Disturbance Analysis and Monitoring using IEC 61850 Sampled Values Data in Digital Substations

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Abstract

IEC 61850 sampled value (SV) based applications are becoming popular in digital substations. In these substations, analog signals from current and voltage instrument transformers (CTs and VTs) are digitized by merging units (MUs), and transmitted over the process bus using Ethernet communications. The process bus network is an Ethernet network that links the primary equipment in a substation with various secondary equipment including protection, control, and monitoring equipment. Digital substations require disturbance analysis and monitoring to ensure correct operation of the devices and equipment in the power system as well as capturing data used to monitor the health of the power system. Monitoring in utility applications includes, but is not limited to, wide area monitoring using synchrophasors, power quality calculations, fault location estimates, power swing detection and harmonic monitoring.

This paper covers the following applications in relation to disturbance analysis and monitoring in IEC 61850 based digital substations:

- Disturbance analysis using transient data at different sampling rates specified in IEC 61850 9-2 standards
- Disturbance analysis using phasor data
- Wide area monitoring
- Capturing of power quality events (harmonics, voltage sags, voltage swells, etc.)
- Calculation of power flows for monitoring purposes

Introduction

IEC 61850 based implementations have made significant progress during the last few years. Major utilities around the world are at various stages of adopting and implementing the IEC 61850 standard. However, most of the focus has been on IEC 61850 Generic Object-Oriented Substation Events (GOOSE) messages and reporting using Manufacturing Message Specification (MMS). As utilities move towards completely digital substations (encompassing digitized currents and voltages, and switchgear statuses and control signals) for protection and control schemes, it is expected that the measurement infrastructure for fault and disturbance recording will change and be based on digitized IEC 61850 sampled values (SVs).

Digital substations require that analog signals from current and voltage instrument transformers (CTs and VTs) be digitized by merging units (MUs), and transmitted over the process bus using Ethernet communication. The process bus is an Ethernet network that links the primary equipment in a substation with various secondary equipment including protection, control, and monitoring equipment. In greenfield digital substations, large-size CTs and VTs can be replaced by non-conventional instrument transformers (NCITs) which directly convert the electrical signals into optical signals.

The IEC 61850 standard was initially released as a standard for ‘communication networks and systems in substations’ by the International Electrotechnical Commission TC 57 WG 10 in 2003 [1]. Part 9-2 of the IEC 61850 standard [2] defines the service mapping required for the transmission of SVs. However, specific implementation requirements were not defined in the IEC 61850-9-2 standard. The IEC 61850-9-2LE implementation guideline [3] was drafted by the UCA International Users Group to fill this gap by providing a guide that defines the logical devices, dataset and attributes, sampling rates, time synchronization requirements, and message format to be used by MUs in publishing SVs.

MUs typically sample analog measurements from current transformers (CTs) or voltage transformers (VTs), convert these analog quantities to digital signals, and then publish them over an Ethernet communication network as Layer 2 IEC 61850-9-2 multicast messages. Sampled values are transmitted using a publisher/subscriber multicast mechanism using two sampling rates. These are 80 and 256 samples per cycle (s/c), respectively. The former is specified for protection applications, while the latter is to be used for measurement-related applications.

Some of the benefits of an IEC 61850-9-2 system include: a decrease in project cost due to the reduction in copper cabling, better system-wide data availability/sharing, and reduced risk of CT saturation. Substation safety is also improved by eliminating concerns associated with open CTs (since electrical signals from the CTs and PTs are digitized).

Technical Considerations

Monitoring devices used in IEC 61850 based digital substations requires multiple features:

- Subscription to IEC 61850 SV and GOOSE data
- Perform mathematical calculations for PQ, harmonics, etc.
- Publish calculated data using IEC 61850
- Perform synchro-phasor calculations and publish the data for wide area monitoring
- Store the fault data and calculated data
- Support network redundancy
- Accurate time synchronization

Subscribing IEC 61850 9-2 sampled value data from multiple merging units

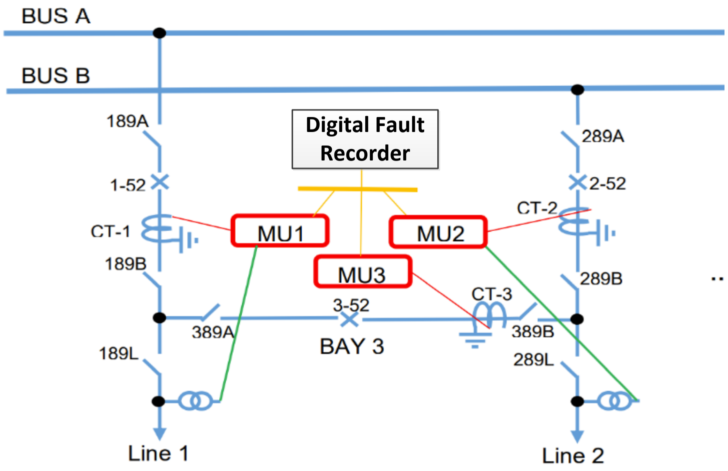


Figure 1: Subcribing data from muliple merging units

IEC 61850 based substations include multiple merging units publishing data. Subscription of data from multiple merging units into a single monitoring device requires higher processing power and higher communication bandwidth. It is important to select a device capable of handling these challenges.

Subscribing to multiple IEC 61850 GOOSE messages

Substations include hundreds of status measurements that are monitored using GOOSE messages. The subscription of multiple IEC 61850 GOOSE messages into a single monitoring device (IED) requires a high level of processing.

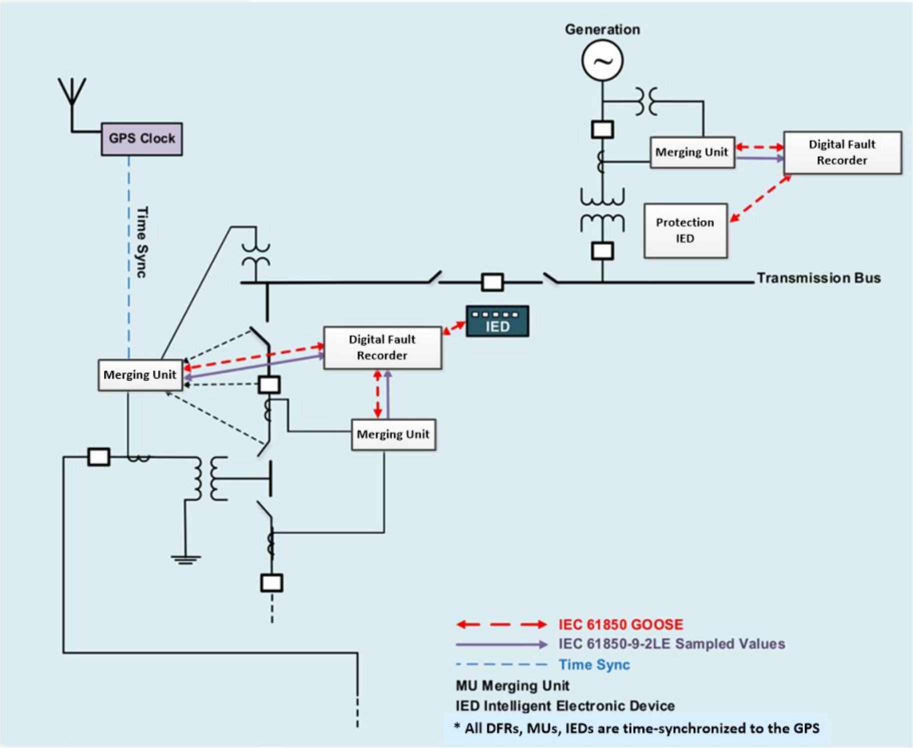


Figure 2: Subscription to GOOSE data

Publishing of IEC 61850 measurements suitable for wide area monitoring

IEC 61850 based wide area monitoring has become useful for digital substation applications. Publishing of IEC 61850 data/measurements requires utilization of IED resources such as processing power and communication bandwidth. In addition, a reasonable latency must be maintained between the publisher and subscriber. When selecting a monitoring device/IED, all these factors must be considered.

Monitoring large substations with multiple measurement inputs

The measurement requirement for larger substations can be as high as 200 (or more) current or voltage analog measurements and 500 (or more) status measurements. The sampling rate for current and voltage measurements can be up to 256 s/c sample rate. The monitoring IED must be capable of handling these requirements without negatively impacting overall performance.

Synchrophasor calculations and streaming synchrophasor data

Standard IEC/IEEE synchrophasor calculations [5] require implementation of P and M class filtering for multiple channels, involving significant computational power. In addition, reporting synchrophasor data as per the IEC/IEEE synchrophasor standard requires publishing calculated/measured data at higher reporting rates. In order to support synchrophasor calculations and streaming synchrophasor data, hardware must be selected carefully.

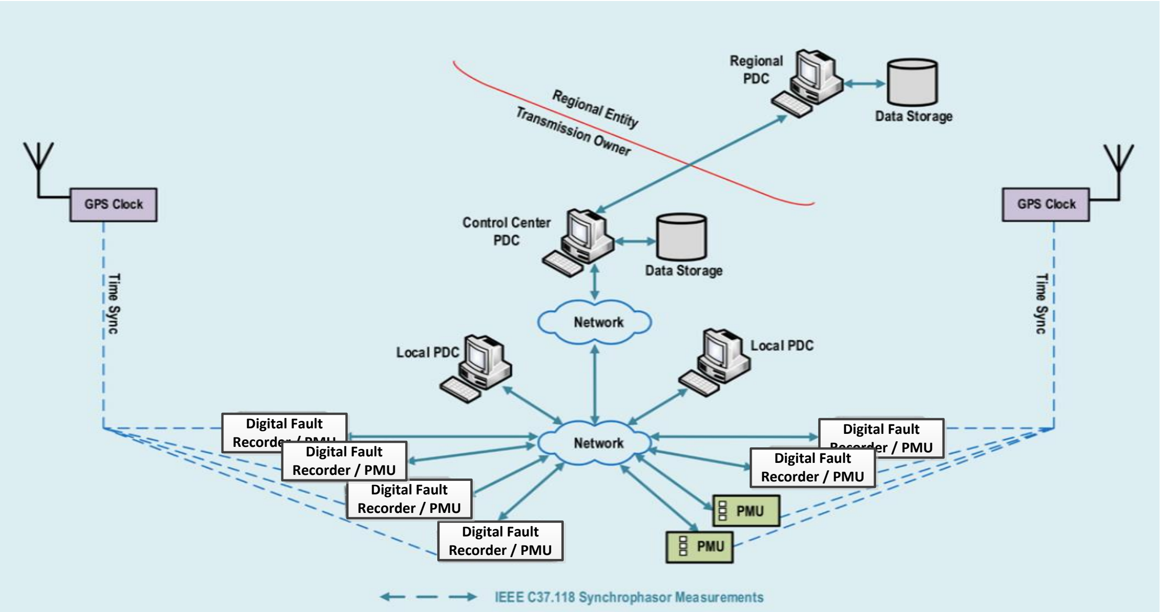


Figure 3: PMU applications

Performing calculations

Multifunctional IEDs used for digital substation are required to monitor quantities that are not directly measured but that are calculated. A list of typical calculated quantities is summarized below:

- Summation channels
- Sequence calculations
- Power quality calculations
- Active power, reactive power and power factor calculations
- Harmonics and THD calculations
- Fault location estimates in transmission lines
- Power swing, voltage sag and voltage swells

All these calculations listed above are performed simultaneously and require digital filtering, discrete Fourier transform, vector transform, additions, subtractions, etc. An IED capable of handling all these functionalities requires a high degree of computational capacity. In addition, some of these calculations require buffering of historical data that demands extensive usage of memory.

In summary, technological challenges demand the following requirements for a monitoring device or IED:

- Adequate processing power to handle extensive calculations, filtering of data, etc.
- Adequate memory to buffer historical data
- Higher communication bandwidth to handle SV data
- Multiple communication paths to publish and subscribe data from multiple IEDs
- Capability to meet network redundancy requirements
- Capability to store large amounts of data or samples

Application

In order to evaluate the operation of a sampled value based digital fault recorder, consider the following application show in Figure 4. In this application, three industrial merging units with IEC 61850 9-2 LE support was considered [7] [8].

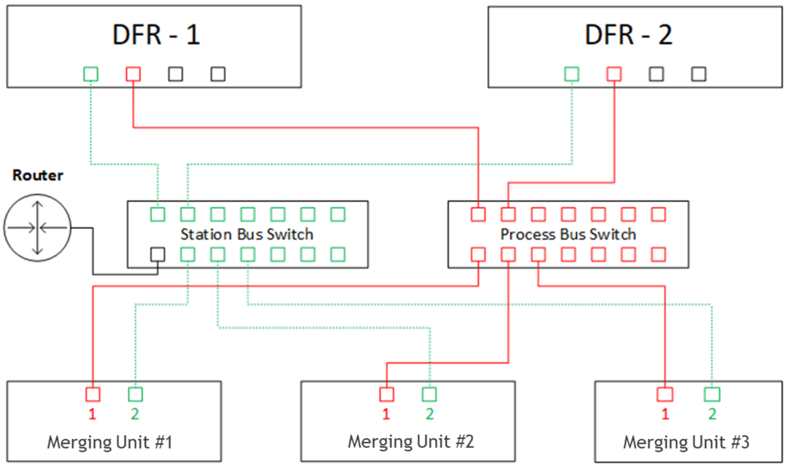
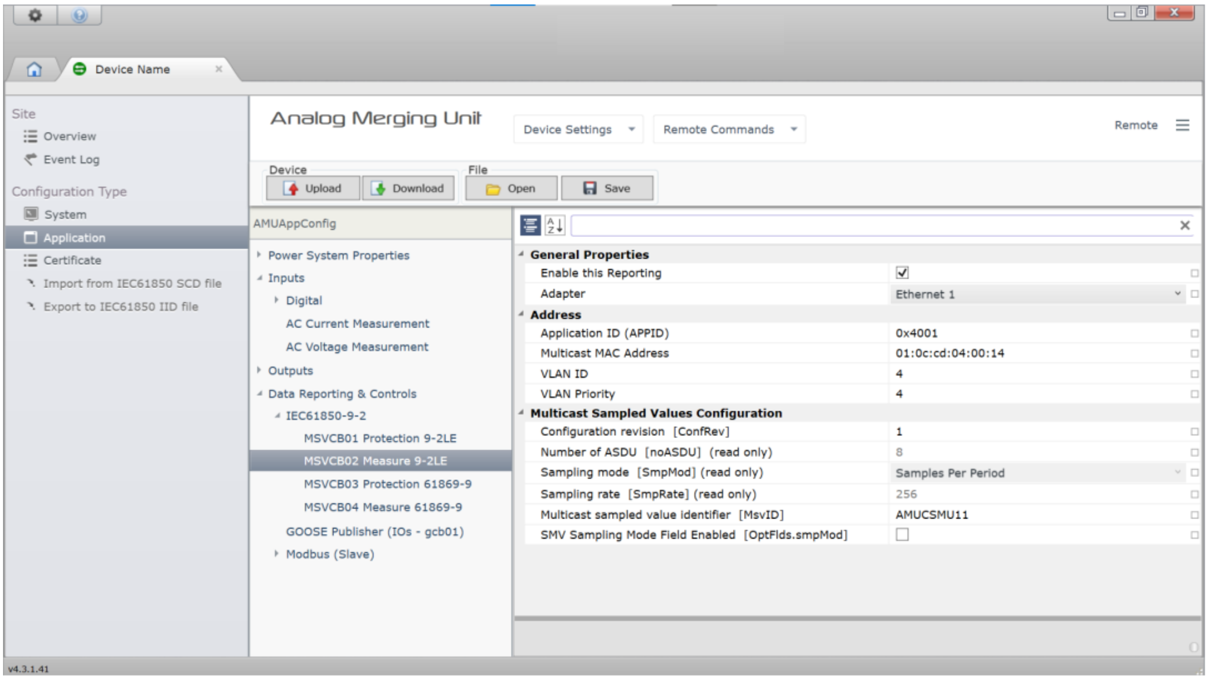


Figure 4: Sampled values based DFR connected to merging units

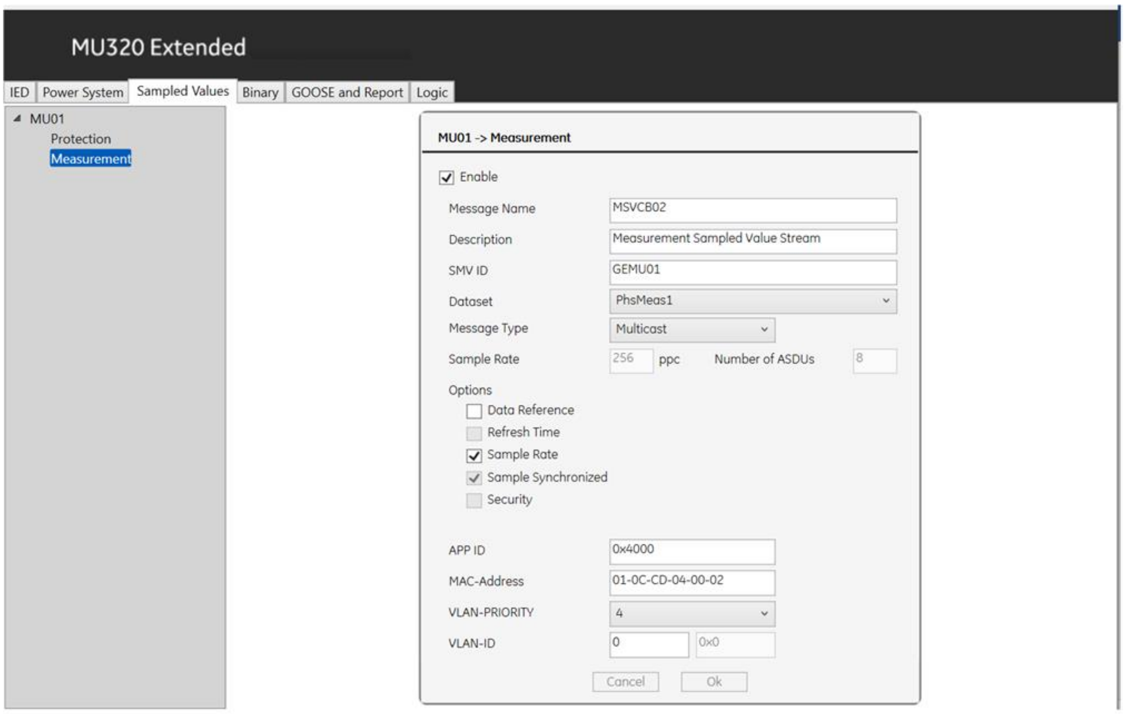
MU Settings

The merging units were configured to publish IEC 61850 9-2 LE data at 256 s/c rate. Figure 5 and 6 show the basic SV configurations used in the industrial merging units.



General Properties	
Enable this Reporting	☑
Adapter	Ethernet 1
Address	
Application ID (APPID)	0x4001
Multicast MAC Address	01:0c:cd:04:00:14
VLAN ID	4
VLAN Priority	4
Multicast Sampled Values Configuration	
Configuration revision [ConfRev]	1
Number of ASDU [noASDU] (read only)	8
Sampling mode [SmpMod] (read only)	Samples Per Period
Sampling rate [SmpRate] (read only)	256
Multicast sampled value identifier [MsvID]	AMUCSMU11
SMV Sampling Mode Field Enabled [OptFlds.smpMod]	☐

Figure 5: MU settings



MU01 -> Measurement

☑ Enable

Message Name	MSVCB02
Description	Measurement Sampled Value Stream
SMV ID	GEMU01
Dataset	PhsMeas1
Message Type	Multicast
Sample Rate	256 ppc
Number of ASDUs	8

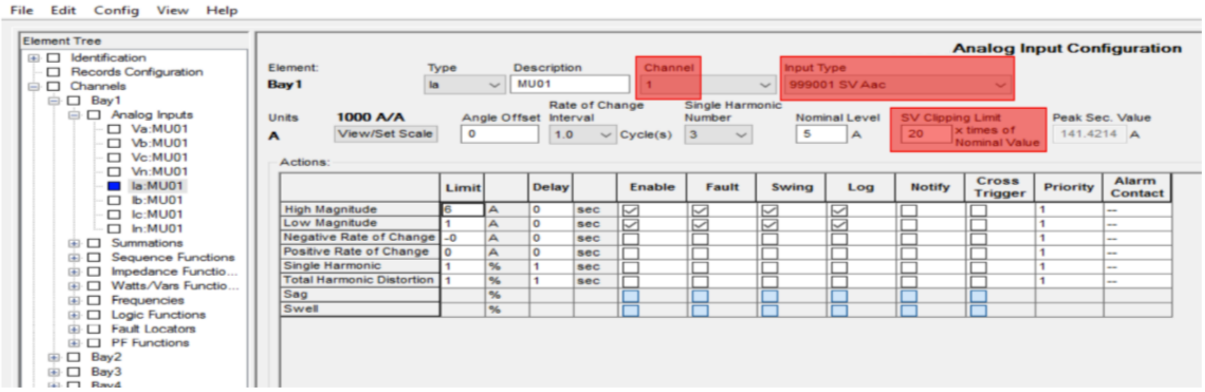
Options
- ☐ Data Reference
- ☐ Refresh Time
- ☑ Sample Rate
- ☑ Sample Synchronized
- ☐ Security

APP ID	0x4000
MAC-Address	01-0C-CD-04-00-02
VLAN-PRIORITY	4
VLAN-ID	0 0x0

Figure 6: MU settings

DFR Settings

Sampled value input channels can be configured as either voltages or currents. Figure 7 and 8 show the process of input channel configuration and process of data mapping.



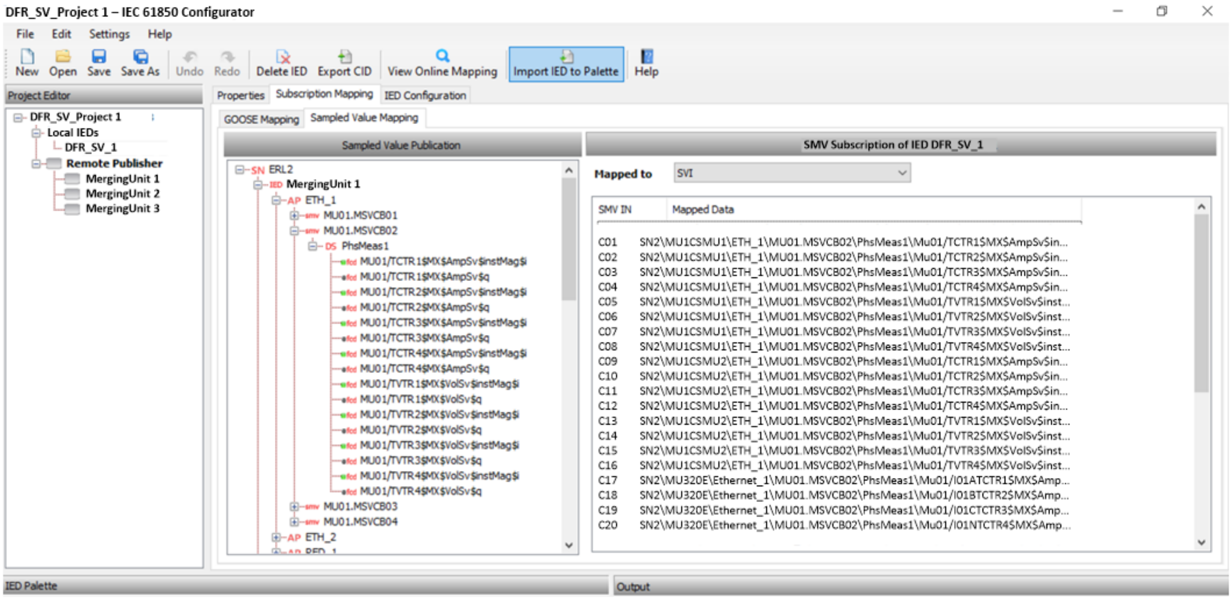
Analog Input Configuration

Element:	Bay 1
Type	Ia
Description	MU01
Channel	1
Input Type	999001 SV Aac
Units	A
	1000 A/A View/Set Scale
Angle Offset	0
Rate of Change Interval	1.0 Cycle(s)
Single Harmonic Number	3
Nominal Level	5 A
SV Clipping Limit	20 x times of Nominal Value
Peak Sec. Value	141.4214 A

Actions:

	Limit		Delay		Enable	Fault	Swing	Log	Notify	Cross Trigger	Priority	Alarm Contact
High Magnitude	6	A	0	sec	☑	☑	☑	☑	☐	☐	1	--
Low Magnitude	1	A	0	sec	☑	☑	☑	☑	☐	☐	1	--
Negative Rate of Change	-0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--
Positive Rate of Change	0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--
Single Harmonic	1	%	1	sec	☐	☐	☐	☐	☐	☐	1	--
Total Harmonic Distortion	1	%	1	sec	☐	☐	☐	☐	☐	☐	1	--
Sag		%			☐	☐	☐	☐	☐	☐		
Swell		%			☐	☐	☐	☐	☐	☐		

Figure 7: Sampled value input channel configuration



DFR_SV_Project 1 – IEC 61850 Configurator

DFR_SV_Project 1
Local IEDs
DFR_SV_1
Remote Publisher
MergingUnit 1
MergingUnit 2
MergingUnit 3

SN ERL2
IED MergingUnit 1
AP ETH_1
smv MU01.MSVCB01
smv MU01.MSVCB02
DS PhsMeas1
fcd MU01/TCTR1MXAmpSv$instMag$i
fcd MU01/TCTR1MXAmpSv$q
fcd MU01/TCTR2MXAmpSv$instMag$i
fcd MU01/TCTR2MXAmpSv$q
fcd MU01/TCTR3MXAmpSv$instMag$i
fcd MU01/TCTR3MXAmpSv$q
fcd MU01/TCTR4MXAmpSv$instMag$i
fcd MU01/TCTR4MXAmpSv$q
fcd MU01/TVTR1MXVolSv$instMag$i
fcd MU01/TVTR1MXVolSv$q
fcd MU01/TVTR2MXVolSv$instMag$i
fcd MU01/TVTR2MXVolSv$q
fcd MU01/TVTR3MXVolSv$instMag$i
fcd MU01/TVTR3MXVolSv$q
fcd MU01/TVTR4MXVolSv$instMag$i
fcd MU01/TVTR4MXVolSv$q
smv MU01.MSVCB03
smv MU01.MSVCB04
AP ETH_2
AP RED_1

SMV Subscription of IED DFR_SV_1

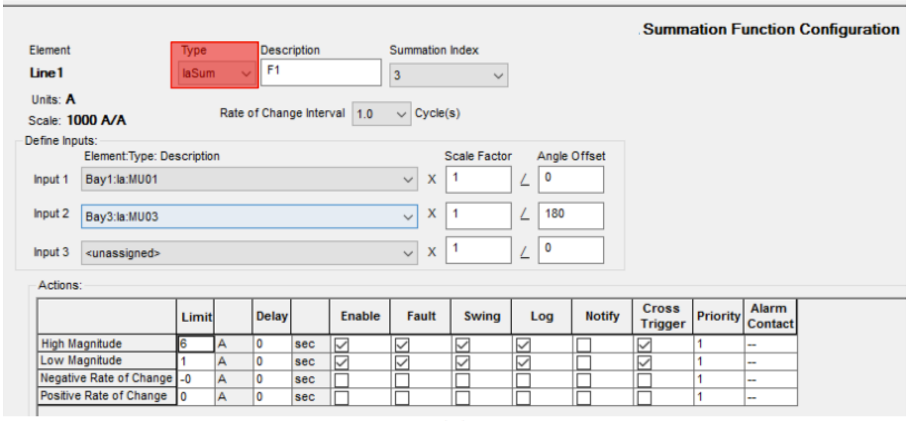
Mapped to: SVI

SMV IN	Mapped Data
C01	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR1MXAmpSv$in...
C02	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR2MXAmpSv$in...
C03	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR3MXAmpSv$in...
C04	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR4MXAmpSv$in...
C05	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR1MXVolSv$inst...
C06	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR2MXVolSv$inst...
C07	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR3MXVolSv$inst...
C08	SN2\MU1CSMU1\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR4MXVolSv$inst...
C09	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR1MXAmpSv$in...
C10	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR2MXAmpSv$in...
C11	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR3MXAmpSv$in...
C12	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TCTR4MXAmpSv$in...
C13	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR1MXVolSv$inst...
C14	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR2MXVolSv$inst...
C15	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR3MXVolSv$inst...
C16	SN2\MU1CSMU2\ETH_1\MU01.MSVCB02\PhsMeas1\Mu01/TVTR4MXVolSv$inst...
C17	SN2\MU320E\Ethernet_1\MU01.MSVCB02\PhsMeas1\Mu01/I01ATCTR1MXAmp...
C18	SN2\MU320E\Ethernet_1\MU01.MSVCB02\PhsMeas1\Mu01/I01BTCTR2MXAmp...
C19	SN2\MU320E\Ethernet_1\MU01.MSVCB02\PhsMeas1\Mu01/I01CTCTR3MXAmp...
C20	SN2\MU320E\Ethernet_1\MU01.MSVCB02\PhsMeas1\Mu01/I01NTCTR4MXAmp...

Figure 8: Sampled value input mapping

Configuration of Summation Channels

IEC 61850 sampled value inputs can be configured for summation calculations, as shown in Figure 9.

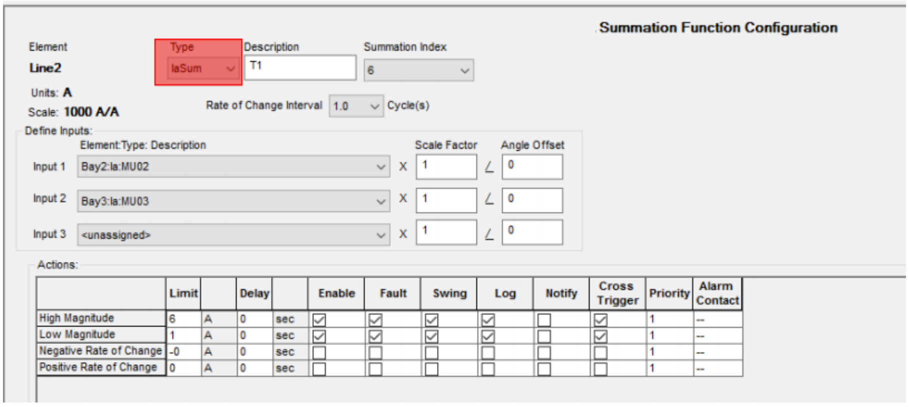


Element: Line1
Type: IaSum
Description: F1
Summation Index: 3
Units: A
Scale: 1000 A/A
Rate of Change Interval: 1.0 Cycle(s)

	Element:Type: Description		Scale Factor		Angle Offset
Input 1	Bay1:Ia:MU01	X	1	∠	0
Input 2	Bay3:Ia:MU03	X	1	∠	180
Input 3	<unassigned>	X	1	∠	0

	Limit		Delay		Enable	Fault	Swing	Log	Notify	Cross Trigger	Priority	Alarm Contact
High Magnitude	6	A	0	sec	☑	☑	☑	☑	☐	☑	1	--
Low Magnitude	1	A	0	sec	☑	☑	☑	☑	☐	☑	1	--
Negative Rate of Change	-0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--
Positive Rate of Change	0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--

(a)



Element: Line2
Type: IaSum
Description: T1
Summation Index: 6
Units: A
Scale: 1000 A/A
Rate of Change Interval: 1.0 Cycle(s)

	Element:Type: Description		Scale Factor		Angle Offset
Input 1	Bay2:Ia:MU02	X	1	∠	0
Input 2	Bay3:Ia:MU03	X	1	∠	0
Input 3	<unassigned>	X	1	∠	0

	Limit		Delay		Enable	Fault	Swing	Log	Notify	Cross Trigger	Priority	Alarm Contact
High Magnitude	6	A	0	sec	☑	☑	☑	☑	☐	☑	1	--
Low Magnitude	1	A	0	sec	☑	☑	☑	☑	☐	☑	1	--
Negative Rate of Change	-0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--
Positive Rate of Change	0	A	0	sec	☐	☐	☐	☐	☐	☐	1	--

Figure 9: Summation channel configuration

Power Calculations

Figure 10 shows an example of power quality calculations using IEC 61850 9-2 LE sampled value data captured during the prototype testing.

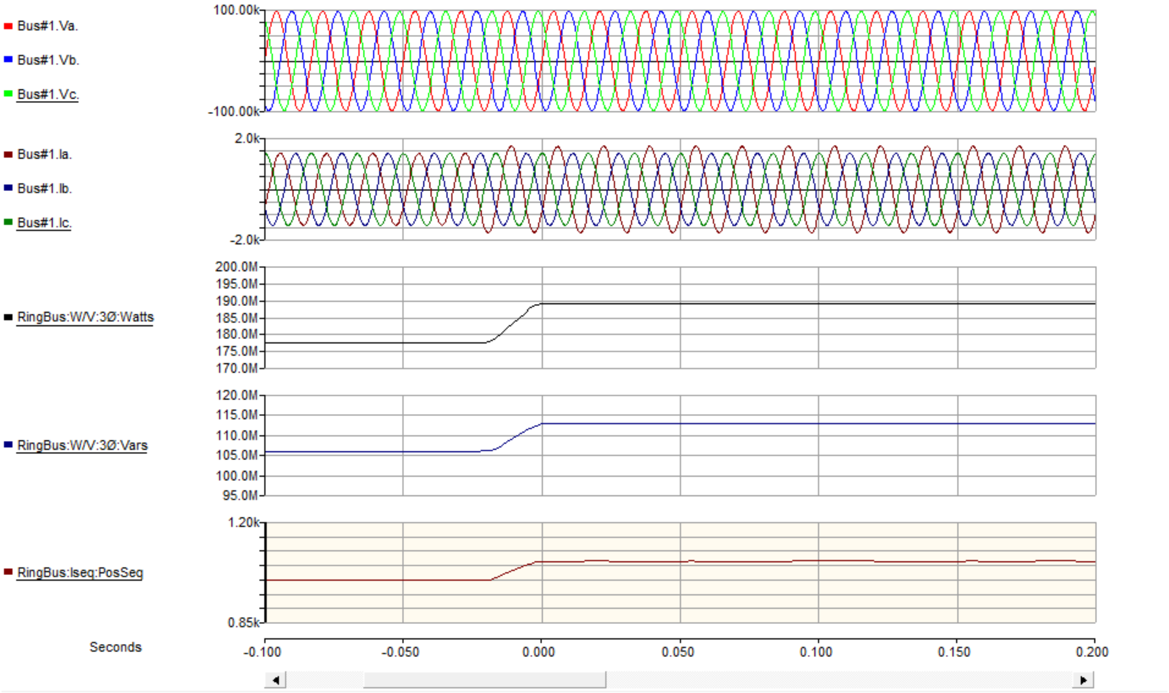
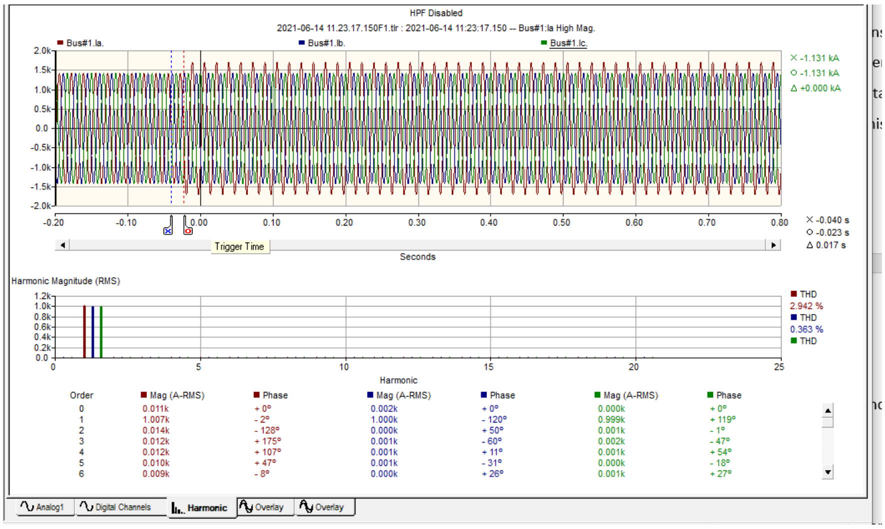


Figure 10: Power calculations

Harmonics

Figure 11 shows the harmonics calculations performed using IEC 61850 9-2 LE data captured by a DFR.

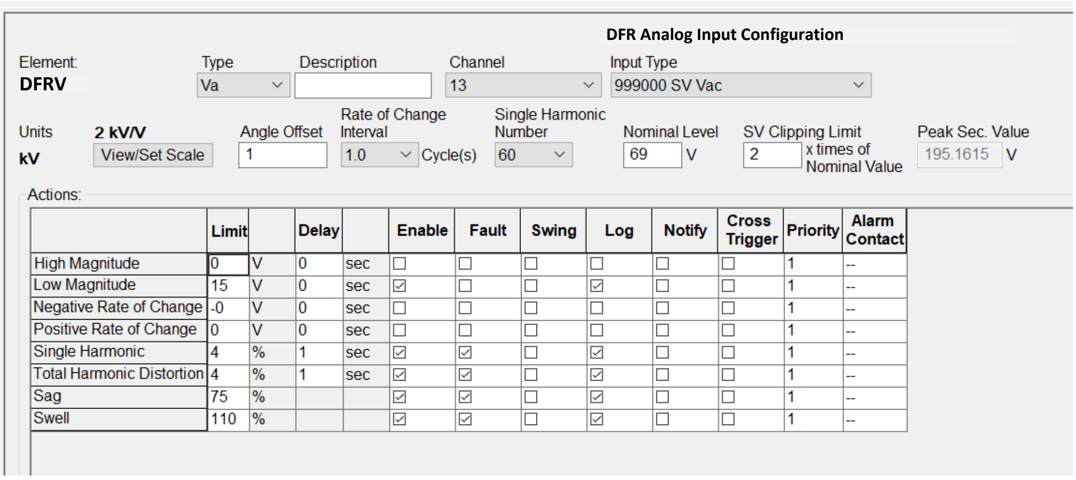


Order	🟥 Mag (A-RMS)	🟥 Phase	🟦 Mag (A-RMS)	🟦 Phase	🟩 Mag (A-RMS)	🟩 Phase
0	0.011k	+ 0°	0.002k	+ 0°	0.000k	+ 0°
1	1.007k	- 2°	1.000k	- 120°	0.999k	+ 119°
2	0.014k	- 128°	0.000k	+ 50°	0.001k	- 1°
3	0.012k	+ 175°	0.001k	- 60°	0.002k	- 47°
4	0.012k	+ 107°	0.001k	+ 11°	0.001k	+ 54°
5	0.010k	+ 47°	0.001k	- 31°	0.000k	- 18°
6	0.009k	- 8°	0.000k	+ 26°	0.001k	+ 27°

Figure 11: Harmonics calculations

Voltage Sag and Swell

The DFRs are capable of capturing voltage sag and swell conditions. Figure 12 shows the settings applicable to voltage sag and swell functions. Figure 13 and 14 show the oscillography captured by the DFR during the voltage sag and swell conditions.



DFR Analog Input Configuration

Element: **DFRV**

Type: Va

Description:

Channel: 13

Input Type: 999000 SV Vac

Units: **kV** **2 kV/V**

Angle Offset: 1

Rate of Change Interval: 1.0 Cycle(s)

Single Harmonic Number: 60

Nominal Level: 69 V

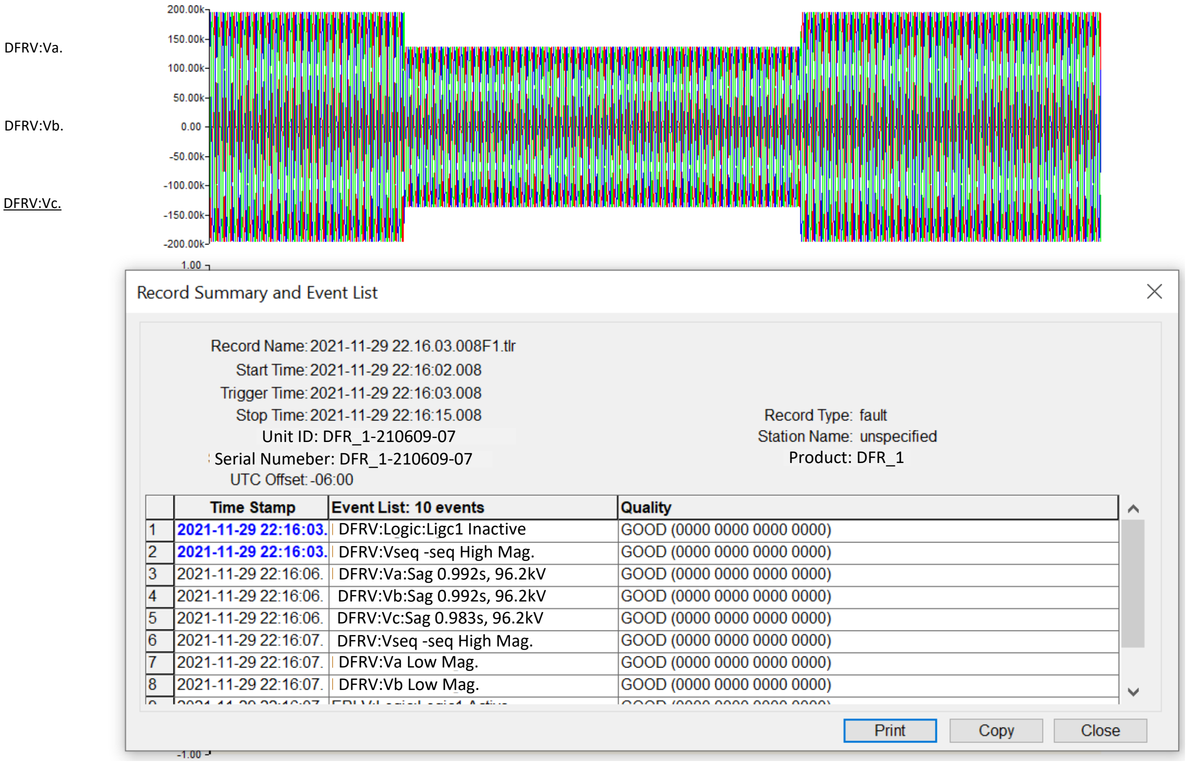
SV Clipping Limit: 2 x times of Nominal Value

Peak Sec. Value: 195.1615 V

Actions:

	Limit		Delay		Enable	Fault	Swing	Log	Notify	Cross Trigger	Priority	Alarm Contact
High Magnitude	0	V	0	sec	☐	☐	☐	☐	☐	☐	1	--
Low Magnitude	15	V	0	sec	☑	☐	☐	☑	☐	☐	1	--
Negative Rate of Change	-0	V	0	sec	☐	☐	☐	☐	☐	☐	1	--
Positive Rate of Change	0	V	0	sec	☐	☐	☐	☐	☐	☐	1	--
Single Harmonic	4	%	1	sec	☑	☑	☐	☑	☐	☐	1	--
Total Harmonic Distortion	4	%	1	sec	☑	☑	☐	☑	☐	☐	1	--
Sag	75	%			☑	☑	☐	☑	☐	☐	1	--
Swell	110	%			☑	☑	☐	☑	☐	☐	1	--

Figure 12: Voltage sag and swell settings



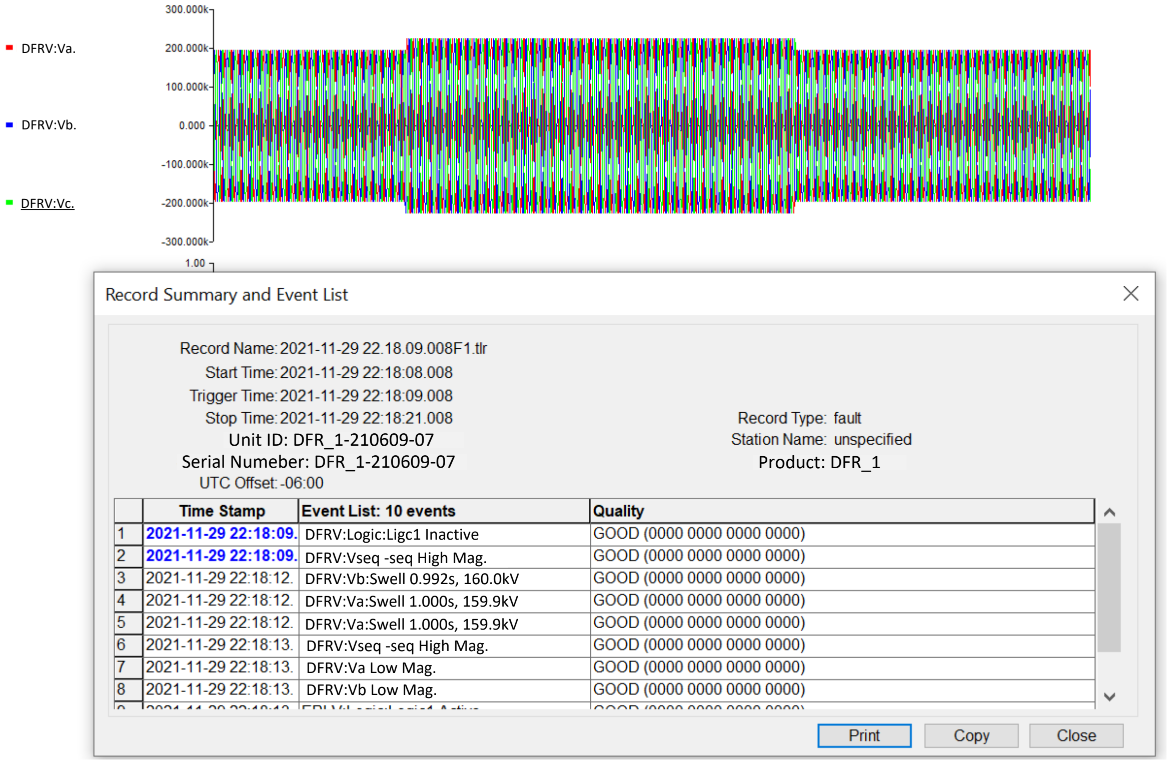
Record Summary and Event List

Record Name: 2021-11-29 22.16.03.008F1.tlr
Start Time: 2021-11-29 22:16:02.008
Trigger Time: 2021-11-29 22:16:03.008
Stop Time: 2021-11-29 22:16:15.008
Unit ID: DFR_1-210609-07
Serial Numeber: DFR_1-210609-07
UTC Offset: -06:00

Record Type: fault
Station Name: unspecified
Product: DFR_1

	Time Stamp	Event List: 10 events	Quality
1	**2021-11-29 22:16:03.**	DFRV:Logic:Ligc1 Inactive	GOOD (0000 0000 0000 0000)
2	**2021-11-29 22:16:03.**	DFRV:Vseq -seq High Mag.	GOOD (0000 0000 0000 0000)
3	2021-11-29 22:16:06.	DFRV:Va:Sag 0.992s, 96.2kV	GOOD (0000 0000 0000 0000)
4	2021-11-29 22:16:06.	DFRV:Vb:Sag 0.992s, 96.2kV	GOOD (0000 0000 0000 0000)
5	2021-11-29 22:16:06.	DFRV:Vc:Sag 0.983s, 96.2kV	GOOD (0000 0000 0000 0000)
6	2021-11-29 22:16:07.	DFRV:Vseq -seq High Mag.	GOOD (0000 0000 0000 0000)
7	2021-11-29 22:16:07.	DFRV:Va Low Mag.	GOOD (0000 0000 0000 0000)
8	2021-11-29 22:16:07.	DFRV:Vb Low Mag.	GOOD (0000 0000 0000 0000)

Figure 13: Voltage sag oscillography captured by a DFR



Record Name: 2021-11-29 22.18.09.008F1.tlr
Start Time: 2021-11-29 22:18:08.008
Trigger Time: 2021-11-29 22:18:09.008
Stop Time: 2021-11-29 22:18:21.008
Unit ID: DFR_1-210609-07
Serial Numeber: DFR_1-210609-07
UTC Offset: -06:00

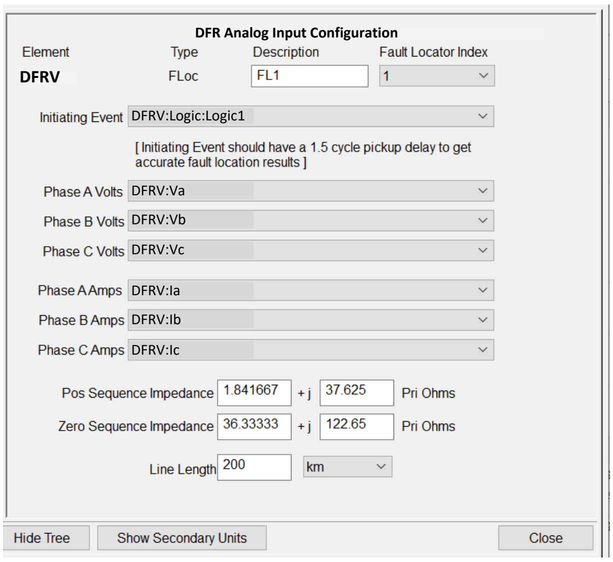
Record Type: fault
Station Name: unspecified
Product: DFR_1

	Time Stamp	Event List: 10 events	Quality
1	2021-11-29 22:18:09.	DFRV:Logic:Ligc1 Inactive	GOOD (0000 0000 0000 0000)
2	2021-11-29 22:18:09.	DFRV:Vseq -seq High Mag.	GOOD (0000 0000 0000 0000)
3	2021-11-29 22:18:12.	DFRV:Vb:Swell 0.992s, 160.0kV	GOOD (0000 0000 0000 0000)
4	2021-11-29 22:18:12.	DFRV:Va:Swell 1.000s, 159.9kV	GOOD (0000 0000 0000 0000)
5	2021-11-29 22:18:12.	DFRV:Va:Swell 1.000s, 159.9kV	GOOD (0000 0000 0000 0000)
6	2021-11-29 22:18:13.	DFRV:Vseq -seq High Mag.	GOOD (0000 0000 0000 0000)
7	2021-11-29 22:18:13.	DFRV:Va Low Mag.	GOOD (0000 0000 0000 0000)
8	2021-11-29 22:18:13.	DFRV:Vb Low Mag.	GOOD (0000 0000 0000 0000)

Figure 14: Voltage swell oscillography captured by a DFR

Fault Location Estimation

The DFRs are capable of calculating fault location on transmission lines during fault conditions. Figure 15 shows the basic parameters (sequence impedances, distance of the line, etc.) used in fault locator settings.



DFR Analog Input Configuration

Element	Type	Description	Fault Locator Index
DFRV	FLoc	FL1	1

Initiating Event: DFRV:Logic:Logic1

[Initiating Event should have a 1.5 cycle pickup delay to get accurate fault location results]

Phase A Volts: DFRV:Va
Phase B Volts: DFRV:Vb
Phase C Volts: DFRV:Vc

Phase A Amps: DFRV:Ia
Phase B Amps: DFRV:Ib
Phase C Amps: DFRV:Ic

Pos Sequence Impedance: 1.841667 +j 37.625 Pri Ohms
Zero Sequence Impedance: 36.33333 +j 122.65 Pri Ohms

Line Length: 200 km

Figure 15: Fault locator settings

Figure 16 show oscillography captured during a single-phase fault. Table-1 show the fault location estimation results.

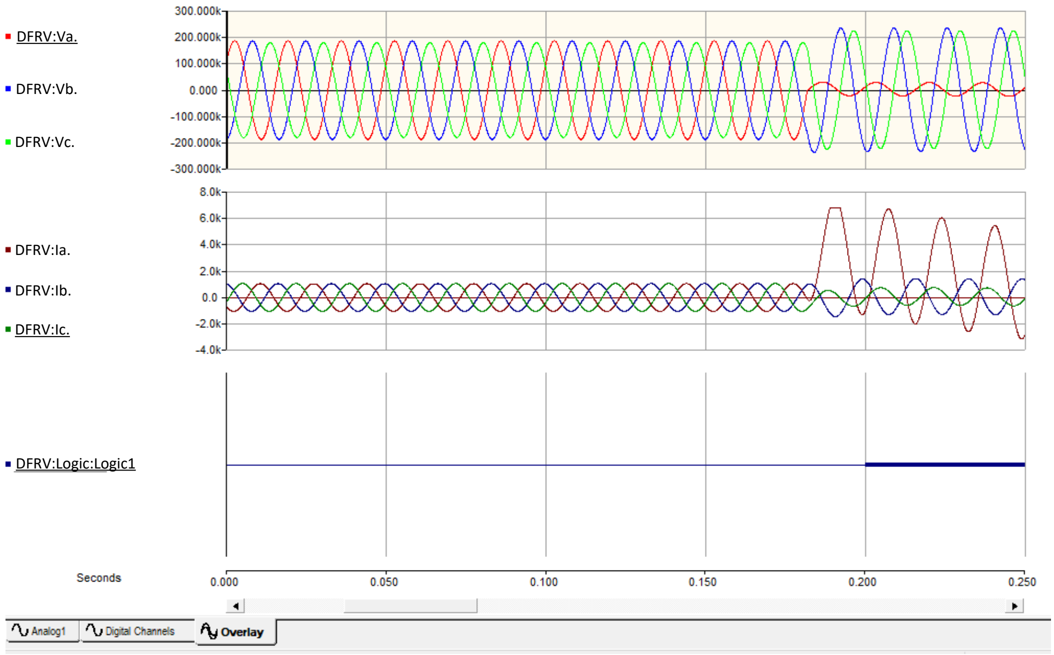


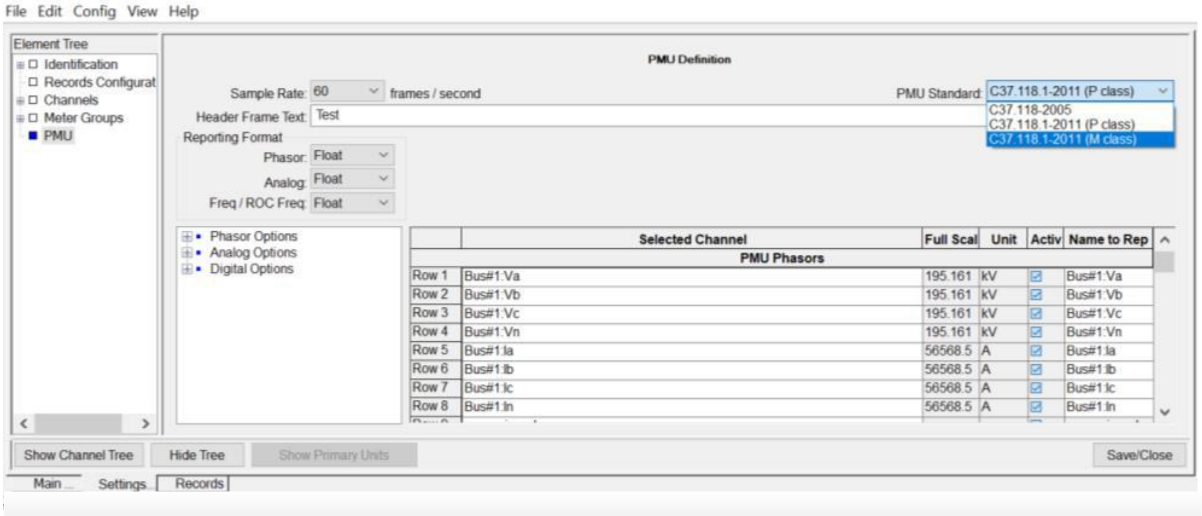
Figure 16: Oscillography captured during a fault

Table-1: Fault Location Results

Type of Fault	Actual	DFR Estimate	% Error
Single-phase fault	20.0 km	20.1 km	0.05
Three-phase fault	150.0 km	151.1 km	0.55

Synchrophasor Application

Figure 17 shows the PMU configuration settings with support for C37.118.1.



Sample Rate: 60 frames / second

PMU Standard: C37.118.1-2011 (P class)

C37.118-2005
C37.118.1-2011 (P class)
C37.118.1-2011 (M class)

Header Frame Text: Test

Reporting Format

Phasor: Float

Analog: Float

Freq / ROC Freq: Float

	Selected Channel	Full Scal	Unit	Activ	Name to Rep
	PMU Phasors				
Row 1	Bus#1:Va	195.161	kV	☑	Bus#1:Va
Row 2	Bus#1:Vb	195.161	kV	☑	Bus#1:Vb
Row 3	Bus#1:Vc	195.161	kV	☑	Bus#1:Vc
Row 4	Bus#1:Vn	195.161	kV	☑	Bus#1:Vn
Row 5	Bus#1:Ia	56568.5	A	☑	Bus#1:Ia
Row 6	Bus#1:Ib	56568.5	A	☑	Bus#1:Ib
Row 7	Bus#1:Ic	56568.5	A	☑	Bus#1:Ic
Row 8	Bus#1:In	56568.5	A	☑	Bus#1:In

Figure 17: PMU configuration

Figure 18 shows the results obtained during the dynamic testing of the PMU. It shows performance of the synchrophasor function using IEC 61850 sampled value data, as per synchrophasor test specifications [6].

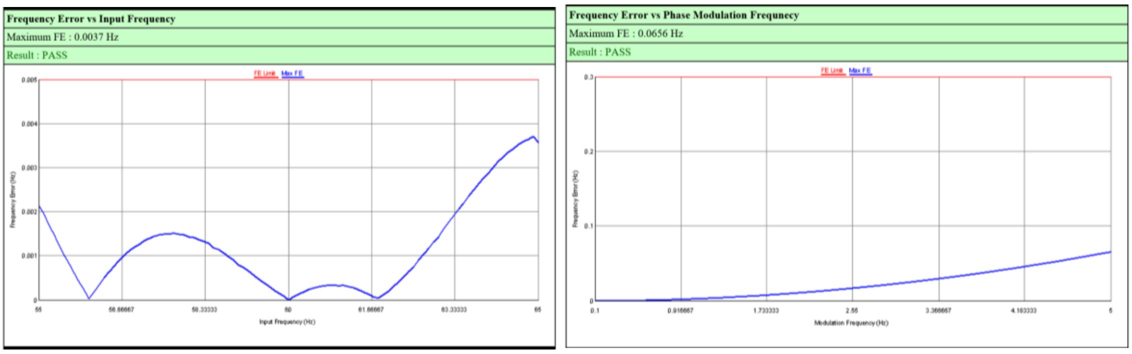
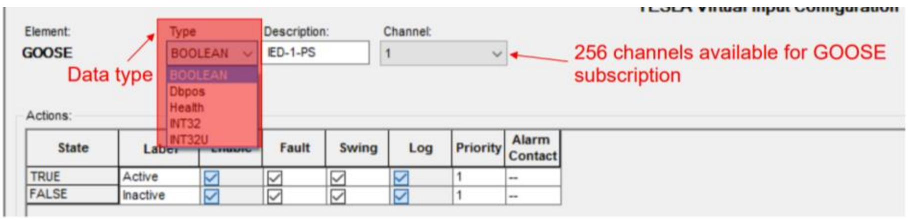


Figure 18: PMU test results

GOOSE Input Monitoring

DFRs can subscribe to single point status (Boolean), double point status, Health, Int32, or Int32u data types, as shown in Figure 19. Figure 20 shows an example of GOOSE data measurements captured by the device.



Element: GOOSE

Type: BOOLEAN

Description: IED-1-PS

Channel: 1

Data type

256 channels available for GOOSE subscription

Actions:

State	Label		Fault	Swing	Log	Priority	Alarm Contact
TRUE	Active	☑	☑	☑	☑	1	--
FALSE	Inactive	☑	☑	☑	☑	1	--

Figure 19: GOOSE subscription settings

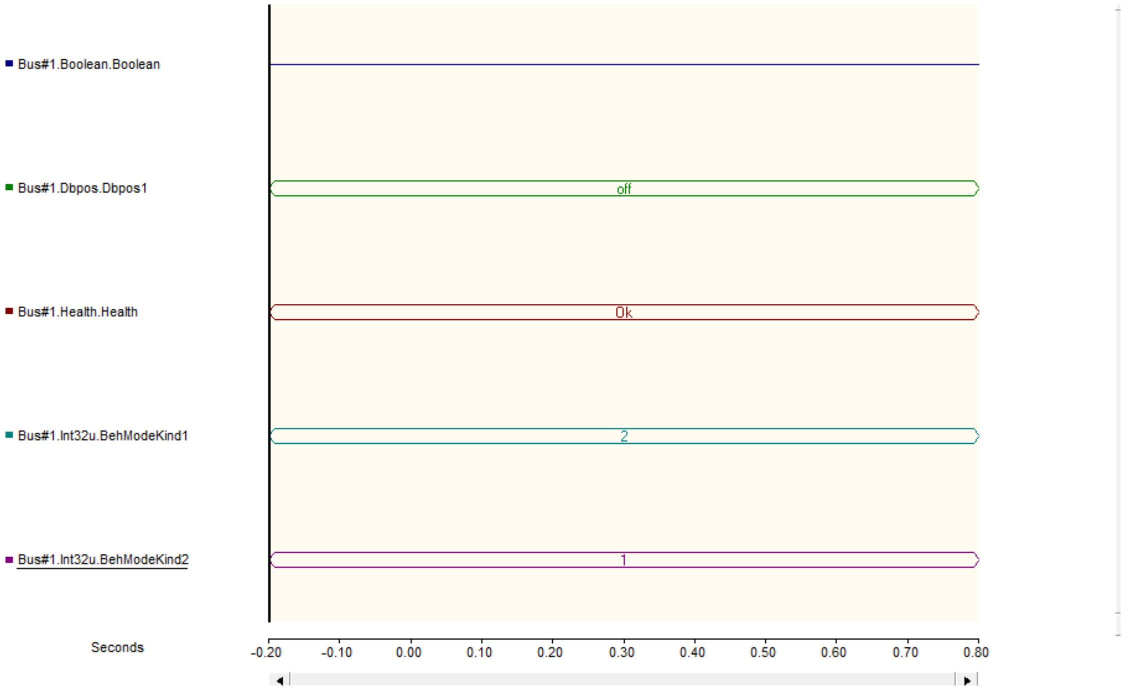


Figure 20: GOOSE data monitoring

IEC 61850 Server Application

Measurements from the IEC 61850 server can be obtained using an IEC 61850 client such as IEDScout software. Figure 21 shows the Phase A current (Figure 21a) and positive sequence voltage (Figure 21b) from the measurement LD of the IEC 61850 server of the IED.

IEDs

DFR_1

IP address: 172.16.128.111

- LN ANLMAGMMXN1
- LN ANLMAGMMXN10
- LN ANLMAGMMXN11
- LN ANLMAGMMXN12
- LN ANLMAGMMXN13
- LN ANLMAGMMXN14
- LN ANLMAGMMXN15
- LN ANLMAGMMXN16
- LN ANLMAGMMXN17
- LN ANLMAGMMXN18
- LN ANLMAGMMXN19
- LN ANLMAGMMXN2

DFR_1 - Data Model - MEAS – ANLMAGMMXN1

LN ANLMAGMMXN1 Non-phase-related measurement

Name		Value
DO Amp		0 A
DA mag	[MX]	0 A
DA q	[MX]	good
DA t	[MX]	2020-01-14 12:11:49.323 PM
DA instMag	[MX]	1000.307 A
DA f	[MX]	1000.307
DA units	[CF]	A
DA db	[CF]	0
DA zeroDb	[CF]	0
DA rangeC	[CF]	
DO Vol		0 V
DO Beh		on

IEDs

DFR_1

IP address: 172.16.128.111

- LN PFMMXN132
- LN SEQMSQI1
- LN SEQMSQI10
- LN SEQMSQI11
- LN SEQMSQI12
- LN SEQMSQI2
- LN SEQMSQI3
- LN SEQMSQI4
- LN SEQMSQI5
- LN SEQMSQI6
- LN SEQMSQI7
- LN SEQMSQI8
- LN SEQMSQI9
- LN SUMANGGGIO37
- LN SUMANGGGIO38
- LN SUMANGGGIO39
- LN SUMANGGGIO40
- LN SUMANGGGIO41

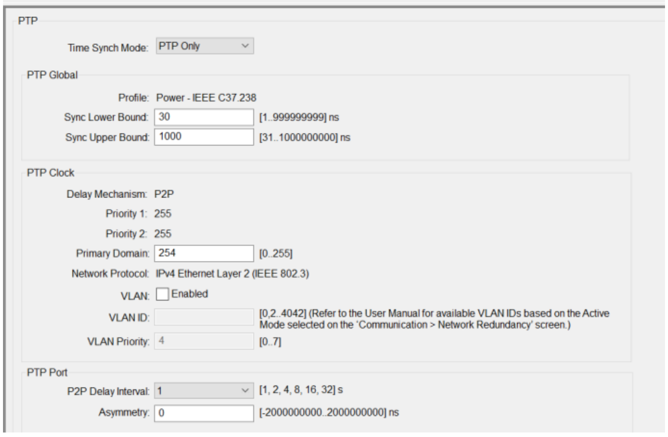
DFR_1 - Data Model - MEAS - SEQMSQI1

LN SEQMSQI1 Sequence and imbalance

Name		Value
DO SeqA		
DO SeqV		
DO c1		0 V ∠ 0°
DA cVal	[MX]	0 V ∠ 0°
DA q	[MX]	good
DA t	[MX]	2020-01-14 12:11:57.823 PM
DA instCVal	[MX]	68.994 V ∠ 0°
DA mag	[MX]	68.994 V
DA ang	[MX]	0°
DA units	[CF]	V
DA db	[CF]	0
DA dbAng	[CF]	0
DA zeroDb	[CF]	0
DA rangeC	[CF]	
DA rangeAngC	[CF]	
DO c2		0 V ∠ 0°
DO c3		0 V ∠ 0°
DA seqT	[MX]	pos-neg-zero
DO Beh		on

Figure 21: Measurements from an IEC 61850 server, including (a) Phase A current, (b) Positive sequence voltage

PTP – Time Synchronization



PTP

Time Synch Mode: PTP Only

PTP Global

Profile: Power - IEEE C37.238
Sync Lower Bound: 30 [1..999999999] ns
Sync Upper Bound: 1000 [31..1000000000] ns

PTP Clock

Delay Mechanism: P2P
Priority 1: 255
Priority 2: 255
Primary Domain: 254 [0..255]
Network Protocol: IPv4 Ethernet Layer 2 (IEEE 802.3)
VLAN: ☐ Enabled
VLAN ID: [0,2..4042] (Refer to the User Manual for available VLAN IDs based on the Active Mode selected on the 'Communication > Network Redundancy' screen.)
VLAN Priority: 4 [0..7]

PTP Port

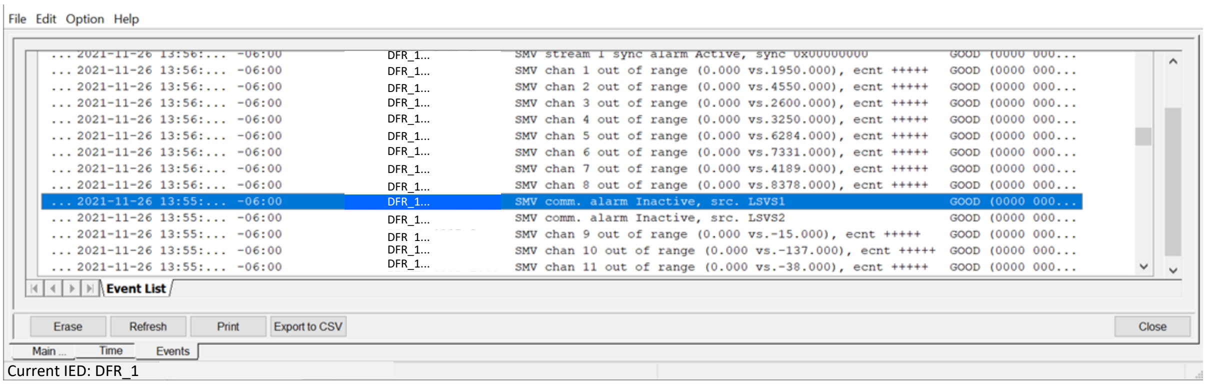
P2P Delay Interval: 1 [1, 2, 4, 8, 16, 32] s
Asymmetry: 0 [-2000000000..2000000000] ns

Figure 22: PTP time synchronization

The DFR under evaluation is capable of providing time synchronization via PTP protocol, which is the preferred method in digital substations where time sync signals come via the communication network.

Monitoring of IEC 61850 Data Streams

Monitoring the health of the IEC 61850 GOOSE and SVM streams is important for troubleshooting purposes. The DFRs under evaluation support the LSVS and LGOS logical nodes. Figure 23 shows an example of LSVS alarm events observed during a failure in SVM data streams.



```
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV stream 1 sync alarm Active, sync 0x00000000          GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 1 out of range (0.000 vs.1950.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 2 out of range (0.000 vs.4550.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 3 out of range (0.000 vs.2600.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 4 out of range (0.000 vs.3250.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 5 out of range (0.000 vs.6284.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 6 out of range (0.000 vs.7331.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 7 out of range (0.000 vs.4189.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:56:...  -06:00    DFR_1...    SMV chan 8 out of range (0.000 vs.8378.000), ecnt +++++   GOOD (0000 000...
... 2021-11-26 13:55:...  -06:00    DFR_1...    SMV comm. alarm Inactive, src. LSVS1                      GOOD (0000 000...
... 2021-11-26 13:55:...  -06:00    DFR_1...    SMV comm. alarm Inactive, src. LSVS2                      GOOD (0000 000...
... 2021-11-26 13:55:...  -06:00    DFR_1...    SMV chan 9 out of range (0.000 vs.-15.000), ecnt +++++    GOOD (0000 000...
... 2021-11-26 13:55:...  -06:00    DFR_1...    SMV chan 10 out of range (0.000 vs.-137.000), ecnt +++++ GOOD (0000 000...
... 2021-11-26 13:55:...  -06:00    DFR_1...    SMV chan 11 out of range (0.000 vs.-38.000), ecnt +++++   GOOD (0000 000...
```

Current IED: DFR_1

Figure 23: Example of LSVS alarm

Simulation Mode

In IEC 61850 testing, the simulation operation mode enables testers to use a control command to put the IEDs into simulation mode. The DFRs under evaluation support simulation mode for GOOSE and SMV subscriptions. Simulation mode is set (on/off) for the entire IED.

Conclusion

As more IEC 61850 based digital substations are implemented around the world, protection and disturbance recording functions are completely digitized and based on communication networks. Monitoring systems capable of providing complete visibility into digital substations are extremely useful. In this paper, key requirements in selecting a suitable monitoring/recoding system have been discussed. The performance of such a fully digital recoding and monitoring system was evaluated using an example scenario simulated in a lab environment including typical functionalities such as PQ, fault location, PMU, etc.

Biographies

René Midence (IEEE M'2007, IEEE SM'2009) is a 1983 graduate from the University of Honduras with a Bachelor of Applied Science degree in Electrical and Industrial Engineering, and with over 35 years of experience in power systems, protection & control, SCADA, substation automation and substation LAN systems. His well-rounded experience covers the fields of consulting and engineering, construction and commissioning, manufacturing, strategic marketing, technical support and training. He has contributed to the development and successful introduction to market of new state-of-the-art protection and control microprocessor-based relays, and Ethernet switches and routers. He is a Senior Member of the IEEE with active participation in the development of IEEE Standards and member of the IEEE Power Systems Relaying Committee (PSRC). He joined ERLPhase Power Technologies in 2010 and currently holds the position of Director of Technical Services.

Anderson Oliveira With over 18 years of experience in the power industry, Anderson Oliveira is registered as a Professional Engineer in the Province of Ontario, Canada, and hold both a Bachelor and Master of Engineering degree in Electrical Engineering. He has worked for utilities, engineering consulting firms, and, currently, he works for a relay, power monitoring device manufacturer, performing engineering activities for generation, transmission and distribution systems on a domestic and multinational basis.

Nuwan Perera (IEEE M'2005, IEEE SM' 2017) earned his BSc Electrical Engineering degree in 2003 from the University of Moratuwa, Sri Lanka and the M.Sc. and Ph.D. degrees from the University of Manitoba in 2007 and 2012, respectively. He is a senior IEEE member, actively involved with various IEEE Power Systems Relaying

Committee (PSRC) working groups. He worked for ERLPhase Power Technologies from 2011 to 2021. Currently, he is working as a Project Engineer at Stantec Consulting. He is also involved in academic research activities as an adjunct professor at the University of Manitoba.

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