Theoretical, laboratory and real life comparison of conventional and IEC61850 process bus based protection systems

GORAN PREGRAD, IVAN VIŠIĆ, MLADEN PERKOV
Pro Integris d.o.o.
Croatia

SUMMARY

Development in technology enabled acquisition, sampling and transmission of measured values with precision that fulfils requirements for secondary protection systems. Deployment of Merging Units (MU) and its IEC61850 standardized sampled values goes hand in hand with both larger implementation of nonconventional instruments, with their advantages, and interoperability, ensuring simultaneous use of different vendor products in same secondary system.
Migration from one to another technology always raises a lot of questions, which can be summarized in two groups: Can new solution fulfil basic system requirements? And what are the characteristic or features of new technology and how they affect system? For power system protection those questions read as: Can process system based on sampled values protect network and its elements with same precision and time response as existing one, maybe even better? What kind of technical characteristic does this kind of system impose on protection scheme and how it could and should change?
Article will give presentation of learned lessons on those two questions trough three stages: theoretical comparison of conventional (analog relay) and process system (MU together with relay that subscribes to it), laboratory benchmark tests of two systems run in parallel and results from installed test process systems in substations run in parallel operation to SS's conventional secondary systems.
In order to check basic protection function requirements two systems were tested in parallel in laboratory conditions, system based on sampled values and conventional system. Several protection functions were tested in order to check precision of thresholds for currents, voltages, impedances, direction etc. as well as time response for pickups and trips.
Together with benchmark tests we tried to evaluate most important impacts of new process system on secondary systems. From obvious migration of copper wired signals exchange to Ethernet based communication over fibre optic resulting in redesign of network topology and enhanced redundancy requirements. Once migrated to communication based solutions physical location of devices but also of functions become much more flexible and open the door for adaptive functions and more complex functions. All of the mentioned have its impact

goran.pregrad@prointegris.hr

on amount of civil and engineering work for erecting and commissioning of secondary system.
All tests done in laboratory gave confidence to put process based protection system in real operation in substation of local network operator. Two bays were equipped with such systems and were in operation for several mounts. Results proved that new system can fulfil basic protection functions in real life environment and gave confidence and ideas for future researches and development of new process bus secondary systems.

KEYWORDS

Merging Unit, Process bus, Sampled Values, IEC61850, Fully Digital Substation

Introduction

Development in technology enabled acquisition, sampling and transmission of measured values with precision that fulfils requirements for secondary protection systems. Acquisition and sampling was widely used for long time, such as in every numerical relay in protection systems, but transmission over network was task not so often performed. There have been cases of transmission of sampled measurements over network interface, but it was always proprietary and fine-tuned for specific function requirements. With first edition of IEC61850 standard part 9-2 there was first framework and definition for transmission of sampled measured data over Ethernet network as fully interoperable and function nonspecific named Sampled Values (SV). The framework left a lot of freedom in its implementation, therefore UCE made a guideline, commonly known as 9-2-LE, specifying more technical details in order to create common data structure and transmission rules.

Introduction of SV changed location of measurement digitalization in secondary system. What it does is removing need for AD conversion form each device that is using measured values and centralises it in one place. Device that does this task is called Merging Unit (MU). Development of MU opened the door for migration of conventional secondary systems based on analog measurements and signals distributed by wire to more digitalized secondary systems based SV, GOOSE and communication over network. In order to evaluate new solution we should first look in to its technical characteristics and requirements, changes and features it is bringing.

Technical characteristics of SV

As specified in guideline 9-2LE Sampled Values are published as multicast stream of data. Main feature of this approach is that SV stream is published on network and from there it is available to all users that might use it. This is similar for example as voltage loop for busbar voltage measurement but it is completely different form having separate current circuit for each protection relay. Basic idea is to separate this traffic from traffic towards SCADA system. This type of network is called Process Bus and it should be (physically) separated form Substation bus used for remote control system.

SV are continuously published to the process bus by the MU with no regard to actual state and number of devices subscribed to its stream. This data, unlike GOOSE messages, are not repetitive; instead, in vein of analogue values, it is a continuous sequence of samples.

A constant and synchronised sample rate is extremely important for MU and system based on SV. For MU it is very important that samples are taken at same time increments in order not to create false oscillations in measurement system. Measurement from each MU needs to be taken at absolutely defined time, synchronised, in order not to create false differences in measurements at their subscribers, for example differential protection. Because of that guideline 9-2LE requires pulse per second (PPS) time synchronization method according to IEEE1588 norm. This is giving each sample inside one second its position and relative time reference. Experiences since guideline has been published are calling for even better synchronization methods. It is expected that system should be synchronized with absolute reference time, so that all measurements could have full time tag. This should be done by using Precision Time Protocol (PTP) form IEEE1588 (IEC61588) standard.

Sampling frequency according to the IEC61850-9-2 LE is given per nominal system frequency. It should be pointed out that sample rate per second is fixed regardless of real time frequency of measured value. Guideline also defines two sample rates for protection and measurement SV. Protection sample rate is 80 samples per nominal line cycle which translates to 4000 samples per second for 50 Hz grids. If every sample has a size of 124 bytes, simple calculation shows how much traffic would pass through the network during one minute for one stream:

$$d_p = 124B \cdot 60s \cdot 80\frac{samples}{Hz} \cdot 50Hz = 30720000B = 28{,}38MB \quad (1)$$

For measurement the number of samples is 256 per nominal line cycle but 8 application service data units (ASDU) are contained in each Ethernet package. Amount of traffic per minute would be:

$$d_m = 833B \cdot 60s \cdot \frac{256}{8}\frac{samples}{Hz} \cdot 50Hz = 79968000B = 76{,}26MB \quad (2)$$

Packet size was measured for MU used in test described below and it is important to note that these figures would slightly differ between different MU’s. Still they give well in sight to network load and importance of network designing for system based on SV.

Big advantage of MU is fact that it could be installed directly on measured value source, CT and/or VT, and only transmits data over Ethernet network. For conventional CTs and VTs this would almost completely remove wiring of its circuits and create much safer environment for its users as it would remove hazards from open CT circuits. On other side standardise transmission of SV is creating big opportunity for nonconventional measurement transformers (NCIT), as MU can be installed on NCIT itself and solve problem of low power signals and utilises SV interoperability to be used in with any Intelligent electronic device (IED) in Protection and Control System (PAC) instead of using to some proprietary protocol. Devices that use SV become easier and cheaper to make from HW point of view, as they do not have to have AD circuits and no isolation from high voltage and high currents is necessary.

Fully digital substation and process bus

With development of MU last big step was done to create fully digital substation. Fully digital substation would be one where all measures are sampled and where all signals and controls are digitalized as close to source and then transmitted to protection and control IED over network. Wiring in such SS would be minimized and replaced by transmission of data trough fibre optic Ethernet network. All physical parts would have their virtualised representation trough logical nodes and functions described by IEC61850 standard. Data would be transmitted form I/O devices over Ethernet network to protection and control IEDs which would acquire and process data and then control system over network back to I/O devices that would execute commands.

Change from wiring based solutions to communication over network in fully digitalized SS creates need and opportunity to rethink location of functions per devices, location of devices and at the end number of devices used in system.

In order to minimise wiring in secondary systems all signals should be digitalised as close to source, but this still needs to be done cost effective. Two possible approaches are:

- To have MU for SV and additional one or more I/O device that would digitalize all switching equipment and signals form switchyard;
- To have MU with binary I/O functionality and complete bay is digitalised trough one device.

Voltage level, physical size of bay and type of primary equipment greatly impact this issue. With all signals coming from bay in digital form location of protection and control devices becomes even more flexible, as cost and technical issues of covering long distances almost completely disappears. With such design protection and control devices are reduced to their essential logical functions as they are stripped of digitalization interfaces. This has two main features: number of available information for each device increases as all data are available on network which provides great opportunities for smarter, adaptive centralized and disturbed automation and protection functions, computing power of IED is only limit of how many functions per bays or even bays per device one IED can protect and control.

Fast and reliable network

With all functions in SS now based on network communication good communication is of crucial significance. Several important requirements need to be fulfilled:

- Necessary data needs to be available uninterrupted and within specified time delay.
- Necessary data means that network needs to be well managed in order to provide data where they are needed but not necessarily in other parts of network where they could create transmission congestions or overload on receiving IEDs.
- Availability needs according to functional requirements, but for most critical functions such as measurements or tripping commands, they need to be uninterrupted. This is imposing good redundancy schemas (RSTP, HSR and PRP) and redundant physical network paths.
- Time from occurrence of event to its processing in IED needs to be within time tolerances and it needs to be monitored. This requires good topology of network, good management of data traffic over network based on data priority and significance and precise time synchronization over network (PTP).

Short evaluation of capabilities of new technologies and solution was given but main lest move to first and basic question: Can new solution fulfil basic system requirements? For protection of power systems those questions read as: Can process system based on sampled values protect network and its elements with same precision and time response as existing one, maybe even better?

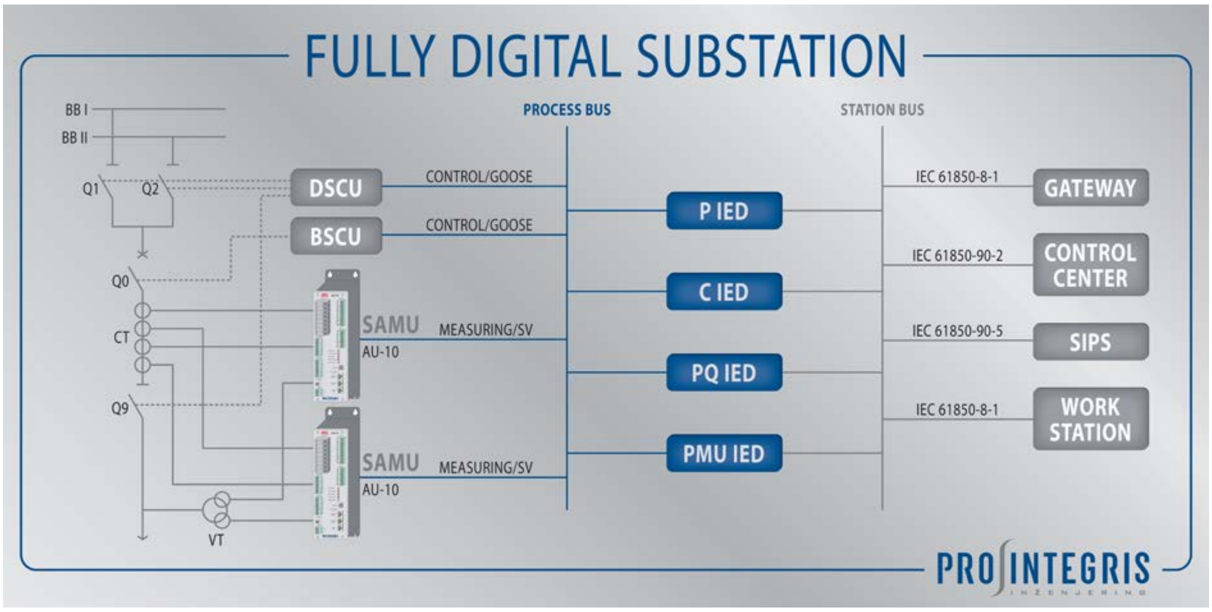

Figure 1 Schema of Fully Digital Substation with process and station bus and its elements

Laboratory Testing of Sampled Values based system

Testing was done with idea to evaluate basic protection functions of system based on sampled values, here refer as process system, and directly compare it with conventional system based on analogue measurements, refer as analog system. MU developed to connect secondary analogue values from conventional measurement transformers on its inputs was basis for this test. Other testing equipment consisted of a secondary injection test set with PPS time synchronization module, standard protection relay using analogue values, protection relay with sampled values and two network switches. Figure 2 shows block diagram of the testing system, while Figure 3 shows the testing equipment.

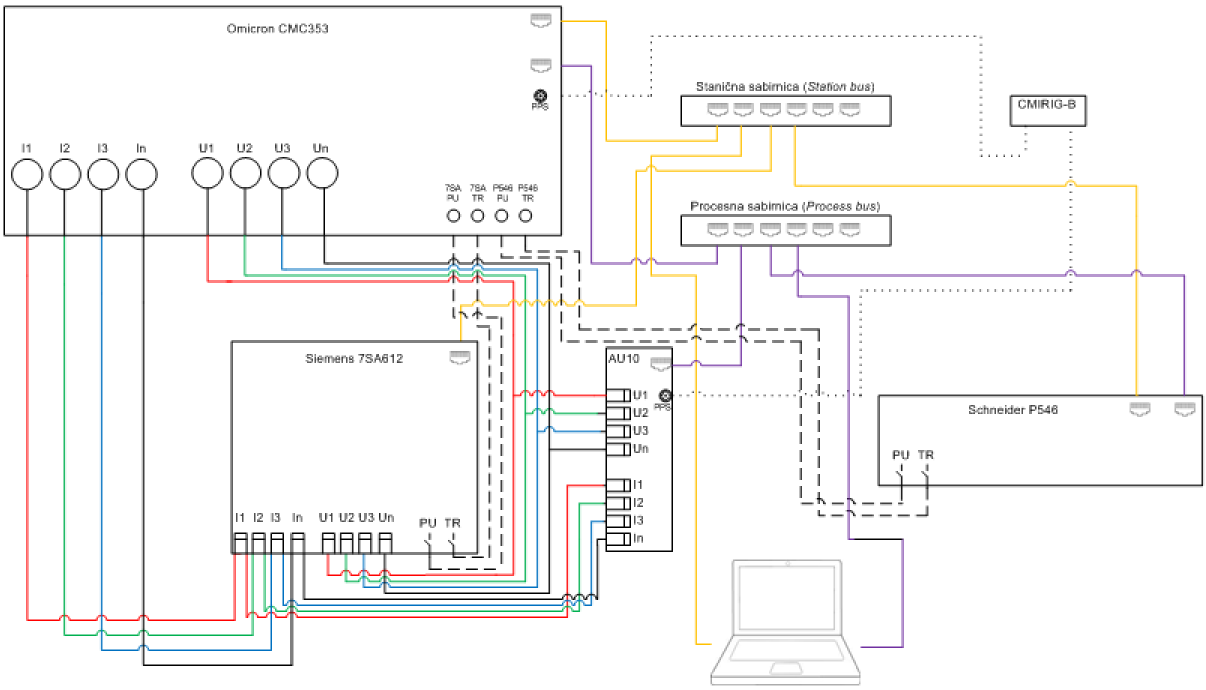

Figure 2 Test setup block diagram

Main goal was to compare pickup and trip times for basic protection functions, as well as to get familiar with a sampled values system and learn more about its characteristics. Currents and voltages were injected into the merging unit and analogue values relay. Merging unit was connected to a switch using an UTP cable and from there to the sampled values relay. The secondary injection test set was also connected to the switch and used to inject sampled values equivalent to analogue ones, in order to compare test set and merging unit waveforms. Pickup and trip signals were routed to the test set from both relays using wires and GOOSE messages in order to compare the speed of both methods. Relays were synchronized through network switch using SNTP protocol; fault recorders and event lists could be compared in this manner. Merging unit and test set were synchronized using a CMIRIG-B interface box so that sampled values could have equal sampling count. Additionally, the system as a whole could have been GPS synchronized, but it was not necessary for this test since it had no effect on the results.

The first question that had been considered was how to prove that the sampled values system is as effective as the conventional system. Usual tests of tripping times and pickup values were done to check system behaviour in normal conditions. Overcurrent and earth fault (directional and non-directional), as well as distance protection functions were tested. Since protection relays made by different manufacturers were compared, test results have to consider differences in protection algorithms and measured values processing. Because of this, special consideration was given to the pickup times, because effect of protection function algorithms on pickup is less significant.

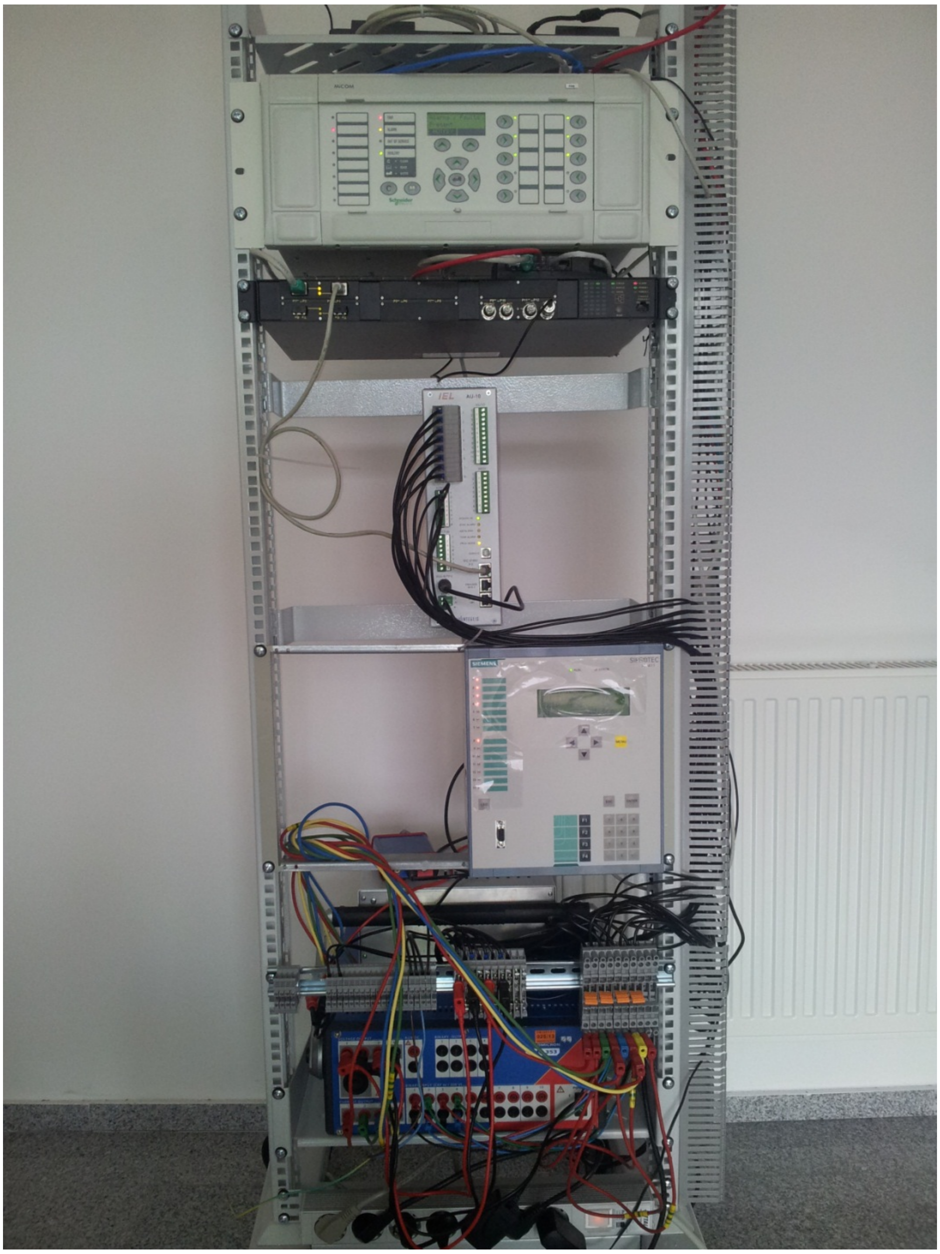

Figure 3 Testing equipment

Test result analysis

To compare two systems, emphasis was put on time delay caused by processing and sending measured values from the merging unit to the protection relay and the effect this time delay would have on the overall protection trip time. Besides pickup and trip via binary inputs and outputs, the same functions were tested using GOOSE messages.

First value that had been monitored was the time measured from the beginning of injection of analogue values to the protection relay pickup. Expected time delay for AD conversion, sending sampled values over the process bus and final analysis inside the relay is in range of microseconds. Results are presented in tables I. and II.

Table 1 Average pickup time

Protection function	Average time $\bar{t}$ [ms]	
	Analogue values relay	Sampled values relay
I>> (ANSI 50)	25,20	22,10
IE>> (ANSI 50N)	28,90	38,50
Z1 (ANSI 21)	18,60	19,50

Even though there are differences in pickup times, they can be attributed to different algorithms that deal with processing analogue values since devices are designed by different manufacturers. Table 1 also includes times necessary for activation of binary inputs which are different in the two relays and on which the merging unit has no effect.

Table 2 Average time from pickup to trip

Protection function	Average time $\bar{t}$ [ms]	
	Analogue values relay	Sampled values relay
I>> (ANSI 50)	1027,00	1037,00
IE>> (ANSI 50N)	1028,00	1044,00
Z1 (ANSI 21)	34,70	22,50

Table 2 sows results for tripping time. There is no clear answer to the question which device is faster; for different protection functions, different device shows advantage. For distance protection, process values relay is faster, and for high-set earth fault analogue values device is faster.

Besides pickup and trip times, pickup thresholds for overcurrent, earth fault and directional earth fault were tested. For directional functions, directional limit lines were also tested., results are given in Table 3.

Table 3 Average time difference from pickup to trip for sampled values and analogue values

Protection function	Pickup			Drop-off		
	Set	Analogue values relay	Sampled values relay	Set	Analogue values relay	Sampled values relay
I>> (50)	1000,00 A	1000,00 A	1005,00 A	950,00 A	921,00 A	946,00 A
IE>> (50N)	1500,00 A	1506,00 A	1509,00 A	1425,00 A	1382,00 A	1410,00 A
IE> (67)	200,00 A	202,90 A	205,10 A	190,00 A	183,00 A	184,40 A
IE> (67)	30,00 °	29,60 °	31,15 °	-150,00 °	-148,10 °	-149,65 °
IE>> (67)	300,00 A	307,70 A	307,40 A	280,00 A	280,50 A	272,50 A
IE>> (67)	30,00 °	28,10 °	28,50 °	210,00 °	209,30 °	209,00 °

Range of these differences is between 0 and 10 ms, depending on the protection function. This shows that protection function algorithms have a greater effect than the sampling and transmission time of the sampled values.

Performing the test using GOOSE messages yields very similar results for both devices which could be expected since each message had to pass through only one network switch. Results for pickup and trip using GOOSE are given in Table 4 and Table 5.

Table 4 Average pickup time with GOOSE messages – measured by the test set

Protection function	Average time $\bar{t}$ [ms]	
	Analogue values relay	Sampled values relay
I>> (ANSI 50)	23,50	31,76
IE>> (ANSI 50N)	25,05	37,06
Z1 (ANSI 21)	10,51	24,76

Table 5 Average time from pickup to trip with GOOSE messages – measured on the test set

Protection function	Average time $\bar{t}$ [ms]	
	Analogue values relay	Sampled values relay
I>> (ANSI 50)	1000,20	1008,04
IE>> (ANSI 50N)	997,90	1007,15
Z1 (ANSI 21)	1,16	7,40

Following directions from IEC61850 standard a circular test for measurement of GOOSE transmission time was performed and the time it took the GOOSE message to go from the test set to the protection relay and back was less than 4 ms. This satisfies the strictest GOOSE message category enforced by the IEC61850 standard which states that the tripping command must travel less than 3 ms. If this demand can be fulfilled using a standard substation network then a system based on sampled values and GOOSE messages is equivalent to a standard wire based system.

Stand-alone MU Pilot project

Presented series of tests proved that SV based system can fulfil basic protection functions as well as conventional. This gave confidence to proceed with realization of two pilot project of installation of that system in substations parallel to SS protection system. Chosen locations were one 110kV OHL and one 20kV OHL. Both locations were chosen as longer OHL with high probability of events occurring. Stand-alone MU (SAMU) was wired in parallel with existing bay protection on same currents and voltage circuits. Process relay subscribed to SAMU and was fully functional with same settings as original bay protection, but did not operate on CB. Bay process bus was kept separated from Substation bus. Additional GPS had to be installed in order to synchronise SMAU with PPS signal, while process relay was synchronised with NTP server in order to have same time as analogue relay for comparison purposes. System for monitoring SV stream was crated with additional feature for recording SV stream during disturbances. In both pilot projects all equipment was installed inside relay house/ protection building.

Periodically system was checked for possible errors of equipment or functionality and for events and recordings. Trough period of one year no problems were detected. SAMU and process relay remained in operation without any issues, but more important were results from recording of events in network. All disturbances that were registered by analogue relay were as well recorded by process relay. Comparison of recorded SV streams and fault recordings form both relays showed:

- Good amplitude and wave form response,
- Good response for DC component
- High disturbance resolution of current and voltages saved from SV stream

Pickup time differences are within same range as in laboratory testing and within expected values for protection functions. Figure 5 and Figure 6 show current s and voltages form one disturbance on 110kV line. Wave form shows identical behaviour of healthy and faulty currents and voltages. There is no phase shift between analog values and SV. DC component can be seen in currents.

Figure 4 Installations of SAMU pilot projects on left side 110kV and or right 20kV OHL

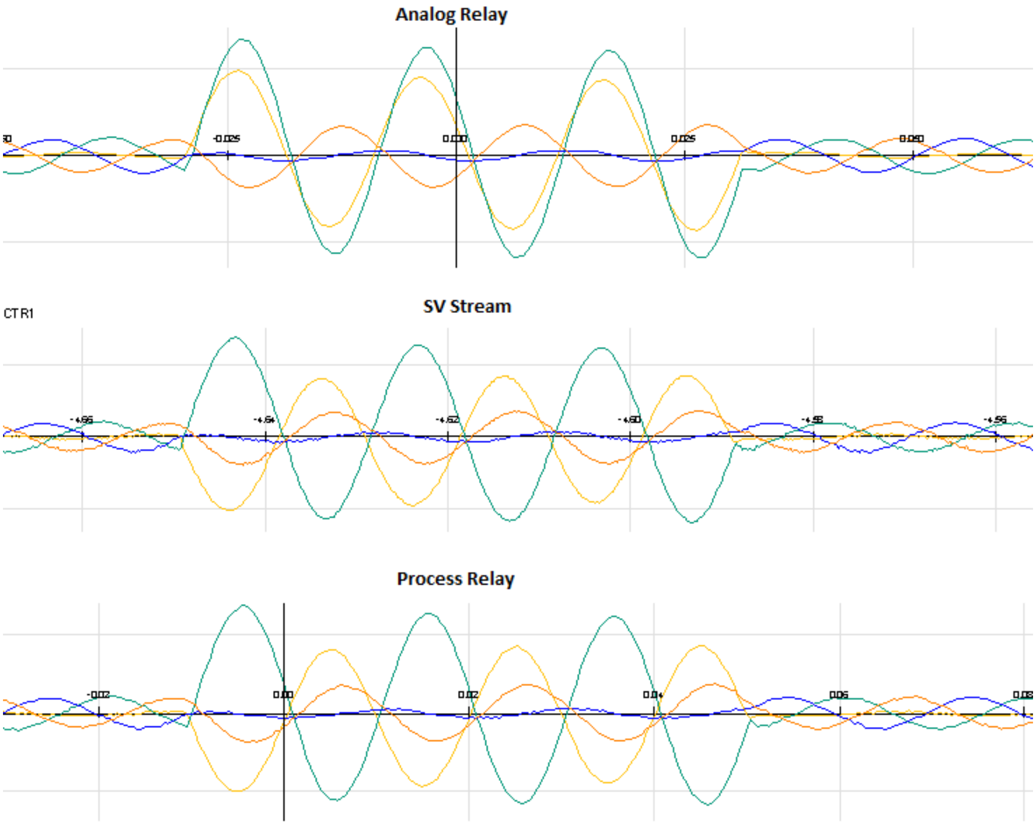

Figure 5 Comparison of currents during disturbance

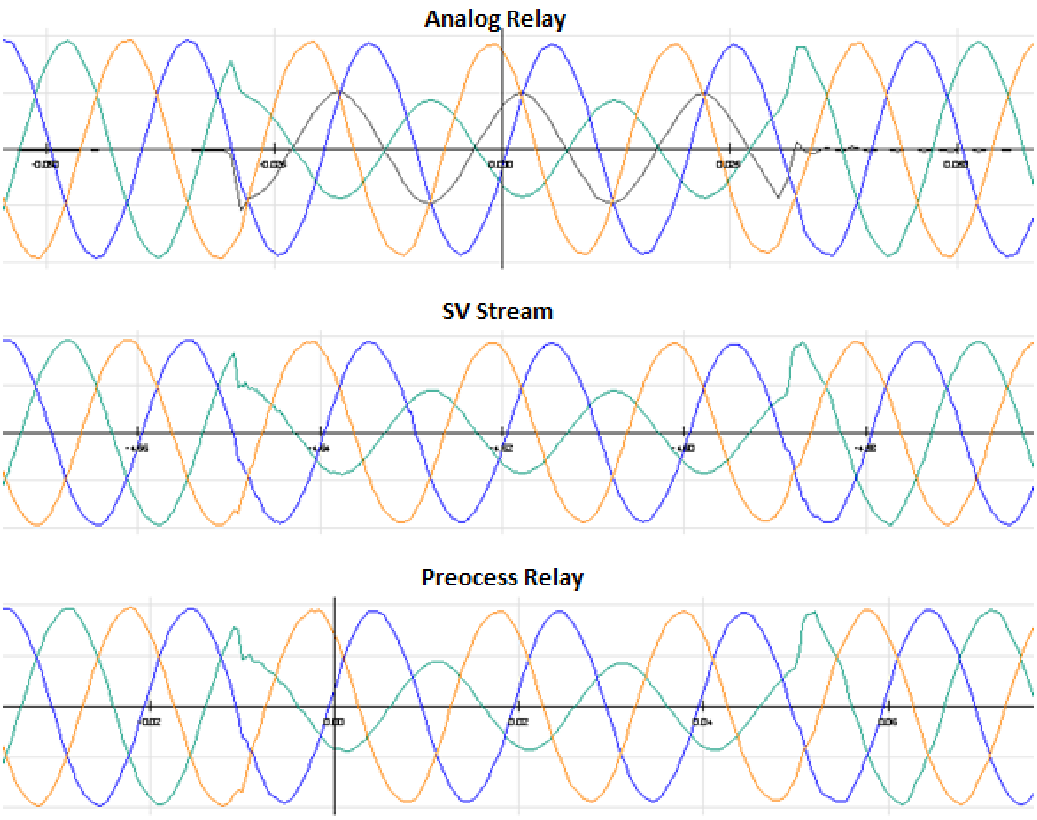

Figure 6 Comparison of voltages during disturbance

Conclusion

Laboratory tests and pilot project installation of system based on SV proved that this new concept of secondary systems can fulfil basic functions of supervision and protection. Laboratory tests were concentrated on evaluation of measurement precision and time necessary for operation. This was done by comparison of functions thresholds, pickups and trip times between analog relay and system based on SV. All test results were inside acceptable protection tolerances, without significant advantage for any of the systems. This proved that time used for sampling, packing, transmission of SV and unpacking measurements is less significant than protection algorithms operation times. Pilot project proved that system can withstand real life working environment and stay stable while correctly evaluating and reacting to system disturbances.

With successful trial runs MU's will evolve to reliable elements of secondary systems and open door for wider use of NCIT and migration to Fully Digital Substations. Fully digital substations are based on data transmission over Ethernet network based on IEC61850 protocol. This is creating many opportunities for redesign of secondary systems in order to make it more capable, more adaptive to changes in power system. With better protection schemes and lower costs of construction this should bring down overall price of engineering of secondary system and full substations construction.

For this to take place comprehensive analysis of communication based solutions is necessary in order to verify that availability, reliability and overall quality of system fulfil strict requirements of power systems.

BIBLIOGRAPHY

Type here the bibliography at the end of your text, according to this presentation (see sample references below). Font to be used is always Times or Helvetica 11 or 12.

[1] IEC61850-7-4 Communication networks and systems in substations – Part 7-4: Basic communication structure for substation and feeder equipment - Compatible logical node classes and data classes, 2003.

[2] IEC61850-9-2 Communication networks and systems in substations – Part 9-2: Specific Communication Service Mapping (SCSM) – Sampled values over ISO/IEC 8802-3, April 2004.

[3] [3]Implementation Guideline for Digital Interface to Instrument Transformers using IEC61850-9-2, UCA International User Group, Modification Index: R2-1

[4] [4] Siprotec, 7SA6xx Manual, C53000-G1176-C156-7, Release date 02.2011

[5] MiCOM P543, P544, P545 & P546 Manual, P54x/EN M/Ka4, 12/2010

[6] Testing an IEC 61850 Compliant Relay, Omicron Test Universe documentation

[7] A.Apostolov: „IEC61850-9-2 Process Bus Applications and Benefits“, DPSP2010, pp.1-5, April 2010.

[8] D.Ingram, P.Schaub, R.Taylor, D.Campbell: „Performance Analysis of IEC61850 Sampled Value Process Bus Networks“, IEEE Transactions on Industrial Informatics,, Volume 9, Issue:3, pp.1445-1554, August 2013.

[9] L.Anderson, C.Brunner:“Substation Automation based on IEC61850 with new process-close Technologies“, Power Tech Conference Proceedings, 2003 IEEE Bologna, Volume 2, June 2003.

[10] J.Tournier, T.Werner:“A Quantitative Evalution of IEC61850 Process Bus Architectures“, Power and Energy Society General Meeting 2010 IEEE, pp. 1-8, July 2010.