a DTT trip on the receipt of a DTT "GOOSE" from either the substation or the inline reclosers.

The new approach is to not indiscriminately trip the DG site off for a communication failure but rather let the system determine if the communication interruption is temporary or permanent in nature. In digital wireless and fiber networked systems we can expect network switches and equipment to reboot during maintenance that can cause temporary interruptions. During these expected temporary communication failures, the DTT system will activate a dynamic state change back up protecting function.

a) Backup Protection Function

The dynamic state change detection technique uses consecutive relay data half cycle samples to evaluate a sudden change in a measured analog value. It is set using the nominal value of a variable, a percentage, and an increasing or decreasing jump or dynamic change. For example, if 100 V is the nominal voltage, the percentage is set to 10% and the direction is falling, then a drop of 10 V or greater from one half cycle to another will trigger the vector jump. If the voltage were to fall to 91 V, a drop of 9 V, then the vector jump would not trigger. However, the vector jump function is still dependent on the nominal voltage, so a jump of 10 V is required.

Table 1. (Protection Elements Used)

Function No	Variable	Percent Change	Direction
Function 2	Forward Power	5	Falling
Function 3	Power Factor	15	Rising
Function 4	Power Factor	15	Falling
Function 5	Voltage	5	Rising
Function 6	Voltage	5	Falling
Function 7	Current	15	Rising
Function 8	Current	15	Falling
Function 9	Reverse Reactive Power	15	Rising
Function 11	Current	80	Rising
Function 12	Voltage	80	Falling
Function 13	Current	Exceeding the threshold	
Function 14	Current	Dropping below threshold	
Function 15	Voltage	Exceeding threshold of 1.1 p.u.	
Function 16	Voltage	Dropping below threshold of 0.88 p.u.	
Function 17	Frequency	Exceeding threshold of 60.5 Hz	
Function 18	Frequency	Dropping below threshold of 59.5 Hz	

As shown in Table 1, protection functions in the DTT controller are configured as jump detectors for various power system parameters including P, Q, V, I, PF, f. These flexible functions provide the capability to detect any power system anomaly.

- Function 2 monitors any negative jump in active power. This function picks up when the DG active power drops below the set % thresholds. This helps detect sudden active power changes.
- Function 3 and 4 monitor any positive and negative jumps in power factor, respectively. These functions pickup when the DG VARs consumption/contribution into the grid exceeds the defined % threshold.
- Functions 5 and 6 monitor any positive and negative jumps in voltage, respectively. This is particularly useful in detecting bolted faults. Functions 7 and 8 monitor any positive and negative jumps in current, respectively. Specially used to determine any fault condition (e.g. transmission level fault, fault between feeder bus and DG, Fault after the DG recloser etc.)
- Functions 9 and 10 monitor any positive and negative jumps in reactive power, respectively. These functions pickup when the DG reactive power changes exceeds/drops below the set % thresholds. They help detect reactive power anomalies.
- Voltage and frequency are key components in the ride through characteristics. Functions 15 through 18 define the upper and lower boundaries for voltage and frequency to be maintained at the DG. Any violation of these limits causes these flex functions to pick up.

Combinations of the functions in Table 1. are used to determine both shading and fault scenarios. These scenarios can look almost identical for conventional time delayed protection functions. Shading at PV sites is when the sunlight is interrupted by variable cloud cover causing sudden and repeated generation changes. Total Harmonic Distortion (THD) is one technique to detect the difference between faults and shading using a voltage measurement. It was decided though to use a combination of voltage and current jump detectors to develop a more reliable protection function. The authors could not determine how other problems in the different types of solar site equipment could affect the THD measurements. Functions 11 and 12 monitor jumps in current and voltage respectively and are set with higher % thresholds to detect an actual fault scenario.

The fault scenarios are identified if all the following hold true:

- Large negative jump in voltage (Function 12 pickup)
- Positive jump in current (Function 11 pickup)
- Sustained undervoltage (Function 16 pickup)
- Sustained undercurrent (Function 14 pickup)

The shading scenarios are identified through:

- Small negative jump in voltage (Function 6 pickup)
- Negative jump in current (Function 8 pickup)
- Followed by small positive jump in current (Function 7 pickup)
- No sustained undervoltage (No Function 16 pickup)
-

The new DTT system design can in addition support future ride through settings and not trip a DG site if DG site stops exporting reactive power within predetermined time frames. The DTT system can differentiate intelligently where a signal is coming from in the substation and know to send a DTT signal for permanent failures from Transformer & Bus faults that do not allow reclosing.

Trips form the transmission system can enable the ride through logic and not trip the site but monitor to make sure the site stops gating reactive power. If the site does not stop gating reactive power within a predetermined time (1st reclosing time), then the system will trip the site and alarm. This supports the new 1547-2018 standard and eliminates adding line side voltage transformers for the feeders in the substation that will enable the protection to perform dead line reclosing which adds additional costs.

b) Backup communications check

General practice is to disconnect the solar site from the Grid in the event of a communication loss. The backup protection will allow the Solar Site to stay online for a set time interval during a temporary communication failure and will allow a 4-minute window for the communications to be reestablished. However, this feature has tripped the site off line four times since commissioned. Event reports show the communication failure resets within a minute after the site was tripped off line. It is being recommended by the authors to remove this feature and depend on the local backup protection. Operations has agreed to allow the sites to operate during the normal operating hours under a loss of communication condition.

During a "Loss of communication" condition or a "hot line tag" condition if a fault occurs, (Fig.6) a Goose message is sent to all the upstream devices in the DTT network. These upstream devices are expected to reply as soon as they receive this message. If the reply from any of the devices are not received in the defined time frame, a trip command is issued to the DG controller.

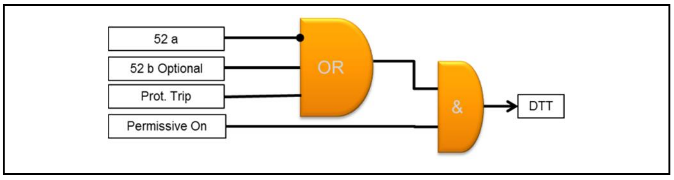
c) DG Communication Failure Trip Scenarios

- DG communications failed with any of the upstream devices – Trip command is initiated after 4 minutes allowing the communication network to recover. This will avoid any nuisance trips caused by temporary communication failures (Ex: restart of a switch/router in the network etc.)
- A hot line tag or Vector Jump at DG will initiate a back communications check. Any upstream device failure to respond within a defined time frame is considered as a reply failure.
    - Hot line tag and reply failure results in trip command to be initiated immediately.
    - Vector jump pickup and reply failure results in a trip command after a defined time delay.
- Hot Line Tag and communication failure will result in a trip command initiation.

All DTT functions will only be executed if the DTT controller permissive is activated locally at the cabinet. The permissive provides a means to preform testing on any component of the DTT system keeping the rest of the system active. The DTT signal is sent from the DTT controller to a different vendor's protection device as a "GOOSE" message. This new intelligent feature was implemented to maximize the possible uptime of the DG site.

2) DTT at Feeder Reclosers (REC)

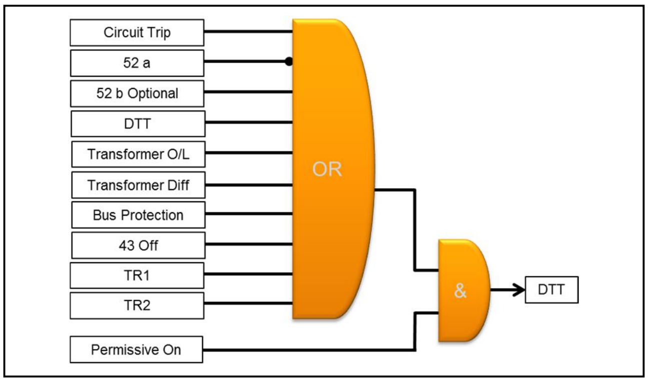
Fig. 7. (Feeder Recloser Direct Transfer Trip logic)



At the inline reclosers the functionality is depicted in Fig. 7. The DTT must have permissive enabled for any DTT "GOOSE" to be generated. The DTT signal is generated by the opening of recloser or a protection trip. The DTT input information was hardwired from the recloser controller and in some instances GOOSE links were implemented.

3) DTT at Substation (SUB)

Fig. 8. (Substation Direct Transfer Trip logic)



The substation functionality is depicted in Fig. 8.
The DTT must have the permissive enabled for any DTT "GOOSE" to be generated. The DTT signal is generated by the opening of the substation breaker, various protection trips or transfer trip signals. All signals are hard wired to the DTT controller through test switches.

VI. CELLULAR COMMUNICATION

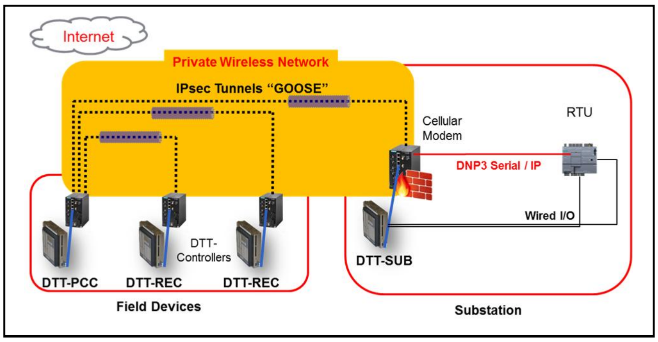
To get this new intelligent DTT approach to work in all projects, it is essential that the field and substation devices communicate and share information in real time. IEC61850 "GOOSE" messages are likely the best possible platform to communicate this information between protection devices.
Although a direct fiber connection between devices is preferable, it will not always be possible to have dedicated fiber ready and available as the communication platform for systems to perform these protection actions. Therefore, it is required that "GOOSE" be able to function over wireless radio systems, and most modern IP based radio systems (Wi-Fi, WiMAX, Cellular 3G, 4GLTE) support Multicast traffic such as "GOOSE".
What makes "GOOSE" ideal for this cellular application?

- It is a small packet protocol, ideal for wireless systems.
- Analog or binary information can be shared for processing by the protection and automation controllers.
- Data traffic can be managed using set time intervals of the "GOOSE" packets.
- The "GOOSE" packets contain quality information. Therefore, devices can filter and discard "GOOSE" packets with incorrect quality information.
- An additional layer of security is added to normal IT cyber security requirements.

The cellular communication consisted of three basic building blocks to achieve the require security. The first element was to get a Private Wireless Network from the cellular provider. This means that this network is not a public network and not connected to the internet. There is no unsolicited traffic on this network. The second is Machine to Machine (M2M) Data Plans for the DTT system's modems. The cellular network is a layer 3 network and "GOOSE" however is a layer two data packet. It is necessary to tunnel these layer two "GOOSE" messages or data packets between DTT controllers over the layer 3 cellular network. The third element is the encrypted IPsec Tunnels. They were setup between all devices using the cellular modems with powerful routing capabilities.
The tunnels are very important as it creates a virtual wire link between cellular modems of DTT systems. "GOOSE" massages are generally broadcasted in ethernet networks, the tunnels cannot be penetrated by unwanted broadcasted "GOOSE" from other DTT or protection systems.
A unique virtual private network (VPN) is also used to separate a DTT systems from all other possible IEC61850 systems.

The DTT controllers provide the final element "GOOSE" Filters to ensure only "GOOSE" associated with the current version of the IEC61850 station will be accepted by the DTT controllers and discard any duplicate or malformed packets that can be maliciously or inadvertently inserted into this VPN.

Fig. 9. (*Basic communication architecture for the DTT systems*)



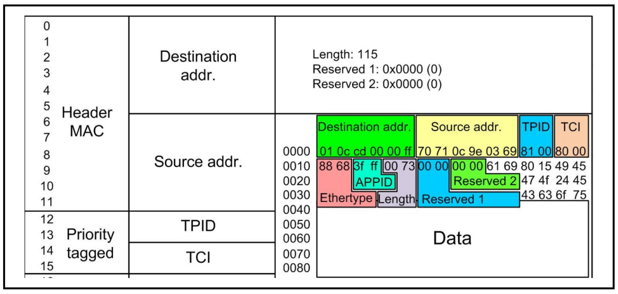
A. GOOSE Structure and Settings

Fig. 10. shows the "GOOSE" message as seen from a Wireshark trace sowing the basic components of a "GOOSE" PDU. Some important components in a "GOOSE" structure include:

- Preamble and start of the frame which is done at the hardware level and not shown in the figure
- Fixed 6-byte size destination and source multicast addresses
- Priority tagging to separate time critical and high priority traffic
- The 802.1Q VLAN (Virtual Local Area Network) is 4 bytes in size and consists of
    - TPID – Tag Protocol Identifier
    - TCI – Tag Control Information
    - Ethertype (0x88b8 for "GOOSE")

- APPID identifies “GOOSE” messages based on their application and is 2 bytes in size

Fig .10. (*Basic components of a GOOSE PDU)*



For DTT applications, numbers of “GOOSE” messages are communicated between all devices in a system. The “GOOSE” structure and settings are adapted for this solution making it possible to work on any IP based communication network (Fiber, WiMAX, Wi-Fi, Cellular etc.). Some of the key settings include:

- Limiting the “GOOSE” application types:
    - Status – Includes “GOOSE” messages related to the open/close feedback from all the devices in the system.
    - Protection – Includes time critical DTT “GOOSE” messages between the devices in the system.
- Modifying parameters of each “GOOSE” application
    - VLAN – Same Layer II VLAN setting for all the “GOOSE” applications
    - Max time setting for each application set to the maximum. In normal conditions, the duration for repetitive “GOOSE” messages (1.5 times the Max time setting) so that the data consumption is minimal at the cell modems.
    - Min time setting is customized for each “GOOSE” application based on the importance. Protection and status applications have sensitive Min time setting compared to the control application.
    - Customized Layer II VLAN priority for each “GOOSE” application. Highest priority is given to Protection and Status applications compared to the control application. These measures guaranteed successful delivery of the “GOOSE” messages with dynamically changing network.

B. Virtual LAN

A virtual LAN (VLAN) is any broadcast domain that is partitioned and isolated in a communication network at the data link layer (OSI layer 2). The Layer II VLAN parameter is the key differentiation feature for an IEC61850 based “GOOSE” message. It is crucial to have a unique VLAN assigned to each DTT system respectively. This VLAN assignment avoids any duplicates and/or collisions of Layer II “GOOSE” messages between devices from 2 different systems. In the discussed system with cellular communications, cell modems are configured with L2TPV3 (Layer 2 Tunneling protocol version 3) which uses the same layer II VLAN assigned to the “GOOSE” messages originating from the controller. Some of the important features of Layer II VLAN include:

- Enhance Network Security – All the “GOOSE” messages with a unique VLAN tag are broadcast within the networks associated on the same VLAN. Each layer II VLAN can be assigned with a specific layer III IP address (tunneling) to pass layer II traffic over a layer III IP network over a secured communication path (tunnel)
- Network Management – At the recipient device in a multi-device network, VLANs provide networking devices (routers) with a capability to easily filter the broadcast traffic based on their VLAN
- Mitigate Network Congestion – VLANs over layer III provide separate communication paths (tunnels) which are peer to peer and have their own tunnel parameters, thus avoiding any collisions.

C. GOOSE over Cellular for Protection Applications

Transmission of many “GOOSE” messages over a cellular network poses several challenges including latency, reliability, data consumption etc. Layer 2 tunneling over Layer 3 IP network (L2TPV3 tunneling) L2TPV3 (Layer 2 Tunneling protocol version 3) VLAN tunnels are configured between the base modem and the end modems to communicate IEC61850 “GOOSE” messages. The tunnel configuration settings include:

- VLAN number – Same VLAN number associated with the “GOOSE” messages originating from the respective device
- Session parameters – Identical session parameters on either side of each tunnel
- Local and remote ports – Unique local and remote ports associated with each tunnel
- Local and remote static IP addresses – Local and remote SIM card static IP’s assigned by the cellular provider

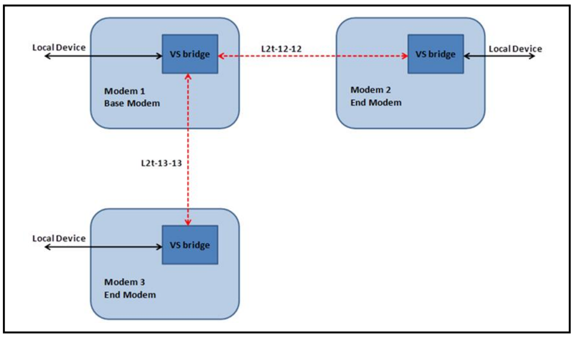
D. Tunnels and IPsec

IPsec is one of the key security features implemented in the cellular modem to provide immunity to cyber-attacks. For DTT applications, IPsec adds an additional layer of security over the existing L2TPV3 tunnels. IPsec is configured to encrypt/decrypt any data entering/leaving the L2TPV3 tunnel respectively. IPsec features include:

- Data Encryption (Data Confidentiality) – Inbuilt 256 Bit AES security algorithms are used to encrypt any data communicated over the cellular network.
- Modems verify pre-shared keys (Unique key can be assigned for each link) before sending/receiving any data.

E. GOOSE Tunnel Architecture

Fig. 11. *(Virtual Switch Logic)*



The Hub and Spoke Model shown in the Fig. 11 illustrates the tunnel setup between 3 cellular modems.

- In each modem, a virtual switch is used in "bridge" mode to connect the local device traffic with the layer III VLAN tunnels originating from the modem
- The hub/ base modem has a VLAN tunnel to every spoke/end modem respectively
- The spoke/end modem has only one VLAN tunnel to the hub/base modem

VII. REDUNDANT COMMUNICATING DTT

In the second Dominion Energy pilot project the authors decided to implement a dual communication strategy of using both Cellular and Fiber Communication. This provide dual communication failure redundancy before a DG site would be disconnected. The expected communication availability is 99.9 % for the DTT system.

A dual communication design was only possible if the DTT system could detect and switch to the available system. All devices must be on the same system. This switching between communication systems at all DTT locations was not implemented in the design. It would have required independent monitoring of both communication systems. If the main system fails all devices must be informed of the failured and requested to simultaneously switch to the backup communication system. A communication failure at one location would cause all devices to change to a backup communication system. A single failure on the backup would cause a complete system communication failure.

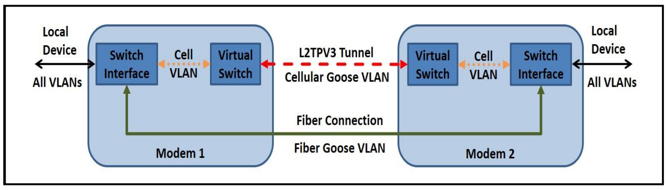
A truly redundant system was required much like a PRP system in a substation. This design will tolerate simultaneous communication failures of both communication systems at different locations.

The major difference is that the DTT device had to broadcast and subscribe to GOOSE from two different communication networks ultimately acting as a logic bridge between two IEC61850 Stations.

A. Redundant GOOSE Communication

In the project both the networks are active all the time. All DTT "GOOSE" communication are shared simultaneously over both the networks. The DTT controllers and the cellular routers are programmed to accept the redundant DTT traffic. The incoming messages from both systems are processed according to a "first come first served" philosophy in the device logic. This implies that the fastest incoming message will trigger the DTT logic and the redundant message is ignored.

FIG. 12. (Redundant Communication Architecture)



- *DTT controller configuration* – The logic in the DTT controller is designed to accept duplicate inputs and provide duplicate outputs which will be forwarded over separate cellular and fiber networks. Each goose message (incoming/outgoing) is duplicated (one for fiber and one for cellular) to suit the redundant networks philosophy.
- *IEC61850 station configuration* – Two goose applications are created for Fiber and Cellular respectively. Each goose application has unique APP Name, VLAN and APP ID. The goose connections between the devices in the DTT system are duplicated in both these applications. This implies that fiber GOOSE application will have exactly same number of GOOSE connections as the cellular GOOSE application. The redundant goose messages configured in the controller are separately assigned in their respective GOOSE applications. Goose messages with fiber logical node are part of fiber GOOSE application and vice versa.
- *Cellular Router Configuration*
    - Switch interface configuration
        - The port connected to the local controller is configured to trunk data from both the VLANs
        - Port with fiber connection is configured as an edge port with VLAN ID of the fiber Goose application (defined in the IEC61850 station)
        - The virtual switch interface is configured to bridge VLAN ID of cellular Goose application (defined in the IEC61850 station) and the cell interface on the modem
    - Cellular interface configuration

- The L2TPV3 (peer – peer) tunnels are defined with VLAN ID of the cellular Goose app
- These tunnels are bridged with the local cellular interface using the virtual switch defined above.

VIII. DEPOLYMENT

A. Installation

Field deployment consisted of the installation of all the control cabinets and substation panels.

Fig. 13 (Typical Installation at PCC and In line Reclosers and Substation)

The deployment was very similar for both projects and is depicted in Fig. 13. DTT cabinets was designed to integrate with the existing protection controllers associated with the reclosers used for the distribution subs, the inline reclosers and the DG site Intertie reclosers. The DTT cabinets housed the DTT controller and the cellular modem/router. The information between the protection and DTT was done using hardware connections. On the Dominion Project "GOOSE" was used to integrate the protection device into the DTT controller.

A directional cellular antenna was installed at every site, either on the pole or the substation cabinet or building. In a few instances the antenna was mounted a bit higher on the pole but always under the conductors. The antenna direction at each locating was adjusted to get best RF signals.

A GPS antenna was installed at each site for each of the DTT controllers. This provided 1ms time stamping and fault recording capability.

The substation integration consisted of 19" panels that housed the DTT Controller with HMI and the cellular modem.

IX. TESTING

In all DTT projects, the systems were tested in a lab environment before actual deployment. The primary gear was simulated by connecting external automation devices to the DTT controllers. The actual M2M plans from the cellular provider was activated on the cellular modems and used in the lab testing. The DTT systems could for the most part be completely lab tested before field deployment. Additional RTDS testing was performed to prove functionality of the backup protection function.

A. RTDS Testing performed by Domuinion Energy

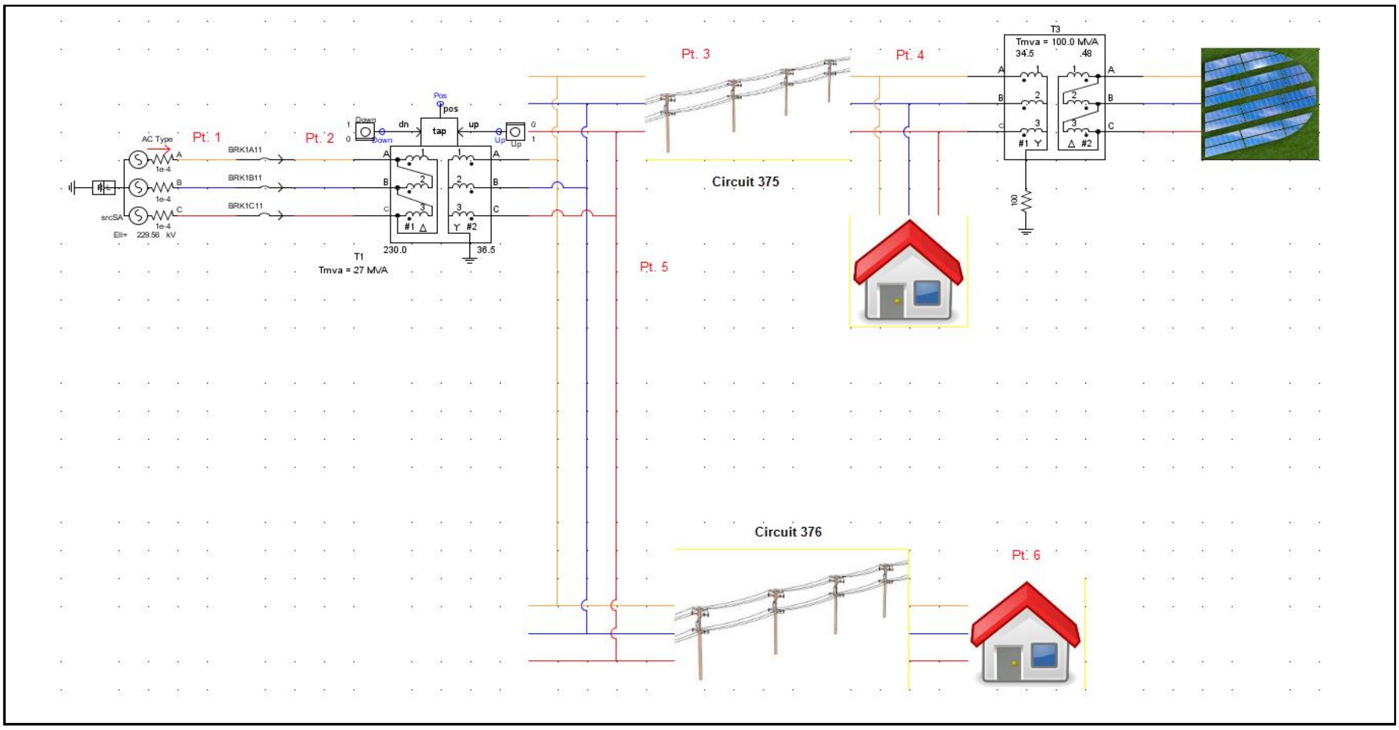
The Siemens 7SC80 was tested in Dominion Energy's RTDS Lab. RTDS hardware-in-the-loop (HIL) testing was performed to get real time responses of the relay unit while interacting with a simulated distribution system. A model of Louisa's distribution system (Pilot Project #1) and the surrounding transmission system was built in RSCAD, Fig.14. The model was verified by placing faults around the system and comparing the fault values to those seen in Dominion Energy's ASPEN model of Louisa substation. The RSCAD model is accurate to less than a 3% difference. The RTDS was connected to a Doble amplifier in order to step up the output to secondary values for proper testing of the relay back up protection settings.

Once the equipment was set up, a variety of scenarios were simulated to determine the ability of the custom logic to properly protect the DG unit and the system it is connected to. Faults were placed on the transmission and distribution system, capacitors were switched in and out, the output of the DG was altered, and the circuit was islanded from the main grid. In total, 48 scenarios were simulated to test the back-up protection logic.

B. Simulation Results

Ideally, the Siemens 7SC80 should only trip the DG offline for any fault in the zones of protection required to isolate the DG. However, due to safety concerns, overtripping for faults on adjacent circuits and transmission lines was deemed acceptable for the loss of communication system in perfect islanding conditions.

Fig. 14. *(RSCAD model of Louisa distribution and transmission system)*



Of the 48 cases, only 1 case gave an unfavorable result. A synchronous generator was placed in parallel with the inverter and the load of the DG circuit was matched to the generation.

The circuit was then islanded. Due to the presence of the synchronous generator the frequency and voltage were maintained at nominal values and any transient effects during the transition to the island were negligible.

Due to the lack of abnormal values, no functions asserted, and no trip was issued. This maybe troubling by itself but Dominion Energy requires all synchronous generators to have transfer trip installed so in practice the synchronous generator would have been tripped offline and the inverter would be unable to maintain nominal conditions by itself, leading to the unit tripping the DG offline.

Most trips were caused by functions 6, 7, and 8. Multiple functions asserted but as time is critical the first function to trip was noted. Power factor, active power, and reverse reactive power all asserted during testing but were not the cause of trips. This is most likely because the calculations of voltage and current are faster than that of power factor, active power, and reverse reactive power. The time from fault to trip output took less than 50 ms in most cases. When the circuit was islanded with only an inverter the trip signal was produced in 104 ms. This is because the relay tripped for function 17, exceeding 60.5 Hz, and the system did not immediately jump above this threshold but instead gradually raised above it in a logarithmic fashion, Fig. 15.

The cases that tripped in less than 50 ms were enabled by a sudden transient in a value, such as the voltage seen in Fig. 16.

Fig.15 (Frequency increase caused by inverter only island)

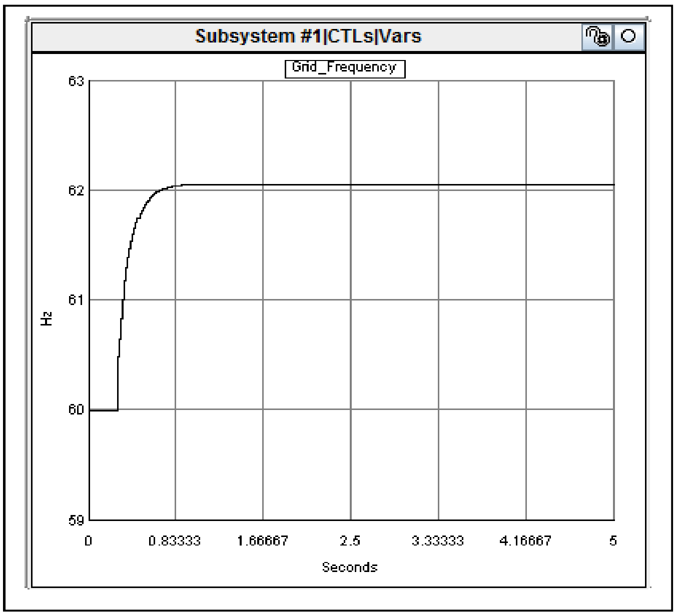
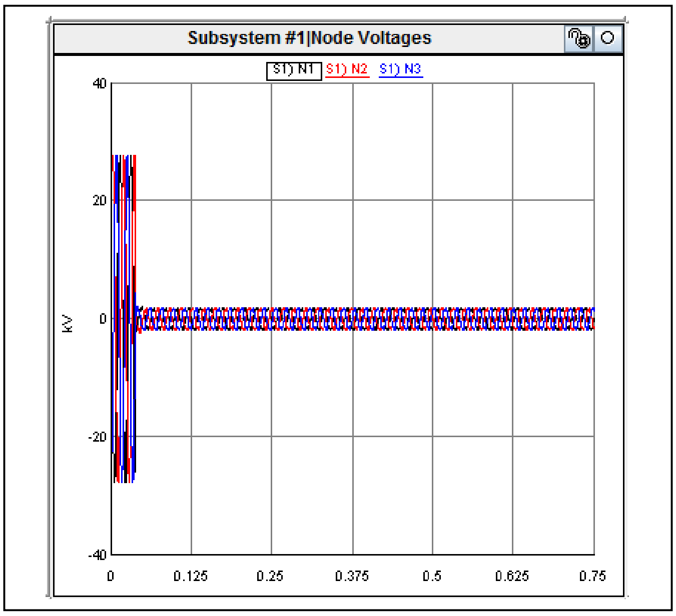


Fig.16. *(Voltage collapse caused by fault on circuit 375)*



C. *Penetration Testing*

Dominion Energy contracted with a third part to perform a penetration test on the RX1400 cellular modem and 7SC80 controller combination. The testing was very successful, and no security risks were identified. All recommendations to further enhance the security of the system were implemented. The DTT communication strategy over the cellular private cellular network followed for the DTT projects is best in class according to the penetration tester. The use of a private network and GOOSE through IPsec tunnels made the system near impossible to penetrate. Remote access to the DTT controller settings and other services is disabled in the 7SC80 and RX1400 making the only possible access point the locked cabinet.

X. COMMISSIONING

Each DTT substation and inline feeder reclosers were bypassed individually and operated to test that the DTT controller was able to receive the required information from the protection controllers and primary gear.

Lastly DTT DG site was bypassed and operated to test that the DTT controller was able to receive the required information and execute a trip of and primary gear. At Dominion Energy the entire DTT systems associated primary gear was bypassed to test the DTT operation of the system. After the integration testing was completed a simulation test was performed to send all DTT and DTC signals to the DG sites. The simulation system simulated the primary gear at each site on the controller at the site.
It allowed the tester to simulate the opening of any substation breaker or feeder reclosers from the Substation HMI to initiate a DTT trip. The system would perform the logic as per the design and the results were recorded.

Fig. 13. *(DTT System HMI at Substation)*

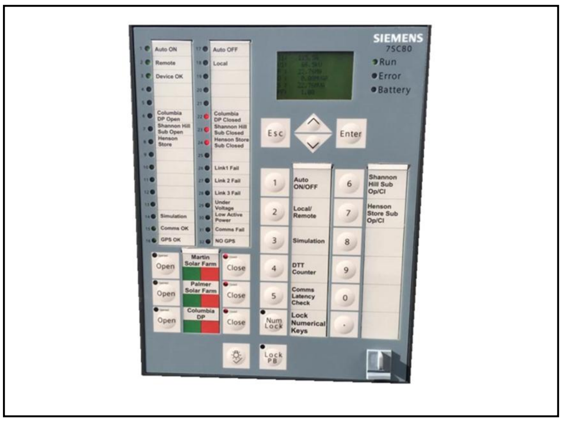


Fig.13. is a picture of the Substation Control HMI at the CVEC delivery point. The HMI provided the status of all primary gear associated with the DTT system. Communication Fail alarms were indicated on the HMI using LED indications. From this HMI all DTT simulated trip tests could be performed.

XI. LESSONS LEARNED

After implementation a few changes had to be made to the CVEC system. The logic for communication fail and DTC had to be modified to ensure correct operation of the DTC function. Logic information that become available after a communication fail conditions caused the DTC not to functions as expected. The Reverse power function over operated due to a too short trigger time. Transmission events cased the function to over operate. A delay was built into the logic to correct for this. The permanent communication fail detection time was increased as temporary communication fail event caused a trigger of the communication fail and unwanted DTT operation. The system at Dominion Energy was the second system to go live and most of the lessons learned at CVEC were implemented from the start of this project. This include individual permissive functions at each DTT location.

Currently the systems perform as designed with excellent reliability. The DTT speed of operation is well within the acceptable limits. Times vary between 80 and 200 milli seconds on the cellular communication systems. The Cellular DTT system at Dominion Energy proved within the first month that it is more reliable that the leased line system. The second pilot proved a new redundant communication and logic DTT system can provide best in class availability for DTT systems. One important factor is the ease of testing communication at each site.
A mobile DTT system was configured and used to test DTT signals back to the Siemens laboratory in Wendell North Carolina from all the Dominion and CVEC Sites in Virginia.

Testing at each site took no more than 5 to 10 min to prove the cellular communication will support the application.

XII. CONCLUSION

DTT over cellular proved to be more reliable than using a leased telephone line system within a few weeks after installation of the DTT systems. It is easy and fast to deploy. Independent penetration testing proved that the methods followed provide best in class security measures to leverage cellular communication for protection applications. Using IEC61850 "GOOSE" made it possible to design and implement more intelligent systems that not merely disconnect a DG site indiscriminately on a communication failure but could determine if a failure was merely temporary in nature and then activated a new dynamic state chance back up protection function to ride through these expected communication interruptions. It was possible to implement a DTC function to automatically close the DG site back in after it was tripped off for a temporary fault on the feeder. A new redundant communication path DTT system was implemented to further maximize the uptime of DG sites. This new digital intelligent DTT system is designed to keep the DG sites connected to the grid, maximizing availability. The new intelligent DTT system is future proof as it provides functionality that can be enabled support IEEE 1547-2018 ride through capability for transmission fault events and act as a monitor for conformance to the standard.

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Solar Shading Vs. Fault Conditions from a Utility View
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