# Some Practicalities of Applying DFRs in IEC 61850 Substations

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# 1 INTRODUCTION

A Digital Fault Recorder (DFR) is a device or application that records binary and analog data at different recording rates for different types of event analysis, with all the data contained in a common, synchronized record, using recording triggers based on event analysis criteria. A substation using IEC 61850-based communications and data modeling opens up the capabilities of DFRs, since the limitation of what can be recorded is no longer field wiring and terminal blocks but is now processing power and network architectures. Therefore, an IEC 61850-based DFR, implemented either as dedicated, standalone hardware, or as an application running on a processing platform, is both more cost-effective than, and can do more than, traditional recording solutions.

There are some practicalities of using a DFR with IEC 61850 data that must be clearly understood, especially in regards to network architecture and the synchronization of data. The protection and control system must be configured so that devices that comprise the system provide the right data to the DFR. The network architecture must support the DFR, the network architecture in an IEC 61850-based substation will be driven by the traffic management required by the bandwidth consumed by sampled values (SV) data. To provide synchronization between devices, IEC 61850 data is natively timestamped. However, different timestamps are available, so it must be clearly understood by manufacturers of DFRs and end users of DFRs what these different timestamps are, and how timestamped of data can be used for quality recordings.

# 2 THE IMPACT OF IEC 61850 ON DFR DATA

The overall goal of a DFR in an IEC 61850-based substation remains the same: capture power system data in a record whose recording is triggered based on power system anomalies, at a high enough sampling rate to provide good resolution, with enough data to be able to analyze protection and power system equipment performance. The difference between an IEC 61850-based DFR and a conventional DFR is how this data is collected.

The data a traditional DFR collects includes current and voltage waveforms, equipment status and position, trip, close, and other protection signals, and alarms. This data is analog, electrical data, so the DFR collects this data by connecting the source of each piece of data to the DFR through a pair of copper wires. Copper wiring winds up limiting how much data a DFR can collect. The cost of installing copper wiring, and the space limitations of terminal blocks on a DFR restricts the number of data channels that a DFR can collect. Since these are electrical signals, a DFR is also limited to collecting data that is available electrically, such as the status of binary contacts, and current and voltage secondary signals. Therefore, any data required from a relay must be configured to an output contact, and that contact wired to the DFR.

Under IEC 61850, all electrical analog data is digitized at the source of the data and is published as IEC 61850 data to an ethernet network. Additionally, other data, such as protective element pickups and dropouts contained in a digital protective relay, can also be published as IEC 61850 data to an ethernet network. A DFR can simply connect to this ethernet network and subscribe to the all the IEC 61850 data that is published to the network and use this data as part of a DFR record. This means a DFR is no longer limited by the physical connections of copper field wiring, and the role of a DFR can be expanded. The limits to a DFR become network bandwidth, the number and types of ethernet ports, and processing power.

## 2.1 IEC 61850 data

The basic mechanism with which data is shared under IEC 61850 is to place data in the data set, then assign the data set to a Control Block. Control Blocks define the message type, and publish the message when a data set item changes value. Data under IEC 61850 means the value of a piece of data contained in a dataset, and self-description of this data to other devices through the IEC 61850 data model. This data model describes a data value with a Logical Node (a specific power system function), a functional constraint (the type of data), a data object (what this data represents), and data attributes that define the data value. Beyond a data attribute that defines the data, all data objects must also provide the quality attribute (data.q) that describes the validity and the usability of the data, and the timestamp attribute (data.t), that identifies when the data described by this object last changed values. Therefore, a protection trip signal from a relay is described as below:

PTRC.ST.Tr.general
PTRC.ST.Tr.q
PTRC.ST.Tr.t

Where:

- "PTRC" is the Logical Node (a specific power system function) for "protection trip". Any protection function in a relay will be routed through PTRC.
- "ST" is a functional constraint that says this this data object and data attribute is a status information, which is Boolean data.
- "Tr" is the actual data object – "Trip", or the operation of this function.
- "general" is an attribute of the Tr data object. General means any phase has operated.
- "q" is the mandatory quality attribute of the data, or if this data can be trusted.
- "t" is the mandatory timestamp of the data. This timestamp is the last time the Tr data object changed state.

When the PTRC.ST.Tr.general data attribute is assigned to a dataset, all subscribing devices know that if the value is 1, a protection trip has been declared. When the value goes from 0 to 1, or 1 to 0, the value of t changes to indicate the time this change occurred.

For DFR applications, the "t" attribute is important, as all data is timestamped at the publisher of the data. Subscribers to this data, like a DFR, must make use of this timestamp to align this data with data coming from other sources.

### 2.1.1 Analog data

Analog data comes from MUs and PIUs that publish sampled values (SV) messages through the MSVCB control block. SV messages use a defined dataset, based on one of the SV application profiles, for the instantaneous samples of currents and voltages. The configuration of SV messages is essentially choosing the profile and assigning the currents and voltages connected to the device to the dataset.

SV messages are published at a defined, periodic publishing rate, and a defined data sampling rate, based on the SV application profile used. As a result, an SV stream consumes significant bandwidth on the network, of between 5 Mb to 15 Mb continuously. SV data therefore significantly impacts ethernet network design.

### 2.1.2 Binary data

Binary or Boolean data is assigned to datasets. These datasets are published as GOOSE messages through a GoCB control block, or as a Report through RCB control block.

#### *2.1.2.1 GOOSE messages*

GOOSE messages are multicast publish-subscribe messages, intended for data that must be quickly shared, without acknowledgement, with other devices. The typical use for GOOSE messages is share protection data such as trip flags and blocking or permissive signals. For this reason, the data timestamp data.t is rarely included in datasets to be published as a GOOSE message. Additionally, some devices have performance limits as to how many timestamp attributes can be placed into datasets.

GOOSE messages publish by exception, meaning they publish when any dataset item changes state or value. In normal operations, most of the data contained in a GOOSE dataset doesn't change state, so the GoCB publishes a heartbeat message at regular intervals, typically every second. When an item does change state, GOOSE messages retransmit the message several times to ensure subscribing devices will receive the message.

As a multicast message, a GOOSE message is published to the network using the basic MAC addressing of ethernet networks. Any device on the network on the network can see and subscribe to this GOOSE message, unless network configuration blocks the message.

#### *2.1.2.2 Reports*

Reports use the two-party association, client-server model of communications defined by MMS (Machine Messaging Specification), which establishes a point-to-point connection through the ethernet network between the server (the source or publisher of the data) and the client (the user or subscriber to the data). MMS does support handshaking and acknowledgement between devices, and uses IP network addresses to support this connection.

Datasets assigned to Reports typically include both binary and measured analog data. There are two types of Report control blocks: buffered and unbuffered. A buffered Report control block means the server will store all data for some time if connection to the client is lost and publish this data once a connection is reestablished. An unbuffered Report control block means a server only publishes data while there is a connection between the server and a client. Reports, like GOOSE, are normally report by exception, though Reports can be configured to support traditional SCADA polling techniques.

#### *2.1.2.3 Sending binary data to a DFR*

An IEC 61850 DFR should subscribe to GOOSE messages used for protection data, and GOOSE messages used for circuit breaker or other equipment status, to include this information in recordings. DFRS will subscribe to many of the protection GOOSE messages to capture this basic protection signaling in a record. As such, GOOSE is intended to send small amounts of data at a time. However, GOOSE is not the best choice to send large amounts of binary data to a DFR. This will place a lot of messaging on the network, and a lot of noise on the network through GOOSE heartbeat messages. However, GOOSE subscription is widely supported by IEC 61850 DFRs. This may require the use of DFR-specific GOOSE messages, simply to share needed data with the DFR.

Reports are a better choice to send large amounts of binary data to a DFR. This data can be placed in a DFR specific dataset in the publishing device assigned to the Report. Reports only publish when a dataset item changes state, so there is less traffic on the network. Reports are the better choice when trying to send SOE data to the DFR. However, to use Reports requires the DFR be an MMS client, and to support a large number of client connections. To date, no commercially available IEC 61850 DFR can act as an MMS client. However, IEC 61850 communications gateways do support a large number of MMS client connections, so they can subscribe to Reports to provide a unified SOE recorder for the substation.

# 3 GETTING DATA TO THE DFR

Getting data to a traditional DFR is straightforward – simply wire an electrical signal from the source measurement to the DFR. A DFR in an IEC 61850-based substation must be able to subscribe to the control blocks and messages available on the ethernet network. This requires an understanding of the sources of data in the substation, and a high-level understanding of ethernet networks.

## 3.1 Sources of data

Any IEC 61850-capable device can be a source of data to a DFR, though there are some data sources that are more appropriate for specific types of information. At a minimum, the DFR needs to subscribe to process data: the basic information about the power system and equipment in the switchyard. Consider the arrangement of Figure 1. The sources of process data are the MU, RIO, and PIU, and the DFR must make use of data from these devices.

To define these devices:

- A merging unit (MU) is a device that connects to instrument transformers and publishes SV data only.
- A remote I/O module (RIO) is a device that connects to primary equipment using contact inputs and outputs, and publishes data via GOOSE, and possibly Report control blocks via MMS.
- A PIU is a combination of a MU and RIO, that publishes SV, GOOSE, and Reports.

Beyond process data from the switchyard, the DFR will need to subscribe to data from other devices to see teleprotection signals, relay trips, and other similar information. Any other device that supports IEC 61850, such as protective relays, power quality meters and recorders, and other IEDs can also be a source of data to the DFR, normally through GOOSE, and possibly through RCBs.

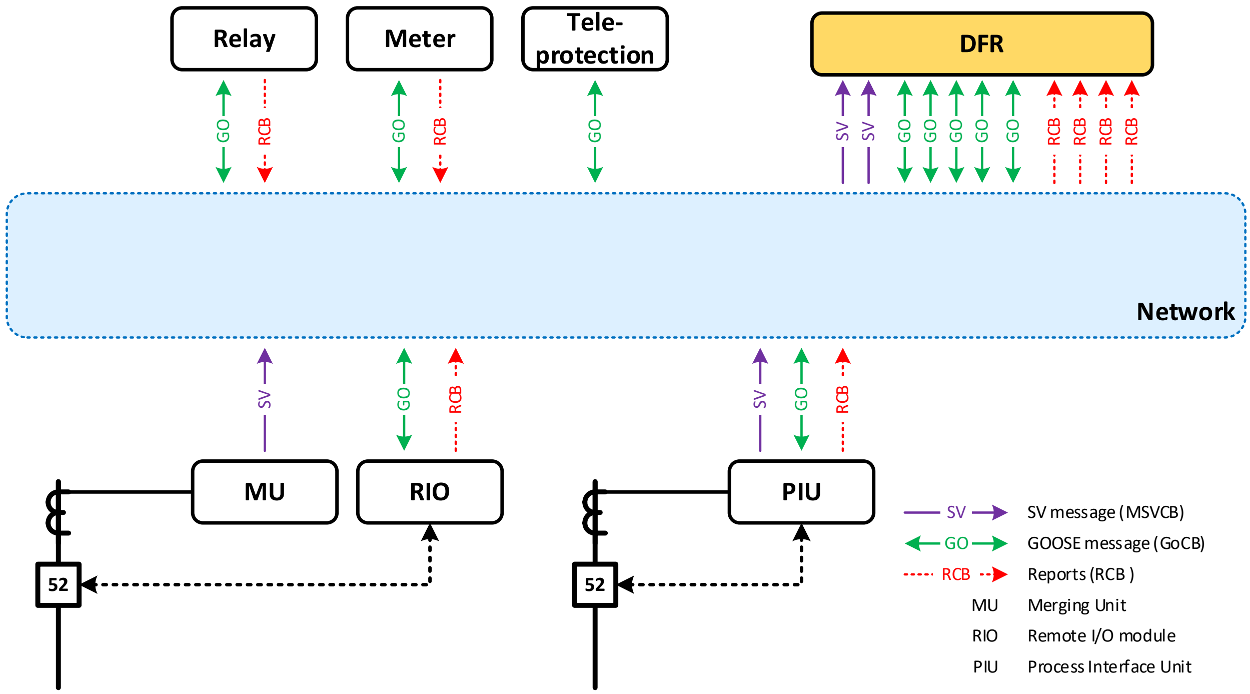


**Figure 1: Sources of data**

The DFR will need to subscribe to messages from the PIUs, MUs, and RIOs, as this is the source of current and voltage waveforms, along with equipment position and status. The DFR will need to subscribe to messages from relays and teleprotection equipment, as these will be the source of trip signals, blocking and permissive signals, and other basic operating flags and indications. All of these devices: RIOs, PIUs, and relays can provide more detailed information, beyond protection signaling, that may be captured in DFR records.

## 3.2 Simple IEC 61850 DFR data example

A simple IEC 61850 DFR data example is shown in Figure 2. The principle behind this example is very simple. Compared to a traditional DFR, an IEC 61850 DFR has access to ***all data*** in the substation by connecting to the appropriate ethernet network:

- ***All*** currents and voltages as SV data published by MUs or PIUs
- ***All*** breaker information published as GOOSE or RCBs by RIOs or PIUs
- ***All*** protection trips and teleprotection signals published as GOOSE or RCBs by relays or teleprotection equipment
- ***All*** device event log information published by RIOs, PIUs, and relays as GOOSE or RCB.

This example has a relay and PIU that holistically act as a protection system, as described in the following sections.

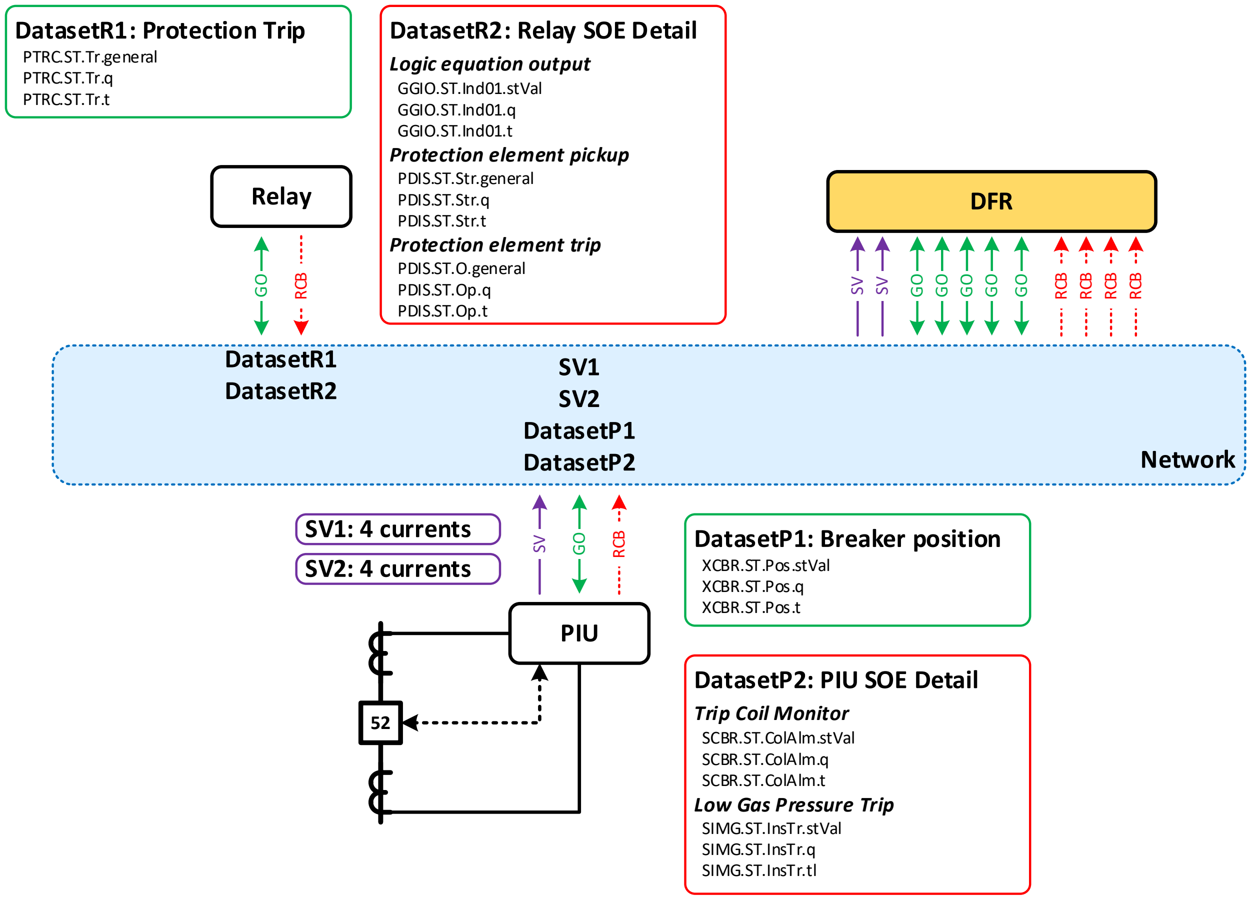


**Figure 2: Simple IEC 61850 DFR data example**

### 3.2.1 PIU

The PIU connects to CTs on both sides of the circuit breaker, and connects to contact I/O at the circuit breaker. The PIU publishes:

- 2 SV streams, 1 for each set of CTs.
- 1 GOOSE message with a dataset containing breaker position information.
- 1 RCB with a dataset containing sequence of event (SOE) data from the circuit breaker, specifically a trip coil monitor alarm, and a low gas pressure trip alarm.

The PIU subscribes to the GOOSE message from the relay. This GOOSE message contains the trip flag for the circuit breaker.

### 3.2.2 Relay

The relay will trip the circuit breaker by publishing a GOOSE message containing a trip flag. The relay therefore publishes:

- 1 GOOSE message with a dataset containing protection trip information.

- 1 RCB with a dataset containing sequence of event (SOE) data from the, specifically the status of a logic equation, and pickup and operation of a specific distance protection element.

The relay subscribes to:

- 1 SV stream from the PIU to provide current for protection elements.
- The GOOSE message from the PIU to get the circuit breaker status.

### 3.2.3 DFR

The DFR will subscribe to the following data:

- Both SV messages published by the PIU. This allows comparison and crosschecking of data for CT accuracy and performance.
- The GOOSE message published by the PIU to include in the oscillography records, and as a trigger source to start a recording.
- The GOOSE message published by the relay to include in the oscillography records, and as a trigger source to start a recording.
- The RCBs published by the PIU and relay to include in the oscillography records. Some of this data may be used as recording triggers.

## 3.3 What a DFR can do / can be under IEC 61850

A DFR has access to all data in the substation. This suggests a couple of possibilities for improving event analysis.

The first concept is simply to have a more comprehensive oscillography record, by including more binary channels in the record. More information can be included, such as the status of any relay logic equations that control tripping, and the pickup and operation of specific protection functions in a relay. This means more granular detail can be provided, tempered by consideration of the right amount of data versus too much data.

The second concept is a unified, station-wide SOE recorder. In this concept, all relay, RIO, and PIU event log data is sent to the DFR via RCBs to simply capture all events in a unified record. This requires the DFR supports MMS, and a large number of MMS clients. The station-wide SOE is possible today, as any IEC 61850-capable communications gateway should be able to do this. Some applications that a DFR capturing more data can support include:

- Support for a NERC PRC-005 monitoring program, to monitor current and voltage measurements provided to relays, as well as equipment status data.
- As data for a condition-based maintenance program for substation equipment.
- Using data analysis to identify hidden failures in the protection system, or incipient failures in power system equipment.

## 3.4 Impacts of IEC 61850 on DFR applications

The first impact of IEC 61850 on DFR applications is that the DFR application must be holistically accounted for during the protection and control system design. This means devices must be selected and configured to provide the appropriate data to the DFR, the ethernet network must be configured so this data is reliably passed to the DFR, and the DFR must be selected and configured to meet the desired application requirements. Specifically:

- The MU/PIU must be selected to provide SV data to the DFR with a high enough raw sampling rate for the desired application. SV sampling rates are determined by the SV profile used. The profiles define a sampling rate for protection data, and a sampling rate for power quality data. If the DFR is providing some power quality recording, then MUs/PIUs that can provide the power quality sampling must be used.
- Devices must be configured to provide data specifically needed by the DFR. Relay, RIOs, and PIUs will be configured with GOOSE messages for protection system needs that the DFR will subscribe to. But these devices can provide additional data to the DFR, either through dedicated GOOSE messages, or through dedicated Reports. The strong preference is to use Reports, but no commercially available DFR can act as an MMS client at this time.
- The ethernet network must be configured to pass traffic through the network to the DFR. SV data consumes considerable network bandwidth, so the network will use traffic management to ensure reliable performance. This network configuration must, however, allow messaging from source devices to reach the DFR.
- The DFR selected must support capturing enough data, with the desired sampling rate, to meet application requirements. The DFR must also support the SV application profile(s) used the MUs and PIUs. The DFR will impact configuration in terms of the number and types of messages and data the DFR can subscribe to, as well as the ethernet network architecture.

DFRs will have to connect to multiple ports on a network to get the required SV data. The bandwidth consumed by SV data requires that ethernet networks use traffic management techniques to maintain network and device performance, so DFRs will need multiple connections to networks.

DFRs must be able to time align data from SV, GOOSE, and Reports. SV messages uses a specific timestamping method, while GOOSE and Reports may have three different timestamps that may be used. End users must be cognizant of these time alignment issues when using records to analyze system performance, while realizing that the time alignment of binary channel information in traditional DFRs has always had some variability.

DFRs must correctly handle data quality as required by the Standard. This includes processing the quality flag, as well as accounting for the known time synchronization of SV data.

The drive should be for DFRs to become MMS client devices, with a significant number of client connections, to collect enough data for more robust recordings. This relates directly to the concept of doing more with the DFR and DFR data, by using captured high-resolution data to better monitor protection system and protection equipment performance.

# 4 NETWORKING, SV, AND DFRS

## 4.1 Network design and data availability

To capture and record data, the DFR must have access to the data. In a digital substation, access to the data is a function of network architecture and network configuration. A DFR must be designed to support multiple different network architectures, and end users must be cognizant of network architecture and configuration as part of installing a DFR for use. For the purposes of this paper, a network is one or more ethernet switches connected together to permit traffic passing between devices.

### 4.1.1 General network architecture

For a full IEC 61850 substation, there are two general network architectures. The first is the network architecture of Figure 1: one common physical network that all IEC 61850 traffic passes over. The other general network architecture is that of Figure 3: separate physical networks generically known as the “station bus network” and the “process bus network”.

The station bus network is normally used for traditional SCADA services, such as data collection through Reports, and SCADA control of equipment (using control services over MMS under IEC 61850). GOOSE traffic between relays may also be on the station bus network. The process bus network is communications between relays, meters, and the process I/O devices of MUs, RIOs, and PIUs. This network will carry SV and GOOSE messages and may also pass Report control blocks. In this second architecture, the DFR must be capable of connecting to both the station bus and process bus networks to have access to all data the DFR needs to capture.

The first practicality, then, is that a DFR will need enough network connections to connect to at least two different networks that provide different data and have the capability to connect to these two different networks. In practice, a DFR will need more network connections to subscribe to all the SV data available in the substation.

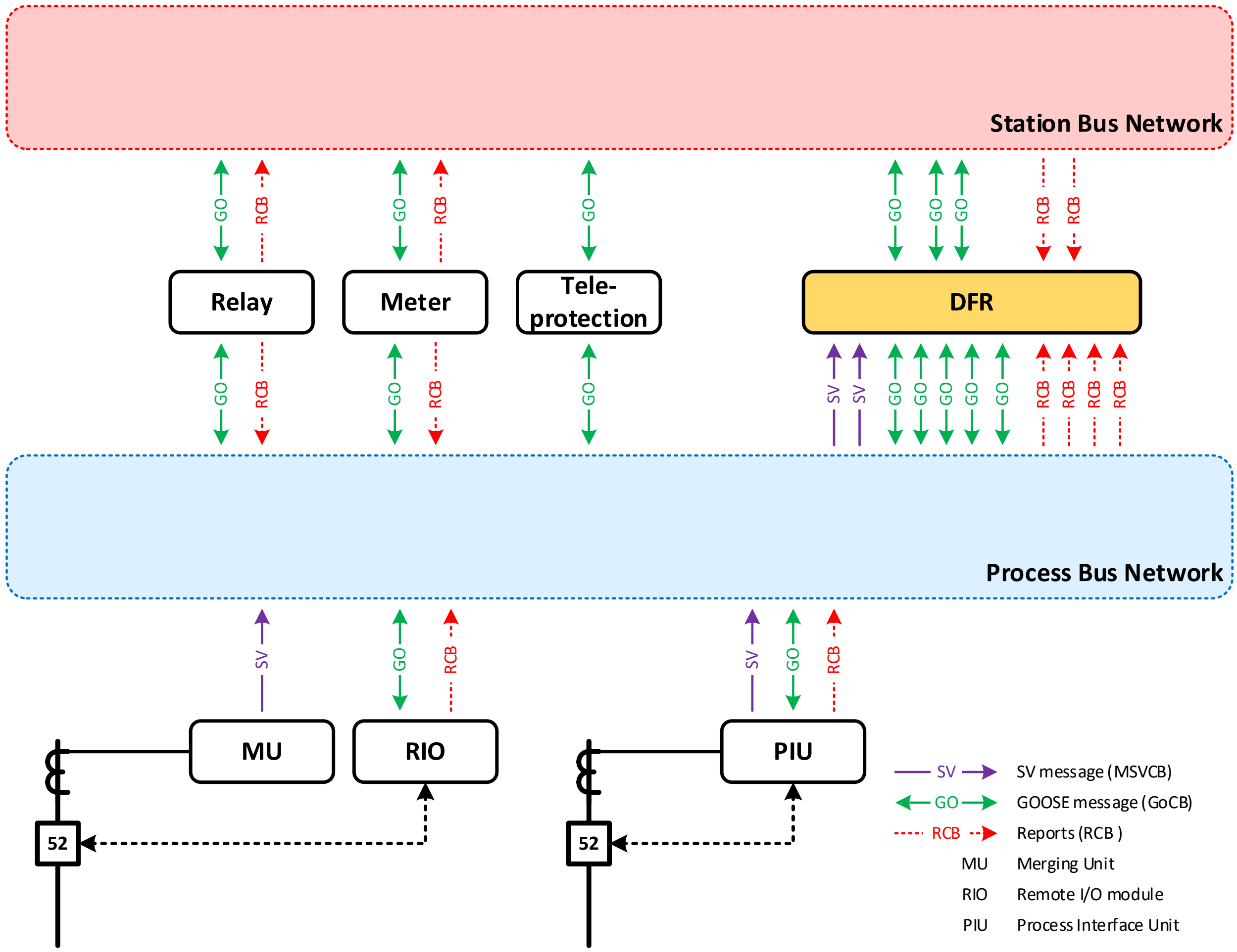


**Figure 3: Separate networks**

### 4.1.2 Example DFR installation

A simple example is useful to discuss the issues around configuring an IEC 61850 DFR system, including MU/PIU selection, device configuration to provide data, network configuration, and DFR requirements. The example substation of Figure 4 represents a common transmission substation: four lines using two breaker-and-a-half diameters. As a starting point for configuration, MUs and PIUs are installed to meet protection system requirements. Each circuit breaker has redundant PIUs. Each VT has redundant MUs. Each line has redundant relays and some teleprotection equipment. Both buses have a bus protection relay. Obviously, 0ther arrangements of PIUs and MUs are possible, obviously, but this architecture provides complete redundancy of analog measurements to ensure protection system reliability. The network architecture for this substation will use the separate station bus and process bus networks of Figure 3.

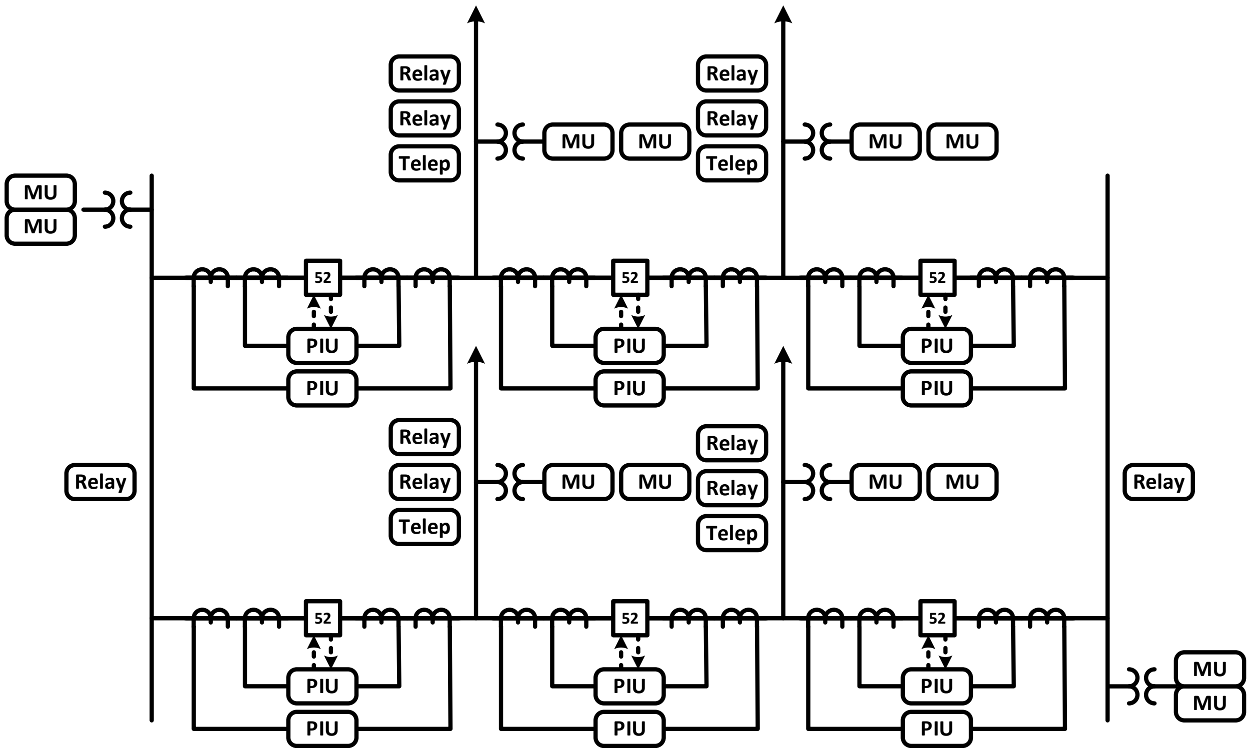


**Figure 4: Example substation**

Each PIU will publish 2 SV streams, one for each set of current measurements. Each MU will publish 1 SV stream for a set of voltage measurements. The sampling rate for this data will be a protection sampling rate. This means there are 36 SV streams available in the substation.

- 12 PIUs x 2 SV per PIU = 24 SV
- 12 MUs x 1 SV per MU = 12 SV
- Total SV = 36 SV

There will be at least 24 GOOSE messages in this substation. Each PIU will publish a GOOSE message for breaker position information. Each relay will publish a GOOSE message to send trip flags and reclose flags to the PIUs, as well as breaker failure trips to other relays. The teleprotection equipment will publish a GOOSE message as blocking or permissive signals from the remote end of the line. these GOOSE messages are protection specific GOOSE messages. However, the DFR were capture and trigger on this data.

- 12 PIUs x 1 GOOSE per PIU = 12 GOOSE
- 8 Relays x 1 GOOSE per relay = 8 GOOSE
- 4 Teleprotection x 1 GOOSE each = 4 GOOSE
- Total GOOSE = 24 GOOSE

There will be at least 20 Reports in this substation. Each PIU will publish a Report for circuit breaker SOE data, including trip coil monitor alarms and various breaker alarms. Each relay will publish a Report that is complete relay SOE data. These Reports, and the underlying datasets, are specifically configured to provide data to the DFR.

- 12 PIUs x 1 Report per PIU = 12 Reports
- 8 Relays x 1 Report per relay = 8 Reports
- Total Reports = 20 Reports

### 4.1.3 The basics of SV data on networks

Ethernet networks of any appreciable size require traffic management to ensure reliable performance of the network. This is especially true for SV data. Each MSVCB message takes significant bandwidth. The basic requirements for SV datasets and control blocks are defined in IEC 61850-9-2, [1] but this messaging is very flexible. There are 2 different application profiles in common use that put some boundaries around SV data to provide realistic interoperability between devices. The most commonly used application profile is the one defined in the IEC 61850-9-2LE Implementation Guidelines [2], commonly known as 9-2LE. The newer application profile is the one defined in the IEC 61869-9 Standard. [3]. Both profiles define MSVCB for protection data, and for power quality data.

**Table 1: SV data streams**

| | 9-2LE Protection | 9-2LE Power Quality | IEC 61869-9 Protection | IEC 61869-9 Power Quality |
|---|---|---|---|---|
| Scaling | Primary | Primary | Primary | Primary |
| Sampling rate | 4800 Hz (@60 Hz) | 15360 Hz (@60 Hz) | 4800 Hz (Preferred) | 14400 Hz (Preferred) |
| Data | 4 I, 4 V | 4 I, 4 V | 4 I, 4 V (Preferred) | 4 I, 4 V (Preferred) |
| Samples / message | 1 | 8 | 2 (Preferred) | 6 (Preferred) |
| Publication rate | 4800 Hz (@60 Hz) | 1920 Hz (@60 Hz) | 2400 Hz | 2400 Hz |
| Bandwidth | 6 Mb | 12 – 15 Mb | 5 Mb | 11 – 14 Mb |

SV data is different from other messaging under IEC 61850 in two important ways. The first is that messages are published periodically at a defined messaging frequency – the publication rate of Table 1. SV messages are therefore published continuously ("streamed") at this publication rate. For example, the 9-2LE protection messages are published at 4800 Hertz, or every 208 µsec.

The second difference is that SV data is not timestamped, but that each SV message carries a pseudo-timestamp based on the message smpCnt. Each SV message includes a smpCnt that is incremented one step from the previous message, as per Figure 5. The smpCnt is reset to 0 at each second. Therefore, the data timestamp is easily calculated by:

data.t = Last Second + (publishing interval * smpCnt)

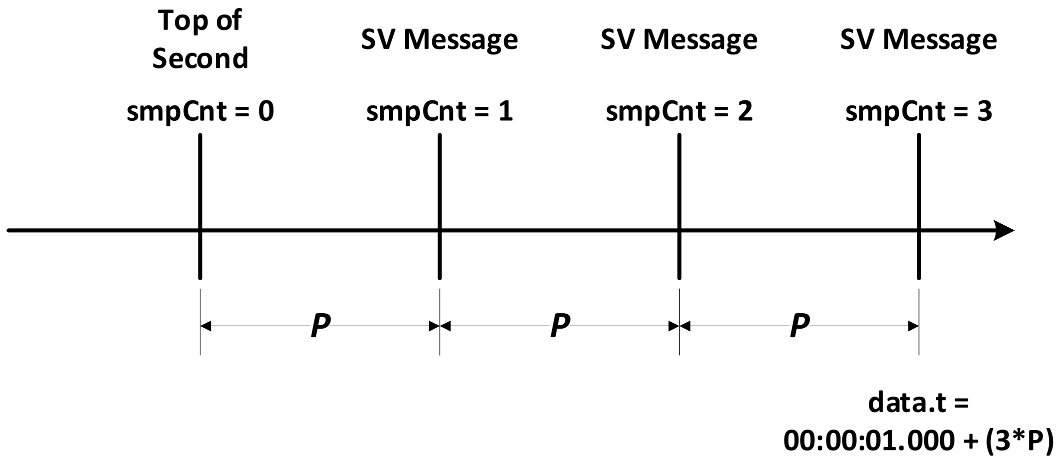


Figure 5: Timestamping of SV data

Every SV message also had a SmpSync attribute, that identifies how accurately time synchronized is the SV data.

- SmpSync = 2 is "global time synchronization", meaning the publishing MU/PIU is time synchronized to global external source. For the utility industry, this means synchronization to a GNSS source such as GPS or GLONASS
- SmpSync = 1 is "local time synchronization", meaning the publishing MU/PIU is time synchronized to local source, such that the time provided by the local clock source is still accurate enough for protection performance.
- SmpSync = 0 is that the data is no longer accurately synchronized and should not be used for protection functions.

### 4.1.4 SV data and network configuration

From Table 1, SV data using 9-2LE Protection datasets takes 6 Mb of bandwidth continuously. This means a standard 100 Mb ethernet network can only pass 12 to 14 SV streams before having reliability and performance issues. Even small substations may have this many SV streams, like the substation in this example with 36 SV streams.

1 Gb ethernet networks can handle this level of network traffic. However, it is still necessary to segment network traffic to limit SV streams to specific parts of the network. This is to ensure reliable network performance, and to prevent overloading the ethernet ports on devices connected to the network.

The basic traffic management technique on a standard ethernet network is to use VLANs or MAC address filtering. A VLAN is a "virtual LAN", as shown in Figure 6. Network ports are configured to only pass traffic assigned to a specific VLAN, creating a virtual sub-network within the larger network. Some SV messages will be assigned to one VLAN. The ports connecting to the publishers of the SV data, and the ports connecting to the subscribers of the SV data, will be assigned to this VLAN. Network ports not configured to use this VLAN will not pass this traffic. MAC address filtering is similar. Network ports are configured to pass only messages with the destination MAC address (the basic store and forward identifier for ethernet switches) to the device connected to the network port, and block all messages with a different destination MAC address. With SV data, both VLANs and MAC address filtering is commonly used.

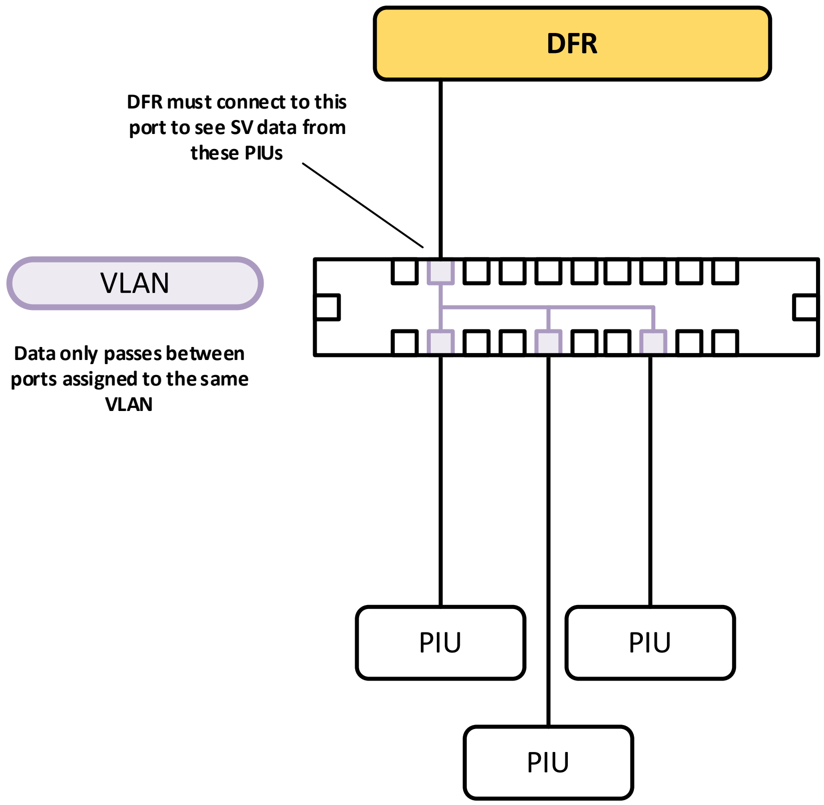


Figure 6: VLANs

Besides standard ethernet networks, there is now an implementation of software defined networking (SDN) commercially available for power system applications. In SDN, traffic management is performed by configuring "flows" between connected devices through the network, where only traffic assigned to a flow may pass through certain ports on the network. Close will be used to manage traffic on an SDN network for the same reason as VLANs are used on traditional Ethernet networks.

Due to the bandwidth required for SV messages, in larger substations with larger networks, due to the needed traffic management to maintain network performance, it is unlikely all the SV streams will be available at one point on the network for the DFR to capture. It is therefore necessary for a DFR to have multiple ethernet connections to connect to multiple points on the network that carries SV traffic.

Figure 7 shows the general concept for a DFR architecture for digital substations. There needs to be a network connection to a separate station bus network, if this network is being used. This can be a 100 Mb network port, as GOOSE and Report traffic does not require a large amount of bandwidth.

There needs to be multiple network connections to the process bus network, to be able to connect to different ports on the network to connect to different VLANs. How many ports becomes a practical design issue. These ports can be 100 Mb ports, limiting the amount of data to 12 protection SV streams or 4-5 PQ SV streams. Or they can be 1 Gb ports, increasing the number of streams each port can handle. Note that the network switch port speed must match the DFR port speed.

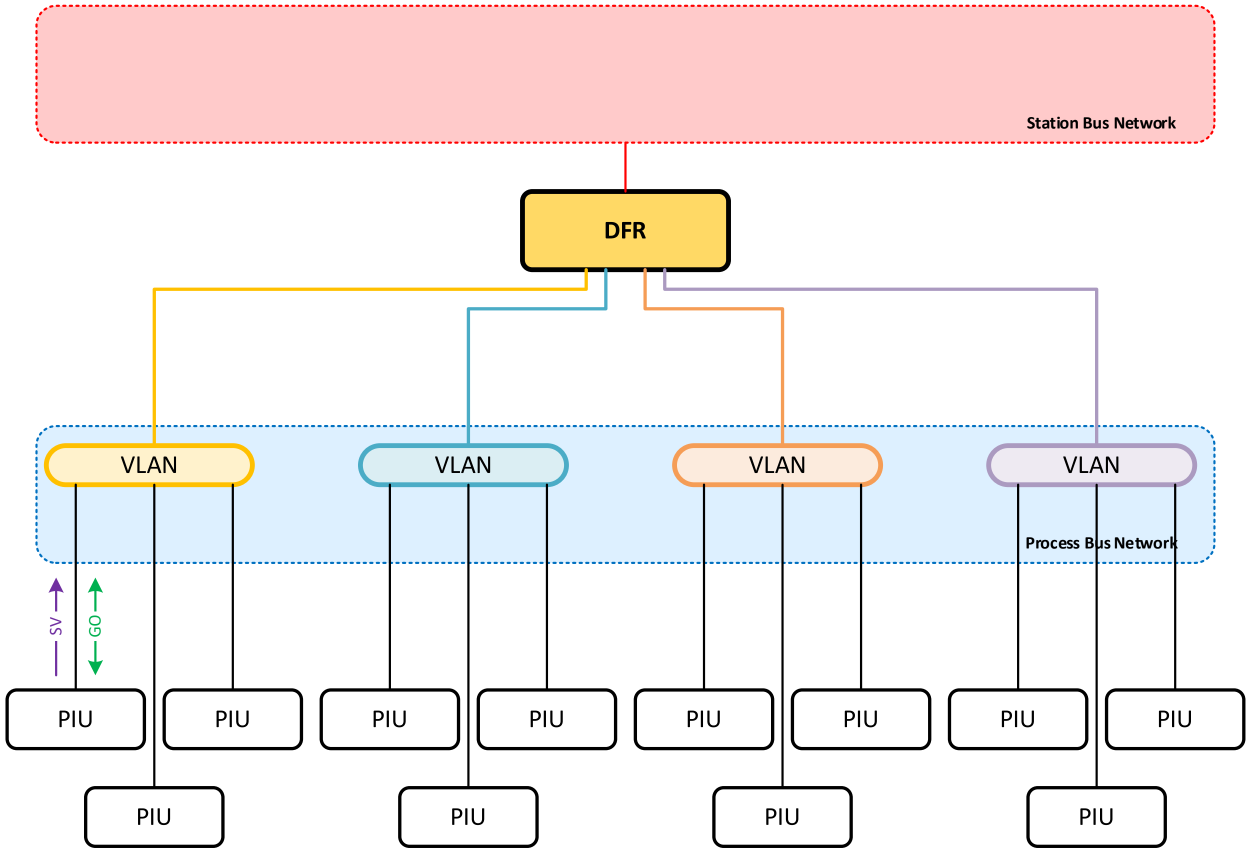


Figure 7: DFR network connections

Another consideration is network reliability. In a fully digital substation, where protection critical traffic such as SV traffic must always get through the network, there are three basic ways to ensure this reliability. The first two ways are those defined in IEC 62439-3:2021 [4]: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). Both of these methods send duplicate frames around different network paths, and therefore require two, linked, network ports for every connection. The third method is a flow failover method implemented in SDN networks. Once again, two ports are required for every network connection. This means the architecture of Figure 7 requires 10 ethernet ports: a pair of ports for all 5 connections shown to support network reliability protocols.

### 4.1.5 Example IEC 61850 design

Based on the understanding of SV data and network configuration, it is possible to do a high-level network design for the example substation of 4.1.2. A typical network design is shown in Figure 8. For the process bus data, there will be one switch for each breaker-and-a-half diameter. (Note that the best practice is to use PRP for reliability, which requires redundant networks and therefore redundant switches.)

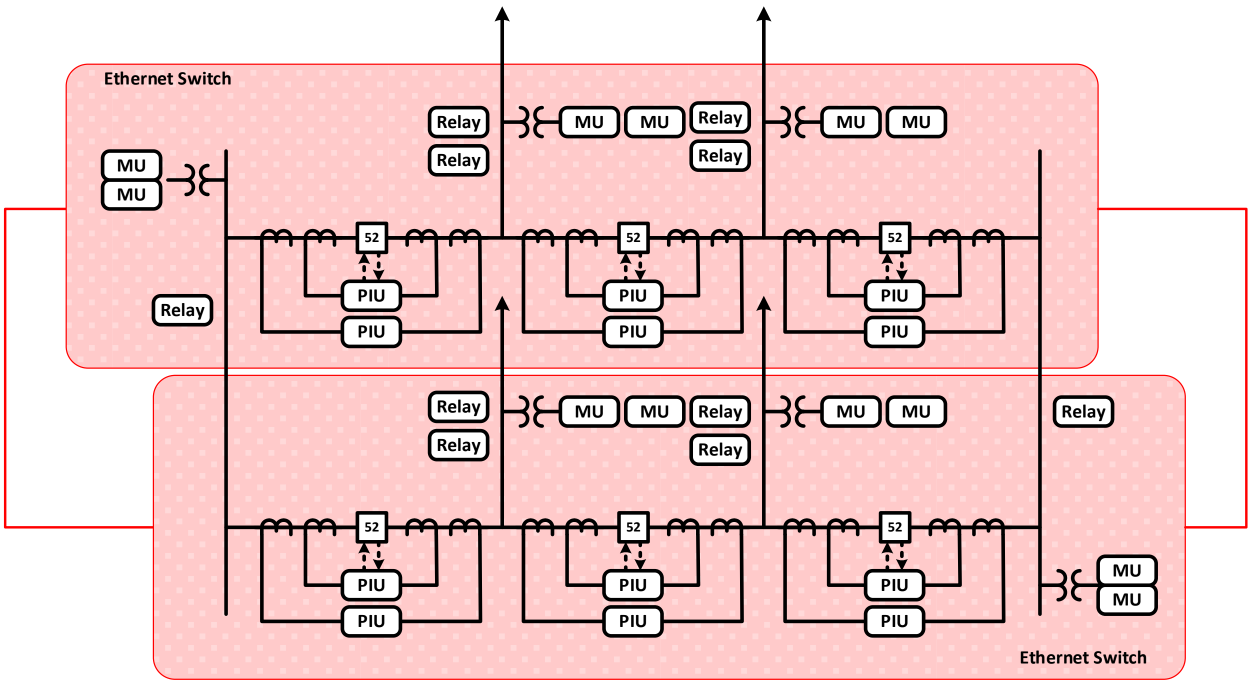


Figure 8: Substation network

In this example, all the SV published by MUs and PIUs will be limited to the switch they are physically connected to, with a few exceptions to bus voltages and currents for bus protection, which need to be shared between switches. Each switch will have multiple VLANs for traffic management purposes. One method for determining VLANs is for each relay to have its own VLAN, which would lead to 10 VLANs across the two switches in this example.

This is obviously not the only architecture and network configuration that can be used, but this is a fairly typical arrangement.

To expand this example, assume a DFR that has 5 network connections: 1 for connection to station bus networks, and 4 for connections to acquire SV data. Each network connection can accept up to 8 SV streams, meaning the DFR can subscribe to and process up to 32 SV streams in total. The DFR can subscribe to up to 300 GOOSE messages and use 300 dataset items from these GOOSE messages as binary data. The DFR does not act as an MMS client, and therefore cannot use or capture Report data. The connections for this theoretical DFR is shown in Figure 9.

The capabilities of the DFR drive some of the network design and network configuration. The network will need to have 4 "DFR ports", 2 on each switch, to provide the DFR access to SV data. Though there may be multiple VLANs used on each switch, these DFR ports need to be configured to pass multiple, but not all, VLANs to ensure the DFR can see all the SV data from that specific switch. All, the appropriate GOOSE messages must use the same VLANs to pass through to the DFR.

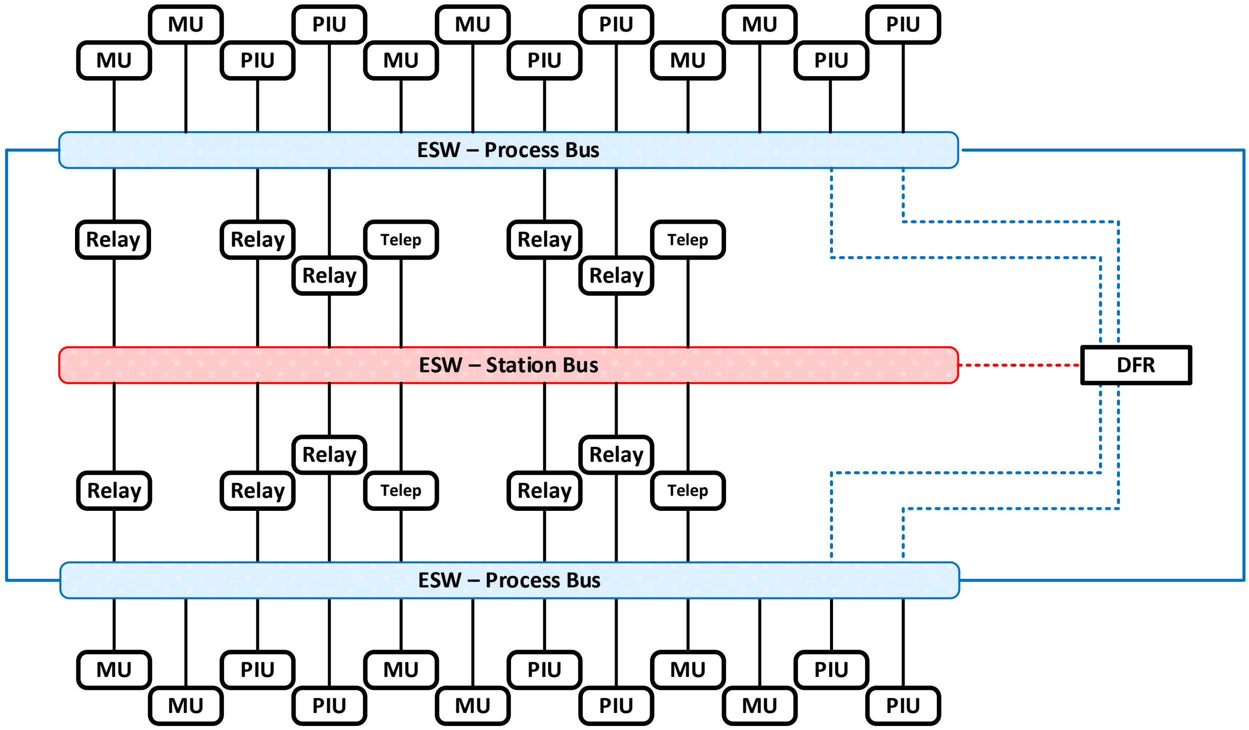


Figure 9: DFR connection

In this example, there are some engineering decisions to be made in regards to the DFR. The DFR can't capture all the SV data. There are 18 SV streams that must be captured (1 stream each for a set of CTs on each side of every circuit breaker, and 1 stream each for every VT). Beyond this, other SV streams could be captured to show MU/PIU performance and for crosschecking and continuous monitoring of current and voltage measurements. Since this DFR doesn't acquire data through Reports, the 20 Reports will be converted to DFR-only GOOSE messages with smaller datasets to capture more data from relays in DFR records.

There is another solution to make sure the DFR captures all SV data: simply add another DFR. The cost to adding DFRs is a marginal cost based almost wholly on equipment cost, panel space, and device configuration, as there is no wiring design involved.

# 5 DATA QUALITY IN THE DFR

There are a couple of aspects of data quality in DFR records. One is the time alignment of data in DFR records based on data or message timestamps. The other is the proper processing of IEC 61850 quality information, including the SmpSync attribute of SV data.

## 5.1 Time aligning data in the DFR

As discussed in Sections 2.1 and 3.4, data in IEC 61850 is timestamped at the source of the data, to account for delays in creating messages, publishing data through an ethernet network, and recognizing the data at the subscribing device. As discussed in 3.4, there are 3 possible timestamps to use for data published via GOOSE and Reports, while as discussed in 4.1.3, SV data uses a pseudo-timestamp of the message. Ideally, then, a DFR will use these timestamps of various data to time align all this data together before capturing records. This discussion assumes all devices are synchronized to a common time source. For IEC 61850, time synchronization over the ethernet network using IEEE 1588 (PTP) [5] is the preferred time synchronization method.

SV data should be the easiest to align. It is periodic, constantly streamed data. If all the SV streams are using the same SV application profile and sampling rate, then it should be possible to align SV data to each other using the smpCnt contained in each message. If different application profiles or sampling rates are used, then alignment at the top of the second (when all smpCnts are reset to 0) should be possible.

Binary data is more challenging. There are 3 different timestamps that could be used:

- Data.t. The timestamp for when the individual dataset item changes state. This is the most accurate timestamping available. However, the data.t attribute must be configured to a dataset for this time to be available. Providing data.t for all data may be problematic for many devices.
- CB.t. The GoCB and RCB control blocks have their own timestamp when the message is published after a dataset item changes state. This timestamp will be different than the data.t time, but it should be a consistent time for every model of a specific device.
- DFR.t. The timestamp at the DFR when the DFR processes the data. This is similar to a traditional DFR, but it does not account for processing time and transmission time of the data.

These timestamps are shown in Figure 10, where a contact closure wired to a RIO or PIU is recognized by the device, and the corresponding dataset item changes state at data.t. A message is published at CB.t, and the DFR recognizes the data at DFR.t

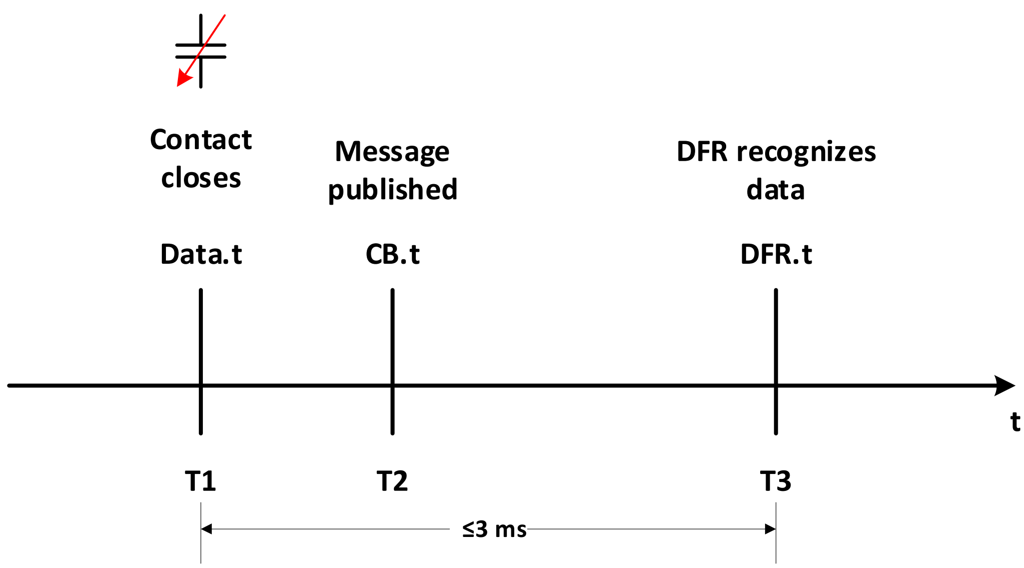

Figure 10: Data timestamps

It is clear how to time align SV data. However, it is less clear how to time align binary data. It is necessary to understand the time difference between all 3 possible timestamps, and when these should be used. As a first understanding, this requires some basic testing of devices.

## 5.2 Testing timestamping of data

A simple laboratory test can illustrate the differences between possible timestamps of data. A test setup similar to Figure 11, and some basic network analysis tools such as the Wireshark[1] network protocol analyzer can easily show the differences between timestamps.

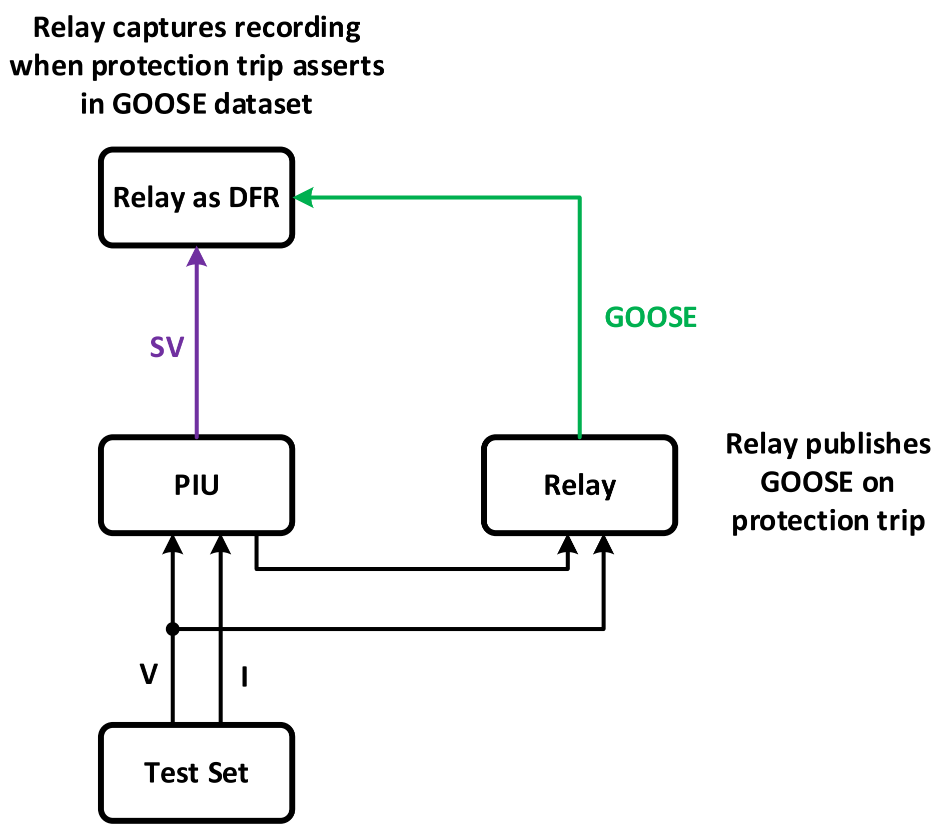


Figure 11: Timestamping test setup

In this setup, a standard relay test set is wired to both a PIU and a conventional relay. An IEC 61850-capable relay emulating a DFR subscribes to SV data from the PIU, and GOOSE message from the conventional relay. The conventional relay will trip on an overcurrent function and publish a GOOSE message on the overcurrent function trip. Data.t is taken from the relay SOE log. CB.t is taken from the GoCB header as captured in Wireshark. DFR.t is taken from the DFR SOE log.

[1] Available at wireshark.org

### 5.2.1 Test results

Testing was performed both for simulated phase-ground and three-phase faults. Performance was consistent for all these events.

#### *5.2.1.1 Representative phase-ground fault*

The performance of the phase-ground fault is shown in the following series of figures, which are captures of GOOSE data, GoCB data, device event logs, and oscillography. The relay data is shown in Figure 12, the time the actual dataset item changed state. The dataset item in this test is PSVGGIO1.Ind21.stVal, the result of a logic equation. This value went to True at 12:46:44.472 as shown in the PSVGGIO1.Ind21.t attribute. The relay then published a GOOSE message at 12:46:44.474 as shown in the GoCB Creation Time of Figure 13. The DFR recognized this data change at 12:46:44.475 as shown in the DFR event log of Figure 14. Figure 15 shows the waveform as captured by the DFR (through SV data) for this fault. shows the waveform as captured by the DFR (through SV data) for this fault.

Of interest to further illustrate the importance of time alignment of data, Figure 16 shows waveforms captured by the relay and the DFR overlaid on each, lined up simply on time data in the oscillography files. It is simple to see that there is slightly less than a 1 ms difference due between the two due to the time it takes to create, publish, and recognize SV data.

| Name | B_4B01_51_SEL451_ALARMS (4) |
|---|---|
| B_4B01_51_SEL451ANN/PSVGGIO1.Ind21 | |
| stVal | True |
| q | [0000000000000] |
| t | 12/11/2022_12:46:44.472,[10010010] |

**Figure 12: Relay data timestamp (data.t) (phase-ground fault)**

| State Number | Sequence Number | GOOSE Control Block Reference | (F | \ St | Creation Time | Received Time Stamp | Time Allowed To Live |
|---|---|---|---|---|---|---|---|
| B_4B01_51_SEL451_GOOSE Count: 5 | | | | | | | |
| 1 | 122 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Cleared by State Change | 12/11/2022_12:39:56.907 | 04/03/2023_15:56:41.107 | 2000 |
| 1 | 330 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Timeout | 04/03/2023_16:00:11.304 | 04/03/2023_16:00:11.305 | 2000 |
| 1 | 332 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Clea by Retransr | 12/11/2022_12:39:56.907 | 04/03/2023_16:00:11.306 | 2000 |
| 2 | 0 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Valid | 12/11/2022_12:46:44.474 | 04/03/2023_16:01:29.547 | 12 |
| 3 | 0 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Valid | 12/11/2022_12:46:44.490 | 04/03/2023_16:01:29.563 | 12 |

**Figure 13: GoCB timestamp (CB.t) (phase-ground fault)**

| Event Number | Date/Time | |
|---|---|---|
| 8 | Dec 11 2022 12:50:45.826060 | SV 1 STREAM TRBL OFF |
| 7 | Dec 11 2022 12:50:13.227178 | SV 1 STREAM TRBL ON |
| 6 | Dec 11 2022 12:50:13.149448 | Dlyd Processing On |
| 5 | Dec 11 2022 12:46:44.498793 | PHASE TOC1 DPO A |
| 4 | Dec 11 2022 12:46:44.475688 | OSCILLOGRAPHY TRIG'D |
| 3 | Dec 11 2022 12:46:44.381882 | PHASE TOC1 PKP A |
| 2 | Dec 11 2022 12:44:44.927430 | OSCILLOGRAPHY CLEAR |
| 1 | Dec 11 2022 12:44:41.204278 | EVENTS CLEARED |

**Figure 14: DFR timestamp (DFR.t) (phase-ground fault)**

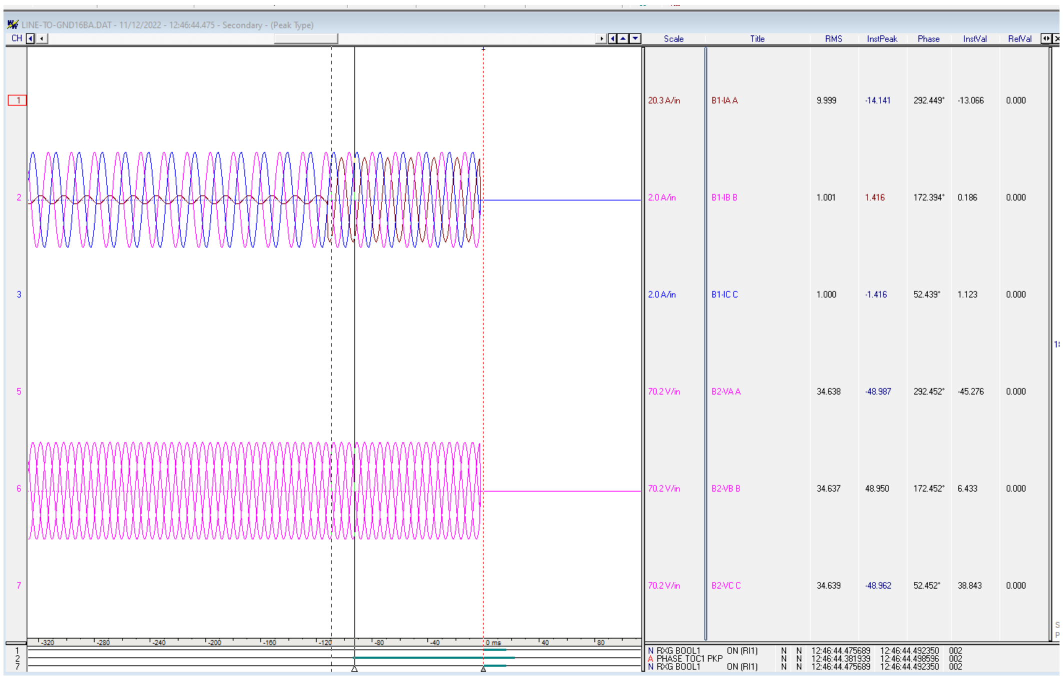

**Figure 15: DFR Record (phase-ground fault)**

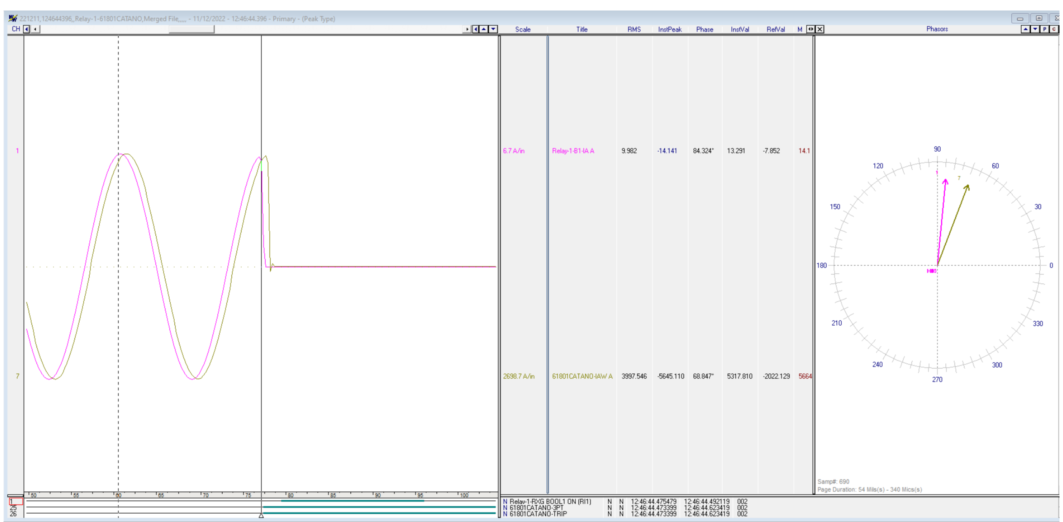

**Figure 16: Merged Records – fault phase only (phase-ground fault)**

### *5.2.1.2 Representative three-phase fault*

The performance of this three-phase fault is shown in the following series of figures, which are captures of GOOSE data, GoCB data, device event logs, and oscillography. The relay data is shown in Figure 17, the time the actual dataset item changed state. The dataset item in this test is PSVGGIO1.Ind21.stVal, the result of a logic equation. This value went to True at 13:47:17.782 as shown in the PSVGGIO1.Ind21.t attribute. The relay then published a GOOSE message at 13:47:17.784 as shown in the GoCB Creation Time of Figure 18. The DFR recognized this data change at 13:47:17.785 as shown in the DFR event log of Figure 19. Figure 20 shows the waveform as captured by the DFR (through SV data) for this fault.

As with the phase-ground fault, Figure 21 shows waveforms captured by the relay and the DFR overlaid on each, lined up simply on time data in the oscillography files. It is simple to see that there is slightly less than a 1 ms difference due between the two due to the time it takes to create, publish, and recognize SV data.

| Name | B_4B01_51_SEL451_ALARMS (42) |
|---|---|
| B_4B01_51_SEL451ANN/PSVGGIO1.Ind21 | |
| stVal | True |
| q | [0000000000000] |
| t | 12/11/2022_13:47:17.782,[10010010] |

Figure 17: Relay data timestamp (data.t) (three-phase fault)

| State Number | Sequence Number | GOOSE Control Block Reference | (F | \ St | Creation Time | Received Time Stamp | Time Allowed To Live |
|---|---|---|---|---|---|---|---|
| B_4B01_51_SEL451_GOOSE Count: 2 | | | | | | | |
| 4 | 0 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Valid | 12/11/2022_13:47:17.784 | 04/03/2023_17:02:02.887 | 12 |
| 5 | 0 | B_4B01_51_SEL451CFG/LLN0$GO $GOOSE | False | Valid | 12/11/2022_13:47:17.809 | 04/03/2023_17:02:02.912 | 12 |

Figure 18: GoCB timestamp (CB.t) (three-phase fault)

| Event Number | Date/Time | |
|---|---|---|
| 17 | Dec 11 2022 13:52:40.896446 | SV 1 STREAM TRBL OFF |
| 16 | Dec 11 2022 13:52:08.217133 | SV 1 STREAM TRBL ON |
| 15 | Dec 11 2022 13:52:08.209631 | Dlyd Processing On |
| 14 | Dec 11 2022 13:52:08.121683 | Dlyd Processing On |
| 13 | Dec 11 2022 13:49:01.891452 | SV 1 STREAM TRBL OFF |
| 12 | Dec 11 2022 13:48:52.010503 | Dlyd Processing On |
| 11 | Dec 11 2022 13:48:29.723141 | SV 1 STREAM TRBL ON |
| 10 | Dec 11 2022 13:48:29.638810 | Dlyd Processing On |
| 9 | Dec 11 2022 13:47:17.808148 | PHASE TOC1 DPO C |
| 8 | Dec 11 2022 13:47:17.808148 | PHASE TOC1 DPO B |
| 7 | Dec 11 2022 13:47:17.808148 | PHASE TOC1 DPO A |
| 6 | Dec 11 2022 13:47:17.785139 | OSCILLOGRAPHY TRIG'D |
| 5 | Dec 11 2022 13:47:17.708147 | PHASE TOC1 PKP C |
| 4 | Dec 11 2022 13:47:17.708147 | PHASE TOC1 PKP B |
| 3 | Dec 11 2022 13:47:17.708147 | PHASE TOC1 PKP A |

Figure 19: DFR timestamp (data.t) (three-phase fault)

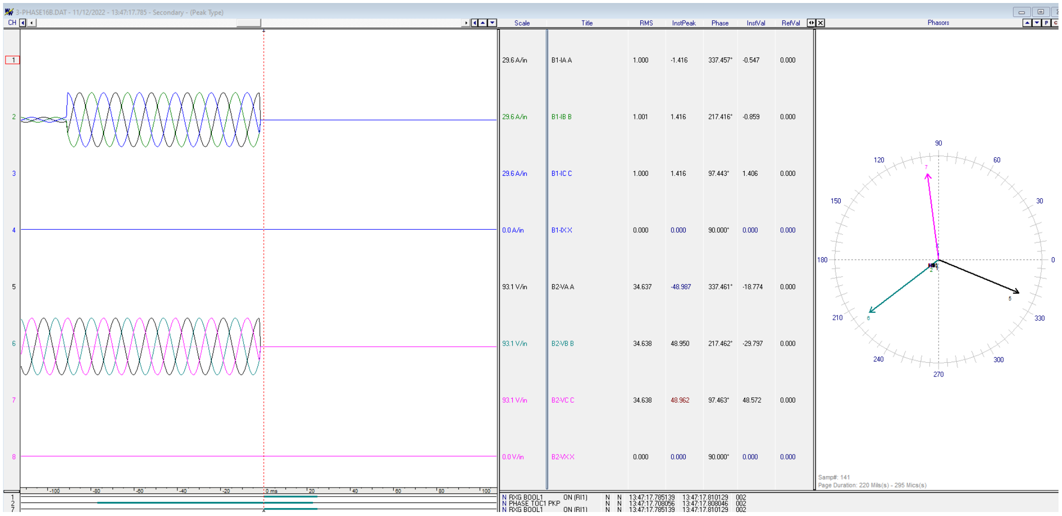

Figure 20: DFR record (three-phase fault)

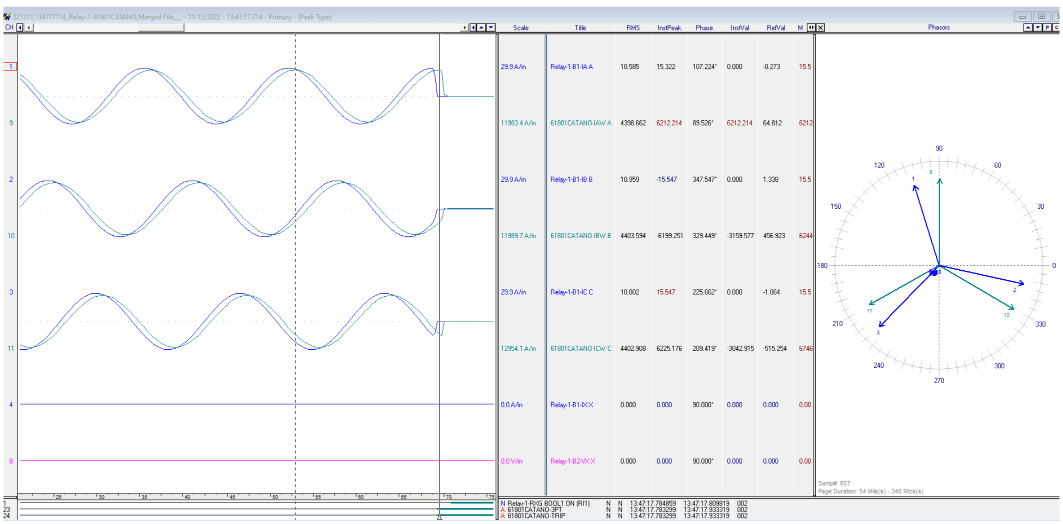

Figure 21: Merged Records (three-phase fault)

### 5.2.2 Test result analysis

The test results from these representative tests are in Table 2. It is obvious that the results are consistent. The time that it takes for this relay to publish a dataset when an item changes state is 2 ms, and it takes 1 ms for the message to pass through the network and be recognized by the DFR.

DFR end users should perform this testing for every device that publishes data that may be used by a DFR. It is important to understand the time differences between data.t and CB.t for every model of device to gain an understanding of how this may impact the data alignment of DFR records and may impact the actual analysis of system events.

Table 2: Timestamp test results

| Test | data.t | CB.t | DFR.t |
|---|---|---|---|
| Phase-ground | 13:47:17.782 | 13:47:17.784 | 13:47:17.785 |
| Three-phase | 12:46:44.472 | 12:46:44.474 | 12:46:44.475 |

An important concept to remember is that data.t is when a device recognizes an item changes state, and is generally the timestamp of the device internal SOE log. For physical inputs, such as breaker contact wired to a RIO or PIU, this data.t may not be the time the contact actually closed. The device will not recognize the contact closure until after any input debounce time, and the timestamp is based on the resolution, accuracy, and processing cycle of the relay event log. This same concern is present in conventional DFRs from when a physical device changes state to when it is actually recognized to have changed state. Therefore, it has always been important to understand that the binary channels in DFR records may not exactly be the time the actual physical output contact closed, and this does not change with an IEC 61850 DFR.

## 5.3 Processing IEC 61850 data quality

Data quality under IEC 61850, as relates to DFRs, can be broken down into three distinct aspects: the state of the data quality attribute, simulation and simulated data, and the time synchronization of SV data.

### 5.3.1 Quality attribute

As described in Section 2.1, every data object has an associated quality attribute data.q. Quality is a bit string that describes the level of trust of the data, and subscribing devices use quality to determine if the data should be used. It is important to remember that quality is the quality of the individual data, not the dataset or message. Therefore, different items in a dataset and message may have different qualities. There 2 indications of quality that DFRs need to be aware of.

The first of these qualities is validity. Data can be “Good”, “Questionable”, or “Invalid”. A DFR should only use data where q.validity = Good. All other data should be ignored and not captured.

The second of these qualities is test. Data can be published as test data, indicated by q.test = True. As per the IEC 61850 standard, a device not in test must ignore all data published with a q.test = True. This means a normally operating DFR will not capture or record test data. However, it is possible to place a DFR in test mode. As per the standard, a device in Test must process both test data (q.test = True) and live data (q.test = False). Having the ability to place the DFR in Test mode is a consideration for DFR manufacturers. While in Test, the DFR could be active during testing and commissioning scenarios where test data is being published. During this condition, DFR records should highlight which channels were test data.

### 5.3.2 Simulation

IEC 61850 supports the concept of simulation of SV messages and GOOSE messages for testing purposes. The concept is that test devices simulate the actual SV and GOOSE messages present in a network to virtually test subscribing devices. Both MSVCB and GoCB control blocks have a Simulation bit. When this Simulation bit is True, then the message is simulated data.

A device in normal operating mode will ignore simulated data. However, a device can be placed in Simulation. When in Simulation, the device can subscribe to normal, live process MSVCB and GOOSE messages, as well as simulated messages published by a test device. Once a device in test receives a simulated message for a subscription, that subscription channel will ignore live process data and only use simulated data until the device is taken out of Simulation. In-service DFRs will not capture simulated data, and there is little value for a DFR to support Simulation.

### 5.3.3 Time synchronization accuracy of SV data

Section 4.1.3 includes a brief description of the SmpSync attribute of the MSVCB control block. The intended use of the SmpSync attribute is for protective relays to determine if SV data is synchronized together well enough for protection functions to still reliably operate. For a DFR, a SmpSync value of 2 (globally synchronized) and 1 (locally synchronized) are accurately synchronized enough to include in DFR recordings, even if some channels have different values of SmpSync. If SmpSync has a value of 0, data can still be recorded so as to capture current and voltage waveforms, but this (lack of synchronization) state needs to be indicated in DFR records.

# 6 RECOMMENDATIONS

Applying IEC 61850 DFRs in digital substation applications requires basic knowledge around IEC 61850, networking to support IEC 61850, and the goals and intent of a DFR. Thought has to be put into what data needs to be recorded, how to get access to this data, and how to handle the quality of the data. This leads to specific and different recommendations for utility end users of DFRs, and to the suppliers of DFRs.

## 6.1 Recommendations to utility end users

- Understand the basics of DFR capabilities, so as to specify and design a recording system. This includes:
    - the number of SV streams the DFR can subscribe to and underlying number of analog channels in the DFR
    - the number of GOOSE messages and dataset items the DFR can subscribe to, and the number of binary channels in the DFR
    - the number of MMS client connections (and therefore number of Reports) the DFR supports
    - the number of network connections, including ethernet port types and speeds, and support for network reliability protocols such as PRP and HSR
    - The maximum sampling rate available in the DFR
- Understand DFR application requirements, including the desired sampling rate for data, as well as what data to include in DFR records.
    - This includes intelligent consideration of what information to put in a DFR record. This should be more data than a traditional DFR to get a clearer, more robust picture.

- Remember that configuring a DFR means configuring the datasets and control blocks in devices (such as MUs, RIOs, PIUs, and relays) that provide data to the DFR, configuring the network such that the DFR has access to this data, and configuring the DFR itself.
- Use MUs or PIUs that provide the SV sampling rates and profiles needed to meet the DFR application requirements. Almost all MUs and PIUs will provide the 9-2LE Protection application profile. Only a few provide power quality application profiles.
- The ethernet network design must account for the DFR. This will include dedicated ports to connect to the DFR, and network configuration to ensure that data, especially SV data, is available at those ports.
- For data quality and data alignment, the best practice should be to include data.t for all data in datasets to be used by the DFR. It is not always practical or possible (due to possible device performance issues) to use data.t in datasets.
- Understand how the DFR handles timestamping and data alignment.
    - As a corollary, it is necessary to understand the time difference between data.t and CB.t in different devices used for DFR data. Different devices will have slight differences.
    - If data is not explicitly time aligned, it is still possible to use this data in event analysis. There has always been assumptions about when the change of state of physical contacts is actually recognized in a record.
- The best practice for sharing large amounts of binary data to a DFR is to use Reports. However, no commercially available DFR can currently act as an MMS client to support this.
- Though it is not discussed in this paper, use the IEC 61850 data model when configuring datasets, to provide context to data, and simplify configuration.
- Think about how to get more out of DFR. DFR records can start to include internal IED data as a matter of course. Can DFRs act as a unified, station-wide SOE log? Can you use DFR data to meet NERC PRC-005 monitoring requirements to delay testing of relays? Can you use DFR data to start a condition-based maintenance program? Detect hidden failures or incipient failures? And what data do you need to support that?
- An ancillary to this is to consider using an IEC 61850-capable communications gateway as a station-wide unified SOE recorder.

## 6.2 Recommendations to DFR suppliers

- A DFR must have multiple network connections. One network connection for a station bus network, and multiple network connections to acquire SV data.
    - Network connections must support network reliability protocols, which requires every network connection have two physical ethernet ports. Support for PRP is a must, support for HSR should be strongly considered, and support for port failover should be strongly considered.
        - SV ports can be 100 Mb or 1 Gb ports. If there is only one hardware option, then 1 Gb is the preferred choice.
- The DFR must support IEEE 1588 (PTP) time synchronization, using either the C37.238-2017 [6] or IEC 61850-9-3:2016 [7] profile.
- The DFR must have an architecture to support large numbers of SV streams.
- The DFR must all time align all SV streams together.

- The DFR can use a user selectable sampling rate. However, this may involve data decimation or estimation based on the raw sampling rate of the SV data.
  - Power quality capabilities will therefore depend on the MUs and PIUs selected by the end user, and the SV application profile used.
- The DFR will need to subscribe to large numbers of GOOSE messages, and a large number of dataset items.
- The DFR will need to time GOOSE channels based on timestamps. The DFR will need to time align binary channels with SV data.
  - Data.t is unlikely to be commonly available, so the DFR must support the use of CB.t for time alignment.
- Should strongly consider making the DFR an MMS client, with a large number of client connections, so as to subscribe to Reports. Reports are a better way of getting large amounts of binary data into a DFR.
- The DFR should correctly support all IEC 61850 data quality requirements
  - Only process data with q.validity = Good
  - Support q.test correctly, and only capture data where q.test = False
  - Consider Test mode support for the DFR.
  - Process SmpSync per SV stream. Should still capture data with SmpSync = 2 or SmpSync = 1. Should capture data with SmpSync = 0, but must flag this in the record.
- IEC 61850 implementation details. Most of this is not directly discussed in the paper, but are important aspects of fully implementing IEC 61850 in a device.
  - Though not discussed in this paper, should provide full support for the IEC 61850 data model to simplify device configuration.
  - The DFR must be able to subscribe to SPS (single point status) and DPS (double point status) information as binary channels. Note the circuit breaker position is a DPS in IEC 61850, so this is very important.
  - The DFR must provide an .ICD file for integration into IEC 61850 substation configuration tools.
  - The DFR must accept an .SCD or .CID file for IEC 61850 data subscription.
  - The DFR must provide all IEC 61850 documentation:
    - PICS - Protocol Implementation Conformance Statement
    - PIXIT - Protocol Implementation Conformance Extra Information for Testing Statement
    - MICS - Model Implementation Conformance Statement
    - TICS - Tissue Implementation Conformance Statement
    - SICS – SCL Implementation Conformance Statement

# 7 REFERENCES

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[3] *IEC 61869-9:2016 Instrument transformers - Part 9: Digital interface for instrument transformers,* Geneva, SU: International Electrotechnical Commission, 2016.

[4] *IEC 62439-3:2021 Industrial communication networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR),* Geneva, SU: International Electrotechnical Commission, 2021.

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[7] *IEC/IEEE 61850-9-3:2016 Communication networks and systems for power utility automation - Part 9-3: Precision time protocol profile for power utility automation,* Geneva, SW: International Electrotechnical Commission, 2016.

# 8 BIOGRAPHIES

***RICH HUNT, MS, PE***, *EXECUTIVE ADVISOR, Protection, Control & Automation,* has over 30 years of experience in the electric power industry, specializing in protective relaying. Over the last 15 years, he has focused on specifying and designing digital substations, including IEC 61850, process buses, non-conventional instrument transformers, networking, and time synchronization.

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