A Standardized Way to Monitor Power System Disturbances Using Modern IEDs and Communication Networks

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A STANDARDIZED WAY TO MONITOR POWER SYSTEM DISTURBANCES USING MODERN IEDS AND COMMUNICATION NETWORKS

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***Summary*—Monitoring substations and their interconnected topologies with precise-time events is vital for modern complex power system networks. Power system faults vary from simple to complex phenomena, requiring the availability of proper time-synchronized digital events and analog data, such as voltages, currents, and frequency. Power system analysts, asset management groups, and engineers must have a holistic view of power dynamics, high-resolution transient fault records, and low-resolution dynamic disturbance records over a longer period than transient fault duration, along with corresponding sequential event records to evaluate both isolated and interconnected power system faults, to accurately find the source of faults, and to take preventive measures to avoid those faults reoccurring.**

Modern substation protection and control intelligent electronic devices (IEDs) provide high-resolution fault recording, time-synchronized phasor data, and time-stamped sequences of events. Since IEDs can be time-synchronized to submicrosecond accuracy through a Global Positioning System (GPS) clock source, modern IEDs are the perfect source for all required data for disturbance monitoring. Substation Ethernet communications networks for supervisory control and data acquisition (SCADA), where IEDs are connected, provide an economical solution to transferring disturbance monitoring data from IEDs to a local archiving system or a remote centralized system.

This paper discusses new, optimized disturbance monitoring system components and their requirements, design, and performance. It shows how an optimized disturbance monitoring system can be economically adapted as a standalone, hybrid, or fully IED-integrated system, depending on the type of substation, infrastructure, or project timeline. It discusses collecting data from different substations and routing them to a centralized location using industrial protocols. It discusses modern techniques for collecting, monitoring, and analyzing high-resolution event data and Sequential Events Records (SER) data for the complete grid in a time-aligned, cybersecure format, which is key for any power utility to empower their planning and asset engineers to conduct accurate root-cause analysis and take preventive maintenance measures. With the new implementation presented in this paper, engineers will be able to better analyze power system faults and make decisions more quickly.

***Keywords*—Centralized Fault Recording System–Power System Disturbance Monitoring–Operational Technology (OT) Networks–Utilization of existing infrastructure and IEC 61850 for fault monitoring.**

I. INTRODUCTION

A. Objective of Power System Disturbance Monitoring (PSDM)

A power system disturbance occurs when one or more electrical parameters, such as voltage, current, or frequency, change from normal to abnormal values. The power grid is a complex, interconnected system where power fluctuation in one location may affect other locations. Variability in generation (e.g., changes in the generation of solar or wind farms), system faults, switching capacitor banks, lightning strikes, sudden load changes, and nonlinear loads provoke power system disturbances. These disturbances vary in severity and duration. The importance of disturbance recording has increased over the past decade with the ever-expanding complexity of generations and loads in the grid. Electrical parameters need to be visualized through disturbance records when a disturbance occurs in a power system. Analyzing power system disturbances

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requires time-synchronized measurements from various locations in the grid. These measurements provide grid operators and engineers with the necessary information to maintain power system stability and reliable electricity.

B. Overview of Various Power System Disturbance Records

Power system disturbances are monitored and analyzed through disturbance records captured at substation level by various substation equipment. There are different types of records categorized by format, content, resolution, and duration of the record. The following list includes the major categories of disturbance records:

- Transient records
- Long-term and continuous records
- Change-of-state records

1) Transient Records

Transient records are also referred as event reports, fault records, oscillography, etc. A transient record consists of time-series analog and digital data sampled typically at higher resolution and captured when a specific trigger condition arises. The total length of the transient record may vary between a few cycles to several seconds. Typical transient recording devices provide configurable pre-trigger durations. Pre-trigger time is usually between 5 to 95 percent of the total length of the record. The total length (LER) and pre-trigger time (PRE) are related in Fig. 1. Analog data are recorded with a typical sample rate of 1,000 samples per second or greater. Digital data are recorded with equal or less sample rate than analog data. The transient records are captured by standalone digital fault recorders (DFRs) or protection intelligent electronic devices (IEDs) at substations. Recording devices store transient records in Common Format for Transient Data Exchange (COMTRADE) or compressed ASCII file format.

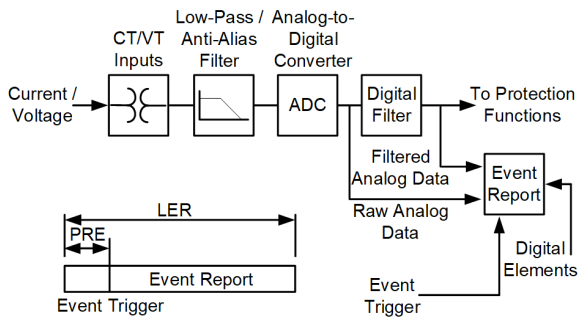

Fig. 1 Event Report Signal Processing in IED

A summary provided by event reports from a line-protection IED often includes the following information:

- Type of event (e.g., Phase A-to-ground fault)
- Trigger time
- Digital statuses (i.e., breaker state)
- Distance to fault
- Pre-fault current and voltage quantities
- Post-fault current and voltage quantities

Power system utility engineers to validate correct protection operation and performance, determine fault location, and verify system model parameters. The transient data within the record are time-aligned with respect to the clock of the recording IED. When transient records from different IEDs are required for event analysis, then all the IED clocks must be synchronized, preferably to submicrosecond accuracy. Modern IEDs can provide transient records at a sample rate of 10 kHz. Traveling-wave-based high-speed relays provide transient records with a sample rate of 1 MHz.

2) Long-Term and Continuous Records

Also described as dynamic disturbance records or profiling records, long-term records consist of power system quantities, such as voltage magnitude, current magnitude, frequency, and real and reactive power. These types of records are recorded for longer durations. In many applications, long-term records are triggered on level-based triggers of analog quantities or digital statuses. The length of the record can be several seconds to minutes with configurable pre-trigger duration. The sample rate is lower and can vary, from one sample per cycle to one sample per second. In other applications, these analog quantities and digital signals may be continuously recorded, removing the need for triggers. These continuous records are saved in discrete files, based on fixed file sizes or recording durations. This method provides convenient data access and data management. Like transient records, long-term and continuous records are often saved in COMTRADE file format.

Synchrophasors provide precisely time-aligned power system measurements from different devices and locations throughout a power system network. These data enable engineers and operators to analyze system performance, behavior, disturbances, and more, across wide areas in the power grid. The device that measures and reports synchrophasors is called a phasor measurement unit (PMU). IEEE C37.118 is the industry standard protocol that defines how to measure, send, and receive synchrophasor messages between PMUs and other devices, such as the phasor data concentrator (PDC). The synchrophasor data from the PMU stream consist of voltage phasors, current phasors, and frequency. Some PMUs also include power quantities, various analog signals, and digital signals. The PMU streams synchrophasor messages at a rate of 1 to 50 or 60 messages per second, depending on the nominal system frequency. The PMUs process the signal and construct the message per IEEE C37.118-2005/2011. The PMU must be time-synchronized with microsecond accuracy. Presently, the PMU measurements are a growing part of wide-area monitoring and control of the power system network. These PMU data are collected at a central location through the PDC and often archived for

historian purposes by system operators. They are also used for real-time monitoring and control applications. Synchrophasor data are a good source for continuous records for the purpose of power system monitoring; hence, there is tendency to combine transient and continuous record from the same devices. Modern protection IEDs feature synchrophasor measurements and stream as per IEEE C37.118 compliance requirements, so users increasingly consider enabling synchrophasor measurements in protection IEDs. Fig. 2 shows synchrophasor signal processing in protection IEDs.

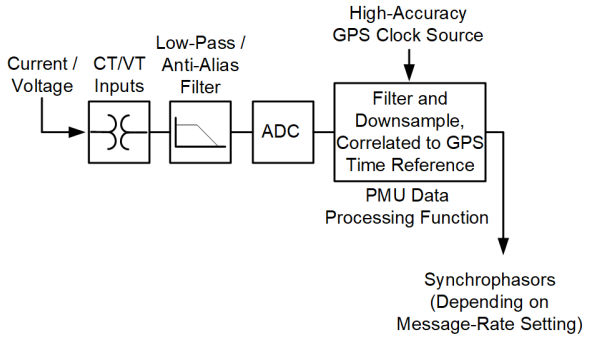

Fig. 2 PMU Data Processing in IED

3) Change-of-State Records

Change-of-state records are also known as sequential event records (SERs) or Sequence of Event (SOE) records. This record captures change-of-state of substation equipment (relay, switchgear, transformer, etc.) schemes as they react to a power system event in chronological order. These records can be from fault or switchgear operations. The data allow the timeline of events to be studied for the causes of the operation of the protection IED and linkages between individual actions and effects. Traditionally, a standalone SOE recorder is employed at a substation with hardwired field signals. This SOE recorder provides stationwide common sequential data. Typically, these records are provided with 1 millisecond resolution. Modern protection IEDs include SER functions that record the state-of-change of individual internal protection elements, commands, controls, and status signals connected through hardwires. Protection IEDs record SERs in on-board memory in file structure, which can be automatically collected at a centralized system. Fig. 3 shows a typical SER capture from an IED. Alternatively, SER for PSDM purposes can be recorded at a centralized system in the substation using IEC 61850-based communications between protection IEDs and a centralized recording system. This arrangement is explained later in Section III.

C. PSDM Components

Power system disturbance-associated records, as discussed in Section I.B, are sourced from different substation-level standalone equipment, like DFRs, PMUs, and SOE recorders. In the optimization process of PSDM, substation IEDs (protection and control IEDs), communication networks, centralized controllers, and other existing components can be considered for implementation.

1) Substation IEDs

The primary purpose of protection and control relays is to protect the power system. Fortunately, with advancements in design, technology, and economic availability in modern relays, these devices can also support supplemental disturbance monitoring by providing all the types of records discussed in Section I.B. As the computational and storage capacities of digital relays increase, the sampling rate of event report data and the associated event report file size similarly increases. By the early twenty-first century, relay event reports were sampled at an interval in the range of hundreds of microseconds. Recently, these reports have progressed to the 1 microsecond sampling interval range (1 MHz sample rate). Many modern relays generate fixed-rate event reports (raw event reports) in addition to the frequency-tracked variable-rate event reports (filtered event reports) described previously. Fig. 1 shows that the raw event report captures analog data before digital filter and filtered event reports and the filtered event report captures analog data after digital filter. Both event reports enable great precision in analyzing and finding the root cause for events [1].

```
Relay 1                                    Date: 03/16/2001  Time: 13:09:29.341
Station A                                  Serial Number: 2001001234
FID=SEL-411L-R101-V0-Z001001-D20010315
#     DATE        TIME          ELEMENT              STATE
6     03/15/2001  00:00:00.004  Power-up             Group 1
5     03/15/2001  00:00:00.022  Relay                Enabled
4     03/15/2001  00:30:00.021  GROUND O/C 1 LINE 1  51S1 PICKED UP
3     03/15/2001  00:30:03.221  GROUND O/C 1 LINE 1  51S1 TIMEOUT
2     03/15/2001  00:32:00.114  GROUND O/C 1 LINE 1  51S1 RESET
1     03/15/2001  00:32:00.114  GROUND O/C 1 LINE 1  51S1 DROPOUT
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SER Number

Relay Element or Condition

Fig. 3 Sequential Event Record from IED

Modern IEDs provide configured SERs with time stamps. They also provide synchrophasor data with an available high-accuracy time source and interface. There are several protective relays currently available in substation protection systems that have PMU capabilities built into their base functions. In parallel to what analog signal relays process for protection functions, they can also be used to measure time-synchronized phasors to send data to the upstream network using the IEEE C37.118 synchrophasors protocol as shown in Fig. 2. The synchrophasor data become significantly important when viewed in a wide spectrum across multiple locations in an interconnected power system. It is vital to have PMU capabilities in protective and control relays and PDC capabilities in optimized PSDM controllers to gather information from multiple PMUs within the substation, concentrate and time-align the phasor data, and send them to the upstream network over the IEEE C37.118 protocol to the control center.

2) Communications Networks

Modern substations already have Ethernet communications networks for the purposes of SCADA or substation automation. Ethernet communications provide a path for data exchange between IEDs and multiple client applications over multiple simultaneous sessions. Therefore, Ethernet communications networks in substations are efficient for transporting data related to disturbance monitoring. Communication and automation technology have changed at a faster pace in the past decade, especially with the fast deployment of substation-oriented protocols, like IEC 61850. The IEC 61850 standard was developed and initially released in the late 1990s. Additionally, the IEC 61850 Manufacturing Message Specification (MMS) file transfer service provides an effective solution for automatic retrieval of event reports and continuous records saved in COMTRADE format in IEDs.

3) Time Sources

IEDs and other substation devices have an internal clock for timekeeping, to log the events with time stamps, and to perform time-synchronized measurements. These internal clocks tend to drift in time relative to each other over a long period; hence, synchronizing them to a common time source is very important. Substation devices accept time input over direct connections, like Inter-Range Instrumentation Group time code format B (IRIG-B) or through networks such as Network Time Protocol (NTP) or Precision Time Protocol (PTP). The substation-based Global Positioning System (GPS) clock provides high-accuracy time references in submicroseconds. The GPS clock serves high-accuracy time synchronization of the connected device over IRIG-B interface or PTP. Moderate-accuracy time synchronization is achieved over Simple Network Time Protocol (SNTP). In most cases, SNTP-based time synchronization is adequate for event report and SER time stamping, but synchrophasor measurements require the high-accuracy time synchronization of IRIG-B or PTP.

4) Automatic Collection and Visualization

Event data may be stored at several locations across the power system network. Engineers who perform post-event analysis require convenient solutions to collect records from the various locations in a timely manner. With advanced centralized controllers, the automatic event collection is done seamlessly using an existing communication local-area network (LAN) and IEC 61850 MMS file transfer services. The events are saved in local memory, then sent to a centralized location (typically a control center) where events are archived for later use. These data are readily available for visualization and analysis.

II. Conventional Arrangement

The power system disturbance is being monitored, analyzed, and evaluated through post-analysis of the data from different substation devices. The conventional arrangement of PSDM is shown Fig. 4. The substation IEDs and substation control and monitoring system (SCMS) human-machine interface (HMI) are connected to a dedicated Ethernet communication network LAN 1. The IEDs serve data to the SCMS client over IEC 61850 MMS report services. The transient records are triggered using one or more standalone DFRs, which provide high-resolution sampled analog and digital data that are hardwired to the DFR. These DFRs are typically connected in a separate LAN 2 network. The IED, the standalone PMUs, and PDC are connected in a separate LAN 3 network. The PMUs stream synchrophasor data to the PDC, which then archives data at the substation level and further streams aggregated synchrophasor data over the IEEE C37.118 protocol to the PDC at the control center. The SOE data are gathered through a standalone SOE recorder, where all the statuses are hardwired to the SOE recorder. Traditional SOE recorders are connected in the LAN 1 network serving substation sequential records to system operators. The growing substation automation field with IEC 61850-based HMI applications serves the SOE data as an alternative to a dedicated SOE recorder.

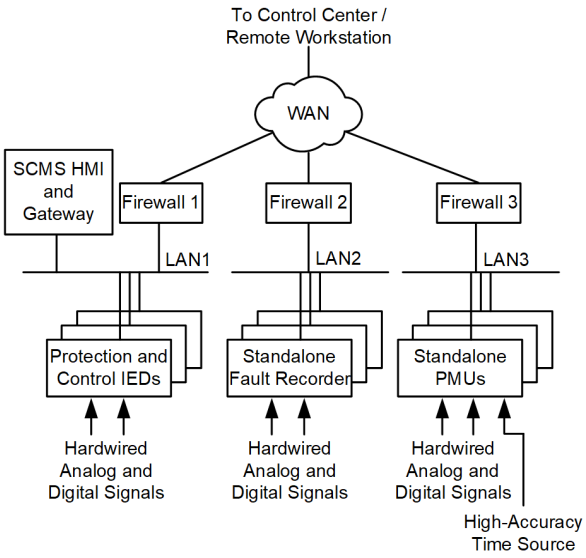

Fig. 4 Conventional Power System Disturbance Monitoring Arrangements

III. Optimized PSDM Arrangements

A. Fully Optimized PSDM Systems

Traditional systems involve hardwired digital inputs, current transformer (CT) connections, and potential transformer (PT) connections that bring analog signals into conventional system panels. In modern substation infrastructure, standardized mechanisms and communication protocols digitize measurements at the source and transfer data between IEDs. Fig. 5 in Section B depicts the usage of multiple suits of protocols involved in a typical modern substation. The IEDs available and deployed today have all these functions to optimize the substation networks and increase reliability. Some utilities strive to minimize traditional conductive wiring connections in substations, as conductive wiring imposes challenges of safety, reliability, maintenance, and expandability. Consequently, the industry has begun adapting the sophisticated communication-assisted mechanisms to replace conductive wiring with Ethernet networks.

For many years, electrical utilities have been monitoring their power systems for various faults, disturbances, transients, and anomalies. Traditionally, it was very common to use paper chart recorders or standalone fault recorders to represent waveforms being recorded whenever there is a fault. At high-voltage and extra-high-voltage levels, traditional DFRs are widely installed and used for locating faults, analyzing waveforms, and predicting maintenance needs. However, at the distribution level, dedicated equipment for fault recording is not as common. In any case, having a dedicated DFR is also not the optimum solution in modern infrastructure where intelligent IEDs are installed at the bay and station level.

DFR functionalities need to be focused on power system transient fault capturing with a high-sampling rate and a slow scan, which is required to capture phasor measurements with several other features, like SER recording and cybersecurity features. DFR systems are designed purposefully to capture all types of power system events. It needs to have a comprehensive multifunction recorder that simultaneously captures transient, SOE, disturbance recording, and phasor measurement data. High-resolution fault data provide substantial context for fast transient events and operations on the power system. The availability of current and voltage samples with multiple ranges of sampling rates, with typical resolution of 8 to 24 kHz or higher, provides visibility for power system protection engineers to analyze faults in depth.

The past decade has brought, a major shift towards the IEC 61850 standard, and the following key features have been adopted widely:

- IEC 61850 is a substation object-oriented protocol that standardizes the signals as per electrical terminologies and primary equipment into the software world. The IEC working group has incorporated the Generic Object Models for Substation and Feeder Equipment (GOMSFE) concept into its standard, which is used to present substation data into objects or blocks. This approach makes it easy for the user to configure, understand, test, and maintain the substations from a centralized server within the substation in a cost-efficient and safe manner.
- IEC 61850 provides signal addressing in the form of intuitive names that are called logical nodes. This enhances the engineers' productivity during the time of commissioning to easily understand and map the signals in software databases. They no longer need to refer to a separate cumbersome signal list that dictates internal register addresses to actual signals, as in the case of Modbus or other earlier protocols.
- The multiple parts of IEC 61850 list the whole infrastructure of protocol with details included for manufacturers to help develop their devices with the same principles. This helps greatly and overcomes the challenge of interoperability between different manufactures' devices. Complete device statuses for digitals, and analogs as well as controls are provided through application-layer MMS services of IEC 61850 protocol in a standardized way to share data between different systems in real time.
- IEC 61850 also governs a unique methodology of peer-to-peer communication to send high-speed signals across the network, which is called Generic Object-Oriented Substation Event (GOOSE) messaging. Along with the flexibility of logics in advanced numerical relays to configure various interlocks, these devices also take an advantage of their fast-

processing capabilities to perform functions on these high-speed GOOSE to replace conventional electrical hardwires between the relays. Comparing hardwired electrical cabling between different devices, GOOSE messaging reduces cost and time to send high-speed signals for intertripping, blocking, etc., over the Ethernet network and still maintains the same performance as required by the protection application.

- Part of the IEC 61850 standard also provides a secure and reliable method to transfer files from one device to another over the same Ethernet medium using MMS file transfer. IEDs, like protection relays, implement MMS file transfer to transfer data as files and to provide the hierarchal structure for those files to manage data. These files may include relay settings, Configured IED Description (CID) files and fault-event files to be collected from IEDs using MMS file transfer.
- The protocol implementation for IEC 61850 MMS services also includes an option of MMS authentication to enhance data transfer security. If MMS authentication is activated with IEDs, the MMS server makes sure that authentication keys (like passwords) are entered correctly by the MMS client before providing access to its services and files. There are also possibilities available in IEDs to activate and generate alarms in case the client enters the wrong key a multiple number of times, and the alarms can be monitored separately to raise security alerts.

Fortunately, in modern systems, a plethora of IEDs record and store even small details of system operations. These may include protective relays, communications processors, DFRs, remote terminal units (RTUs), voltage regulator controls, programmable automation controllers (PACs), and recloser controls, to name a few. The IEDs log and time-stamp data from the power system, including analog waveforms, contact statuses, internal device binary states, trip and reclose signals, and many more. While all of these data aid in analyzing and improving system performance, they can only do so if the data can be extracted from the IEDs and organized in an intelligible manner. Each IED time-stamps data items relative to some internal time source. Thus, the accuracy of the internal time source is critically important if the recorded data are to be useful in a larger system analysis [2]

With all the digital information available through substation IEDs, operators in the control center can use the IEC 61850 data received for fault records, SER over MMS file transfer, digital data over GOOSE messages, and synchrophasor data with the IEEE C37.118 protocol to analyze and troubleshoot the fault in the holistic power system view. While transient fault records captured in COMTRADE files provide instantaneous raw samples of currents and voltages with before, during, and after fault conditions, synchrophasor data provide dynamic information over a longer period with phase and angle quantities monitored continuously with a 1-microsecond time stamp. Along with these, SER data provide time-stamped information on the type of fault that occurs at a particular analysis instance. This information can be sent through an optimized PSDM controller in the substation over IEC 61850 MMS protocol with unsolicited reporting and with an accurate time stamp with 1-millisecond precision on SER data.

B. Optimized PSDM Controller and Architecture

Fig. 5 is an illustration of a typical data flow for a centralized disturbance and fault recording system from an optimized PSDM controller perspective within a substation.

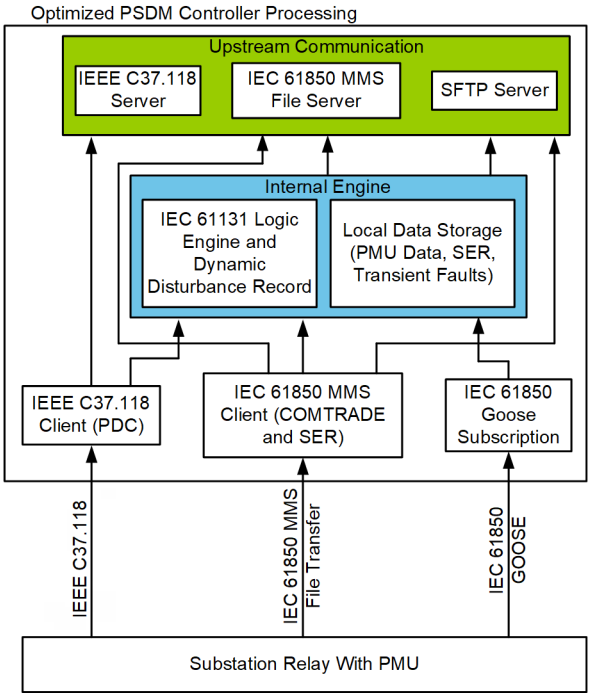

Fig. 5 Optimized PSDM System Data Flow

The intelligent optimized PSDM controller, shown in Fig. 5, has an embedded real-time operating system and not a Windows-based operating system, as embedded controllers provide better performance, more reliability, and less maintenance over the period and are cybersecure and robust in nature. Windows-based systems need regular patching and rely on several external factors, like end-of-life, for their operating system, the services they are running, memory exhausting, etc., which are not adequate to operate over a long period of time. Users need to maintain the system on a regular basis and, ultimately, need to replace hardware and software on which a Windows-based system is running. For this reason, industries are moving more and more towards embedded controllers for such power system-related applications.

The optimized PSDM controller is capable of operating multiple Ethernet communications networks. It provides a combination of functions that include deterministic logic processing with powerful deterministic processing rates as fast as 1 millisecond, automatic transmission of outgoing messages, processing of responses, data scaling, data aggregation, simultaneous collection of data from multiple server devices, and simultaneous data access for multiple client (master) devices. It can provide fault data concentration and time alignment as a synchrophasor logic processor, controller, or combination of the two. By supporting the IEEE C37.118 protocol, it can act as client and server to collect synchrophasor data from multiple PMUs in the substation and to send data to multiple control centers for wide-area monitoring systems (WAMSs). It can collect and process synchrophasor messages at a data rate up to 240 messages per second that include magnitude, angle, and time stamp for each measured quantity on PMUs and associated digital data channels. For upstream communication to the control center, typically the same data rate is provided when the controller works as an IEEE C37.118 server to communicate with the control center. The IEEE C37.118 protocol typically uses TCP, UDP, UDP_T or UDP_S for communications to upstream control center networks to interoperate and optimize the design with lower bandwidth consumption.

Once IEEE C37.118 data are retrieved from the PMUs within the substation, internal counters are required to trace the time stamp of the first data message received and the latest data for the same sample to time-align those samples before sending them to the control center. This functionality makes sure that synchrophasor data collected from different substations can be correlated at a given time to analyze the phasors accurately for power system stability studies.

While deploying such hybrid systems, it is important for controllers in the substation to provide deterministic processing cycle capability of 1 millisecond with an IEC 61131 logic engine. Getting data processed in IEC 61131 logic at this rate enables engineers to perform high-speed tasks, like intersubstation load-shedding schemes, also referred to as remedial action schemes (RASs), to control and manage loads in different geographically located substations based on power system frequency, voltage magnitudes, and angles.

Reliability considerations for choosing substation equipment like PSDM controllers is vital when deploying such monitoring systems. When power system reliability and operations is considered, it is very important to think about the ruggedness of equipment we use to protect our power system. The core of power system protection relies on protective relays on the secondary side. The relays are typically designed, manufactured, and tested with various IEEE and IEC standards to meet the goals of providing a reliable protection system with a longer lifetime. Similarly, the reliability of other IEDs in the substation is equally important, as continuous and interruption-free system monitoring is important to plan any outage ahead of faults occurring or equipment failing. The hardware of these monitoring systems shall operate reliably in harsh environments and conform to IEEE C37.90 and IEC 60255 protective relay standards, to mention a few.

C. Typical Optimized PSDM System Architecture

The optimized PSDM architecture is shown in Fig. 6 to illustrate how IEDs can be connected to optimized PSDM controllers in each substation to communicate via IEC 61850 MMS protocol. Ethernet switches, connection topology, and security firewalls are shown for further illustration. The topologies can be designed in accordance with IED-network capabilities of dual port and switching/failover capabilities. The system is also capable of integrating with IEDs over different topologies like Parallel Redundancy Protocol (PRP), ring, star/dual star, or failover schemes.

The communication design is substation-hardened Ethernet switching communication architecture with redundant Ethernet ports at 380 kV and 154 kV bay control units and 36 kV bay protection IEDs supporting PRP or failover connection. The IEDs (control and protection relays) are connected to two different Ethernet network switches for redundancy in star or ring topology. The substation Ethernet network is typically formed by rugged substation-grade switches. This system arrangement assures no single point of failure where a minimum of two separate hardware and/or cabling failures must occur to lose communication to any substation.

Control and protection devices are connected to the LAN with a typical communication speed of 10 or 100 Mb per second depending on the device speed, and 1 Gb per second for all upstream connections between switches or to an optimized PSDM controller. This is a commonly used substation architecture where multiple devices communicate to each other over Ethernet LAN. In modern substations, IEDs do have capabilities to communicate multiple protocols, like IEC 61850, Modbus, DNP 3.0, and IEEE C37.118.

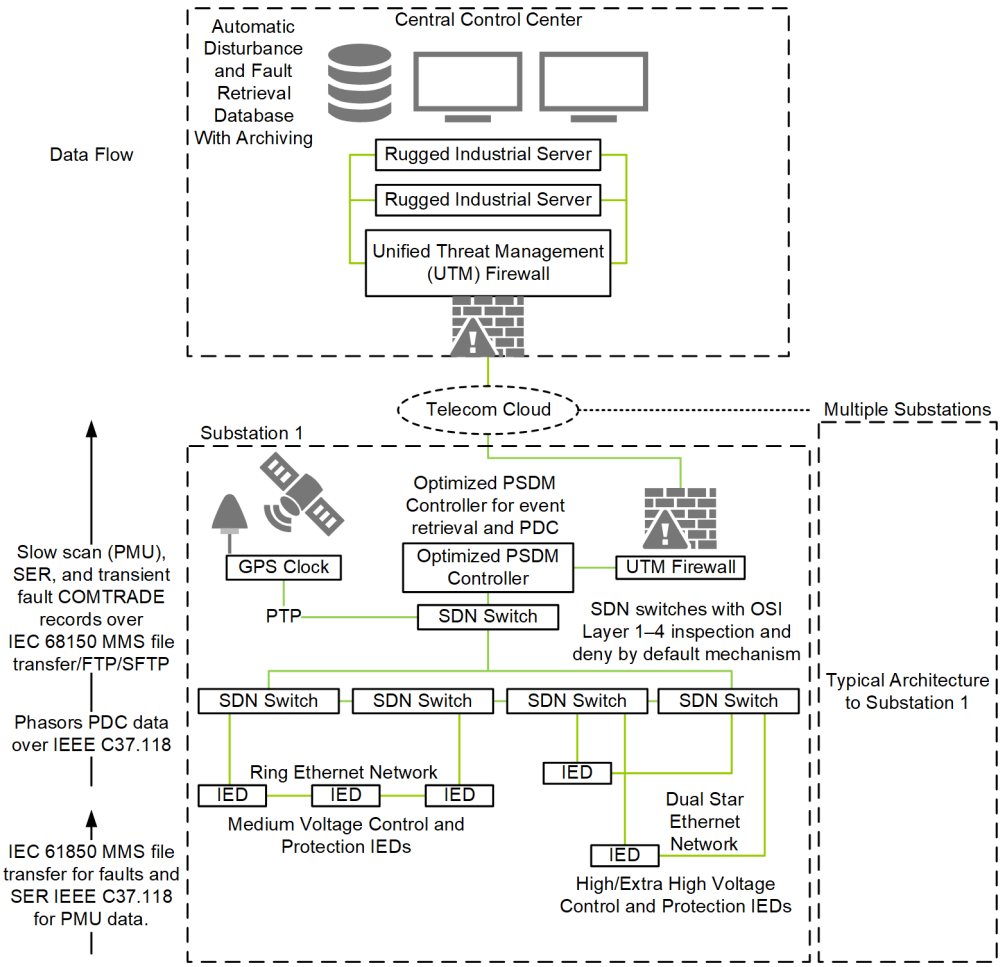

Fig. 6 Typical Optimized PSDM System

The optimized PSDM controller Ethernet connection provides remote access to the optimized PSDM controller system to configure the devices, monitor logs, and collect diagnostics. The system at the control center provides secure access to the optimized PSDM controller file structure at each substation using Secure Shell (SSH)-encrypted channels. All the fault records that are collected from substation IEDs over IEC 61850 MMS file transfer are stored in the optimized PSDM controller at each substation in the following fashion.

The optimized PSDM controller MMS client collects all COMTRADE event files, including the combinations of COMTRADE extensions, which are .HDR, .CFG, and .DAT files. The optimized PSDM controller collects the COMTRADE files regardless of whether an event is zipped or separated into individual files on the server (IEDs). Once the optimized PSDM controller collects the files from the server, it stores the files on the optimized PSDM controller file system as a ZIP file regardless of the original storage format of the COMTRADE file(s). All collected events are stored in the following location: /COMTRADE/[IED name]/[directory structure in servers COMTRADE folder]/[event name on server].zip.

The following text is an example of file naming and location:

IED Name.
Relay_1
Event Location on Server.
/COMTRADE/BKR_A/EVENT_00001.zip
Event Location on OPTIMIZED PSDM CONTROLLER.
/COMTRADE/Relay_1/BKR_A/EVENT_0001.zip

The time necessary to collect event files from a server is dependent upon the capability of the server. IEC 61850 Edition 2 servers typically support the directory listing (/*), which returns a list of all files on the server in a single response. Using this response, the MMS client efficiently finds the new COMTRADE files to collect. If the server does not support this capability, the optimized PSDM controller searches the servers file system one directory at a time. This may require many file directory polls to find all possible COMTRADE files and result in additional time for the MMS client to find and collect all COMTRADE files. Hence, Edition 2 compliance is mandatory on optimized PSDM controllers, and it is recommended on the IED level to achieve faster operation.

A provision is provided to download fault events locally at each substation by manually accessing optimized PSDM controller or remotely by manually accessing the optimized PSDM controller HyperText Transfer Protocol Secure (HTTPS) web interface.

Moreover, the system at the control center automatically retrieves these files and archives them for a long time (depending on system memory).

D. Designing an Ethernet Network for an Optimized PSDM System

As the operational technology (OT) industry has widely adapted Ethernet networks in power system networks, it is vital to consider performance and cybersecurity while designing the network. Power system OT networks require high availability, speed, reliability, and security as compared to information technology (IT) networks. In OT networks, the delivery of information within the span of a few milliseconds is critical, while in IT networks, it is the amount of data that matters since the network can wait for seconds for delivery. OT uses information for critical power system protection control and monitoring while IT moves information. One of the most critical applications in OT networks is IEC 61850 GOOSE messaging, as it requires high-speed peer-to-peer communication transfer of messages within 20 milliseconds. As GOOSE messages are dependent on Ethernet networks and they are replacing critical electrical hardwired signals, power system protection, control, and monitoring functions increasingly rely on Ethernet. Electrical hardwired signals have been used and proven effective for more than 50 years, but Ethernet networks are relatively new. This brings a lot of challenges, questions, and sensitivity while moving from hardwired signals to communication-assisted protection. Engineers are required not only to maintain protection and control devices but also to carefully handle Ethernet networks, as those are an integral part of the overall system function. However, Ethernet networks bring a lot of advantages as well. There is a huge amount of cost savings by replacing large amounts copper cables with a few fiber optics while still gaining the same functionalities. Ethernet networks based on fiber optics are safe, easy to troubleshoot, expandable, and maintainable as compared to copper electrical cable infrastructure.

For an optimized PSDM, GOOSE messaging is used for cross triggering the faults and storing the SOE. Hardwired signals are limited to their respective bays and do not need to connect to DFR panels, as is the case in a conventional system. Protection and control IEDs, which are connected to the field equipment through hardwires, contain complete information about the breaker, disconnector, secondary circuits, and primary equipment status, to mention a few. This information from each bay can be transferred to the optimized PSDM system via IEC 61850 GOOSE messages to make sure that the system is receiving these statuses in real time. Upon receiving this information about digital signals, an optimized PSDM can act immediately to trigger a transient fault to record voltage and current raw samples in COMTRADE format or the CTs/PTs connected to it. An optimized PSDM can also store these digital statuses in its local SOE archive.

With this widespread focus on implementing Ethernet networks in OT, it recommended that the hardware used to develop network components is rugged (i.e., Ethernet switches shall have no moving parts, the design should be fanless and meet IEC 60255, IEEE 1613, and IEC 61850-3 standards) to meet electric power substation communication devices requirements. The operating temperature range of the Ethernet should be –40 to +85 degrees Celsius (–40 to +185 degrees Fahrenheit) and support conformal coating (optional) circuit boards for harsh environments.

Apart from hardware compliance, the switch should be able to meet application requirements to meet electrical system performance criteria. With the advent of software-defined networking (SDN), it is possible to achieve the required speed to handle network traffic for IEC 61850 data and secure it through allowlisting technology. SDN uses centralized software for engineers to develop complete network path configurations at one place. Since substation OT networks are static and devices have fixed physical connections, media access control (MAC) addresses, IP addresses, and protocol, engineers can design their network before deploying it. SDN switches function by matching rules defined by the engineer during the precommissioning stage to allowlist network flows. Every incoming packet to the SDN switch is matched against the ingress physical port (Open Systems Interconnection [OSI] Layer 1), Ethernet source or destination MAC address (OSI Layer 2), Ethertype, VLAN identifier, IP source or destination address (OSI Layer 3), TCP IP port (OSI Layer 4) and others. Engineers can then predefine the actions for these incoming packets which can be matched to various criteria and egressed to the desired ports to reach to the destination. Additionally, users can use a set of counters to monitor the ingress and egress of traffic and the overall network health.

SDN natively achieves the OT performance criteria and its allowlisted nature is best suited for critical substation networks in terms of cybersecurity. It provides multiple layered inspection on-the-fly approach on Ethernet traffic without degrading the packet delivery time. It is pertinent to mention that SDN deployment can help utilities achieve defense in depth security to substation OT network with Layer 1 to Layer 4 inspection at each node in the network. This kind of inspection provides security against inwards and outwards intrusion attacks as switches are designed to process the predefined path flows and inspects each packet up to Layer 4 to make sure it originated and is targeted to the defined location. SDN is different from a

firewall as it does not perform routing and provides fast throughput and high-speed failover within 100 microseconds if a path fails. This is extremely critical for GOOSE messages, which need to be transferred in 3 milliseconds as per IEC 61850-5 Type 1A, Performance Class P2/P3 in normal network conditions, and a maximum delay of 18 milliseconds during failover [3].

Furthermore, with SDN, the traffic path planning is done with central controller software, which handles control plane, maintenance, and installation, so it is efficient and scalable. In summary, SDN induces an allowlisted cybersecure environment, more robust submillisecond healing, and greater than N-1 redundancy in the network. Traditional networks use features like MAC tables, Rapid Spanning Tree Protocols (RSTPs), and cast types for IT-related conveniences and plug-and-play functionality. However, these features make traditional networking vulnerable to cybersecurity threats, including MAC flooding and table poisoning, Address Resolution Protocol (ARP) spoofing, Bridge Protocol Data Unit (BPDU) attacks, and more. Whereas, SDN is inherently resilient to these attacks because of its allowlisted path planning design and Layer 1–4 inspection.

With SDN, all network flows and backup paths are specifically defined in the controller, so there is no need for MAC tables or RSTP protocols. In addition, SDN uses traffic engineering to process forwarding behavior, rather than relying on cast types, which pose security risks. In SDN, it is easier to manage large amounts of network traffic than with traditional networking. The difference is that SDN eliminates unnecessary traffic on an OT network. Instead of having a node broadcast to all other nodes on the LAN, specific paths can be engineered to remove the extraneous ones. This capability ensures bandwidth availability and high performance in critical applications for anyone transitioning to the IEC 61850 standard.

Mission-critical processes demand mission-critical performance. The SDN switches failover occurs in less than 100 microseconds, compared to 10 milliseconds for traditional networks. Because of the innovative approach to SDN technology, users get the proactive advantage of engineering all primary and failover circuit paths prior to commissioning. No more waiting for discovery or convergence times—the network already knows the next path.

E. Time Synchronization in Optimized PSDM

The importance of time synchronization can be understood by the fact that the power grid is a single, complex, interconnected system. Events and transients that happen at one end affect the other.

As there is currently widespread deployment of integrated systems, like IEC 61850 in the power industry, substation communications are drastically changing over time. IEC 61850 is based on Ethernet communications, so other applications like optimized PSDM tend to take advantage of such an integrated network to provide advanced functions, as explained in this paper. Since all IEDs are interlinked through Ethernet networks and communicate to each other over the protocol, it is vital to have accurate time synchronization between them to correlate their events to analyze cascade or even isolated events. Usually, cascading events in a power system can cause a blackout, which generates the need to evaluate time-correlated events in various IEDs across different substations.

With an optimized PSDM, transient fault records, dynamic records, and SOE records can be collected at a central location. But to evaluate them efficiently and logically, these events must have highly accurate time coherence, which means that the IEDs generating these events are capable to be synchronized with a high-precision satellite time reference. The core function of these IEDs in the substation is to log and time-stamp data from the power system, like analog waveforms, digital status, device trips, and control signals. Although IEDs log these data in their local memory in chronological order, they can be useful only if they are organized in a meaningful way. Each IED adds a time stamp on data records with respect to its internal clock. Therefore, it is extremely important to synchronize its internal clock to an external universal reference to which all other IEDs can also be synchronized. In this way, all the logged data in each IED can be correlated in the same time frame and analyzed with the same time reference to see what is happening in relevant IEDs while analyzing a power system event.

When examining any substation event, time synchronization is needed in the IED from which that event is taken, but there is a debate on how much accuracy is required. This can be analyzed with respect to the power system frequency. In a 50 Hz system, a power cycle is 20 milliseconds in length. This leads to the fact that the time synchronization in IED functioning on this frequency needs to be accurate to some level less than 20 milliseconds. However, most of the protection IEDs perform analog data processing in about a quarter of a power cycle or faster, which is typically between 2 to 4 milliseconds. An IED internal clock is more precise than its data processing capabilities, as they need to have data time-stamped for logging purposes and better visibility of the system engineers [3]. Time stamps, along with frequency, are both critical to the success of replaying a COMTRADE file into a protective relay. If there is an error in the recorded sampling rate used to acquire the data, the quality of the data in the COMTRADE file can be affected [3].

Since IEDs record first-hand information in the form of transient records for any power system fault, they need to be synchronized with 1-millisecond or 1-microsecond accuracy, depending on the following requirements. IEDs send transient fault COMTRADE files to an

optimized PSDM through the IEC 61850 standard, so the reference of the fault transient files remains the IED time stamp; hence, it is important to synchronize them with a GPS time source over a commonly available synchronization mechanism. Typically, 1-millisecond synchronization accuracy is achieved using the NTP time-synchronization method over an Ethernet network. It is relatively easy to achieve this accuracy over commonly available components in the substation, but some applications require more accurate time synchronization, up to 1 microsecond. These applications include long-term or continuous records referred to in this paper. Long-term records use the synchrophasor measurement from the IEDs to which their phasors are time-synchronized with 1-microsecond accuracy to be precisely time-correlated with other IED phasor data. Time accuracy of 1 microsecond or better provides IED capability to measure voltage and current phasors with total vector error (TVE), frequency error, and rate-of-change-of-frequency error within the required limits as per the IEEE C37.118 standard. The PMU IED assigns the time stamp for each phasor measurement as per the sample taken from a particular instance of time from the sinusoidal signal. These continuously time-tagged phasor samples, along with the time stamp taken by the IED, is sent to the optimized PSDM at a speed of a defined rate (i.e., 10 to 60 Hz typically).

There are two mechanisms in a substation to achieve 1-microsecond time synchronization in IEDs: IRIG-B and PTP. IRIG-B is distributed through coaxial cables to substation IEDs. PTP can be distributed using an Ethernet network. But to gain submicrosecond time-synchronization accuracy in IEDs, it is mandatory for all the devices in the network to support PTP, so they can have hardware time stamping to maintain precise time end to end.

F. SOE Data Collection

The system also provides the ability to collect SOE data in the optimized PSDM controller. The SOE data are viewed using the SOE Viewer inside the software. The SOE collection from the optimized PSDM controller includes IED statuses and other statuses from substation controllers, like device health and security alarms. Also, there is a provision in control and protection IEDs to record SOE records locally in their memory and send them to an optimized PSDM controller via IEC 61850 MMS file transfer as a file. Additionally, immediate alarms can also be notified by the controller through IEC 61850 GOOSE messages from IEDs, and the controller can log in to COMTRADE files and SOE records, so users have concentrated digital alarm information at the same place for the whole substation. Using SOE collection from an optimized PSDM controller, every device health status and many other parameters are monitored from each station to have a centralized monitoring system. This way, the user is able to monitor downstream relays' connection status for each MMS IED connected to an optimized PSDM controller at the substation level. Users can also define customized SOE in an optimized PSDM controller to be collected at a central software server. Moreover, there are multiple filtering and SOE handling options that users can customize per their requirements.

G. Cybersecurity in an Optimized PSDM System

The controller system should be non-Windows-based, as the operating system is vital for the overall operations of critical monitoring systems. Non-Windows-based solutions provide a long-lasting, maintenance-free system that runs as rugged as the protective relays in the substation. Monitoring faults in a timely and secure way is an important tool for power system utilities to restore their network in an efficient way.

The optimized PSDM controller should provide secure operation and access with allowlist antivirus technology to protect against cybersecurity threats. This avoids the need to implement denylist anti-malware technology, which is hard to implement in a substation environment. A substation environment, commonly referred to as OT, is static in nature, which means that IEDs inside a substation are not going to change frequently.

With an optimized PSDM system, it is possible to secure operation and access allowlist antivirus technology to protect against cybersecurity threats. Allowlisting technology ensures that only authorized programs operate. The system also sends alerts via Syslog, text, email, and local SOE logging. There is another important security factor that is widely used in the modern world (i.e., to provide multiple user access to various groups in the organization). These groups have different roles in the company to perform dedicated tasks. They might be classified into these categories: administrators, engineers, and operators. Administrators are typically required to have full access to the system, to configure from basic- to advanced-level parameters. Engineers need to have limited access with restricted access to system configurations but full access to the substation assets for engineering analysis. Operators need to have view-only access to the applications like alarms and events related to the substation to provide timely alerts and take mitigation actions on the field. To achieve this, the optimized PSDM controller incorporates independent role-based security with strong passwords, role-based accounts, and an integration to a centralized account management system, like a Lightweight Directory Access Control (LDAP)/Remote Authentication Dial-In User Service (RADIUS) domain controller (DC). With DC servers, it is possible to manage the whole organization from a centralized location. System administrators are able to manage company user roles and access to multiple assets from a central location. This reduces the manual handling of user accounts and enhances audit. The optimized PSDM

system typically provides a mechanism to map user activities and security-related system tags into Syslog messages. These Syslog messages can be transferred to Security Information and Event Management (SIEM) centers for continuous monitoring and audit trails. The maintenance-free allowlisted control feature is usually provided in an integrated PSDM system for anti-malware protection. The controllers used are embedded real time in an allowlist manner to eliminate the need for denylist signature updates. With allowlisted functions in a PSDM controller, the overall system security is increased as it provides restricted mandatory access to the services only allowed for the application. Eventually, allowlisting helps mitigate attacks against the system and eliminate costly patch management and antivirus signature updates, which are required if Windows-based systems or denylisting is used.

To access the system remotely, the controller shall support HTTPS, X.509, and CA certificates for remote retrieval of data and secured channels with Transport Layer Security (TLS). The controller also performs Denial of Service (DoS) monitoring and generates an alarm in such an event. The controller supports encryption of all Ethernet communications using SSH and Secure Sockets Layer (SSL)/TLS tunneling. It has a Syslog collection for more than 60,000 messages and generation to collect Syslog messages from other devices to store and forward messages, map relevant data to other protocols, or create custom logic to operate on critical messages. The controller should also act and automatically log into its Syslog if a allowlist firmware integrity failure is detected.

H. A Hybrid PSDM System

The electrical industry is moving towards more automated and integrated systems. IEDs with available multiple communication protocols and robust mechanisms make the developers' job easy to design the mixed hybrid system for PSDM. IEDs are capable of capturing transient records with an average sampling rate up to 8 kHz, PMU data for steady-state recording over a long period of time, SOE alarm information with a millisecond time stamp and transferal of these files over IEC 61850. In a hybrid PSDM design, utilities can take advantage of utilizing modern IEDs to collect this information and having a dedicated hardwired CT/PT and digital input/output (I/O) connected to it. Getting separate data from dedicated hardwires is useful for the feeders where existing IEDs are not capable of recording and transferring the previous data through IEC 61850 and IEEE C37.118 protocols.

Detecting faults, protecting primary equipment from those faults, and recording the data during the faults are the key functions of any protective relay. However, it is also necessary to share this information in a timely manner with peer devices to trigger or block operations during a fault condition in a particular feeder. Sharing this information has different applications, as discussed previously: IEEE C37.118 PMU or IEC 61850 MMS data. But there is sometimes a higher need for some applications, in terms of high-speed data sharing for IEDs among themselves, and that is achieved by GOOSE messages. One of the applications includes sending peer-to-peer digital signals to the optimized PSDM controller over GOOSE.

There are multiple reasons the optimized PSDM controller needs to get this information in time, including the following:

- A hybrid deployment of an optimized PSDM system may include hardwired CTs or voltage transformers (VTs) connected to the controller. In such a scenario, the optimized PSDM controller is required to get high-speed signals from the protective relays in real time to record and trigger the fault currents and voltages.
- The application explained in the previous bullet is a replacement of conventional hardwired (digital I/Os) from protective relays to a DFR or any other system that needs to get statuses from the relay, such as breaker trips, power system faults, and intertrips. The speed and reliability required to replace hardwired signals with communication-assisted messaging can only be met by GOOSE messaging, as it is designed for this purpose.

In Fig. 7, data flow is shown from bottom to top. With a hybrid PSDM system, utilities are able to gather data collected through multiple ways into the same centralized location with the same infrastructure. These data can be useful to have a holistic view of the substation and allow forensic analysis of fault recordings in combination with SOE data to compare different feeders' current, voltage, and frequency during a power system disturbance. Users are able to capture a high-sampling rate, like 24 kHz with direct hardwire connected to hybrid system, and still collect fault records provided by IEDs installed in the feeders at a low-sampling rate, typically up to 8 kHz. This way, users are able to view different sampling rate data, with respect to the same time reference, to easily correlate analog values and their behaviors.

It can be seen in Fig. 7 that data flow from bottom to top is streamlined with substation topology. Substation relays at the bottom have control and protection functions and can also act as a PMU. Since these relays are already connected to the protection class CT/PT or metering class CT/PT, the same circuit can be used to monitor current- and voltage-phase magnitude as well as angles. In a hybrid model of PSDM, fault data available inside substation relays are collected over standard protocols, like IEC 61850 MMS file transfer and synchrophasor data over the standard protocol IEEE C37.117. At the same time, hardwired data can be directly connected to a PSDM, as shown in Fig. 7. This

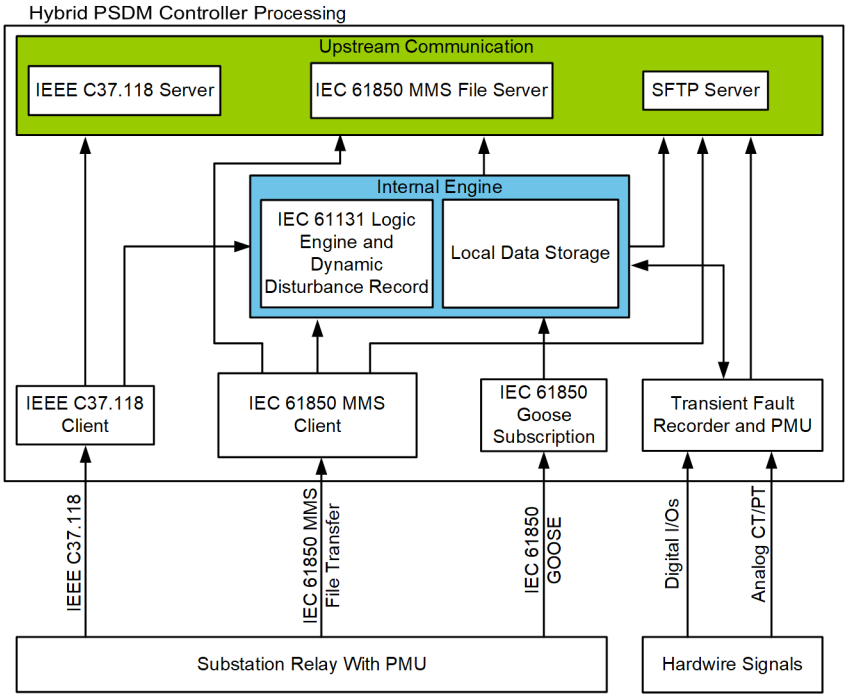

Fig. 7 Hybrid PSDM System Data Flow

is useful for cases where some feeders do not have modern IEDs, which can transfer data over Ethernet protocols. With this direct hardwired connection, PSDM can generate transient fault records with high-sampling rate and collect PMU data. These data can be available to the internal engine of a PSDM controller as well as to the upstream client. The internal engine on the diagram shows that data collected through IEDs or generated by PSDM through hardwires are available to perform local logics, if required. These logics can be used to generate control and high-speed intertrip applications. The controller generates the COMTRADE files containing PMU data collected from substation relays and hardwired CTs/PTs connected to it. It also acts as a PDC, time aligns the collected phasors, and sends synchrophasor data to the control center over the IEEE C37.117 protocol over TCP/IP or UDP Ethernet connection.

I. Remote Centralized Collection and Visualization at the Control Center

The software consists of the Archiver Database, an Open Database Connectivity (ODBC)-compliant database that is used to store normalized event report data. The main components of the software provide automatic retrieval of event reports from substation controllers, translate event report files into normalized device data, and record this information in the database. The software also has a component that provides event data visualization. The mechanism to access fault records has a web interface and structured folders through timeline representation in the software.

The optimized PSDM controller can collect event reports from connected devices and store those event reports in its internal database, as explained previously. The optimized PSDM controller therefore removes direct device event retrieval from the control center software to substation IEDs, which greatly accelerates the overall collection process. An optimized PSDM controller collects event reports from many relays without the control center software being connected or involved. And then, at a specified time, the control center software polls the optimized PSDM controller to retrieve the event reports (polling), or the optimized PSDM controller can be configured to notify the control center software that event reports are available for retrieval (listening). Control center software communicates with an optimized PSDM controller over a Telecom network with SSH or TLS encryption for Ethernet interface. Software can retrieve event reports from many optimized PSDM controllers simultaneously distributed over different substations. Once connected over TCP/IP, software only needs about 2 seconds to retrieve an event report from an optimized PSDM controller (the optimized PSDM controller has already retrieved the event report from the substation relays).

In control center software, the retrieved events have accurate time stamps (logged by relays) with respect to the live-view option for overall system view faults. This gives a broader perspective of fault analysis over vast distributed substations events to give a one-screen view for live reports on current faults. In addition to live reports, users also have historical data.

IV. Conclusion

In summary, conventional monitoring and automation systems are isolated, with limited interconnections between IEDs and slow scan rates. Optimized or hybrid PSDM systems capitalize on features in intelligent controllers that are not available with standalone, conventional architectures. A PSDM deployment replaces standalone components like intersubstation load-shedding schemes, PMUs, DFRs, RTUs, SOE recorders, and annunciators with a single, centralized system. This cost-effective approach uses existing IEDs, standard data collection methods, and cybersecure architecture to record and respond to systemwide disturbances. Power grid operators can use optimized PSDM or hybrid PSDM schemes for comprehensive control and monitoring. They can also economically scale these systems to accomplish monitoring over widespread geographical locations.

V. References

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VI. Biographies

Ammad Ali is a senior application engineer in the sales and customer service division of Schweitzer Engineering Laboratories, Inc. (SEL). He earned his bachelor's degree in electronics engineering from the GIK Institute of Engineering Sciences and Technology in Pakistan. He is a member of IEEE and has 13 years of experience in the field of substation automation and communications. He has contributed to projects with various utilities and industrial customers in the Middle East and North Africa region.

Rajkumar Swaminathan is a protection engineering manager in the sales and customer service division of Schweitzer Engineering Laboratories, Inc. (SEL). He received his bachelor's degree in electrical and electronics engineering from the University of Madras, India, in 1997. Rajkumar has over 23 years of experience in power system protection application, design, and testing and commissioning. He worked as a commissioning engineer at M/S Voltech Engineers in India and as a senior technical support engineer at Schneider Electric in Saudi Arabia before joining SEL Bahrain.

VII. Appendix A

In a fault condition, a relay triggers data recording and stores raw samples of analog data of current and voltage in the COMTRADE format. Fig. 8 is an example of a relay event record.

#	DATE	TIME	EVENT	LOCAT	CURR	GRP
10009	22/04/2022	16:28:10.607	ABC T	99.95	1502	1

Fig. 8 Relay Event Record Example

This example shows fault-event transfer over IEC 61850 MMS file transfer protocol. In this case, the MMS client (an optimized PSDM controller) IP for file collection is 192.168.2.88 and the MMS server (i.e., protection relay) IP is 192.168.2.234. Fig. 9 is an excerpt from a network analysis tool that captures Ethernet packets on the wire and four packets are explained further in the following figures.

Fig. 9 shows part of IEC 61850 MMS communication session where the client is requesting fault-event status for a new event in three sets of requests and the IED responds. Each set contains fileOpen and fileClose sessions.

There are three sets of requests because the COMTRADE file format includes three extensions .CFG, .DAT and .HDR. Fig. 10 shows the client request for the filename and the server response with the data, corresponding to Event Number 10009. Details of request can be seen in the filename column where the client is polling data from the server with a specific path of a specific event, individually for three extensions.

Details of previous packet are shown in Fig. 11 where the client is requesting File Event 10009, which is triggered by the relay in the previous picture in Relay Record under the Events folder of the relay file system.

Upon receiving the previous file open request, the MMS server responds with file record information and transfers the file. It can also be noticed that file retrieved through the IEC 61850 MMS protocol contains its original trigger date and time in UTC, generated by the IED, along with other information related to that fault record (Fig. 12).

Once the file transfer is complete, the client sends a request to close the opened file session for the same file resource ID 282390912 as shown in invoke ID 27984 following (Fig. 13).

Upon receiving this request from client, the MMS server responds with the file closure confirmation, as shown in Fig. 14. By this time, the fault record COMTRADE is successfully collected in the client database.

No.	Time	Source	Destination	Protocol	Lengtl	confirmedServiceRequest	Info
6763	646.236557	192.168.2.88	192.168.2.234	MMS	163	fileOpen	27983 confirmed-RequestPDU
6767	647.694412	192.168.2.234	192.168.2.88	MMS	126		27983 confirmed-ResponsePDU
6771	647.739592	192.168.2.88	192.168.2.234	MMS	101	fileClose	27984 confirmed-RequestPDU
6775	647.746438	192.168.2.234	192.168.2.88	MMS	97		27984 confirmed-ResponsePDU
6779	647.814546	192.168.2.88	192.168.2.234	MMS	163	fileOpen	27985 confirmed-RequestPDU
6783	648.979957	192.168.2.234	192.168.2.88	MMS	127		27985 confirmed-ResponsePDU
6787	649.017603	192.168.2.88	192.168.2.234	MMS	101	fileClose	27986 confirmed-RequestPDU
6791	649.024401	192.168.2.234	192.168.2.88	MMS	97		27986 confirmed-ResponsePDU
6795	649.092564	192.168.2.88	192.168.2.234	MMS	163	fileOpen	27987 confirmed-RequestPDU
6799	650.275314	192.168.2.234	192.168.2.88	MMS	127		27987 confirmed-ResponsePDU
6803	650.314589	192.168.2.88	192.168.2.234	MMS	101	fileClose	27988 confirmed-RequestPDU
6807	650.321639	192.168.2.234	192.168.2.88	MMS	97		27988 confirmed-ResponsePDU

Fig. 9 IEC 61850 MMS File Transfer Sequence for One COMTRADE Event Capture With Three Extensions Showing File Open and Close Sequence

No.	Time	Source	Destination	Protocol	Lengtl	confirmedServiceRequest	FileName item
6763	646.236557	192.168.2.88	192.168.2.234	MMS	163	fileOpen	/COMTRADE/210605,162525108,0t,xxxSS,MPINC,DEWA,HR,10009.CFG
6767	647.694412	192.168.2.234	192.168.2.88	MMS	126		
6771	647.739592	192.168.2.88	192.168.2.234	MMS	101	fileClose	
6775	647.746438	192.168.2.234	192.168.2.88	MMS	97		
6779	647.814546	192.168.2.88	192.168.2.234	MMS	163	fileOpen	/COMTRADE/210605,162525108,0t,xxxSS,MPINC,DEWA,HR,10009.DAT
6783	648.979957	192.168.2.234	192.168.2.88	MMS	127		
6787	649.017603	192.168.2.88	192.168.2.234	MMS	101	fileClose	
6791	649.024401	192.168.2.234	192.168.2.88	MMS	97		
6795	649.092564	192.168.2.88	192.168.2.234	MMS	163	fileOpen	/COMTRADE/210605,162525108,0t,xxxSS,MPINC,DEWA,HR,10009.HDR
6799	650.275314	192.168.2.234	192.168.2.88	MMS	127		
6803	650.314589	192.168.2.88	192.168.2.234	MMS	101	fileClose	
6807	650.321639	192.168.2.234	192.168.2.88	MMS	97		

Fig. 10 IEC 61850 MMS File Transfer Sequence for One COMTRADE Event Capture With Three Extensions Shown: .CFG, .DAT, .HDR

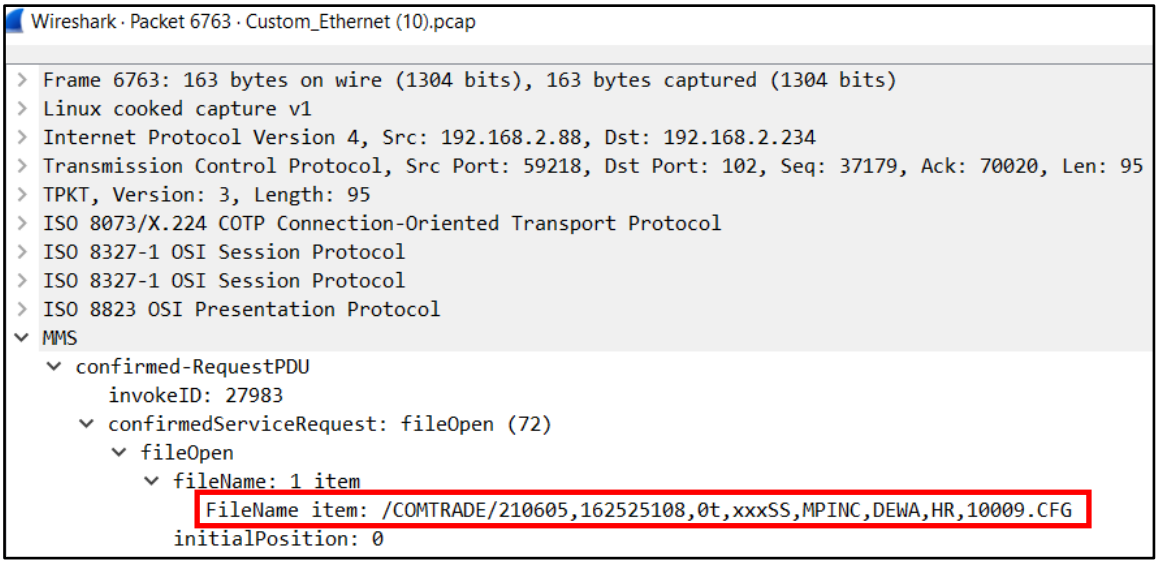

Fig. 11 Packet 6763 Details of MMS Request for .CFG fileOpen by Client

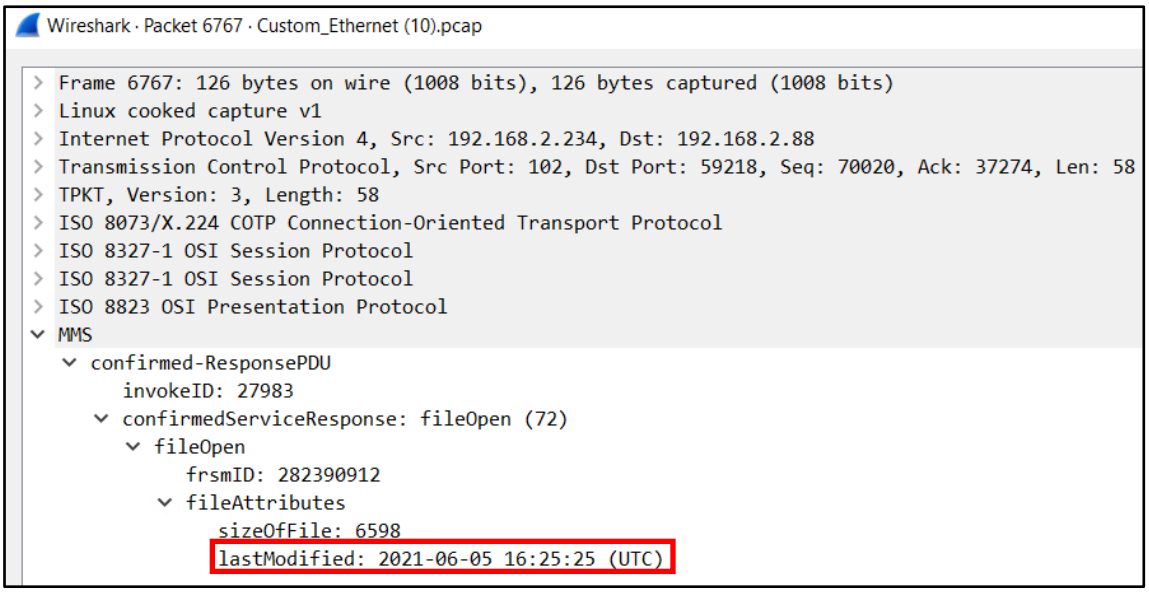

Fig. 12 Packet 6767 Details of MMS Response for .CFG fileOpen Response by Server IED

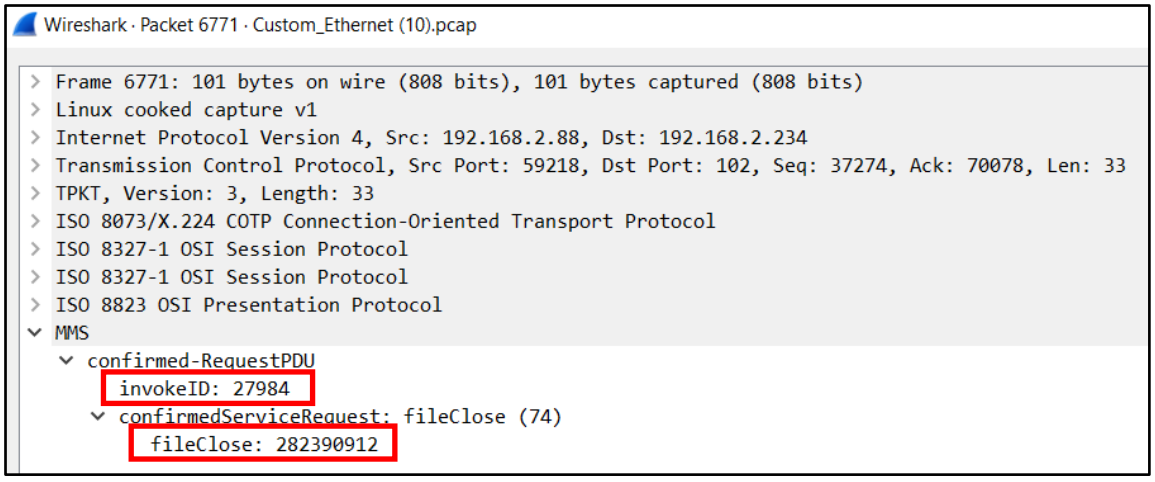

Fig. 13 Packet 6771 Details of MMS Request for .CFG fileClose by Client

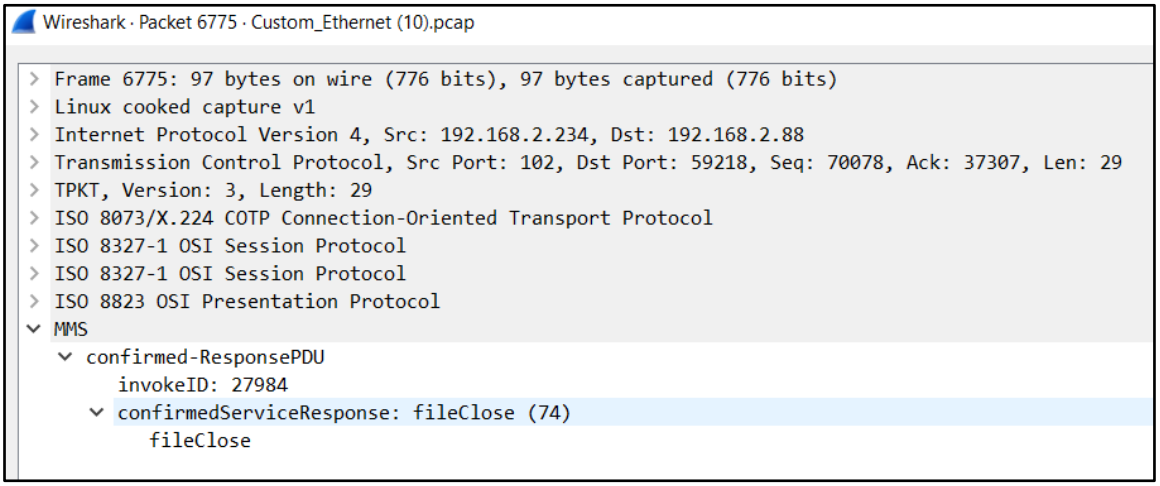

Fig. 14 Packet 6775 Details of MMS Response for .CFG fileClose Successfully by Server IED