

Integrated Simulation Model of Power System Protection Schemes and Process Bus Communication Networks

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Abstract—An integrated simulation model of power system protection schemes and IEC 61850 process bus communication models was developed for the design of substation automation systems of the future. The model is capable of reproducing a sequence of the relevant events and equipment states under different operation scenarios, including normal operation and power system fault disturbances. The model includes a description of the power system, the protection scheme, including its several intelligent electronic devices, and the process bus communication network. The model allows an assessment of the functional correctness of steady-state operation of the protection scheme as well as during a power system fault clearance process. It also allows the performance evaluation of the underlying communication network. The capabilities of the model are illustrated with an example scenario of power system fault followed by circuit breaker failure.

Keywords—Substation automation system, Process Bus, Protection scheme, Integrated Simulation.

I. INTRODUCTION

The foreseen substation automation systems (SAS) to be used in transmission and distribution networks in the future will be designed to fully support the IEC 61850 communication standard [1]. This comprehends combined use of intelligent electronic devices (IED) and a local area network (LAN) to implement protection automation and control (PAC) functions and additionally monitoring functions. Typical LAN network architectures used in substations comprehend two segregated networks, the first named station bus is used by SAS functions for alarming, signaling and maintenance; the second, named process bus, is used by the most critical functions such as tripping and blocking.

The IEC standard specifies communication system requirements for the communication network operating under any power system condition and SAS state, i.e. during failure and repair stages of IED and communication devices. The

requirements include failure conditions, redundancy design, recovery times and message transfer time. Accordingly, for designing the SAS, in view of all these requirements, the combination of different studies is required, namely conducting reliability studies [2, 3] and dynamic performance studies [4-7]. Furthermore, some of the studies may require the combination of different domains for analyzing the mutual impact between domains. This may include simulation, emulation and testing real systems.

Concerning simulation, the SAS may either be modeled in a given simulation environment [9] or split in different environments [10] by means of joint and synchronized simulation, allowing to benefit from using the most appropriate models from each simulation environment. Typically, this concerns the combined simulation of power systems and information and communication technology (ICT) systems using Distributed Computer Simulation Systems compliant with the IEEE std. 1516 – High Level [11]. A comprehensive overview of various simulation environments and their characteristics aiming at performing combined power systems and communication network simulation has been published by Mets et al. [12]. Most of the application examples overviewed in the study have been applied to wide-area monitoring, protection, control and demand side response, showing the wide application spectrum of combined simulation in power systems.

As per the use of integrated simulation for SAS studies, IED 61850-based and communication equipment models are usually developed for substation communication network performance, such as for comparison studies of LAN topologies, ring versus star [5], or to validate the adequacy of new proposed LAN architectures concerning maximum transfer time defined in the IEC 61850 standard [6].

As per the use of combined simulation for SAS studies, special simulation environments and IEC61850 based models are developed, enabling to run a combined simulation of power systems and communication networks for analyzing the

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interactions between the wide area protection and control system components, including communication delays and hardware execution times of the applications [13, 14].

As regards emulation and testing real SAS, it normally requires very complex and dedicate hardware testing components, such as Ethernet traffic generators, Ethernet network impairment devices and open loop and close loop PAC testing equipment, including real time power systems simulators [15, 16].

Most application examples aim at analyzing LAN performance, but by lacking a functional description of the protection and automation functions included in the SAS, the result may differ significantly from reality. This is especially important when analyzing protection schemes that encompass several IEDs, in the same substation or in different substations, with coordinated operation in order to achieve a defined goal, e.g. fault clearance or load shedding. In these cases, combined LAN background traffic with spontaneous event driven traffic exists, for example, during simultaneous messages publishing by different IEDs that results in traffic congestions.

The present paper describes an integrated simulation of power system protection schemes and process bus communication networks that includes the use of a Generic IED model. This model contains highly abstracted protection functions, which can be combined in complex protection schemes involving several IEDs by means of publishing/subscribing different IEC 61850 traffic profiles.

It is intended that the integrated simulation is capable of reproducing time sequences of events describing the protection scheme behavior during power system disturbances. The time sequence of events produced during a transmission line fault followed by a breaker failure event is exemplified.

II. SIMULATION ARCHITECTURE

The dynamic performance of IEC 61850 protection schemes requires the simultaneous simulation and interaction of three domains: the power system, the ICT and the PAC. Simultaneous analysis is required as the domains interact with each other affecting the course of events.

A schematic view of the interaction between the three domains during a simulation is presented in Fig. 1. The PAC system comprehends several IEDs that are part of the protection scheme, and make the interface between the power system and the ICT system.

The IEDs interface with the power system by continuously measuring analog voltage and currents and by operating circuit breakers during power system disturbance. The IED interfaces with the ICT network by publishing and subscribing, to/from other IEDs, messages of different traffic profiles. The ICT network traffic corresponds to background and spontaneous traffic that is generated during a power system disturbance.

Power system simulation comprehends the computation of branch currents and node voltages present in the power system

during the simulation time span. Protection schemes simulation consist in simulating the behavior of several coordinated protection functions during a power system disturbance. ICT simulation comprehends the Ethernet network infrastructure, including IED interfaces, switches and cables.

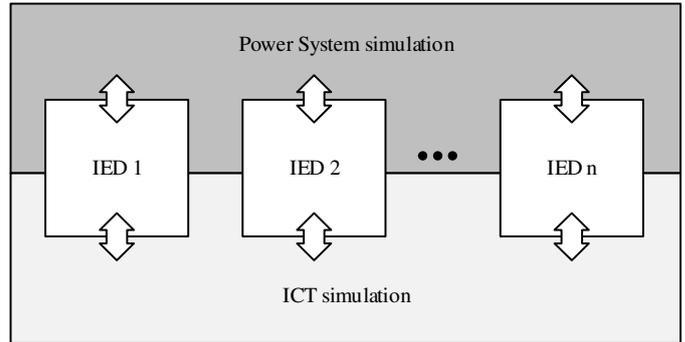


Fig. 1. Protection scheme simulation architecture.

The three domains may be implemented in a given simulation environment, when one or two of the domains can be significantly abstracted. This has the advantage of not needing time synchronization between simulators as all models, i.e PAC, ICT and power system, are running in the same simulation environment. Additionally, this is a straightforward approach for quick implementation, simulation and gathering of useful results concerning the protection scheme and its several components, like the communication network performance.

Notwithstanding, simultaneous simulation is challenging due to the fact that protection systems and communication networks have different reaction times, in the order of 1 to 1000. Protection systems usually have operation time multiples of a power cycle, while transmission delay times in communication systems are just a few μ s.

For the purpose of this work, the integrated simulation is made in a commercial ICT simulation environment, the Riverbed Modeler [17]. The power system and the IED are modeled with a high level of abstraction, but sufficient detail to reproduce the expected behavior during a power system disturbance, and which is relevant in the interaction with the ICT network.

The simulation outcome is a time sequence of events describing the behavior of the protection scheme during a power system disturbance. The information contained in the outcome is sufficient to understand the correct operation of the protection scheme and to analyze the operating time and the message transfer times during the disturbance.

III. POWER SYSTEM MODEL

The highly abstracted modeling of the power system requires a logic description of: (1) the substation busbar topology and associated circuit breakers, e.g. double busbar with bus coupler or breaker and half topology; (2) the number

of bays, including its physical location in the substation and; (3) the bay location of power transformers, when more than one voltage level exist. In complex busbar topologies such as double busbar with bus coupler, the description of to which busbar each bay is connected is also included.

Additionally the model includes the description of the failure condition of each bay and circuit breaker. When a bay is in fault condition, for example during a power system fault, the corresponding IED, responsible for detecting this status, initiates the predefined actions required to return the bay back to the non fault condition, i.e. to clear the power system fault. When a circuit breaker is in fault condition it will fail to operate when commanded to open. The fail conditions are time scheduled in the power system model.

An example of a highly abstracted model of a power system is presented in Fig. 2. In this example, a double busbar with bus coupler is represented. The station has four bays equally distributed between the two busbars. Bay 4 and its circuit breaker (CB) are in a fault condition.

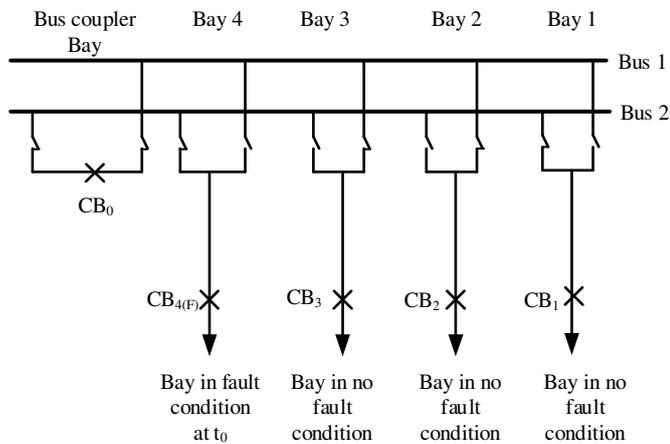


Fig. 2. Abstracted model of a double busbar with bus coupler station. Bay 4 and its circuit breaker in fault condition (F).

IV. ICT MODEL

The ICT model defines how the IEDs are interconnected through the Ethernet network infrastructure, as well as how the traffic flows are treated inside the network. This includes the implementation of the Ethernet protocol, dimensioning the switches (e.g., number of ports) and speed of the links, as well as defining the connections among IED interfaces and switch ports.

The simulation environment already offers an implementation of Ethernet, including Virtual LAN (VLAN) and prioritization. However, process bus communication relies heavily on multicast transmission at the Ethernet protocol layer, which is treated by default as broadcast traffic in the simulator. The use of broadcast in the process bus is very inefficient, since each message will be forwarded to all IED interfaces, including those IEDs that do not subscribe to the messages. As such, traffic partitioning was implemented by proper multicast filtering at the Ethernet switches. During the simulation initialization stage, a Configurator Module reads

the Generic Object Oriented Substation Events (GOOSE) and Sample Values (SV) subscription files, as part of the protection scheme description, which specifies the respective traffic profiles (see below), including the respective multicast group addresses. Based on this specification, the Configurator Module configures multicast filters at switch port outputs, following the shortest path between each publisher and subscriber as provided by the Dijkstra algorithm. From then on, the Ethernet module at each switch output port will look at the destination address of all frames and discard all multicast frames whose destination address is not in the filter list, while letting all the other frames go into its output link. The final result is that each IED will only receive the GOOSE and SV messages for which it is actually a subscriber.

V. GENERIC IED MODEL

For the purpose of integrated simulation the development of a generic IED model is required, which will publish and subscribe SV and/or GOOSE messages. This includes an interface with the power system simulation model and an interface with the ICT simulation model.

The model comprehends a logical processing sub-model and a communication sub-model, which includes highly abstracted IED logic, based on chain state rules, on how the IEDs react to incoming messages and to power system faults. The chain state rules takes into account: (1) the IED type; (2) the location in the substation and protection scheme, (3) its status, operational or faulty and; (4) the received message types. The communication sub-model is responsible for managing the communication incoming and outgoing messages.

Upon the reception of a message, or the occurrence of a power system fault, the IED may send several messages to other IEDs and/or operate a circuit breaker. The IED reacts to incoming messages from the ICT model and compares the received payload with the last received payload of the same profile and transmitter. If, and only if, the received payload is different from the previous value, the content is forwarded to the logical processing model. A general view of the IED generic model process flow is presented in Fig. 3.

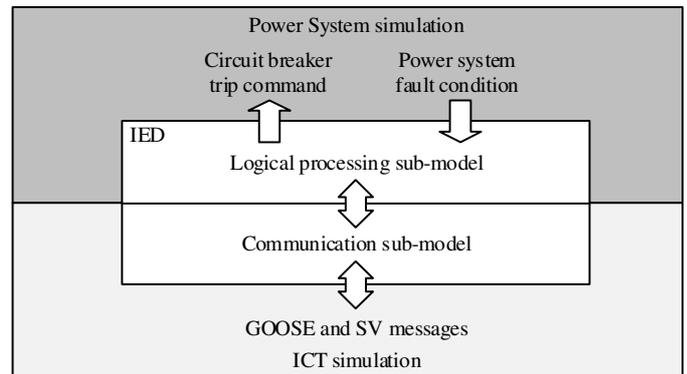


Fig. 3. The generic IED model.

The communication sub-model complies with the different traffic profiles used by critical protection and automation functions, i.e. the GOOSE traffic profile described in the IEC 61850-9 [18] and; the SV traffic profile described in the IEC 61869 [19].

The GOOSE traffic profile

The GOOSE messages are a type of messages used by protection schemes especially for tripping and blocking. The IEC 61850 standard defines the maximum total transmission time to be 3 ms, from which only 20 % is allocated to the communication transmission, i.e. 600 μs.

The GOOSE messages are of several sizes, being dependent on the message content. TABLE I. shows packet sizes of typical GOOSE messages, referred here as GOOSE types.

TABLE I. EXAMPLE OF GOOSE PACKET SIZES.

Type	Packet size [Byte]
Type A	230
Type B	309
Type C	275
Type D	249
Type E	202
Max Data	1548

The timings of GOOSE messages are not constant. During steady state, each IED generates messages with interval T0, e.g. 5 s. The different IEDs are considered to be unsynchronized, meaning that they all start generating messages at some random time and not all in the same instant. This randomness is achieved through a Gaussian distribution (with zero average and standard deviation of 2 μs) applied to each T0 interval, whose probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi \times 2^2}} e^{\left(-\frac{x^2}{2 \times 2^2}\right)} \quad (1)$$

where x is the time (in μs, positive or negative) that is added to T0. When there is an event, the IEDs involved in the event generate immediately a new GOOSE message with the new value, and change the generation interval to T1, e.g. 2 ms. After generating two repetition messages, the generation interval is changed to T2, e.g. 4 ms. After generating another repetition message, the generation interval is changed to T3, e.g. 8 ms. After generating a final repetition message, the generation interval is changed to T0, and the steady state is reached again. When changing to the steady state, it is assumed that the IEDs involved in the event will not be synchronized, generating messages with random different time offsets. It should be noted that considering the previous time intervals, during an event (T1 interval), traffic rises 2500x above the steady state rate. About 16 ms (2*T1+T2+T3) after an event the steady state is reached again.

The Sample Values traffic profile

The SV messages are a type of messages used by the SAS to transmit analogue current and voltage measurement. UCA’s Implementation Guideline for Digital Interface to Instrument Transformers using IEC 61850-9-2, also known as 61850-9-

2LE (Light Edition) [19], defines a packet format for Sampled Values (SV) [2] traffic including 4 voltages and 4 currents. The proposed IEC 61869-9 [20] will standardize the digital interface for instrument transformers, defining other packet formats further than the original format in the Light Edition. This proposal introduces the FfSsIiUu notation for the SV stream, where: f is the digital output sample rate expressed in samples per second; s is the number of Application Service Data Unit (ASDU) (samples) contained in a sampled value message; i is the number of current quantities contained in each ASDU and; u is the number of voltage quantities contained in each ASDU.

TABLE II. shows the most relevant SV stream types, and for each, the sampling period, the packet size at the physical layer and the binary data rate produced by one SV stream.

TABLE II. TYPICAL SV PACKET SIZES.

SV stream	Period [μs]	Packet Size	
		[Byte]	Rate [bit/s]
F4000S1I3U3	250	163	5216000
F4800S2I3U3	416.7	245	4704000
F12800S8I3U3	625	727	9305600
F14400S6I3U3	416.7	567	10886400

VI. PROTECTION SCHEME MODEL

A protection scheme comprehends several IEDs working in a coordinated manner to achieve fault clearance during a power system disturbance. In the foreseen SAS, the IEDs interact with each other using the available process bus LAN, by means of GOOSE and SV messages, and with the high voltage equipment using copper wire or optical fiber.

The protection scheme description encompasses the several chain state rules of all IEDs, all GOOSE message formats and a traffic subscriber list, being each line a publisher/subscriber pair and the message parameters. This file has the following columns:

1. Message Id: Containing the encoded name of the publisher IED and published profile;
2. Subscriber IED: The encoded name of the subscriber IED;
3. Type of GOOSE/SV.

An example of a traffic subscriber list is presented in Fig. 4. The first line of the list informs that the GOOSE message 201CBC1G1 published by CBC1 IED located in bay number 201 is of type A and is subscribed by 201M1 IED. The fourth line informs that the SV message 201MUPAC1SV1 published by MUPAC1 IED located in bay number 201 is of type F4000S1I3U3 and is also subscribed by 201M1 IED.

1-	201CBC1G1	201M1	T.GOOSE_TypeA
2-	201CBC1G1	201M2	T.GOOSE_TypeA
3-	201M1G1	CBC1	T.GOOSE_TypeA
4-	201MUPAC1SV1	201M1	F4000S1I3U3
5-	201MUPAC1SV1	201CBC1	F4000S1I3U3
6-	201MUPQ2SV1	201PQBay1	F12800S8I0U3

Fig. 4. Example of traffic subscriber list.

As regards the GOOSE message format inside the simulator, this is used to send information, but is not used in the calculation of the packet size. Each packet sent between IEDs via a communication network, or between the logical and communication part inside the nodes, has a value of the INT-type with a width of 32 bits. The highest 8 bits of the INT are used to store the message type, e.g., 201CBC1G1. The remaining 24 bits contain data, with a specified format for each message type. As an example, the GOOSE message used to operate a circuit breaker contains 8 bits of data, which are Double Point (DP) indications of which phases should be tripped or closed, with one bit pair associated with each of the three phases and another bit pair used when the command is issued to the three phases at the same time. Each bit pair contains one of the following command codes: Trip (01) or Close (10). The other values are reserved for future use. If the message intends to trip phase three only, the message content will be the following: 00 00 01 00.

With this description, a single scheduled power system fault event initiates a chain reaction, which propagates through the ICT network via a chain of events. The event triggered in IED1 sends a GOOSE message after a small delay to take the processing of the event in IED1 into account. IED2, upon receiving the GOOSE message from IED1, will simulate an action and send out one or multiple GOOSE messages. IED3 receives the GOOSE message from IED2 and reacts to it and so on.

VII. APPLICATION EXAMPLE

A. System description

The developed simulation methodology is applied to the SAS system of the two bay double busbar with bus coupler station presented in Fig. 5. In this example, the bay 202 feeder is connected to busbar 1, while the bay 203 feeder is connected to busbar 2. Each bay xxx encompasses one main protection xxxM1, one circuit breaker controller xxxCBC, one merging unit xxxMU1 and one communication switch xxxSW. At station level there is a busbar protection 2BBP and one central switch 2SW.

The merging units MU are used to measure and publish the analog currents flowing in the bay. The main protection M is used to detect power system faults in the bay feeder and issue a trip command to the associated circuit breaker. In the circuit breaker controller CBC, the protection and automation functions associated to the circuit breaker control are executed, e.g., breaker failure. Additionally, it is used to interface the SAS to the circuit breaker control mechanism. The busbar protection BBP is used to detect and clear busbar faults as well as to clear the busbar when there is a breaker failure trip command.

The actions to be taken by M1 during a power system fault are described in TABLE III. If the device detects a power system fault, it will send a trip GOOSE message with GoID xxxM1G1 to the CBC1 of the same bay. Simultaneously, it

will also send an xxxM1G2 message (breaker failure start) to the same device. The GOOSE message xxxM1G1 contains 8 bits of data indicating phase segregated open/close commands, Trip (01) or Close (10). GOOSE message xxxM1G2 contains 3 bits of data comprehending phase segregated breaker failure start signals.

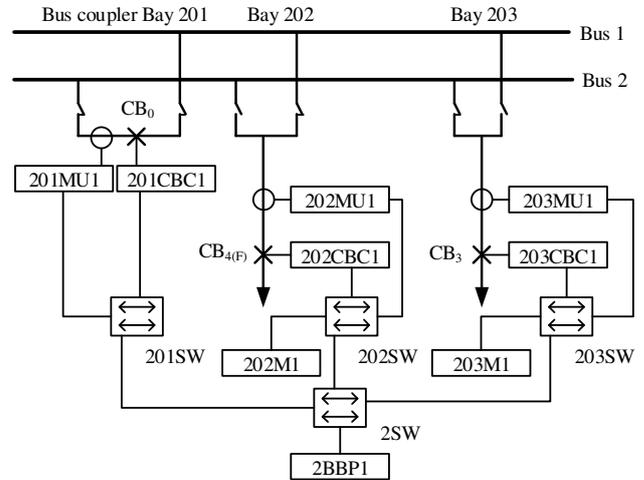


Fig. 5. Two bay double busbar with bus coupler station and associated SAS.

The Circuit Breaker Controller is responsible for operating the circuit breaker. Based on whether the circuit breaker fails or not, a different action is required, as presented in TABLE III. The GOOSE message xxxCBC1G1 contains 3 bits of data indicating the circuit breaker position Open (01) or Close (10) and the circuit breaker failure trip command (1). As regards the busbar protection, in the case it detects a bus fault, it will transmit a trip GOOSE message with GoID xBBPyG1 to all breakers connected to the faulty bus. The same message will also be sent upon the reception of a breaker failure trip from a CBC, as shown in the chain state rules in TABLE III. The GOOSE message xBBPyG1 contains a number of bits equal to the number of bays, each bit being a mask for the bay-id to trip.

1	201CBC1G1	2BBP1	T.GOOSE_TypeA
2	201MUPAC1SV1	202CBC1	F4000S1I3U3
3	201MUPAC1SV1	2BBP1	F4000S1I3U3
4	202M1G1	202CBC1	T.GOOSE_TypeA
5	202M1G2	202CBC1	T.GOOSE_TypeA
6	202CBC1G1	202M1	T.GOOSE_TypeA
7	202MUPAC1SV1	202M1	F4000S1I3U3
8	202MUPAC1SV1	202CBC1	F4000S1I3U3
9	202MUPAC1SV1	2BBP1	F4000S1I3U3
10	203M1G1	203CBC1	T.GOOSE_TypeA
11	203M1G2	203CBC1	T.GOOSE_TypeA
12	203CBC1G1	203M1	T.GOOSE_TypeA
13	203MUPAC1SV1	203M1	F4000S1I3U3
14	203MUPAC1SV1	203CBC1	F4000S1I3U3
15	203MUPAC1SV1	2BBP1	F4000S1I3U3
16	2BBP1G1	201CBC1	T.GOOSE_TypeA
17	2BBP1G1	202CBC1	T.GOOSE_TypeA
18	2BBP1G1	203CBC1	T.GOOSE_TypeA

Fig. 6. Traffic subscriber list for the two bay double busbar with bus coupler station.

TABLE III. IED CHAIN STATE RULES.

Device	Event	Publish	Delay [ms]
Main device M	On the occurrence of a power system fault	xxxM1G1	0
		xxxM1G2	0
	After power system fault clearance	xxxM1G2	0
		xxxM1G1	>= 100
Circuit Breaker Controller CBC	Open circuit breaker		50
	Circuit breaker successfully opens	CBCyG1	0
	Breaker fails (after 150 ms)	CBCyG1	0
Busbar Protection BBP	On the occurrence of a busbar fault	xBBPyG1	0
	On the reception of xxxCBC1G1	xBBPyG1	0

The subscriber list of the SAS in this example is shown in Fig. 6. This list contains all publisher/subscriber pairs of messages of type GOOSE and SV that will be transmitted/subscribed in the ICT network.

B. Event list during a circuit breaker failure

A simulation was run to analyze the generated bus traffic during a circuit breaker failure event in bay 202. This event starts with a power system fault in the circuit connected to bay 202, followed by fault detection by the corresponding main protection 202M1. The main device published a GOOSE trip and a breaker failure start command to the circuit breaker controller 202CBC2. This device is unable to mechanically maneuver the circuit breaker and interrupt the fault current and after 150 ms the breaker failure function in the 202CBC will publish a breaker failure trip GOOSE command to the Busbar protection 2BBP1. The BBP will forward this trip to CBC devices of all bays connected to the same bus of bay 202, i.e. Bus 1. In this case it is only the circuit breaker of the bus coupler bay, commanded by 201CBC1. Once the circuit breaker of the bus coupler bay successfully interrupts the fault current, the power system fault extinguishes and both the protection function in the 202M1 and the breaker failure function in the 202CBC reset. As a consequence the busbar protection 2BBP1 stops forwarding the trip command to the bus coupler bay 201CBC1. The process should not take longer than 250 ms.

The output of the simulator is given in the textbox of Fig. A.1 (in appendix), where a line-number is added to the output. Only the relevant trace-lines have been inserted. The Power System Module sets a power fault on line connected to 202 bay (Line1). The module informs the main device in bay 202 to send the Breaker Open Request (xxxMyG1) and the breaker failure start signal xxxMyG2 (L2,L3). The breaker open request is received by 202CBC1 (L4), which will try to open the circuit breaker but, since it will fail, it will set the status to OPEN_FAILING and schedule a timeout of 150ms. When this timeout expires (L6), the module will instruct the CBCs of the

bay to send a breaker failure message to the BBP (L7). This will cause the BBP to send a breaker open request to all CBCs of the same voltage level and connected to the same busbar (L8), which are received in L9-11. Only the CBC of bay 201 (bus coupler bay) will try to open the circuit breaker, as bay 203 is connected to a different busbar (L12). After opening the circuit breaker, the CBC of the bus coupler bay will send a CB Opened message (xxxCBCyG1) (L13) to the BBP (L14).

In L15, the Power System Module detects that the fault in bay 202 is no longer active and will inform the Main devices from this bay to send the Trip Off and Breaker Failure Start Off messages (L16-17). The CBCs of bay 202 also detect, around the same time as the Main devices, that the fault has been cleared and will send the circuit breaker status message with Circuit Breaker Closed, No Trip (L18).

In L21, the BBP receives the Fault Clear message from 202CBC1. By now, the BBP has received the No Trip message from all CBCs of the same voltage level and busbar and will send a message to all CBCs of the same voltage level, indicating that the power fault has been cleared (L22).

VIII. CONCLUSIONS

This paper has presented an integrated simulation model of power system protection schemes and process bus communication networks. The implemented simulation model provides a detailed trace of IED communications and network operation, allowing the assessment of the functional correctness of protection functions, as well as the communication performance during critical event scenarios (e.g., circuit breaker failure events).

As a drawback, integrated simulation requires increasing the abstraction level of the power system and IEDs, since it may be too time consuming to implement the required detail of the power system network models and the protection functions under test, including all possible interactions that may exist between the three domains.

Accordingly, it is intended to pursue this research towards the establishment of a co-simulation architecture capable to

simulate very large power systems combined with complex protection and automation schemes integrated on fully compliant IEC 61850 SAS.

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APPENDIX

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1) 7.000000: Power System Module: Setting bay 202 to status 1 (Fault)
2) 7.000000: IED 202M1 sends Message MyG1 with data (Ph1 - Trip - On, Ph2 - Trip - On, Ph3 - Trip - On, 3Ph - Trip - On).
3) 7.000000: IED 202M1 sends Message MyG2 with data (Ph1 - Breaker Failure Start - On, Ph2 - Breaker Failure Start - On, Ph3 - Breaker Failure Start - On).
4) 7.000041: IED 202CBC1 received from 202M1 a MyG1 message with data (Ph1 - Trip - On, Ph2 - Trip - On, Ph3 - Trip - On, 3Ph - Trip - On) forwarding to PSystem Module.
5) 7.000061: IED 202CBC1 received from 202M1 a MyG2 message with data (Ph1 - Breaker Failure Start - On, Ph2 - Breaker Failure Start - On, Ph3 - Breaker Failure Start - On) forwarding to Power System Module.
6) 7.150041: IED 202CBC1 sends Message CBCyG1 with data (CB Closed, BF Trip).
7) 7.150138: IED 2BBP1 received from 202CBC1 a CBCyG1 message with data (CB Closed, BF Trip) forwarding to PSystem Module.
8) 7.170138: IED 2BBP1 sends Message BBPyG1 with data Bay (201, 202).
9) 7.170219: IED 202CBC1 received from 2BBP1 a BBPyG1 message with data Bay (201, 202) forwarding to Power System Module.
10) 7.170219: IED 203CBC1 received from 2BBP1 a BBPyG1 message with data Bay (201, 202) forwarding to Power System Module.
11) 7.170219: IED 201CBC1 received from 2BBP1 a BBPyG1 message with data Bay (201, 202) forwarding to Power System Module.
12) 7.220219: Power System Module: Open Circuit Breaker 201.
13) 7.220219: IED 201CBC1 sends Message CBCyG1 with data (CB Opened, No Trip).
14) 7.220299: IED 2BBP1 received from 201CBC1 a CBCyG1 message with data (CB Opened, No Trip) forwarding to PSystem Module.
15) 7.238299: Power System Module: Setting bay 202 to status 0 (Normal Fault)
16) 7.238299: IED 202M1 sends Message MyG1 with data (Ph1-Trip-Off, Ph2-Trip-Off, Ph3-Trip-Off, 3Ph-Trip-Off).
17) 7.238299: IED 202M1 sends Message MyG2 with data (Ph1 - Breaker Failure Start - Off, Ph2 - Breaker Failure Start - Off, Ph3 - Breaker Failure Start - Off).
18) 7.238299: IED 202CBC1 sends Message CBCyG1 with data (CB Closed, No Trip).
19) 7.238341: IED 202CBC1 received from 202M1 a MyG1 message with data (Ph1 - Trip - Off, Ph2 - Trip - Off, Ph3 - Trip - Off, 3Ph - Trip - Off) forwarding to PSystem Module.
20) 7.238375: IED 202CBC1 received from 202M1 a MyG2 message with data (Ph1 - Breaker Failure Start - Off, Ph2 - Breaker Failure Start - Off, Ph3 - Breaker Failure Start - Off) forwarding to Power System Module.
21) 7.238388: IED 2BBP1 received from 202CBC1 a CBCyG1 message with data (CB Closed, No Trip) forwarding to PSystem Module.
22) 7.239388: IED 2BBP1 sends Message BBPyG1 with data (none).
23) 7.239469: IED 202CBC1 received from 2BBP1 a BBPyG1 message with data (none) forwarding to Power System Module.
24) 7.239469: IED 203CBC1 received from 2BBP1 a BBPyG1 message with data (none) forwarding to Power System Module.
25) 7.239469: IED 201CBC1 received from 2BBP1 a BBPyG1 message with data (none) forwarding to Power System Module.

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Fig A.1 Sequence of events of a power system fault followed by breaker failure.