Design and Performance Testing of a Multivendor IEC61850–9-2 Process Bus Based Protection Scheme

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***Abstract*—The deployment of IEC61850–9-2 process bus increases the possibilities that new and refurbished substations will be based on the use of Ethernet communication networks with free allocation of Protection and Control functions. The design and performance testing of a multivendor prototype protection scheme based on the process bus for use in a mesh transmission substation is presented. A practical test setup is developed to evaluate the performance of the protection scheme, including interoperability between different manufacturers, degree of maturity, robustness, and possible benefits. This integrates network analysis software, test sets, conventional hardwired and IEC61850–9-2LE protection Intelligent Electronic Devices, Merging Units, Ethernet Switches, Fiber Optic communications and an IEC61850 process bus. The worst case scenario of traffic based on the current 100 Mbps network is created and the system responses investigated. Recommendations for process bus communication requirements are presented to avoid the degradation of system performance.**

***Index Terms*—IEC61850–9-2, intelligent electronic devices, merging unit, process bus, protection & control, sampled values.**

I. Introduction

THE IEC61850 standard ”Communication Networks and Systems for Power Utility Automation” permits utilities to consider new possibilities for secondary systems in new and refurbished substations [1]. Process bus technology utilises the transmission of Sampled analogue Values (SVs) of currents and voltages according to IEC 61850–9-2 and trips by high-speed peer-to-peer communications of Generic Object Oriented Substation Event (GOOSE) messages according to IEC 61850–8-1 over Ethernet [2]. In comparison with a conventional hardwired protection scheme, Merging Units (MUs) are introduced and work as the interface between current/voltage transformers, switchgear, and bay devices such as protective relays, bay controllers or meters.

The primary plant and instrument transformers used in transmission substations generally remain in-service for many decades, typically 40 – 70 years, and are renewed only when physically or mechanically life-expired. However, the secondary systems, which include protection and control, are changed significantly more frequently. The current replacement rate for protection and control on the UK transmission network is about 5% per annual, i.e., it takes approximately 20 years to complete the replacement cycle. However, the asset life of numerical protection and control is often considered to be 15 years, although in many cases, 10 years may be more realistic due to declining technical knowledge and support, product obsolescence and difficulties in obtaining spares.

The application of process bus in substations can overcome this problem (i.e., better lifecycle co-ordination between primary and secondary systems) and is expected to bring significant benefits. This includes cost reduction of the system by removing conventional copper wiring, reduced project duration as secondary equipment renewals can be undertaken in a safer, quicker and easier way, simplification of configuration changes required during the lifetime of a substation, enhanced protection and control flexibility, improved vendor and different generation interoperability, simpler factory and site acceptance testing, greater safety of personnel involved in the maintenance process, etc.

Adequate architecture design and appropriate system configuration are essential to ensure the performance of the protection and control scheme using IEC61850 process bus meets or exceeds that of the hardwired scheme. The need to restrict multicast process bus traffic to specific subscribers and to avoid overloading the network with excessive numbers of data streams was investigated using multiple Merging Units supplied by different manufacturers and the OMICRON CMC 256plus and CMC 850 test sets. This is based on a 100 Mbps network and the overall system response investigated. The lessons learnt can provide a reference for all the participating parties and create a roadmap to achieve the most efficient application and wide deployment of the next generation of digital P&C systems, based on the IEC61850 process bus.

II. Lab Prototype Design and Test Setup

The key objective of this project is to investigate, quantify and optimise the level of security, dependability and operating speed of the protections used in a mesh substation as shown in Fig. 1. A mesh busbar scheme is frequently used at the 400 kV or 275 kV transmission level in the UK. A transformer and a feeder are linked at each corner of the mesh and four circuit breakers used to complete the mesh interconnection. A fault at any corner trips the two breakers associated with that corner and initiates

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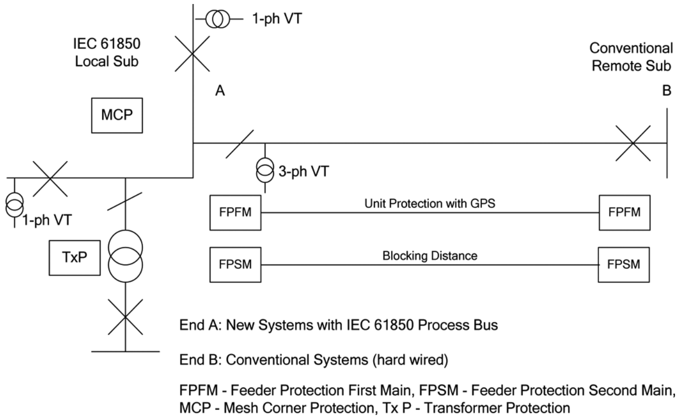


Fig. 1. Schematic diagram of a mesh substation.

intertripping necessary to open the circuit breakers at the remote ends.

The local substation A in Fig. 1 uses IEC61850 process bus architecture and the remote ”double busbar” substation B uses similar but conventional hardwired protection. The Local Top (LT) and Remote Top (RT) P545 relays of the panels are configured as a Feeder Main-1 current differential scheme, the communication links between LT and RT are fiber optic, whilst Local Bottom (LB) and Remote Bottom (RB) P545 relays are configured as a Feeder Main-2 distance scheme. Standard 100/1000TX electrical cables with RJ45 connectors were used to connect the Local Panel’s IEC 61850 version protective IEDs to the Ethernet communication network.

The Merging Units used in this project were designed according to the UCA International Users Group Implementation Guideline. It specifies the data set ”PhsMeas1” with 8 elements (4 currents and 4 voltages) and transports the sampled values of 3-phase plus neutral currents and voltages. MUs from different manufactures have been wired into the system to investigate the interoperability.

OMICRON CMC 256plus and CMC 850 test sets provide analog signals to the remote P545 hardwired relay and IEC61850–9-2 SVs (direct injection or via Merging Units) signals through a Ethernet switch to the local P545 61850 relay. ”Star” process bus architecture was adopted and network analysis software (Wireshark and SVScout) were used to provide detailed views of messages transmitted along the process bus. The relays responses can then be recorded and analysed.

III. Result Investigation and Discussion

A. Characteristic Verification Tests

The operating characteristics of the hardwired and IEC 61850–9-2 relays were verified by comprehensive tests, i.e., ”differential configuration, operating characteristic, trip-times and harmonic restraint” tests for the differential scheme and ”shot/check/search” tests for the distance scheme.

Both LT and RT differential relays remain stable during the differential configuration test, which simulates a fault outside the protection zone. The differential operating characteristic test proved that the IEC 61850 relay trips in accordance with the same characteristic as the hardwired relay [3], [4].

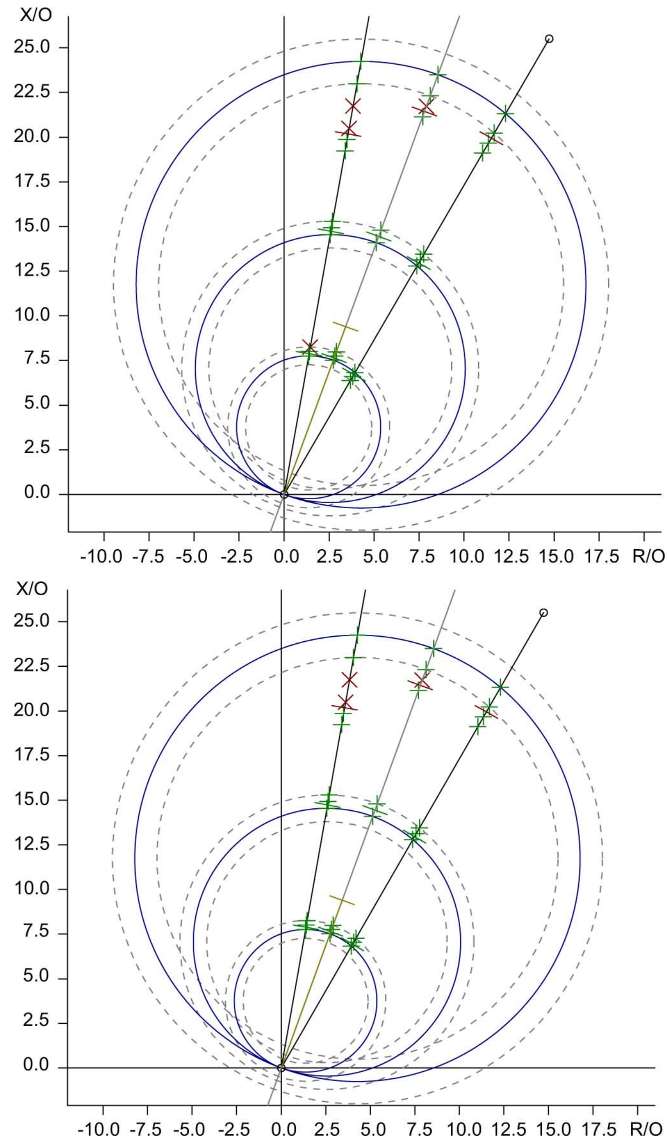


Fig. 2. Search test for LB (left) and RB (right) P545 Distance relay-L1-E.

Table I gives the shot test results for LB and RB P545 when applied with L-E fault. Three check lines at 40r, 70r and 100r were defined to test zone reaches. Three search lines at 60r, 70r, 80r with fault inception angles at 0r, 30r, 60r, 90r were defined to test the boundary between the zones. Examples of search test results for both distance relays are presented in Fig. 2 (L-E fault with fault inception angle of 60r). The differences between LB and RB P545’s operating speed performance are similar to that of two identical hardwired distance relays. The results obtained from these tests illustrate that the performances of the IEC61850 relays are comparable with the conventional hardwired relays.

B. MUs Interoperability and Time-Offset Tests

Interoperability is one of the major advantages of IEC 61850. Protection systems with devices from a single manufacturer generally work well together. In this project, some third party MUs-MU from vendor A and B are connected to the current differential scheme to verify interoperability. Fig. 3. shows the

TABLE I
SHOT TEST FOR LB AND RB P545 DISTANCE RELAYS-SINGLE PHASE FAULT.

Fault Type	|Z| (Ω)	Phi°	t_{nom} (ms)	t act. (ms)		Dev.
			LB RB	LB	RB	Difference (LB-RB)
L1-E	5.000	70.00	0.000	18.70	19.70	-1.00ms
	12.50	70.00	200.0	218.4	216.2	1.1%
	20.00	70.00	600.0	617.8	616.0	0.3%
L2-E	5.000	70.00	0.000	20.40	18.80	1.60ms
	12.50	70.00	200.0	219.2	216.3	1.45%
	20.00	70.00	600.0	619.4	618.8	0.10%
L3-E	5.000	70.00	0.000	19.30	19.70	-0.40ms
	12.50	70.00	200.0	218.4	217.1	0.65%
	20.00	70.00	600.0	618.4	617.7	0.117%

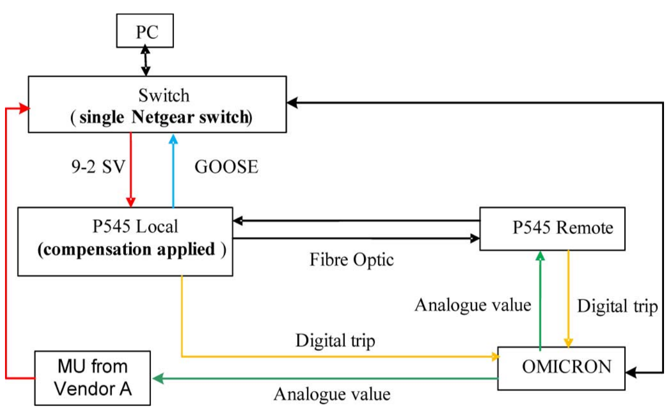


Fig. 3. Interoperability test setup with vendor A MU.

interoperability test setup with a MU from vendor A, where local P545's time compensation is applied.

No GPS time synch signal was sent into the MU supplied by vendor A, OMICRON test set was configured to generate two analogue data streams, one hardwired to the remote P545 and the other to the local P545 through vendor A MU. When first connected to this MU, local P545 became slow in responding when navigating the readings from the relay's front panel (necessary to wait about 5 10 seconds for the screen to update after pressing the button). The results indicate that with 881 No. of Adjustments (N.o.A-this manual adjustment function is designed to automatically compensate the MU delay and one step of adjustment equals 1ts) available in the local P545, the communication of this multi-vendor system is initially healthy, i.e., the local P545 is able to interpret the SV packages sent by MU from vendor A. However, after a very short time, local P545 relay issued phase A&B/3 phase trip signals and also inter-tripping to remote P545, whilst the readings were approximately the same as before the tripping.

The combination of vendor A MU and P545 relay resulted in a mal-operation. It appears, the third party MU and the P545 can not communicate with each other correctly and the inference is the relay is mal-operating. It is likely to be a compatibility issue between the two IEC 61850 implementations or a timing issue.

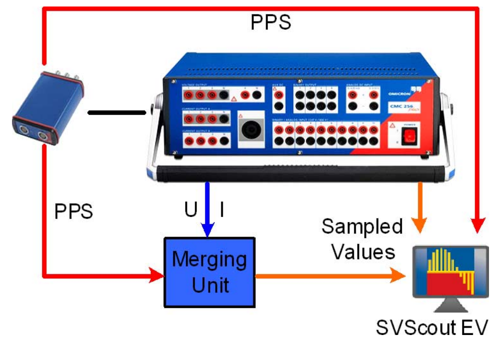


Fig. 4. MU time offset test setup using SVScout EV.

The time-offset of the MUs was tested using the CMIRIG-B unit working with the CMC 256 plus test set as the time source, as shown in Fig. 4. The SVScout EV works in combination with a special PCI-Express network adapter which assigns highly accurate time stamps to the captured packets. The special network adapter can also be synchronized with the same pulse per second signal (PPS) that is used for synchronizing the merging unit. So not only the relative timing of the packets, but also the absolute delay from the theoretical sampling time can be measured. Typical MU delay is 2 3 Samples, which works out to be 500ts 750ts@80 samples/cycle, the max MU delay should be 3 ms+10%. The time offset introduced by the IMU (prototype MU supplied by P545 manufacturer) is less than 500ts, the results obtained for vendor A is 350ts, for vendor B is 200ts; all well within the standard requirement.

All the MUs from three manufacturers together with the SV data stream generator of two CMC test sets were connected to a "Star" topology process bus and their interoperability was further investigated. The number of data streams from different SV sources was gradually increased from two to ten. The SV generated by vendor A MU would drop off and disappear when the number of total data streams reaching six. The vendor A MU's SV data stream appears to be more data-heavy, whilst the remaining nine data streams can operate together in the same network even when left running continuously. This was both captured and proved by SVScout and Wireshark, and the detailed investigations are shown in Table II.

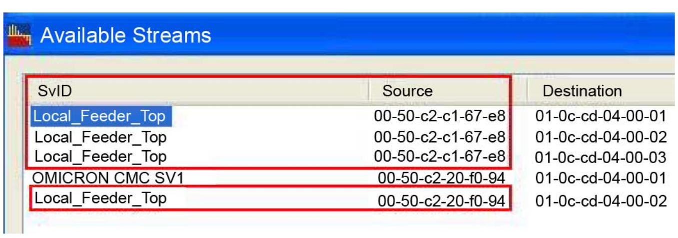
The readings of both relays are stable with or without compensation over a given time period. Considering the system was working at ambient temperature, the drifting offset was as expected negligible

C. Stressed Process Bus Communication Tests For Current Differential Scheme

Process bus traffic was deliberately stressed using two approaches. The first approach created "misconfigurations" by setting identical SVID data streams to "confuse" the subscriber relay. The second approach overloaded the 100 Mbps process bus by the inclusion of an excessive number (up to 9) of SV data streams from the multivendor MUs and CMC test sets. The system responses were then investigated.

TABLE II
INTEROPERABILITY TEST RESULT FOR MULTI-VENDOR MUs.

IMU	Vendor A MU	Vendor B MU	CMC 256	CMC 850	Total No. of SVs	Results
1	0	1	0	0	2	√
1	1	0	0	0	2	√
1	0	0	1	0	2	√
0	1	1	0	0	2	√
0	0	1	1	0	2	√
0	1	0	1	0	2	√
1	1	1	0	0	3	√
0	1	0	2	0	3	√
0	1	0	0	3	4	√
2	1	1	0	0	4	√
3	1	1	0	0	5	√
3	0	1	1	0	5	√
0	1	0	1	3	5	√
0	1	0	2	3	6	MUA SV lost
0	1	2	0	3	6	MUA SV lost
3	1	1	1	0	6	MUA SV lost
3	0	1	2	0	6	√
3	0	1	2	3	9	√


Available Streams

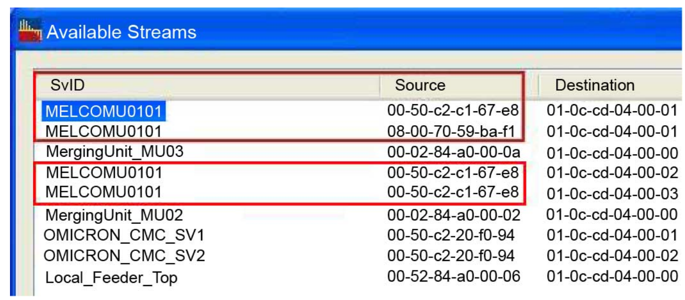
SvID	Source	Destination
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-01
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-02
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-03
OMICRON CMC SV1	00-50-c2-20-f0-94	01-0c-cd-04-00-01
Local_Feeder_Top	00-50-c2-20-f0-94	01-0c-cd-04-00-02

Fig. 5. SVs capture of current diff test sets direct injection-misconfiguration.


Available Streams

SvID	Source	Destination
OMICRON_CMC_SV1	00-50-c2-20-f0-94	01-0c-cd-04-00-01
OMICRON_CMC_SV2	00-50-c2-20-f0-94	01-0c-cd-04-00-02
MergingUnit_MU02	00-52-84-a0-00-06	01-0c-cd-04-00-00
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-01
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-02
Local_Feeder_Top	00-50-c2-c1-67-e8	01-0c-cd-04-00-03
MergingUnit_MU03	00-02-84-a0-00-0a	01-0c-cd-04-00-00
Local_Feeder_Top	00-02-84-a0-00-02	01-0c-cd-04-00-00
MELCOMU0101	08-00-70-59-ba-f1	01-0c-cd-04-00-01

Fig. 6. SVs capture of current diff ALSTOM IMU injection-misconfiguration.


Available Streams

SvID	Source	Destination
MELCOMU0101	00-50-c2-c1-67-e8	01-0c-cd-04-00-01
MELCOMU0101	08-00-70-59-ba-f1	01-0c-cd-04-00-01
MergingUnit_MU03	00-02-84-a0-00-0a	01-0c-cd-04-00-00
MELCOMU0101	00-50-c2-c1-67-e8	01-0c-cd-04-00-02
MELCOMU0101	00-50-c2-c1-67-e8	01-0c-cd-04-00-03
MergingUnit_MU02	00-02-84-a0-00-02	01-0c-cd-04-00-00
OMICRON_CMC_SV1	00-50-c2-20-f0-94	01-0c-cd-04-00-01
OMICRON_CMC_SV2	00-50-c2-20-f0-94	01-0c-cd-04-00-02
Local_Feeder_Top	00-52-84-a0-00-06	01-0c-cd-04-00-00

Fig. 7. SVs capture of current diff vendor B MU injection-misconfiguration.

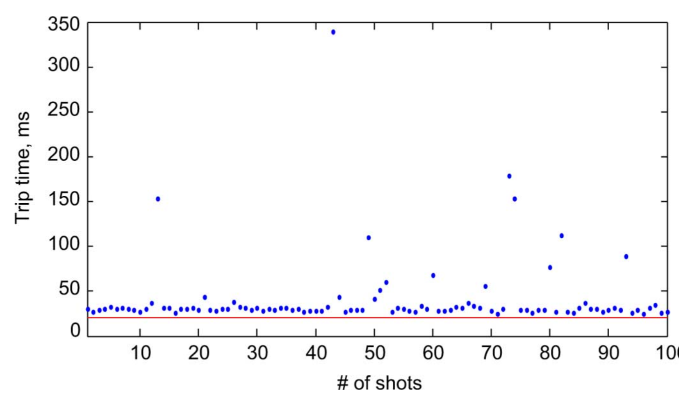


Fig. 8. Misconfiguration trip time distribution for LT P545 with IMU.

Three different configurations were constructed to test the current differential scheme's responses with misconfiguration on the process bus (this may be caused by human error). These involved test sets direct injection, with the IMU and with the third party vendor B MU. Star topology with a single Ethernet switch from Netgear was used throughout the tests. Test results obtained without misconfiguration were used as a benchmark.

The LT P545 was injected using multiple SV data streams configured with the same SVID, but from different sources. This was designed to confuse the relay, as shown in Fig. 5. Similarly, Figs. 6 and 7 demonstrate the process bus SVs captures with the IMU and the vendor B MU. Two shot test points were selected, one in the tripping area of the lower percentage biased characteristic and the other in the tripping area of the higher percentage biased characteristic. Each test was repeated 100 times and the P545's manual adjustment was enabled during all the tests.

For the shot test in the lower percentage biased characteristic with the IMU, the relay appeared to have a delay in operating speed and a higher standard deviation, as shown in Fig. 8, where the red line works as the 20 ms benchmark. For all the other test cases, the average operating performance is acceptable. These tests indicate that with misconfiguration on the process bus, there is a risk of confusing the relay, consequently unacceptable delayed operation may occur. This must be avoided before the commissioning of the system to ensure the dependability of the protection scheme.

With a similar setup as the "misconfiguration" test, the overloading scenarios were created by connecting all the available SVs sources to the process bus (9 SV data streams). Test results obtained without the overloading of the process bus were used as a benchmark, as shown in Table III, see test type "Base" row. The results prove that the current differential scheme's operating speed performance is not degraded with the relays compensation function applied, the only case showing 3 ms delay is the multi-vendor connection with vendor B MU and test point in the tripping area of the lower percentage biased characteristic. The N.o.A in this case is as high as 940 and the relay's MU delay needs to be set to 3 ms to ensure the combined multi-vendor system operates correctly.

Theoretically 20 SV (5.3 Mbit/s@50 Hz) data streams would occupy the full network capacity, but normal expectations are

TABLE III
TEST RESULTS FOR CURRENT DIFF SCHEME WITH STRESSED COMMUNICATION.

Test type	Statistic (ms)	Lower bias characteristic (100 shots respectively)			Higher bias characteristic (100 shots respectively)		
		Test set direct (N. o. A: 168)	IMU (N. o. A: 237)	Vendor B MU (N. o. A: 940 MU delay=3ms)	Test set direct (N. o. A: 168)	IMU (N. o. A: 234)	Vendor B MU (N. o. A: 940 MU delay=3ms)
Base	Average	25.059	25.336	28.039	24.346	24.633	24.774
	Standard Deviation	1.3691	1.4512	1.5804	1.3408	1.2956	1.3488
Mis Conf.	Average	26.06	**41.273**	28.437	24.290	25.004	24.808
	Standard Deviation	1.9208	**40.0809**	1.2249	1.3040	1.2554	1.4003
Over-loading	Average	24.978	25.686	28.397	24.204	24.635	24.923
	Standard Deviation	1.2551	1.2848	1.7035	1.3314	1.2764	1.3893

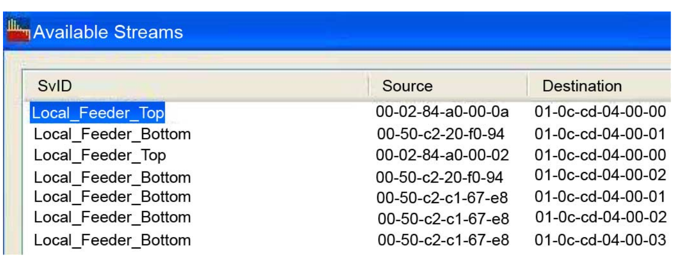


Fig. 9. SVs capture of test sets direct injection- LB misconfiguration.

around 12 14 streams when using a star architecture. These tests indicate that for nine SV data streams, the process bus network can cope correctly, introducing no significant impact on the relays performance.

D. Stressed Process Bus Communication Tests For Distance Scheme

As in section C, with the test sets direct injection configuration, a test point was placed in distance Zone 1 (at 4O), five SV data streams were configured with the same SVID, as shown in Fig. 9, tests were performed 100 times and compared with the same incorrect configuration for the current differential scheme, the distance relay had more maloperations as shown in the trip time distributions plotted in Fig. 10. The misconfiguration scenario must be avoided for the LB P545 to operate correctly.

Similar overloading test was carried out on the distance relay and the results prove that the distance relay's operating speed performance is not degraded for L-E and L-L faults, but it is slightly delayed and has higher standard deviations for three phase faults, when 8 SV data streams are running along the network [5].

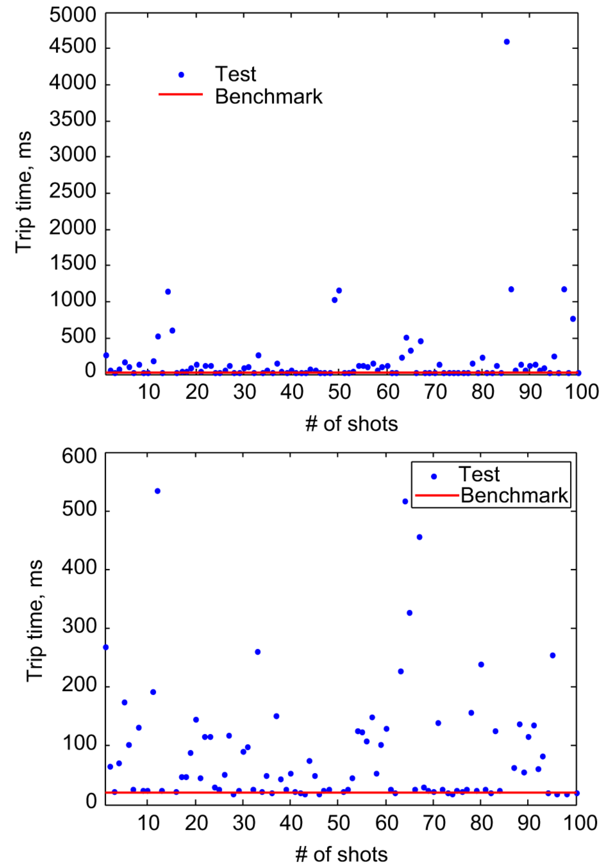


Fig. 10. Misconfiguration test trip time distribution for LB P545.

IV. CONCLUSIONS

A prototype protection scheme based on the IEC61850–9-2 process bus was designed for use on the mesh-corner of a UK transmission substation. Comprehensive tests were carried out on conventional hardwired relays and IEC61850–9-2LE based relays. Results indicate their operating performance is compatible. Multivendor prototype MUs were connected to a process bus and the interoperability and time offset were assessed. Instantaneous interoperability between different suppliers is not optimal and does not currently work in some vendor combinations.

The protection scheme performance was further evaluated in the worst case scenario of process bus traffic with "misconfiguration" and "overloading" conditions. Recommendations for process bus communication requirements were presented to avoid the degradation of system performance. Possible causes of relays incorrect operation were recognised and then corrected. The lessons learnt can help increase utilities acceptance of IEC61850 process bus based protection technology and the implementation of the "copper-less" secondary systems.

Multi-vendor solutions remain the target to achieve. Conformance certifications of products and tools should be reinforced and unambiguous. The final goal of the IEC61850 standard should be to contribute a solution based on optical fibre and digital communication that offers all of the flexibility of copper wiring, specifically in terms of interoperability and ease of configuration. This requires all IEC61850 stakeholders to take the appropriate actions to ensure the success of IEC61850 and guarantee the standard, and the technologies developed around it, remain sustainable and provide significant benefits for all stakeholders and the community.

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