Creating a Real Time Digital Interface for IEC 61850 SV Relays in China on a Real Time Digital Simulator

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Abstract

The IEC 61850-9-2 standard describes the abstract model of the digital voltage and current sampled values (SV) used by 61850 enabled intelligent electronic devices (IED). IEC 61850-9-2 is very flexible and can be implemented in a multitude of configurations and does not specify a fixed configuration. This brought about the commonly used 9-2LE configuration, which is an implementation agreement of 9-2 adopted by a majority of IED manufacturers. China however did not adopt this configuration and used a configuration more akin to the IEC 61850-9-1 configuration. This paper describes the development of an IEC 61850-9-2 configurable interface firmware and a software model for use on a Real Time Digital Simulator (RTDS®)

1 Introduction

The IEC 61850-9-2 standard is very robust and the 9-2LE configuration as well as the results from the latest UCAIug interoperability meeting in October, 2013 indicate that. Seven companies participated and showed inter-operability in both publication and subscription of the 9-2LE data stream. There are several companies in China that use IEC 61850 technology for GOOSE, SV, and MMS in their IEDs and merging units (MU) but the SV configuration is not identical to the 9-2LE configuration. The SV configuration in China is more akin to the deprecated IEC 61850-9-1 standard and the new IEC 61869-9 standard which is the specification of the digital interface for instrument transformers. The main difference is that 9-1 uses a point-to-point connection between the IED and merging unit while 9-2 uses a properly engineered network, commonly referred to as the process bus. With the new IEC 61869-9 standard, technology will again move ahead with the implementation of SV as it clearly adopts some standard configurations and allows for the legacy 9-2LE configuration. Test results at Beijing Sifang Automation Co. Ltd, XJ Electric Co. Ltd in Xuchang, and SEPC lab in Chengdu have proven the correct implementation of the Chinese national standard for SV has been achieved by RTDS Technologies Inc. Using an RTDS as the source of SV data streams for IEDs used in China requires an accurate simulation time-step that receives synchronization from an accurate time source. Additionally, the simulation time-step must maintain synchronism during the entire length of the simulation, i.e. there should be minimal deviation and no drift away from the time source.

2 Development of a Non-9-2LE DataStream

Several things are similar between IEC 61869-9 and the version of SV adopted in China, but there are differences that need to be considered when developing the interfaces. A critical aspect to the development of a new SV interface is having a good understanding of the present 9-2LE implementation agreement, the IEC 61869-9 standard, and the Chinese National Standard for merging units.

China investigated IEC 60044-8, IEC 61850-9-1 and 9-2 and provided pros and cons about each method while developing their standard [2]. IEC 60044-8 was initially introduced as a method to transfer sampled values in a digital format and used a peer-to-peer connection with a fixed channel configuration, fixed frame length, and maximum sampling rate. IEC 61850-9-1 is essentially the same as IEC 60044-8 configured as Ethernet packets /transfer and is not supported by the IEC. The most flexible and interoperable standard is IEC 61850-9-2 although the intended network mode of operation is not implemented in China.

The Chinese National standard, “Technical Specifications of Protection for Smart Substation” calls for merging units to use a time source such as GPS to help synchronize samples from different devices. The IEDs do not need to use the time source to acquire and uses the SV data from the MUs. The connection between the MU and IED is done using fibre optic connections without going through an Ethernet switch in a point-to-point connection. When point-to-point mode is used, as the protection device and the control device are directly connected with fiber, the delay of transferring the sample value can be fixed. Thus, the original data sampling time can be obtain from the local packet reception time at the IED by subtracting the fixed delay time. According to one paper [2] published in China “When transferring IEC 61850-9-2 data frames in peer-to-peer mode, it will retain the benefits of flexible configuration and high compatibility of IEC 61850-9-2, and provide much more reliability for the protection system with fixed data transferring delay.”

The point-to-point mode does create some obvious challenges with design and application of the MUs and IEDs. This is due to the additional requirement of providing a single point of connection to every device that requires the sampled values. For example a MU may be required to provide sampled value data for line protection, breaker failure protection, bus protection, differential protection, stability control systems, transient fault recorders, SCADA devices, etc… Typically 8 Ethernet ports are required on one MU to supply the individual point-to-point connection requirements. In the case of bus bar differential IEDs there may be 24 bays that all need to communicate to the same device. This IED would be required to service all 24 Ethernet ports at a combined bandwidth of up to 192 Mbits/second. The Ethernet interface needs to support independent access to all ports and use minimal CPU/DSP resources. There are Ethernet cards that have been designed in China to meet bandwidths of up 800 Mbit/sec for 8 ports. These Ethernet cards are suitable to service IEC 61850-9-2, GOOSE, MMS, 1588 all at the same time. Because IEDs designed for SV use in China do not require the IED to be synchronized to an external time source, the merging unit [1] must be capable of providing a reliable SV data stream with less than 10 µsec of jitter between samples.

The sample rate of a MU in China is 4000 Hz or 250 µsec between samples. Table 1 shows the dispersion of a single network port on transmitting SV over a duration of 1 minute of +/- 1 µsec of jitter [2].

Sending Interval Error µ s	**Quantity**	**Percentage 100%**
(10,+∞]	0	0
(1,10]	0	0
[0,1]	137101	58
(-1,1)	99312	42
(-10,-1]	0	0
(+∞, -10]	0	0

Table 1: TX Dispersion statistics of a single port

Since standard 9-2 SV streams use a global time sync to synchronize the samples in the SV stream, the receivers are generally insensitive to jitter. Devices which transmit SV packets may take advantage of this characteristic and may not transmit packets with such low jitter, as was the case with the original GTNET-SV design. To achieve a maximum of 10 µsec of jitter a new software and/or hardware architecture must be developed for such networked SV systems. The GTNET-SV firmware that was developed to provide the 9-2 interface from the RTDS Simulator to IEDs in China must be able to achieve a maximum of 10 µsec of jitter. The low jitter requirement must also be tested using specialized test software and hardware. Omicron SV Scout software with a special network adapter that delivers highly accurate time tags for the received packets with an error well below 1 µsec was used to test the dispersion on the GTNET-SV data stream using the new GTNET-SV firmware.

Packet delay (delay between successive packets) is measured and the time offset (time intervals from the theoretical sampling time to the reception of the corresponding packet) for packet 0 is also measured.

Figure 1 shows the packet delay test result of the new lower-jitter Non-9-2LE GTNET firmware with a 50 Hz nominal SV stream running a simulation at 50 µsec, the simulation duration was 19 hours, 7 minutes, 11 seconds.

Packet delay is the frequency of occurrence of the measured packet delays (time intervals between the Sample Values packets) within the time intervals is displayed.

There are almost an equal number of packets that are +/- 1 µsec from the theoretical 250 µsec sample interval. The ratio of perfect samples at the theoretical interval compared to samples that are +/- 1 µsec from the theoretical is approximately 99.99%.

For a long term duration of over 19 hours with 275,325,230 samples there were only 2 samples that were +/- 2-3 µsec from the theoretical interval , only 39,845 samples that were +/- 1 µsec from the theoretical interval and 275,285,383 samples that were at perfect theoretical interval.

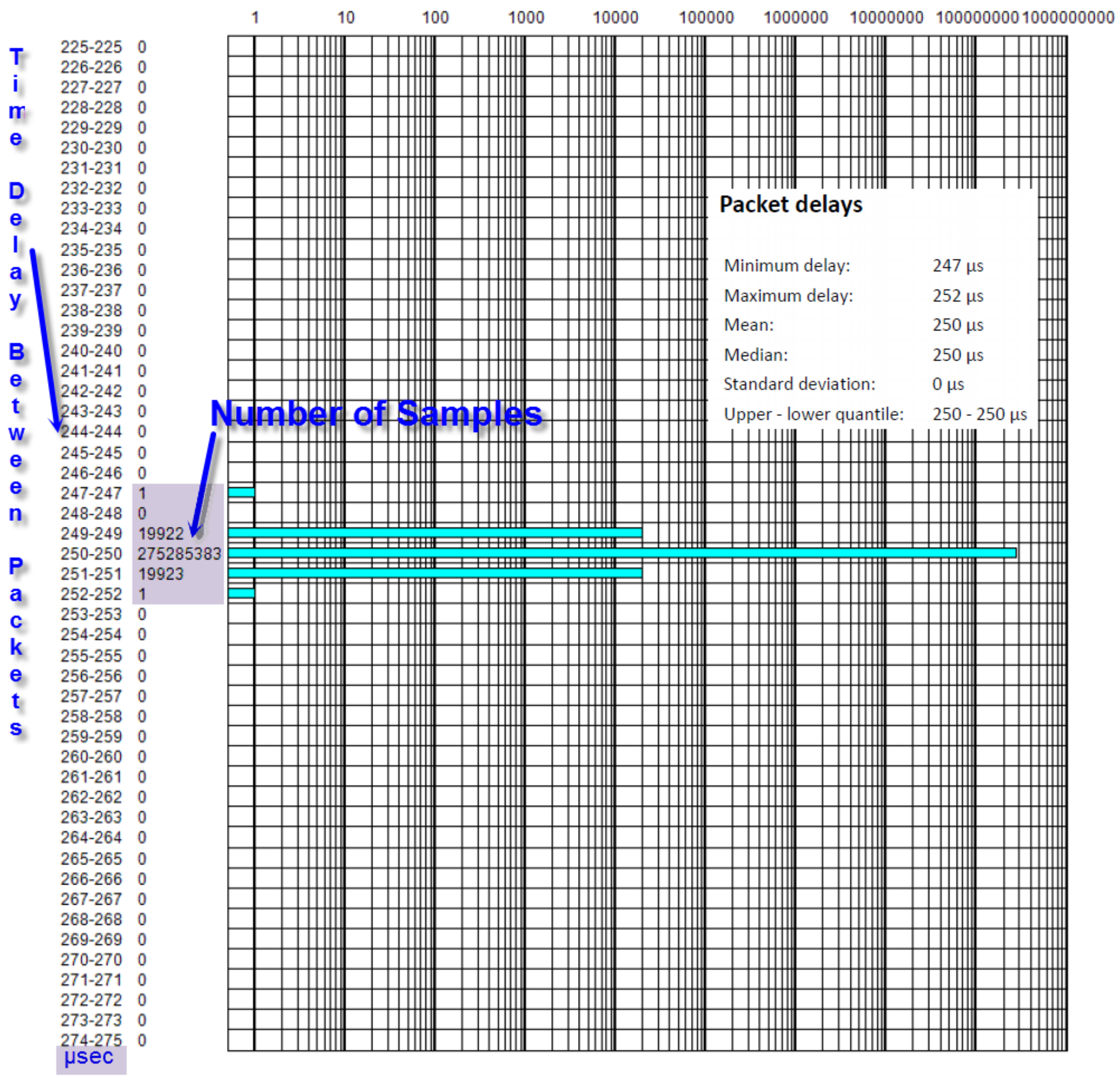


Figure 1: Packet Delay in µsec from GTNET-SV

Figure 2 shows the time offset delay for packets with sample counts equal to 0 from the 1PPS signal test result of the new GTNET-SV firmware with a 50 Hz nominal SV stream running a simulation at 50 µsec.

The sample rate can be extracted from a quick review of the test results. For example there are approximately 275,325,230 samples captured and 68832 packet 0s' captured which equals to 4,000-to-1 which is the sample rate of 80 samples/cycle at 50Hz (4,000 Hz).

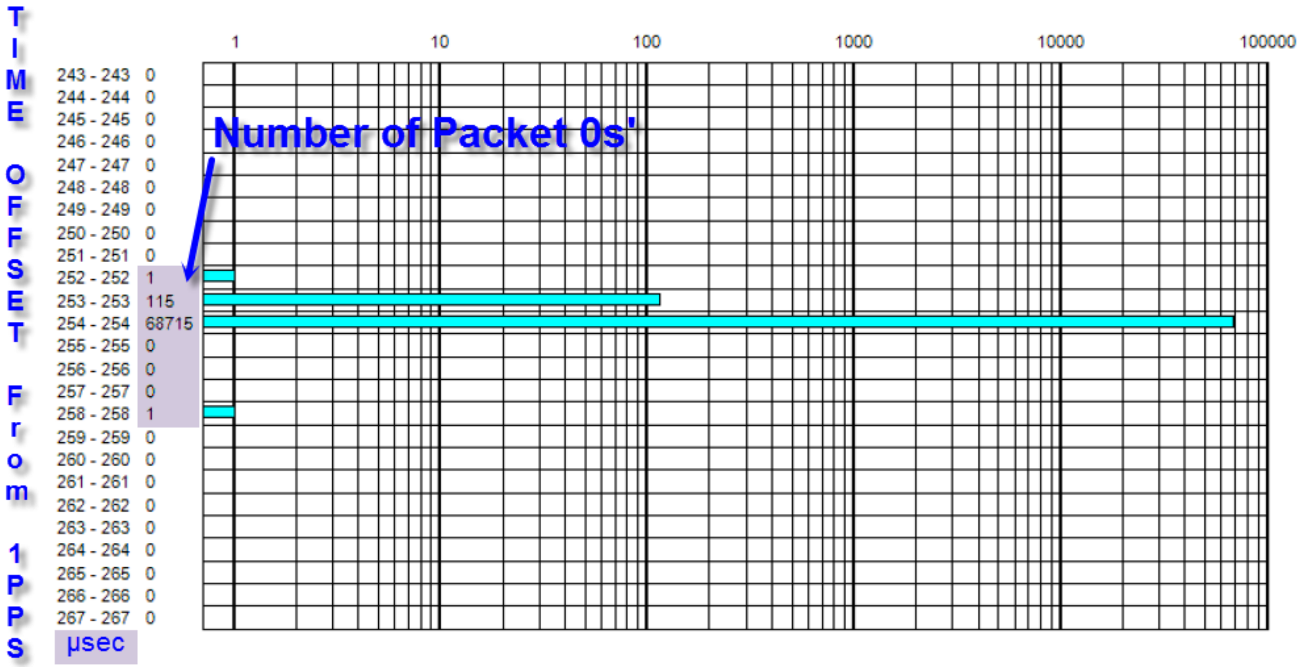


Figure 2: Time Offset from 1PPS in µsec from GTNET-SV

Time Offset The frequency of occurrence of the measured time offsets (time intervals from the theoretical sampling time to the reception of the corresponding packet 0) within the time intervals is displayed.

2.1 Non-9-2LE Implementation

According to the "Technical Requirement for Merging Unit" [2] the MU shall output the overall time delay of the electronic transducers. The 1st channel in a SV data stream is the time delay information and specifies the overall delay of the connection from the MU to the IED. The sample delay is a fixed value, which includes the delay of the transformer sensing and low-pass filtering as well as the forwarding delay of merging unit; the "time-delay" must be less than 2mS. The IEDs will employ an interpolation algorithm to synchronize the samples from different devices. In January of 2011, for the 500 kV Lanxi substation upgrade project, the peer-to-peer method using IEC 61850-9-2 was applied and supported by State Grid Corporation of China using technology developed by NARI Relays.

Similarities exist in the Chinese version of SV, 9-2LE, and IEC 61869-9 these similarities are sample rate and physical connectors. The sample rate used in China is 80 samples per cycle at a nominal system frequency of 50 Hz which matches the 9-2LE configuration for protection systems. The type of connection used on the MUs and IEDs are LC type connections and use 1310nm, multi-mode, full-duplex, two strand fibre optic cables which matches IEC 61869-9. The use of duplex LC connections eliminates the Rx/Tx cross connection issues that are common with ST type connections. Although the IEC 61869-9 standard provides a flexible dataset configuration compared to 9-2LE, it still has limits on the configurability. For example, the minimum number of currents or voltages is 1, the maximum number is 20 for general measurement and protection; the maximum number is 8 for quality metering; and the maximum number is 20 for DC instrument transformers. The Chinese version of SV has a minimum of 12 channels but does not specify the maximum number. We have seen configurations up to 24 channels. The SVID in 9-2LE is a fixed format in the 9−2 message where the MsvID is created from the user configurable attribute LDName. The LDName is configured by adding a user configurable prefix and suffix to the string "ppppMUss01" or "ppppMUss02" where "pppp" is the parameter "LDpre" and "ss" is the parameter "LDsuf". The string MU and 01/02 are fixed and cannot be changed by the user. The value 01 is used for 80 samples/cycle and the confRev value and the sample sync also user configurable. The SVID in data streams from a MU in China is not fixed and can be set by the user.

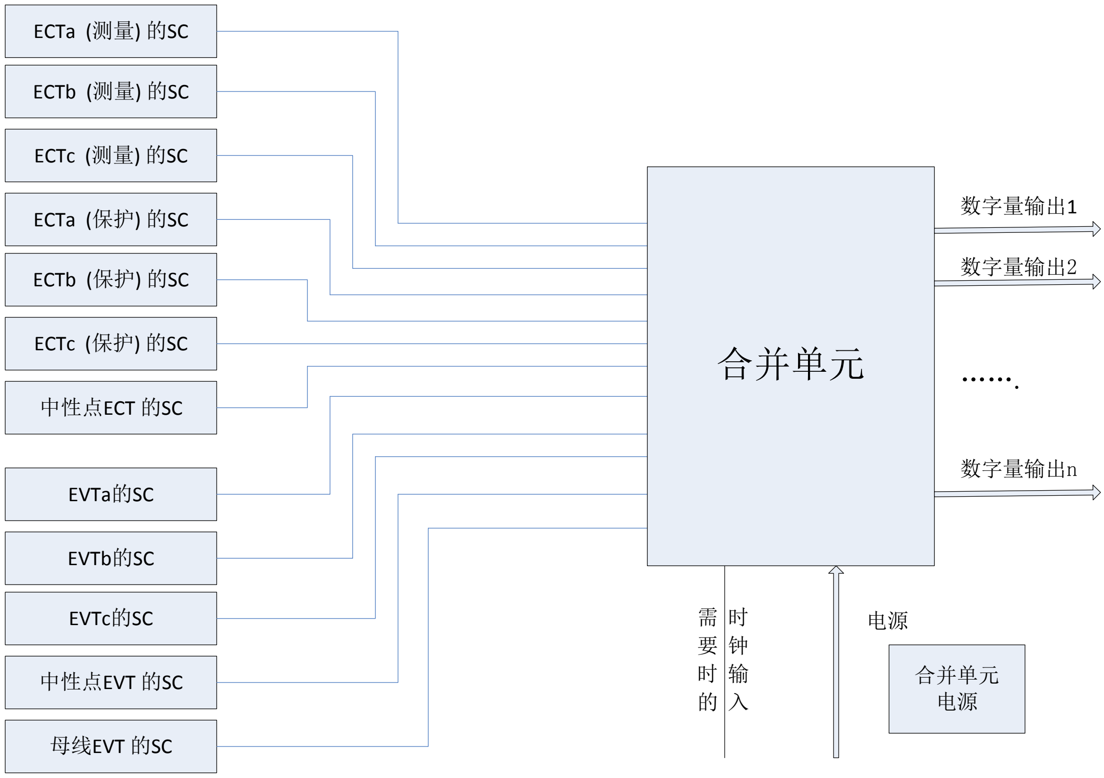


Figure 3 shows a typical configuration of a Chinese merging unit and system architecture of the electric transducer. Note that is typical channel input layout, the channel input layout might be different.

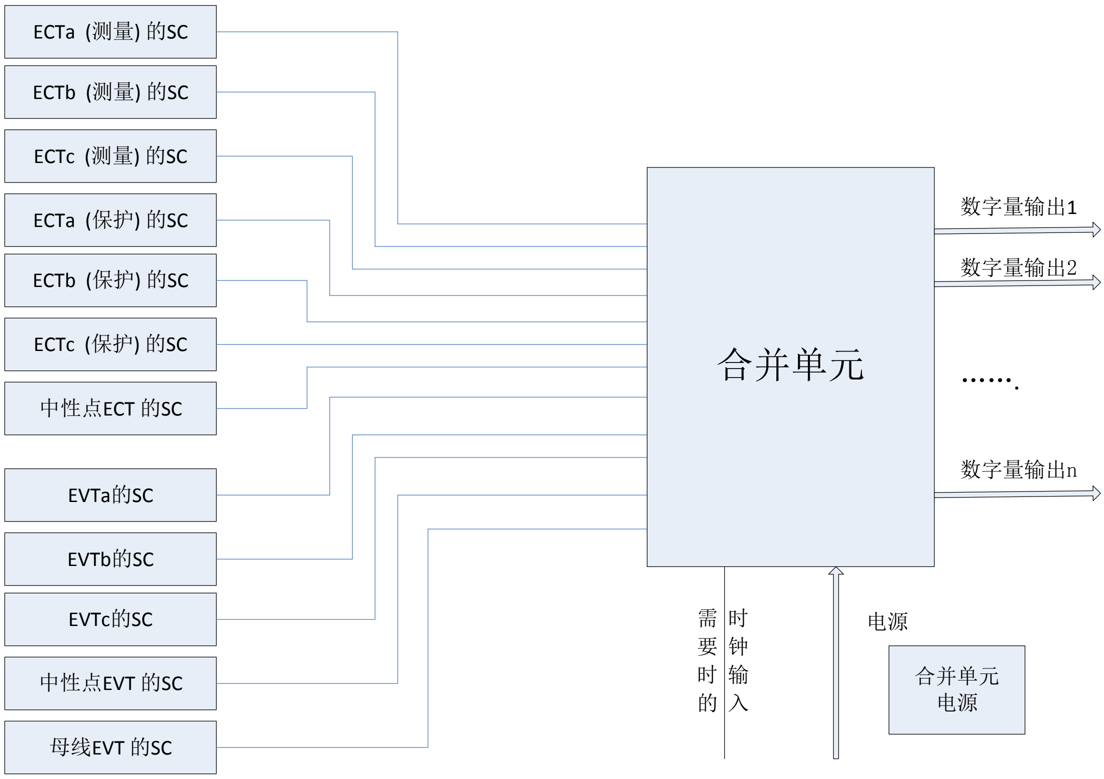


Figure 3: Typical Configuration of Chinese MU

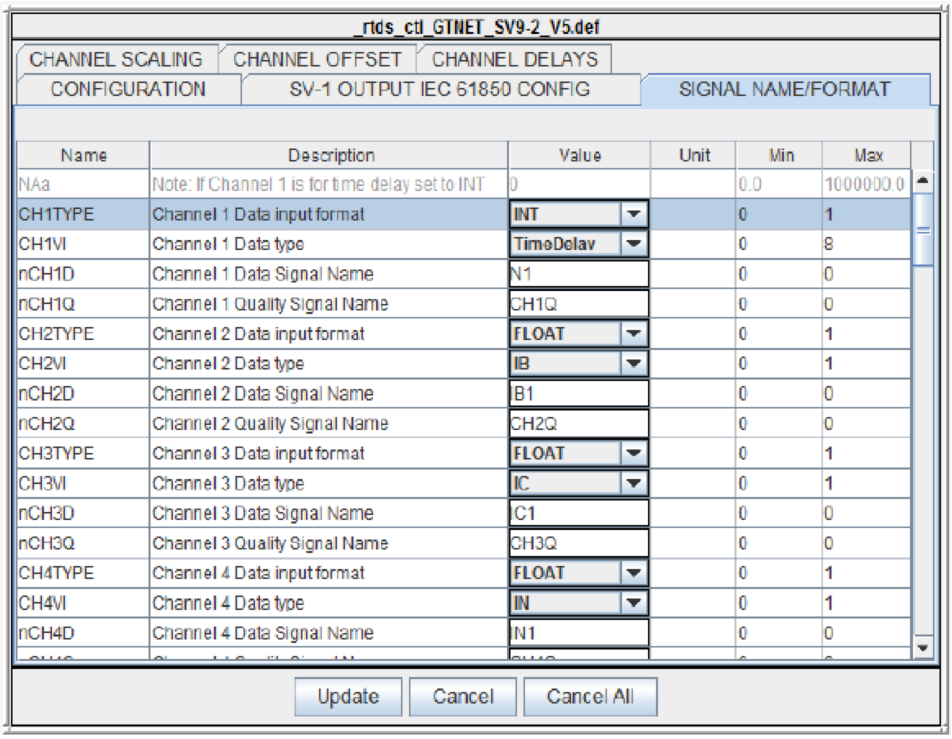
The 12 channels typically might be:

- ECTa(Measure), ECTb(Measure), ECTc(Measure),

- ECTa(Protection), ECTb(Protection), ECTc(Protection),
- Neutral ECT,
- EVTa, EVTb, EVTc,
- Neutral EVT,
- EVT(Busbar voltage).

Changing 9-2LE firmware to the more generalized Chinese version of SV required changes to allow configurable datasets, changes to the SCL file, and more importantly changes to ensure low jitter transmission of Ethernet packets. The maximum number of channels is 24, each channel can be a Float or an Integer, and each channel can be a voltage or current, while channel 1 can also be selected as Time Delay. As mentioned earlier, many devices transmitting SV packets will not meet the low jitter requirement of 10 μsec or less. The existing GTNET-SV SV packet transmission performance was not capable of meeting this requirement and needed to be improved. The original GTNET architecture for processing SV messages was deemed inadequate and required reworking of the FPGA firmware to provide a hardware-assist to ensure very low-jitter when transmitting SV packets to the PHY. With the new GTNET FPGA, SV packets are buffered and an FPGA module is used to transmit the packet to the Ethernet controller at a precise time instant. This results in better jitter performance than could be achieved by the previous GTNET-SV software-based packet transmission architecture.

Figure 4 shows the configuration of the GTNET-SV using the lower-jitter Non-9-2LE option. Note that the channel 1 data type is set to "TimeDelay" and the data input type is set to "INT".



Name	Description	Value	Unit	Min	Max
NAa	Note: If Channel 1 is for time delay set to INT	0		0.0	1000000.0
CH1TYPE	Channel 1 Data input format	INT		0	1
CH1VI	Channel 1 Data type	TimeDelay		0	8
nCH1D	Channel 1 Data Signal Name	N1		0	0
nCH1Q	Channel 1 Quality Signal Name	CH1Q		0	0
CH2TYPE	Channel 2 Data input format	FLOAT		0	1
CH2VI	Channel 2 Data type	IB		0	1
nCH2D	Channel 2 Data Signal Name	B1		0	0
nCH2Q	Channel 2 Quality Signal Name	CH2Q		0	0
CH3TYPE	Channel 3 Data input format	FLOAT		0	1
CH3VI	Channel 3 Data type	IC		0	1
nCH3D	Channel 3 Data Signal Name	C1		0	0
nCH3Q	Channel 3 Quality Signal Name	CH3Q		0	0
CH4TYPE	Channel 4 Data input format	FLOAT		0	1
CH4VI	Channel 4 Data type	IN		0	1
nCH4D	Channel 4 Data Signal Name	N1		0	0

Figure 4: Configuration of GTNET-SV

3 Testing of the IEDs using SV

Two networks were used to test a line distance protection relay and a transformer differential relay at 2 different manufacturers. The manufacturers were Beijing Sifang Automation Co. Ltd, XJ Electric Co. Ltd. The results were correct but to limit duplication, the results are presented from XJ. It should be pointed out that the same Ethernet port from the XJ device under test was used for SV, GOOSE, and MMS during the test.

Typical configuration of the SV reception and GOOSE reception from the RTDS is shown in Figure 5 for the transmission line network. Note: black text is translation of the description and is not part of the original file.


```xml
<?xml version="1.0" encoding="utf-8"?>
<CFG>
  <NPI board="0" gs_port_list="2-A;2-B;2-C;2-D;2-E;3-A;3-B;3-C;" sv_port_list="2-F;2-G;2-H;3-D;3-E;3-F;3-G;3-H;">
    <SMV_RECV eth_id="0" sampleIn="2" pro_chl_count="19">
      <SMV>
        <SMV_INI eth_map_link="2-B" cascade="0" eth_id="3" appId="16388" mac="01-0C-CD-04-00-04" svid="GT801TMU0101" vlanId="0" priority="4" conRev="1" format="smv92" />
        <SMV_CHL id="0" desc="合并器额定延时" pro_id="0" /> (Rated MU time delay)
        <SMV_CHL id="1" desc="保护电流A相1" pro_id="1" /> (Protection current Phase A 1)
        <SMV_CHL id="2" desc="保护电流A相2" pro_id="2" /> (Protection current Phase A 2)
        <SMV_CHL id="3" desc="保护电流B相1" pro_id="3" /> (Protection current Phase B 1)
        <SMV_CHL id="4" desc="保护电流B相2" pro_id="4" /> (Protection current Phase B 2)
        <SMV_CHL id="5" desc="保护电流C相1" pro_id="5" /> (Protection current Phase C 1)
        <SMV_CHL id="6" desc="保护电流C相2" pro_id="6" /> (Protection current Phase C 2)
        <SMV_CHL id="7" desc="电压A相1" pro_id="7" /> (Line voltage Phase A 1)
        <SMV_CHL id="8" desc="电压B相1" pro_id="8" /> (Line voltage Phase B 1)
        <SMV_CHL id="9" desc="电压C相1" pro_id="9" /> (Line voltage Phase C 1)
        <SMV_CHL id="10" desc="电压A相2" pro_id="10" /> (Line voltage Phase A 2)
        <SMV_CHL id="11" desc="电压B相2" pro_id="11" /> (Line voltage Phase B 2)
        <SMV_CHL id="12" desc="电压C相2" pro_id="12" /> (Line voltage Phase C 2)
        <SMV_CHL id="13" desc="I母保护电压A相1" pro_id="13" /> (Bus I voltage Phase A1)
        <SMV_CHL id="14" desc="I母保护电压A相2" pro_id="14" /> (Bus I voltage Phase A2)
        <SMV_CHL id="15" desc="I母保护电压B相1" pro_id="15" /> (Bus I voltage Phase B1)
        <SMV_CHL id="16" desc="I母保护电压B相2" pro_id="16" /> (Bus I voltage Phase B2)
        <SMV_CHL id="17" desc="I母保护电压C相1" pro_id="17" /> (Bus I voltage Phase C1)
        <SMV_CHL id="18" desc="I母保护电压C相2" pro_id="18" /> (Bus I voltage Phase C2)
      </SMV>
    </SMV_RECV>
    <GOOSE_SEND eth_id="2" redirect="0" redir_eth_id="2" redir_eth_id_mask="0" redir_filter="0" pro_io_groups="1" t0="5000" t1="2" t2="4" t3="8">
      <GOOSE gocbRef="WBHPIGO/LLN0$GO$GO_Gcb1" dataSet="WBHPIGO/LLN0$dsGOOSE" goID="PIGO/LLN0.GO_Gcb1" dacount="27" cpu_no="0">
        <GOOSE_INI eth_id="1936" appId="277" mac="01-0C-CD-01-01-15" vlanId="0" priority="4" conRev="1" />
        <GOOSE_TDL name="tdl0" tdl="Bool" />
        <GOOSE_TDL name="tdl1" tdl="Bool" />
        <GOOSE_TDL name="tdl2" tdl="Bool" />
        <GOOSE_TDL name="tdl3" tdl="Bool" />
        <GOOSE_TDL name="tdl4" tdl="Bool" />
        <GOOSE_TDL name="tdl5" tdl="Bool" />
        <GOOSE_TDL name="tdl6" tdl="Bool" />
        <GOOSE_TDL name="tdl7" tdl="Bool" />
        <GOOSE_TDL name="tdl8" tdl="Bool" />
        <GOOSE_TDL name="tdl9" tdl="Bool" />
        <GOOSE_TDL name="tdl10" tdl="Bool" />
        <GOOSE_TDL name="tdl11" tdl="Bool" />
        <GOOSE_TDL name="tdl12" tdl="Bool" />
        <GOOSE_TDL name="tdl13" tdl="Bool" />
        <GOOSE_TDL name="tdl14" tdl="Bool" />
```


Figure 5: Configuration of SV and GOOSE reception for Line Protection Tests

Figure 6 shows the result of a BC fault at 50% of 97 km long transmission line. Sampled values were generated by the RTDS and transmitted to the IED using the format described in figure 3. GOOSE messages were transmitted and received by the both the RTDS and the IED. The RTDS provided the circuit breaker status while the IED provided the Trip and Reclose messages using GOOSE.

Figure 6: Line Protection Tests Result for fault at 50% of line

Figure 7 shows the network configuration used to test the Sifang and XJ transformer protection relays. A wye-wye-delta connected transformer was used with faults switches to cause internal faults and saturation to test inrush conditions during transformer energization. The results of metering on the relay during normal operation was overlaid onto the figure and show negligible differential currents Ida, Idb, and Idc.

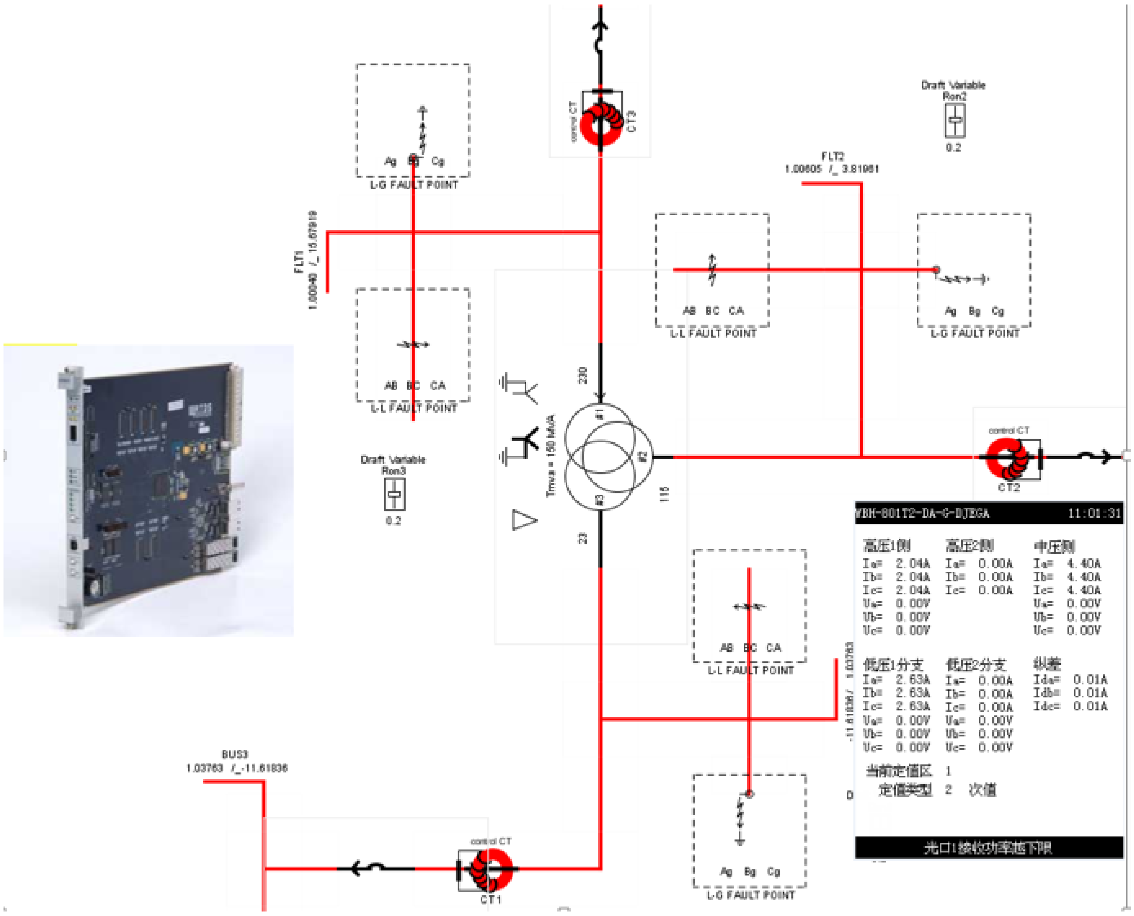


Figure 7: Configuration of Network for Transformer Protection Tests

Figure 8 shows the control logic to operate circuit breaker 2. This logic is used to create maximum Inrush current conditions by opening the circuit breaker after the flux (FluxA) has a positive zero crossing. Closing the circuit breaker when the winding voltage (N22) has a positive zero crossing will cause the worst case inrush current conditions.

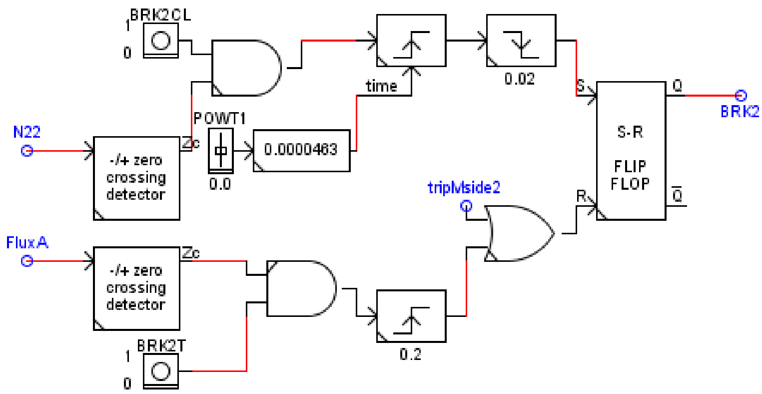


Figure 8: Control Logic to Trap Flux

Figure 9 shows the faulted current waveforms for an internal phase A-Neutral fault that caused the differential relay to operate. IBUR1A, B, C is the current in the delta connected 23kV winding, IBUR2A, B, C is the current in the wye connected 115 kV winding and IBUR3A, B, C is the current in the wye connected 230 kV winding. A total of 19 channels including the MU time delay channel were used for the SV data in the simulation. The black digital trace IED1BI1 is the GOOSE signals mapped from the relay to the RTDS to provide tripping. The other digital traces BRK1, 2, and 3 are the signals to control the 3 circuit breakers connecting the transformer to the electrical network. The status of each breaker was also transmitted from the RTDS to the IED via GOOSE.

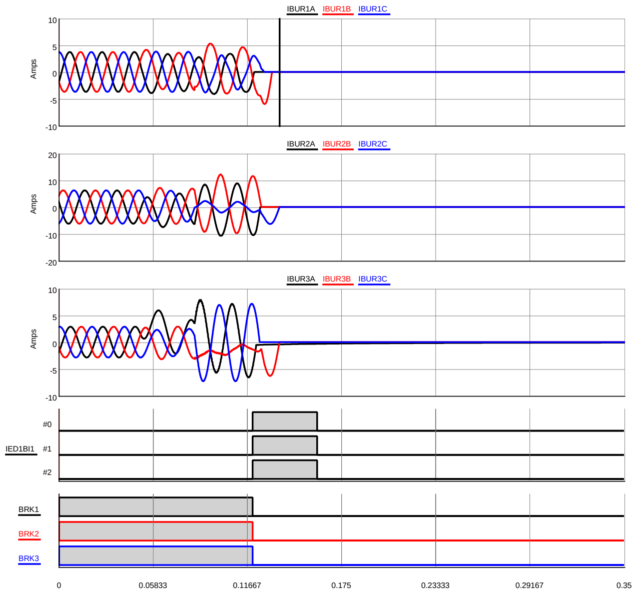


Figure 9: Internal A-N fault and IED operation

Figure 10 shows the inrush current waveforms during energization of the transformer which did not cause the differential relay to operate. Circuit breaker 2 is closed and a resultant inrush current with harmonic content is subjected to the relay.

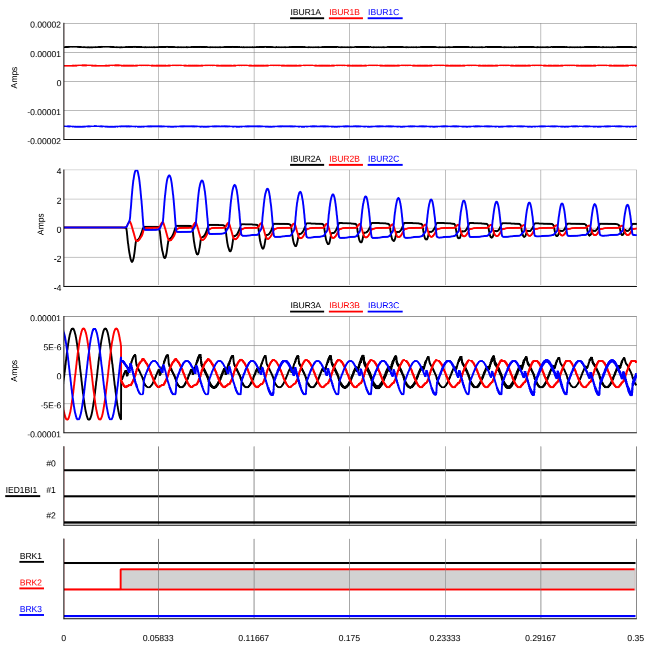


Figure 10: Transformer Inrush Current

4 Conclusions

In this paper there were four major items discussed that affect the design and implementation of SV enabled merging unit and IEDs' in substations.

The mode of operation between the MU and the IED is the main factor that will affect the overall design and implementation. Using a properly engineered process bus network (one-to-many) with 9-2LE or 9-2 versus individual 9-2 point-to-point connections changes the MU design and the IED design as well as the design of the time distribution in the substation. And of course the software and hardware tools used to configure and test the point-to-point SV will be different as well. The test results conducted by RTDS during development and during filed testing in China have shown that a Real Time Digital Simulator can be used to faithfully produce the point-to-point SV configuration used in China.

The Chinese SV point-to-point connection between the MU and IED have shown requirements of Ethernet controllers on the IED and MU that can operate and service as many as 24 concurrent connections with bandwidths of up to 192 Mbits/second. MUs' and IEDs' in China have Ethernet designed and built to handle the increased complexity and increased CPU requirements for point-to-point operation with SV. The Ethernet can also handle the GOOSE, MMS, and IEEE 1588 traffic besides the SV all at the same time, as was done during the tests at XJ Electric Co. Ltd in Xuchang, China.

The differences between 9-2LE and the Chinese version of SV are not overly complex when comparing the datasets. Both datasets use 80 samples per cycle while the 9-2LE dataset is fixed configuration with 8 channels while the Chinese version is a variable configuration with up to 22 channels. The Chinese version of SV must also use channel 1 to indicate the overall point-to-point time delay from the MU to the IED. The inclusion of a time delay channel is required for the IED to time align samples from different MUs'.

GPS time synchronization of the MU and IED is not needed when the point-to-point method is used and can simplify the distribution of a time source within a substation to some degree but it is still necessary to distribute the time source to all the merging units within a substation. It would seem that having all the IEDs' within a digital substation use a common time reference is a logical choice especially when using events from multiple IEDs' for post fault analysis.

References

[1] Realization and Application of Peer-to-peer IEC 61850-9-2 Sample Value Transmission in Digital Substation protection IEC 61850-9-2

[2] Electric power industry standard of the people's Republic of China- DL／T 282—2012