TravellingWave Fault Location System based on IEC61850

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Abstract. Travelling wave fault location (TWFL) system has been matured in recent years due primarily to the availability of high speed sampling techniques, fast communications technology and GPS time synchronization. However, it has not yet been fully integrated into the digital substation based on IEC61850 standard. Proposal for modeling the TWFL system by the IEC61850 standard has already been proposed in another paper. This paper focuses on the communication requirements of the TWFL system in a digital substation, both at the station level and the process level. The application of GOOSE messages and the need for high speed sampling merging unit are discussed. The paper also reports on the latest research into the electronic transformer technology which can satisfy the high speed sampling requirements of TWFL.

1. INTRODUCTION
The theory of travelling wave (TW) fault location for a transmission line is available since the 1950s. Its application is only matured in recent years due to the availability of high speed sampling techniques, fast communications and the high accuracy GPS clock. In the meantime, digital technology and data communications are being applied rapidly to all the protection, control and measuring devices within the substation. This has raised the issue of data compatibility between devices from different manufacturers. The IEC61850 standard is used to harmonize the data communications between different manufacturers to achieve interoperability. It also standardizes the architecture of a digital substation based on the different types of the data communication requirements. It is not just a communications protocol, but is also a modeling tool to model the function of the devices, so that from the communications point of view, the functional interface and the data exchange are standardized.

As the fault location technique using travelling wave is gaining popularity, the need to integrate this technique into the digital substation through the IEC61850 standard is becoming more and more important. The modeling aspects of the TWFL have been discussed in another paper. This paper focuses on the communication requirements of the TWFL within a digital substation and the issues associated with the integration of this technology into the IEC61850 environment. It also discusses the application of GOOSE messages and the need for high speed sampling merging units. The paper also
presents the latest research into the electronic transformer technology which can be applied in conjunction of the high speed sampling requirement of the TWFL.

2. Travelling Wave Fault Location

The two techniques for travelling wave fault location without signal generated circuitry consist of the single-ended method (type A) and the double-ended method (type D). This section details the principle of the two techniques [1].

Single-ended fault location requires only one unit per line. The method captures the transient components using a high frequency fault recorder and measure the time delay between the arrival of the fault initiated surge and the first fault reflected surge. Double-ended method does not depend on multiple reflections between the station bus and the fault, but rather detects the time of arrival of the first fault generated transient at each end of the transmission line. The time of arrival is precisely logged using GPS synchronized clock, with a resolution better than 1 μs.

This method uses only the following information:
- The cable length of the line (l)
- The propagation speed of the traveling wave (γ)
- The time difference between the arrival times of the traveling waves at each side (t_s - t_r)

The equation used to calculate the location of the fault is given by:

\[ d = \frac{(l + 2 \gamma (t_s + t_r))}{2} \]  

The travelling waves can also be generated by other conditions, such as circuit breaker switching operation and lightning strikes. In order to provide more information for a particular incident and to identify its cause, the fundamental component magnitudes of the currents are calculated at the time of the trigger. The CB positions are also monitored. These additional data are important for the master station to determine the types of events when a traveling wave trigger occur.

3. Digital Substation based on IEC61850 Standard

3.1. What is IEC61850 Standard

SCADA protocols such as IEC 60870-5-101/-104 and the derivate DNP3 support the standardized exchange of data like a double point or an analog value with quality information and time stamp. IEC 61850, while supporting that as well, does much more. IEC 61850 allows protection and control functionality in the substation to be modelled into different logical nodes, and grouped under different logical devices. This saves considerable time in implementing new protection devices because it is no longer necessary to map device points to SCADA points as in the case of DNP protocol.

The definitions of IEC 61850 start at the application layer or above. IEC 61850 does not define protocols for any OSI layer, it refers to existing protocols like MMS on the application layer or TCP on the transport layer and of course Ethernet on the data link layer. Parts of the ACSI can be considered as a high level application protocol defining (e.g. with GOOSE) a sophisticated information exchange service.

IEC 61850 is the cooperation of American Electric Power Research Institute (EPRI), Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC). Its purpose is to create a truly global standard, to solve the substation automation system functions and communications. With the maturity of the IEC 61850 technology and the expansion of its applications, IEC 61850 second version has been expanded to outside substation, involving the communications of hydropower station, distributed energy, substation and substation, substation and control centre. Its name has also been changed from "Communication Networks and Systems in Substations" to "Communication Networks and Systems for Power Utility Automation" [5, 6].

3.2. Digital Substation Architecture

Digital substation based on IEC 61850 standard has a three-level architecture: station level, bay level, process level, as shown in Figure 1. Using this hierarchical structure, it is easy to realize the sharing of information, together with convenience in system integration.
The process level contains circuit breaker, disconnector, current/voltage transformer (CT/VT), merging unit (MU) and other primary equipment and corresponding intelligent unit (IU). In traditional systems, this level does not exist and information from high voltage (HV) equipment is directly transmitted to protection unit by point to point wiring mode. In a digital substation, MU provides synchronous digital sampling. Traditional HV equipment is re-developed by combining with intelligent unit to implement the integration of measurement, control and monitoring. Owing to unified communication protocol, sample values (SV) and status information of HV equipment can be transmitted to higher level (bay level) through the process bus. Generic object oriented substation event (GOOSE) commands including tripping/closing signals can also be sent from higher level to operational equipment[7,8].

Bay level is connected to process level via process bus and is connected to station level via a station bus. It is the integration of secondary devices such as relay protection and system monitoring. Using local area SV information, the secondary devices carry out corresponding protection and control functions and send commands to local primary equipment. PMU can also be installed at the bay level as the data acquisition unit for wide area protection and control functions.

The digital substation should be able to manage substation-area conditions dynamically and establish effective and reliable information connection with system and dispatching centre. Therefore, functions of station level include substation area monitoring, control, alarm, SCADA (system control and data acquisition), and protection information management. A master clock is needed for the provision of synchronous time signals at this level. There are two main methods: hardware clock (such as GPS) and software clock (such as (SNTP) Simple Network Time Protocol).

IEC61850 defines the functions of a substation automation system. The functions can be distributed between different IEDs on the same or on different levels of the substation functional hierarchy. Figure 2 shows the communication interfaces between different devices within the substation hierarchy. IF1 to IF10 define the different types of communication interfaces between devices [4].

**Figure 1.** Digital substation based on IEC61850
IF1: protection-data exchange between bay and station level
IF2: protection-data exchange between bay level and remote protection
IF3: data exchange within bay level
IF4: CT and VT instantaneous data exchange (especially samples) between process and bay level
IF5: control-data exchange between process and bay level
IF6: control-data exchange between bay and station level
IF7: data exchange between substation (level) and a remote engineering workplace
IF8: direct data exchange between the bays especially for fast functions like interlocking
IF9: data exchange within station level
IF10: control-data exchange between substation (devices) and a remote control center

With the wide-spread acceptance of the IEC61850, the standard is now extended beyond substations. Figure 3 shows the communication interfaces between substations.

3.3. Advantages of applying IEC61850 to the travelling Wave fault Locator
IEC61850 is a standardized and future-proof communications. With the application of IEC61850 to the travelling wave fault location system, the system will be able to inter-operate with other equipment in the substation based on the same standard. The information it produces are compatible and can be integrated in a digital substation environment. For example, its information can be combined with information from other IEDs to provide more intelligent fault location and line monitoring features. An open system encourages third party development with more innovation ideas. This will open up a lot of application opportunities [3].

4. Communication Requirements of the TWFL in a Digital Substation

The TWFL system consists of the traveling wave data acquisition devices installed at substations, the master station that runs traveling wave analysis software deployed in the control center, and the communication network. The traveling wave data acquisition device records the traveling wave transients in the power lines. It continuously samples the secondary outputs of a current transformer (CT) or a voltage transformer (VT) and stores the sampled data in a circular memory buffer. When the unit is triggered, i.e., the deviation of any input signals exceeded the preset threshold level, the prefault buffered data and the transient data, within a preset time frame, are transferred to nonvolatile memory. The unit also calculates the RMS value of the three phase currents and voltages based on their fundamental components at triggered time. The acquired data are then sent to the master station via the communication network for further processing. The detector monitors the CB operation and sends the event to the master station with a time tag.

The master station collects the transient data acquired by the traveling wave data acquisition devices installed at the substations and calculates the distance to the source of the disturbance automatically. It examines the RMS magnitudes and the CB operation information to determine whether this is a fault, CB operation or other disturbance. It also allows users to view the transient waveforms and compute the distance to the disturbance point by analyzing the reflections within the faulty line section. The functions of the TWFL system is shown in Figure 4.

The master station consists of a communication server, a database server, a web server, and a workstation. The communication server collects the recorded data from the traveling-wave data acquisition devices installed at the substations, calculates the distance to the disturbance point, and stores the record and location results in the database server. The workstation is used to configure and maintain the master station software. The web server publishes the traveling wave fault location result and the current status of devices in operation to the utility so that the patrol crew can quickly locate the fault point and restore power. The communication architecture is shown in Figure 5. In a digital substation environment, this architecture requires communication interfaces IF4, IF5 and IF7.

![Figure 4. Functionality of a Typical Travelling Wave Fault Location System](image-url)
5. GOOSE messages and Sampled Values (SV)

GOOSE messaging and Sampled Values (SV) communicate through the process bus, its nature is entirely different from the station bus. The station bus is using MMS protocol which operates over connection oriented ISO, or TCP/IP. SNTP operates over TCP/IP or UDP/IP. It is essentially a client-server communication. In the process bus, the sampled values and GOOSE data map directly into the Ethernet data frame thereby eliminating processing of any middle layers and providing very fast response. They communicate in a publisher-subscriber mode of operation. The differences can be illustrated with the following diagram.

Figure 5. Communication architecture of a travelling wave fault location system

Figure 6. IEC61850 protocol stack

5.1. Process Bus with GOOSE messaging
Within a digital substation, the trip command and CB status are communicated through the process bus from GOOSE messaging. Apart from the obvious benefits of the reduction in wiring, the digitalization of the command and status information also facilitates reliability, redundancy and data integrity.

TWFL requires secured CB status information in a digital substation to determine the cause of a particular travelling wave incident. This information can be acquired from the process bus with a correct time-stamp under time synchronization within the substation.

5.2. Process Bus with Sampled values (SV)

TWFL requires high speed sampling of the input voltage and current signals, in the region of MHz. The existing digital CTs and VTs can only achieve sampling at the rate of several KHz, the resolution of which is not sufficient for the TW applications. Therefore, at present the analogue data will be acquired through conventional VTs and CT methods. Research is ongoing to develop an electronic system capable to achieving high speed sampling of current signals in the regions of MHz together with an appropriate merging unit to acquire this data. The TWFL can then be interfaced to the process bus through Ethernet to access these data. Thus the true benefits of a digital substation can be realized.

TWFL demands a higher effective signal bandwidth to reach the M-Class, the required bandwidth can also be up to 500K even with the line traps. However, the sampling frequency of the existing electronic transformer can only achieve 12.8K level, thus is not applicable to TWFL in the digital substation.

A pure light electronic current transformer is used to realize broadband data transmission and a smart traveling wave fault location device which directly receives the sample data values for fault location [2]. The design uses shunt sampling method to acquire the data from the electronic transformer, and the merging unit using FPGA for data processing. As shown in Fig 7, the electronic CT produces two outputs. One output meets the general (or fundamental) signal requirement of the digital substation bay level devices, the other output meets the traveling wave signal requirement for the wave fault location device.

![Figure 7. Design of the electronic transformer interface](image)

The travelling wave signal merging unit accepts GPS clock to ensure it is synchronized with the other substation equipment. It acquires data from the electronic CTs, and performs processing to package the data with the correct time stamp. The data package is encoded in IEC61850-9-2 standard format and is sent via optical fibre to the travelling wave fault location device.

The travelling wave fault location system uses linear interpolation method to synchronize samples from different acquisition units, in order to ensure synchronisms of data from various quarters. It accurately extracts the wave head and communicates the information with the master station for fault location purpose.
6. Conclusions
The technology for fault location based on travelling wave principle is now matured, because of the sophistication of micro-electronics and the availability of the GPS clock. As the technology is being accepted by the utilities, the need to integrate this functionality into the digital substation based on IEC61850 is becoming more and more important.

This paper presents the background of different types of travelling wave fault location techniques, explains the features and benefits of the IEC61850 standard, and presents the communications requirements of the TWFL in a digital substation. The use of process bus for GOOSE communications, and for sample values are also explained. The research on a digital CTs capable of high sampling rate is also discussed.

7. References
[1] Gale PF, Crossley PA, Xu BY, Ge YZ, Cory BJ, Barker JRG. Fault location based on travelling waves. Proceedings of the Fifth International Conference in Power System Protection, 1993.
[2] DONG YH, Sun TJ, Xu BY, Smart travelling wave fault location system based on electronic transformer, CICED 2012, Shanghai, China.
[3] Chen Y, Dong L, Xu BY, Wide-area travelling wave fault location system based on IEC61850, IEEE Transactions on Smart Grid, Vol 4, No.3, June 2013.
[4] IEC61850-5. Communication networks and systems in substations part 5: Communication requirements for functions and device models
[5] Han GZ, Xu, BY, Chen ZW, Distribution automation communications technology based on IEC16850 and web services. Proceedings of 5th international Conference on Electricity Distribution (CICED), Shanghai, 2012.
[6] Li YL, Li G, An introduction to 2nd edition of IEC61850 and prospects of its application in smart grid, Power system Technology, 2010 Vol 34 (4).
[7] IEC61850-8-1 Ed.2. Communications networks and systems for power utility automation – Part 8-1, Specific Communications Service Mapping (SCSM) to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3.
[8] IEC61850-9-2. Communication networks and systems in substations Part 9-2: Specific communication service mapping (SCSM) sampled values over ISO/IEC 8802-3.