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 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 DG by preventing the indiscriminate disconnection of the sites. Traditionally Direct Transfer Trip Signals (DTT) has been sent between substations and remote Distributed Generation (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.

Using cellular or wireless communication systems it must be expected that there will be communication interruptions during normal maintenance actions. 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) was 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 equipment assist within a protection scheme, to disconnect other power sources quickly, and protect e.g. the DG site's generator from any damages and ensuring that a DG site will not feed into a faulted circuit.

Due to the highly specialized and critical nature of direct transfer trip (DTT) the equipment including communications equipment must be extremely reliable and it is recommended that all DTT equipment is substation class with DC power for all the equipment.

The use of traditional leased lines is becoming more and more problematic as telecommunication companies are moving away from this technology or even providing this as a service.

Installation of fiber is not always feasible due to the cost of installing fiber for long distances that could separate the substations or DG sites from substation sites.

This paper will discuss 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 to.

Two new innovations will be discussed that was 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.

Using cellular or wireless communication systems it must be expected that there will be short communication interruptions when these systems are maintained. During these times the DG site device activates this 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 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 an actual case study of 2 installed DTT systems that use cellular communication. The one system is at Central Virginia Electric Cooperative (CVEC) and the other at

Dominion Energy. We will report on the design, implementation, performance and issues encountered during and post project execution.

The two systems differ in design to achieve a common goal that was achieved to provide a cost-effective yet reliable, smart DTT alternative.

These new intelligent DTT systems are designed increase the availability of DG sites and not indiscriminately disconnect 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 in turn supply power to CVEC and required CVEC to implement a DTT system from the Dominion delivery point to the DG sites. 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 for the more traditional DTT communication system was cost prohibitive.
CVEC implemented a distribution automation and protection system on a remote distribution system that use cellular communications to 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 lease 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 of land line telephones, cell or internet phones are the norm today. 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.

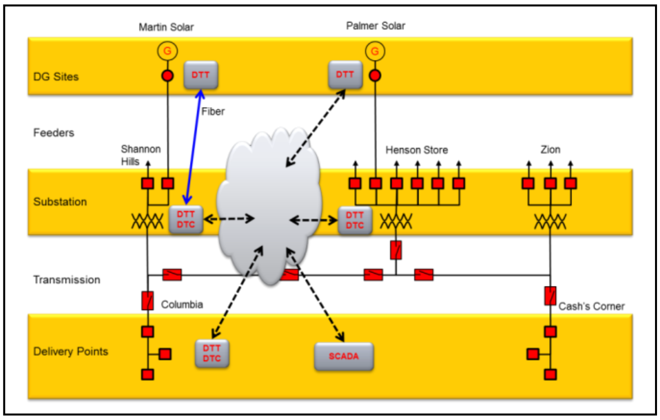
III. IEC61850 “GOOSE”

Using the IEC61850 “GOOSE” messages bring 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 inelegance 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 just disconnect a DG site from the grid.

IV. DTT System Topologies

A. CVEC Project

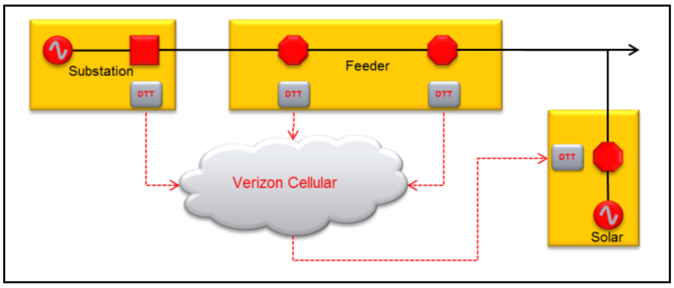
Fig. 1. *(CVEC DTT Project Topology)*



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 a 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 DTT functionality.

This existing DTT systems' communication reliability caused unwanted disconnect of the solar site. The existing system is an analog based DTT system. A closed loop hardwired circuit energized relays, if the circuit is broken the relays are degenderized 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, the opening any one of the inline reclosers or a remote transfer trip signal. The system has no intelligence and every time that 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 both 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 to 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 form the primary feeder breaker and other required DTT signals to send a DTT signal to the PCC-DTT.

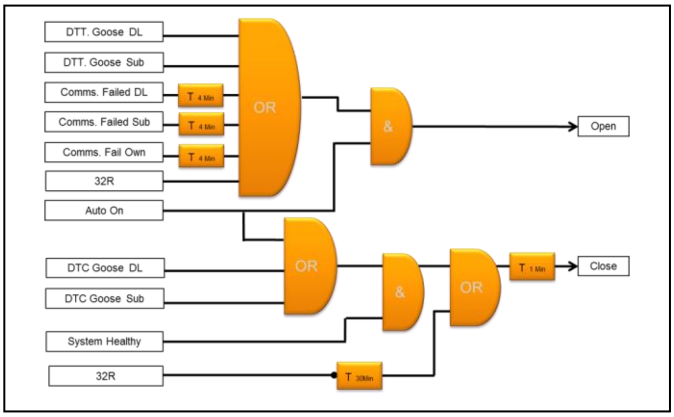
The basic building blocks for the systems consisted of a DTT controller, and a cellular modem or router. The DTT controller interfaced to the protection and primary gear though binary inputs and outputs or "GOOSE" where applicable. The DTT controller is connected to the cellular modem though an Ethernet 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.

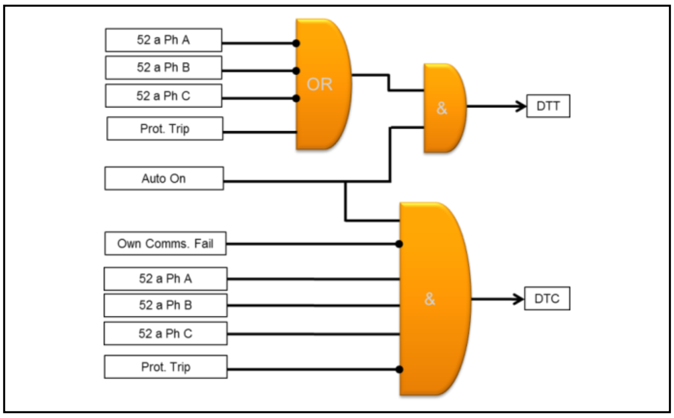
The system Auto Mode must be enabled to allow a DTT trip to occur.

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 had to ensure the DG site was connected automatically without having to wait for an operator to be available, maximizing the possible uptime DG site.

2) *DTT at Distribution Substation*

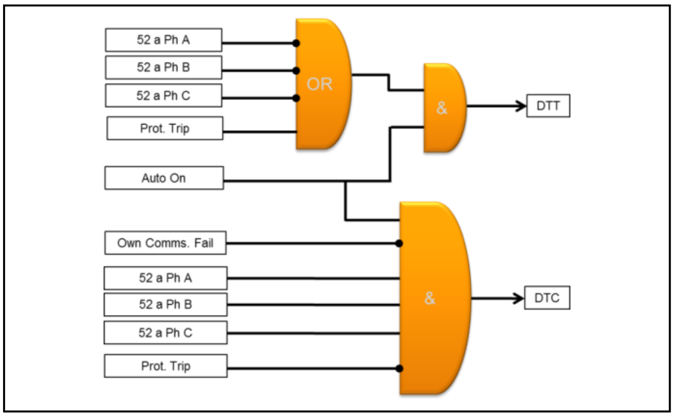
Fig. 4. (Distribution Substation Direct Transfer Trip logic)



At the distribution substations the 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)

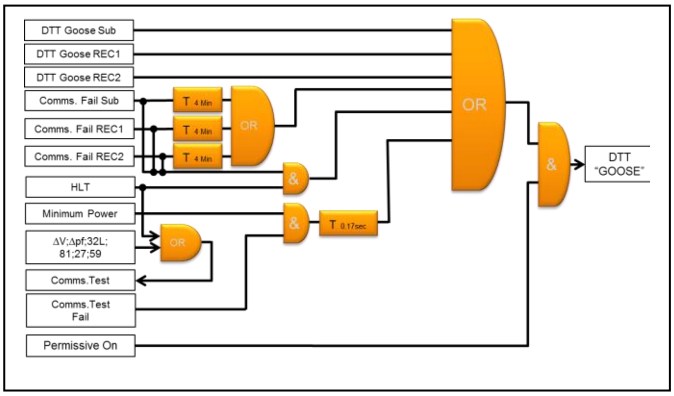


At the transmission substation or delivery point from Dominion Energy to Central Virginia Electric Cooperative the functionality is depicted in Fig. 5. The DTT must be in the Auto Mode for any DTT or DTC "GOOSE" to be generated. The DTT signal is generated by the opening the substation breaker, a protection 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 Feeder (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 in addition if a sustained communication failure is detected indicating a permanent communication failure at any of the DTT devices.

A Hot Line Tag (HLT) condition on the feeder with a communication failure pick up will lead to an immediate trip. The communication failure is a delayed detection and can take up to 2,5 minutes. If a HLT is applied a communication test "GOOSE" is generated immediately. If one of the DTT controllers does not reply immediately to the test "GOOSE" the system will issue a trip.

A new approach is to not just indiscriminately trip the DG site off for a communication fault but rather let the system determine if the communication interruption is temporary or permanent in nature.

In wireless networked systems we can expect equipment to reboot when maintained that can cause temporary interruptions.

During these expected temporary communication failures, the DTT system will activate a dynamic state change protecting feature. If this function detects a sudden change in Voltage, Power factor, an under or over frequency or an under or over voltage it will lead to a trip and only if a minimum power limit was exceeded indicating the DG site was delivering power into the connected grid.

All DTT functions will only be executed if the DTT controller permissive is activated locally at the cabinet.

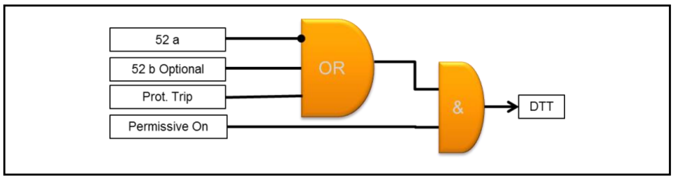
The permissive provides a means to preform testing on any component of the DTT system keeping the rest of the system active.

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)*

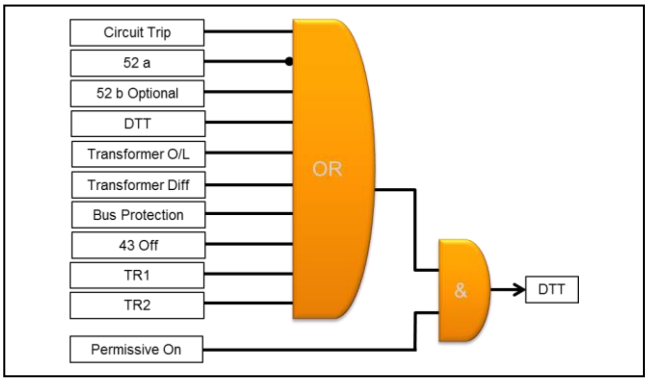
Fig. 7. (Feeder Recloser Direct Transfer Trip logic)



At the inline reclosers the functionality is depicted in figure 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.

3) *DTT at Substation (SUB)*

Fig. 8. (Substation Direct Transfer Trip logic)



At the substation the 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 the substation breaker, various protection trips or transfer trip signals.

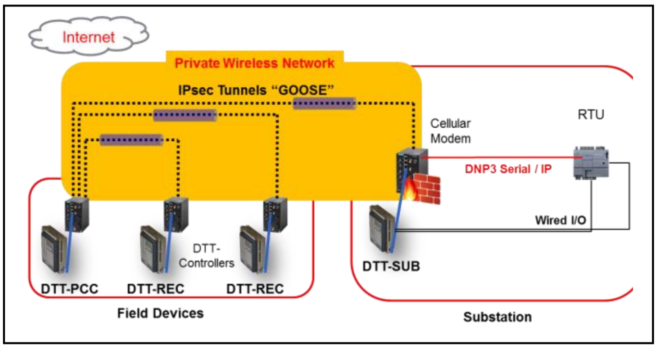
VI. Cellular Communication

To get this new intelligent DTT approach to work in both 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 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. A unique virtual private network (VPN) is used to separate a DTT system 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*)



This decentralized DTT system requires high speed peer-to-peer communication between all devices. In the IEC 61850-8-1 standard, one of the messages associated with the GSE services are the Generic Object Oriented Substation Event ("GOOSE") messages that allow for the broadcast of multicast messages across the Local Area Network (LAN). It was designed to share data between protection points through an Ethernet network on a peer to peer basis, and is the standard communication protocol for protection applications, with each device periodically multicasting the "GOOSE" messages to the other devices. Note, if a cellular network is used, the cell modems are required to be setup for point to multipoint communications.

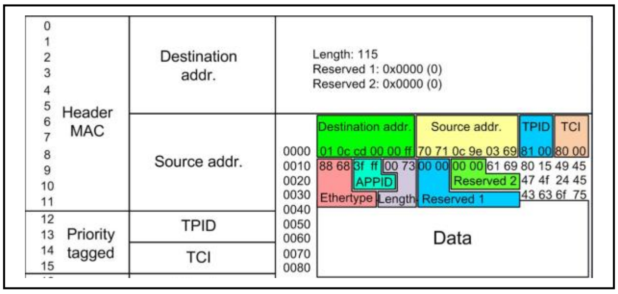
A. *GOOSE Structure and Settings*

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 IEC 61850 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

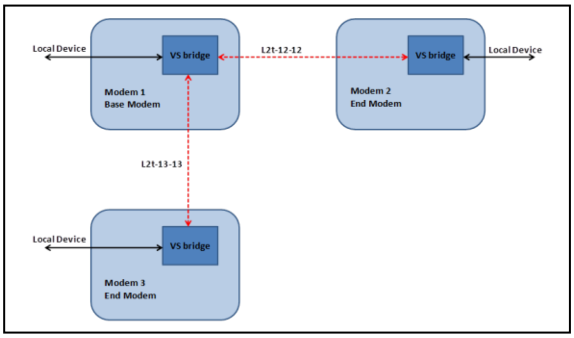
D. Tunnels and IPsec

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. Deployment

A. *Installation*

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

The deployment was very similar for both projects and is depicted in Fig. 12. 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.

Fig. 12 (Typical Installation at PCC and In line Reclosers and Substation)

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.

VIII. Testing

For both projects the systems was 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.

IX. Commissioning

Each DTT substation and inline feeder point was bypassed individually and operated to test that the DTT controller was able to receive the required information form 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 open any substation or feeder breaker from the Substation HMI to initiate a DTT. The system would perform the logic as per the design and the results were recorded.

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

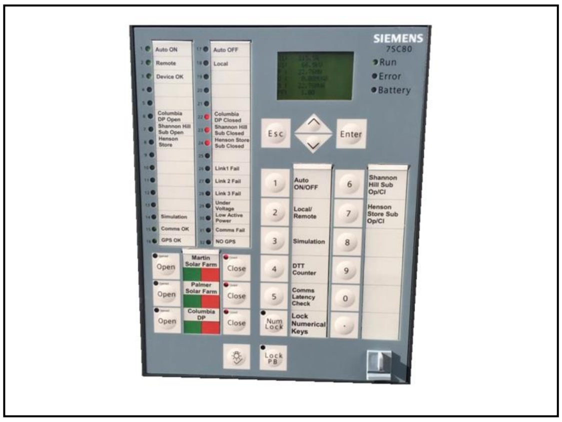


Fig.13. is a picture of the Substation Control HMI at the CVEC delivery point. The HMI provided the status of all primary gear associated with the DTT system. Communication Fail alarms were indicated on the HMI using LED indications. The system performed a link fail test for every operation and once every 24 hours to alarm for any slow communication links.

X. Lessons Learned

After implementation a few changes had to be implemented 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 becoming 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.

Currently the systems perform as designed with excellent reliability. The DTT speed of operation is well within the acceptable limits. Times vary between 100 and 200 ms 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.

XI. Conclusion

DTT over cellular is more reliable than using a leased telephone line system.

Using IEC61850 and in particular the “GOOSE” made it possible to design and implement a more intelligent systems that not merely disconnect a DG site indiscriminately on an communication interruption but could determine if a failure was merely temporary in nature and activated a new dynamic state chance 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.

This new DTT system is designed to keep the DG sites connected to the grid.

XII. References

PAC World Article: Wireless Communication Systems Supporting IEC61850 Applications - Andre Smit & Suraj Chanda - Siemens Industry, Inc. Raleigh, NC, USA Terry Fix - Dominion Energy Richmond, VA, USA

PAC World Paper: Intelligent DTT Over Cellular Communications - Andre Smit & Suraj Chanda – Siemens Industry, Inc. Raleigh, NC, USA Terry Fix - Dominion Energy Richmond, VA, USA

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