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Digital Substation Evolution in the Journey of Smart Grid

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Abstract

IEC61850 as a globally accepted standard has paved the path for the realization of digital substations. A substation protection, automation, monitoring and control system based on the concepts of IEC61850 can be built faster, more efficiently, and more repeatably by replacing physical wiring with digital communications. This involves learning & understanding several parts of IEC61850 standard parts. IEC61850 standard parts consist of ten main parts with several other associated parts. While a utility decides to implement an "IEC61850 Digital substation", the user must understand that to design such substation, the user not only has to understand the key terms, usage of standard but also what can be the potential benefits and what is the current trend in this space of digital substation. This paper presents architecture and evolution of the digital substation, present stage of implementation, at the same time potential benefits explained with some key case studies on protection, monitoring and control.

Keywords: Control, Digital, Grid, Monitoring, Process, Relay, Station, Substation, IEC61850

1. Introduction

In general, the electrical grids are the most reliable systems worldwide. As these electrical grids are huge interconnected networks, they are subject to large number of challenges like transmission to meet the growing demand, constructing new generation stations near to load centers, heavy infrastructure, complex distributed networks, reactive power compensation, balance load profile, etc. Grid also requires system reliability, sustainability, continuous operation, and quality and grid equipment management. Grid infrastructure is improved from ages based on grid reliability, availability and fast demand restoration. The breakthrough was the microprocessor-based grid equipment. Even though, microprocessor based IED's are fully accepted by utilities, electromechanical and solid state IED's still exists in grid, which increases maintenance of equipment's and cost of failure. One of the major reasons is, even though legacy IED's exceeded their life span but still continue to perform well. Reluctant to upgrade to modern microprocessor based IED's at initial stages was much change in protection design philosophy, microprocessor-based technology has short life span, huge number of settings for each functionality, complexity in firmware and software options, etc. One more major crux of digital IED's is huge data overload.

System Protection and control algorithms should be updated to meet advanced technologies, this is important for fast restoration of large interconnected grid. Real time monitoring and control of this large interconnected system is way required to have secure and reliable system. This is one way achieved with the help of advance technologies in communication systems with advanced infrastructures.

Taking into all such considerations, a major revolution is evolved in electrical industry. Utilities need to have a new reliable, secure and intercommunicate and interoperable system[1], across all vendors. In this context, Digital Substations was a solution which was introduced in different strategies. IEC61850 was a communication protocol, which is used by all utilities and vendors across all regions in the globe to have standardized approach.

This paper discusses various stages of digital substation in the journey of smart grid along with its architectures,

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case studies, recent trends, advantages and future scope of work.

2. Digital Substation Journey

Modern Grid has undergone considerable changes since its beginning to meet the increasing power demand and modernization, and one of the disruptive technologies in standardized information exchange area is IEC61850, which enabled digital transformation. The requirement for standardized and vendor independent information exchange is increasing, and IEC61850 is proven as the best fit for achieving the goal of Digital Substation. IEC61850 has provisions to address the challenges in every stage of the supply chain function, right from the conceptual stage to design, commission, testing and maintenance aspects of the digital substation, and no other existing alternatives can emulate these functionalities[2].

The basic building blocks of IEC61850 based digital substation as depicted in Figure 1. A practical process bus architecture 1[3] are:

Station Bus: The IEC61850 station bus interconnects all the bays within the substation to the station supervisory level, which carries the measurement, equipment and interlock states and control sequences, typically using the IEC61850 MMS and GOOSE.

Process Bus: The IEC61850 process bus interconnects the merging units in substation switchyard and digital protective relays in the control house, which carries the digital transmission of real time measurements typically using the IEC61850 9-2 sampled values[4], normally at 4kHz sample rate for protection application and 12.8kHz sample rate for measurement applications at 50Hz nominal frequency[5].

Standalone Merging Unit (SAMU): An interface unit that accepts multiple analogue CT/VT and binary input signals and generates the time synchronized digital data, typically using the IEC61850 9-2 sampled values.

Non-Conventional Instrument Transformer (NCIT): An instrument transformer implemented with merging unit functionality.

The technology embracing is a stepwise iterative process, and like any other technology, the adoption of IEC61850 went through different stages before accomplishing the end goal of Digital Substation as depicted in Figure 2. This section summarizes various stages of Grid Modernization in high level and how

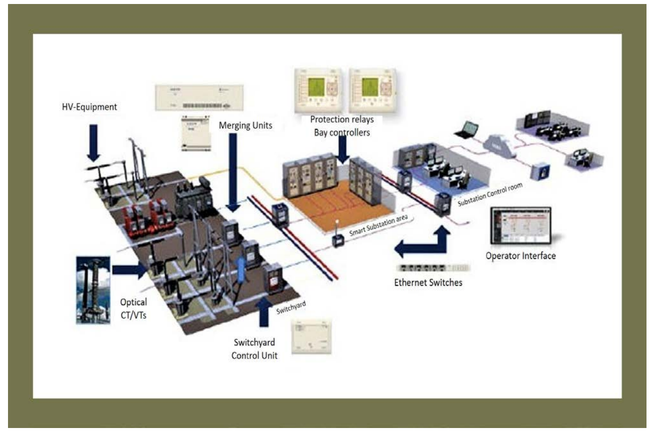

Figure 1. A practical process bus architecture.

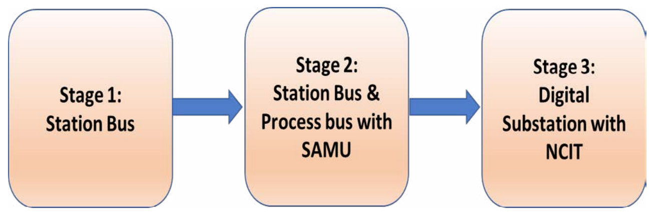

Figure 2. Stages in substation modernization.

IEC61850 enabled the unseen opportunities in achieving digital substations.

Where,

SAMU – Standalone Merging Units

NCIT – Non-Conventional Instrument Transformers

The stages include,

- Stage 1: Implementation of Station Bus using IEC61850 client/server.
- Stage 2: Addition of process bus using IEC61850 9-2LE implementation in standalone merging units.
- Stage 3: Introduction of NCIT (Implementation of MU functionality in instrument transformers – IEC61869-9).

Stage 1: Station Bus

In this early stage, typically the IEC61850 entry point into the station bus, between the substation gateway/ HMI and the protection units, as illustrated in Figure 3[4]. The IEC61850 Client/Server services are implemented in station bus, that uses MMS reports to fetch the Events, equipment status and measurements (dead banded) for different SCADA applications such as station HMI and gateways. The GOOSE messages share the critical states/ trip messages in less than 1/4th cycle time, however the adoption in early phase is limited for sharing the interlock states and indications across the devices connected on station bus. The wiring efforts and costs are significantly reduced by utilizing the station bus bandwidth for these signals, and thus construction costs by reducing the need for trenching, ducts, conduit, etc. Lowered the transducers costs, as the signals is shared via GOOSE[2].

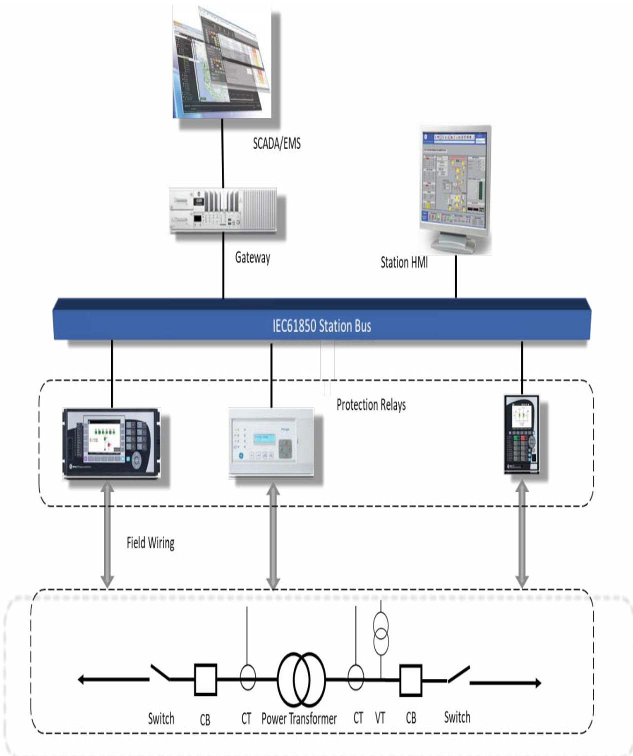

Figure 3. Stage 1- IEC61850 station bus.

In the initial phase, the IEC61850 suffered few interoperability issues, however the implementations are matured to a level that IEC61850 met all the requirements in stage 1 and has disclosed many unseen opportunities to solve various challenges in terms of cost and time for commissioning. IEC61850 engineering process considerably reduced the cost to configure and commission the devices, as the applications no longer need to be manually configured. The configurations between the devices are exchanged via SCL files, which eliminated majority of the human effort and the configuration process is error free with less rework. IEC61850 built in testing capabilities (like test mode, Simulation mode and virtual isolation) are well accepted by many utilities, that reduced the configuration testing time and maintenance time drastically.

Stage 2: Station and Process Bus with SAMU

Another major milestone for IEC61850 digital substation is the introduction of the process bus, that interconnects the merging units in substation switchyard and digital protective relays in the control house as shown in Figure 4. Standalone Merging Units (SAMU) converts the current and voltage signals from primary equipment into IEC61850 9-2LE sampled values. Unlike the conventional substation, primary process data (Current, Voltage and status signals) is limited to substation switching yard. Merging units are located near to primary equipment and process data is digitized near the source, which has potential CAPEX and OPEX benefits[2]. MUs multicast the digitized 9-2LE sampled values over fiber optic network, which is connected between MUs in the station yard and protection units in the station control room.

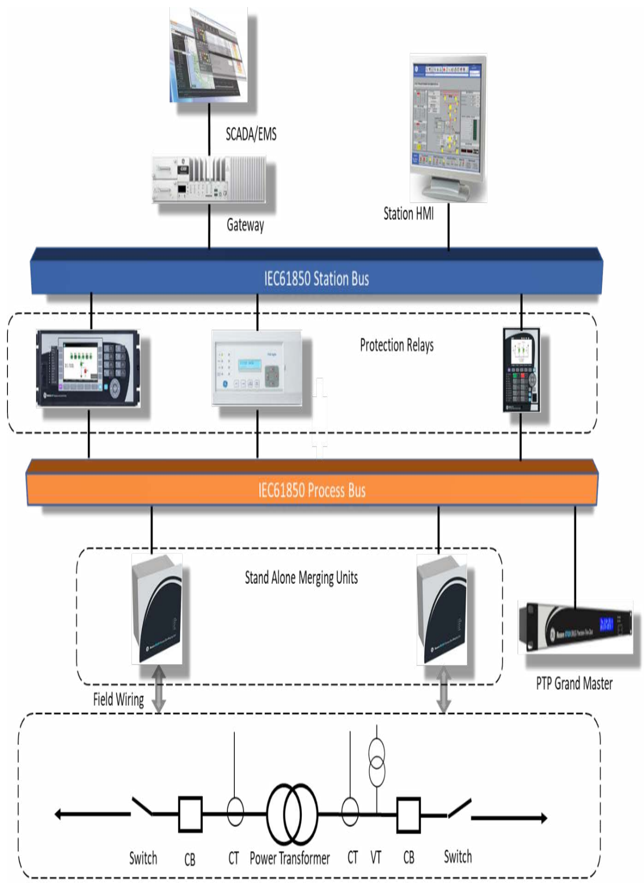

Figure 4. Stage 2- IEC61850 process/station bus.

As per IEC61850 9-2LE, Sample values are multicoated at a rate of 80 samples per cycle for protection applications and 256 samples per cycle for measurement applications. The protection units and the merging units shall a common time reference with 1 microsecond accuracy for achieving the sample coherency, which requires either IRIG-B or PTP time synchronization is process bus.

With process bus implementation, as the field wiring is terminated in the field itself, the major benefits include[7]:

- Huge reduction in copper.
- Reduced requirement of trenching (about 95%).
- Reduced commissioning time and labor.
- Operational safety.
- Maintenance cost and time.
- Accidental risk.
- Smaller panel and substation sizes.

In addition, there are many other challenges faced by utilities in terms of infrastructure aging and increase in demand for refurbishment, which makes the process bus an attracting alternative to conventional. A practical process bus solution must support the business objectives of reducing the amount of time to design and install the process measurement network, and lessening the skills needed to design, and especially install, this network. By solving this problem, process bus also helps utilities meet their financial objectives (build more, build faster, build more cost-effectively) while meeting new market demands[6].

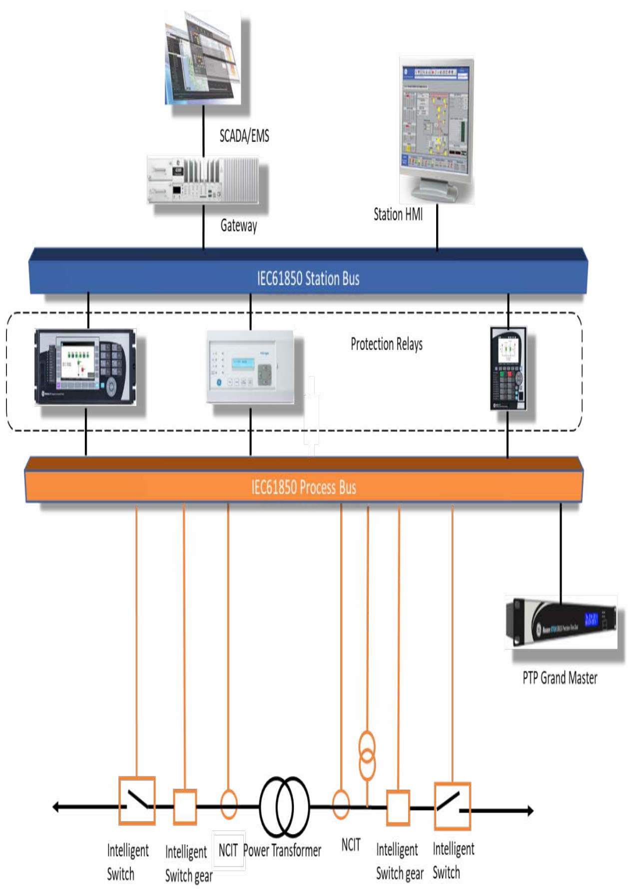

Figure 5. Stage 3- IEC61850 process/station bus with NCIT.

Stage 3: Digital Substation with NCIT

The stand-alone merging units are replaced by the Non-Conventional Instrument Transformers (NCIT) and intelligent switch gear as depicted in Figure 5. IEC61869-9 specifies the guidelines for implementing the merging unit functionality in instrument transformers. Based on the nominal frequency of the system, NCIT may choose to publish sampled values at a rate 4000 samples per second or 4800 samples per second for protection applications. In order to reduce the bandwidth usage, provisions are made to combine two samples (ASDUs) in one frame. Also, the PTP is made mandatory for this generation of digital substation and IEC61850 defined new power utility profile (IEC61850 9-3) for PTP time synchronization.

The ultimate goal of IEC61850 digital substation is achieved with this, where the process level data digitalization is implemented in primary apparatus and intelligent breaker/switch with embedded controllers. This is the final goal for the utilities, which are looking for a complete digital Protection, Automation and Control schemes.

2.1 Modern Digital Relays Footprint

It has been proven that state-of-the-art protection and control systems relays[8] – have wide range of protection and control solutions with high performance protection, expandable I/O, integrated metering and monitoring, high-speed communications, and extensive programming and configuration capabilities. These relays offer key applications across Generation, transmission, distribution, motor protection, monitoring, metering & control. These products are flexible with multiple I/O options, modular and customizable for specific solutions.

In the digital substation area, todays advanced relays such as[8] support IEC61850 Edition 2 communication with rich data modeling on station bus and support the in-built IEC61850 testing capabilities of virtual isolation, simulation mode, adhering to the IEC61850 standard. The relays support GOOSE P1 class performance on both station bus and process bus.

With respect to process bus, these relays already advanced to be in stage 3 and the protection relays can accept the sampled values from both standalone merging units (9-2LE) and NCIT (IEC61869-9)[8]. The hybrid solutions between stage 2 and stage 3 are feasible and can yield better savings, which is already proven in many utility pilot projects done across the world[9]. The PTP implementation on process bus module is compatible with IEEEC37.238 power profile and IEC61850 9-3 power utility profile. A unique feature in digital substation compliant relays is that, If the PTP grandmaster is not available or lost, based on user configuration one of the relays can switch to PTP master mode, so that other devices can have a common time reference, which increases the availability of protection functions at missing time synchronization scenarios[8].

Thanks to the increased processing capability embedded in protection relays, which enabled the huge data processing required in process bus. Digital substation relays can process up to 16 sampled values streams, which is a best fit for bus protection unit for moderate substations[8].

In the network base process bus solution, reliability is the biggest concern due to a greater number of nodes/ devices compared to conventional system. To ensure the reliability and redundancy, some relays can even connect to two merging units that measure data from same location and has the ability to crosscheck measurements against each other sample-by-sample[8]. If the measurements differ significantly from each other, indicating a problem with one of the measurement paths, the relay blocks selective protection functions which depend on that measurement source. If the communication is lost to one merging unit, the relay can use data from the second merging unit, or block protection functions, a choice made during relay configuration. Therefore, the system maintains the reliability with redundant measurement paths[8].

Many utilities prefer the IEC6180 9-2LE based point to point solution in process bus[4], due to its deterministic delay between relay and merging unit and the solution is more secure and reliable. Advanced relays[8] support the point to point solution on process bus, where the merging unit (either IEC61850 9-2LE standalone MU or IEC61869-9 NCIT) can directly connect to the relay process bus module fiber-optic port. In this mode, the relay synchronizes all the connected merging units by acting as PTP master and thus no addition grandmaster is required.

3. Digital Substation- Design Case Studies

The following are some of the key design case studies in realizing the digital substation.

3.1 Digital Substation Design

Comparison between conventional substations and digital substations, impact of the digital process bus in substation design can be analyzed with different optimization parameters like protection and control room sizing, switchyard sizing, raw material requirement, etc[10].

Efficient sizing of protection and control rooms, panels and cubicles can be achieved by upgrading the substation from conventional copper cables with fiber optic cables. This will enhance the protection relays and control units by decreasing much hardware like conventional input and output cards. Copper cable terminals to the relays and control units are removed, which significantly reduces the size of protection and control panels. Thereby reducing the space needed for Control rooms. To replace copper cables with fiber optic cables, digital process bus in the switchyard to be implemented. Conventional analog signals from Current transformers and voltage transformers in the switchgear must be converted into digital signals in switchyard, this can be achieved with the help of merging units. These merging units to be placed inside switchyard near to the primary equipment's, which converts analog current and voltage signals to digital. Merging units also used to convert binary signals into digital signals like binary signals from earth switches, disconnectors, circuit breakers. Information from merging units to control rooms and different clients to be transmitted using IEC61850 protocol. These merging units also need to be time synchronized with the help of time-sync devices for proper protection and control functions.

Replacement of conventional copper cables with fiber optic cables also provides many advantages like minimization of concrete structures, elimination of huge cable ducts in switchyard, cable trench in and out of control rooms and control panels, decrease in size of protection and control units results in fewer number of panels, thereby reduction in control room sizing.

Effectively approximate reduction of 30% in switchgear footprint, protection and control room footprint and raw material requirement.

Savings of these parameters will be different based on different aspects. Major variation will be based on substation type – whether its Air Insulated substation or Gas Insulated substation. Other design references which affect the savings parameters will be based on voltage level considered, design technology used, applicable substation design standard, based on substation configurations, based on regional design constraints.

Implementation of digital substations can be possible for both greenfield and brown field substations[11]. In greenfield substations, design of digital substations can be implemented in depth for both primary and secondary equipment level, which provides much optimization in different aspects. Whereas, for brownfield substations, retrofit of old existing substation is possible for certain extent at each station bus level and process bus level. Few features in retrofit are possible like, IEC61850 station bus communication gateway, communication between station bus and station level, communication between protection and control IED's, communication between IEC61850 station bus and process bus, IEC61850 9-2 analog sample values between bay and process level, binary data conversion in merging units and communication with protection and control IED's.

Digital substation improves safety, operation and maintenance in substation design, installation and workplace. Digital substation improves safety of personnel in substation operation. Major breakthrough in digital substation is isolation of electrical connection between primary equipment and protection and control devices, thereby creates optical isolation between bay equipment and process bus. This also helps in testing of protection and control equipment, as injection of high voltages and currents are reduced. This decreases high safety risk of personnel by injecting digital signals for testing the IED's.

Equipment's, protection and control functions can be defined as logical nodes, data classes and data attributes. This is very useful feature in IEC61850, which is used for communicating substation process and station bus, which is used for data transfer, monitoring, controlling the substation and asset monitoring. This provides much advantage in operating and maintaining grid assets and ensuring stable operation of grid.

Consequence of failure and probability of failure of substation equipment's is a major concern for many utilities in substation maintenance. IEC61850 provides many functions to ease the maintenance of utilities with varied inbuilt features.

3.2 Bus Bar Protection

A Bus bar protection is usually considered as a station level protection, as it uses majority of the measurement (CT/VT) signals available in the substation[7]. Depending on the architecture, it may cross all the zones within the substation. In a conventional substation, as all the measurements and equipment status need to be physically wired to the bus protection system, "Centralized Busbar protection" has challenges in terms of field wiring and data collection. "Distributed Busbar protection" partially address this challenge by installing bay units in the line bays that simplifies the field wiring and data collection. However, the process bus busbar protection is architecturally like the distributed busbar protection as illustrated in Figure 6.

The bay units are replaced with the Merging Units (MU) and the MUs converts the electrical signals from Switchgear equipment into IEC61850 9-2LE or IEC61869-9 sampled values. The equipment status and operate signals are exchanged using GOOSE messages, between the MUs and the bus protection unit. The process bus busbar solution eliminates the challenges of conventional solution of field wiring, simplifies testing and improves the communication reliability and stability. Since the process bus busbar protection is based on IEC61850, the configuration of busbar protection unit and merging units are simplified due to IEC61850 Engineering process, and hence the commissioning time is reduced.

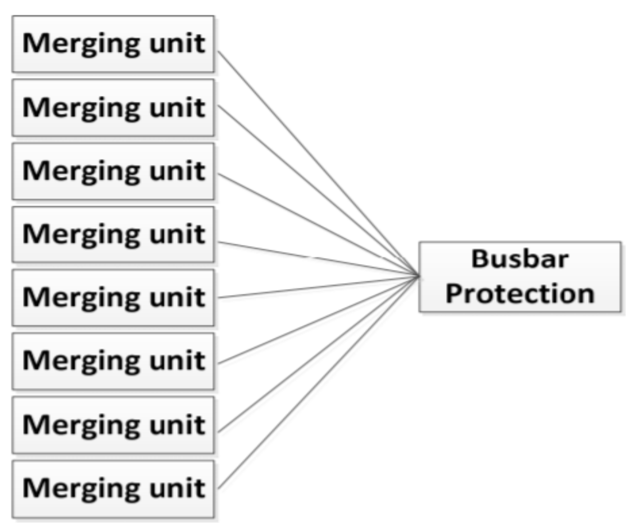

Figure 6. Process bus solution.

The network-based process bus busbar solution has the benefit of network redundancy, using the high availability network protocols like HSR and PRP, as illustrated in Figure 7 and Figure 8[7].

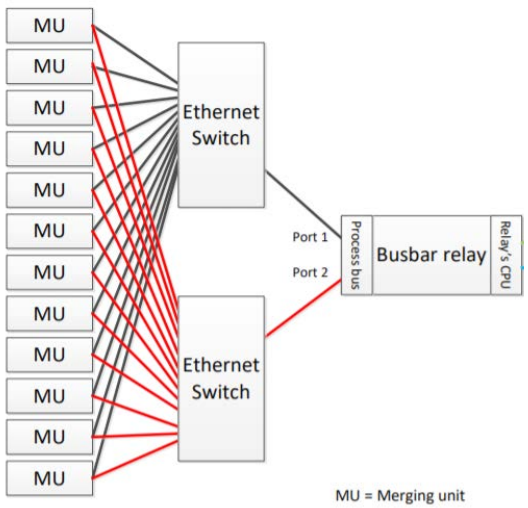

Figure 7. Process bus protection with HSR.

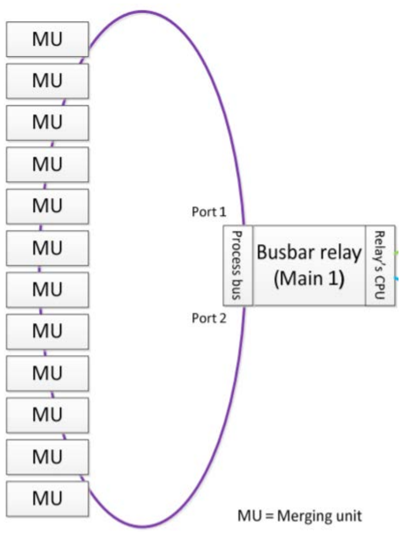

Figure 8. Process bus protection with PRP.

3.3 Transformer Monitoring

Power Transformer is one of the critical component or asset of substation and plays a vital role in stepping up or stepping down of the power. Further transformer will have different sub-systems like tap changer, bushing, main tank etc. which needs to be continuously protected and monitored parameters to be trended for analysing the health degradation or condition of the asset. In order to continuously monitor voltages, currents, temperatures, oil level, tap position etc. these analog measurements through Current Transformer (CT), Potential Transformer (PT), RTD's, transducers etc. must be sent to control room from each transformer in yard through hard-wired cables to protection relay, BCU, RTU etc. At the same time Dissolved Gas Analysis (DGA), bushing monitor and tap changer monitor devices connected to transformer must send the measurements data at regular intervals for continuous online monitoring of transformer as depicted in Figure 9. If we analyse this scenario, lot of signals are transferred through hard-wire cables increasing cost, all the measurements names from different devices like relays, DGA etc., are user defined causing confusion to operators, visualization and trending of the data for different transformers will become complex as there is no common way of looking all transformers data or for correlation purpose. All these problems can be addressed with digital substation implementation as explained further.

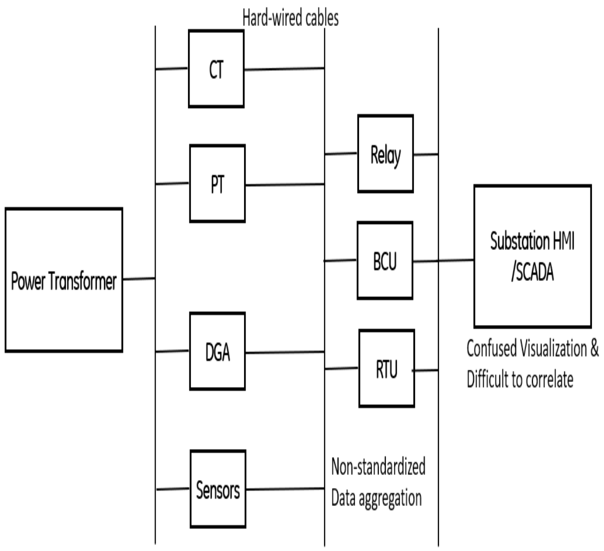

Figure 9. Conventional transformer monitoring.

The IEC61850 series of standards for communication which are meant primarily for digital substations has become widespread in today's scenario. The main advantage of this standard is the interoperability between various devices connected to same or different assets in electrical substations. This means that multiple electronic devices can communicate and share information, without detailed knowledge of the asset or protocols. Based on this digital substation standard a comprehensive modelling of power transformers including advanced on-line monitoring functions is defined and the implementation into the protection and control system is possible seamlessly as depicted in Figure 10. All the analog signals are digitized in the field itself using merging units, non-conventional instrument transformers are used in place of conventional CT/PT's and just a redundant fibre-optic cable carries all the information to control room reducing cost of hard-wired cables. At the same time the information is coming with standardized naming conventions as mentioned in standards which makes data logging, trending and visualization common across different assets and even helps in correlation of different assets information. The model for power transformer consists essentially of the following logical nodes: 1. YPTR Power Transformer 2. SPTR Power Transformer Supervision 3. SIML Insulation Medium Supervision 4. CCGR Cooling Group Control 5. MMXU Measurement 6. ZBSH Bushing 7. SPDC Monitoring and Diagnostics for Partial Discharges 8. YLTC Tap Changer 9. SLTC Load Tap Changer Supervision. These logical nodes represent information of monitored data and are defined according to IEC61850 part 7-4 at the same time logical nodes of protection, metering functions related to transformer too are also mentioned in 7-4. Further this lays a path for coming up with digital twin concept of the asset i.e., transformer in future.

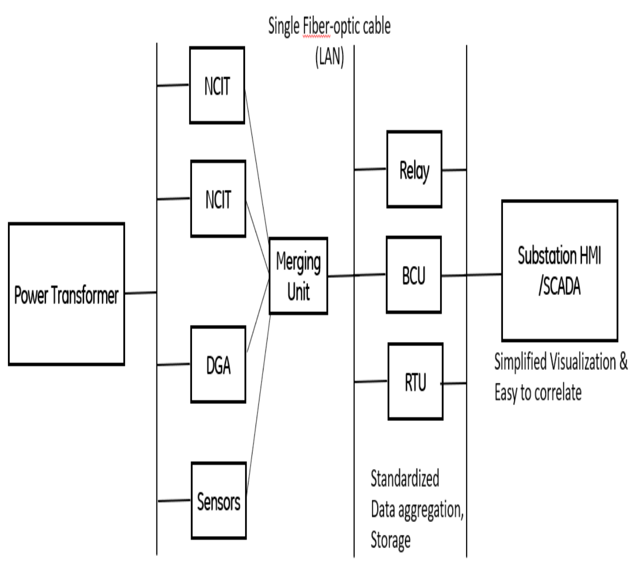

Figure 10. Transformer monitoring in digital substation.

4. Advantages of Digital Substation

The digital substation offers numerous advantages over a conventional substation:

- Easier and simpler installation (with very less wiring).
- Interoperability between various substation devices by different manufacturers.
- Improved reliability and availability of substation.
- Improved measurement accuracy and recording of data & information in a standardized manner.
- Improved commissioning ease & time and post installation operations.
- Easy incorporation of modern electronic NCIT sensors.
- Better EMC performance and isolation of circuits.

Some of the disadvantages include higher capital cost, training requirements for new user, wider acceptance of NCIT's.

In nutshell substation of the future is:

Fully modular, in that individual logical parts of the system, even at the primary equipment, have a defined functionality and a defined interface between different modules.

Fully digital, in that all connections between the modules uses communications as defined by the IEC61850 Standard.

Virtual, in that every control and monitoring function is an independent application operating in a local application server.

5. Future Scope of Work

The future scope of work in digital substation include

- The digital substation laid the platform for the intelligent substation, which enables the self-healing capability to grid. The fault restoration happens more intelligent way than before, reducing the down times.
- Digital substations enables adavnced cloud based monitoring of assets in substations by gathering near real-time monitoring data remotely and helps in predictive based monitoring of assets and also correlation of different assets information.
- Entire asset management can be performed by representing all assets as per IEC61850 standard logic nodes so that data storage, retrieval, representation and visualization becomes easier and uniform.

6. Conclusion

A digitally enabled substation is necessary in the current times to enable substation systems to adapt to the new realities of changing distributed energy resources impacting feeder power flow, voltage, and protection functions, and the changing operating requirements brought on by widely distributed, inverter-based resources. The only way to provide the adaptability and flexibility, with the speed, is using an application driven, hardware and vendor independent ecosystem, where the substation is a critical control point to manage and improve power system operations. Hence the substation of the future is completely modular in design, completely digital in communications, and fully virtual in functionality. This allows faster, more repeatable, lower cost design, build, and refurbishment of substations of substation control systems. The important ability will be to quickly develop control applications to meet the changing requirements of power systems. The first steps on this path are modular design of process bus systems, use of the advanced gateway application servers and multi-zone protective relays as discussed in the paper, plays key role in digitizing the substation. Further the case studies discussed clearly depicts the possible potential benefits of digital substation.

7. Acknowledgment

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