Hardware-in-the-loop (HIL) Nuclear Power Plant Training Simulation Platform Design and Validation

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Abstract

The design, development and validation of a hardware-in-the-loop (HIL) simulation platform are presented. An Invensys Triconex Tricon v9 safety PLC is interfaced to a nuclear power plant (NPP) simulation suite, replicating the operation of Darlington NPP. Communication between the simulator and external hardware is supported by a National Instruments (NI) data acquisition system (DAQ) and a customized virtual instrument (VI). Event timings within the control loop are thoroughly investigated and an acceptable method for HIL platform communication is developed. A sample application (primary shutdown system (SDS1)) is implemented and evaluated. SDS1 evaluation is performed with focus on steam generator (SG) level low trip scenarios. For this purpose, a design basis accident (DBA) associated with SDS1 regulatory standards is applied to the HIL simulation environment and compared with simulated expected plant operation. Further, the role of the Tricon v9 system within the HIL loop is investigated to establish a basis for the future integration of the entire SDS1 control logic.

1 Introduction

Often, to assist with the incorporation of new technologies, system functionality is validated through simulation. Hardware-in-the-loop (HIL) simulations focus on the inclusion of the physical controller hardware in question within a simulation environment. HIL simulation can therefore be used to validate the correct execution of control logic within prospective new or replacement digital controllers [1]. Benefits associated with a HIL simulation include:

- wide selection of relevant operational scenarios,
- ability to replicate scenarios over multiple iterations,
- reduction of on-site configuration,
- replication of system operation for hazardous scenarios,
- convenience of validating control logic on physical controllers for inaccessible control systems,
- resulting simulations most closely resemble the performance of the prospective controller [2].

Further, real-time HIL simulation can provide an environment that mimics almost exactly the plant process as it exists in the physical world.

It is well known that existing nuclear power plant (NPP) control systems contain many components which are becoming increasingly obsolete. CANDU NPPs unfortunately follow the same trend. Studies have been conducted to deal with control system hardware obsolescence [3]. One commonly proposed solution is the replacement of obsolete control systems with modern digital controllers, programmable logic controllers (PLC) and distributed control systems (DCS). Capabilities of these modern controllers include, advanced control logic algorithms, communication modules, built-in redundancy, self-diagnostics, predictive maintenance functions, online remote monitoring and intelligent control capabilities. These new technologies also support standardized components and communications and are often modular, a feature that facilitates replacement and maintenance schedules.

To maximize the longevity of existing NPPs, it is essential to provide solutions to the growing need for replacement control system hardware. Further, extending the capabilities of the previous control systems may allow for increased NPP operational performance, reliability, and security. HIL simulation can assist with these objectives through extension of industry approved training simula-

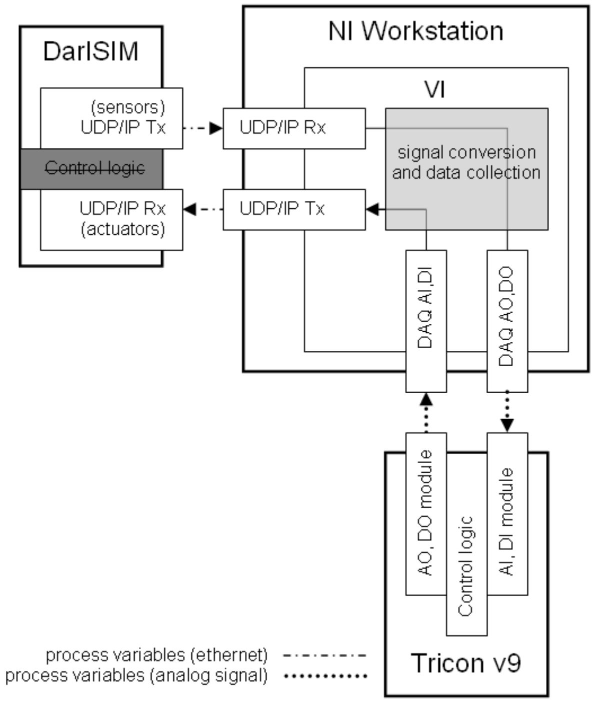

Figure 1: HIL simulation environment.

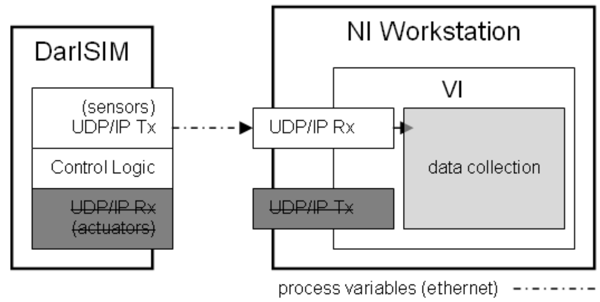

Figure 2: NI-DarlSIM simulation environment.

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Ontario Power Generation (OPG) maintains a UNIX based training simulator, referred to within this paper as DarlSIM. DarlSIM replicates the operation of the Darlington NPP. DarlSIM therefore encompasses an extensive collection of NPP related control loops. These simulated control loops access plant specific process variables and emulate the physical control devices within the plant. In establishing an interface between the software simulated (DarlSIM) process variables and external physical hardware, a HIL simulation platform is developed.

This paper is intended to discuss the development of the aforementioned HIL simulation platform and the implementation of a sample application within the simulation environment. The paper is organized as follows. Section 2 includes a description of the developed simulation platform. The procedure for validating the HIL platform is presented in Section 3 and for implementing the sample application in Section 4. Analysis of the HIL platform, the HIL validation simulations, the expected response of DarlSIM, and the sample application system response are included in Section 5. Finally, concluding remarks and recommendations for HIL control system simulation are provided in Section 6.

2 Simulation Environments

The investigated HIL simulations are composed of six major components; DarlSIM, Tricon v9 PLC, NI workstation, control logic, a communication script and a process variable conversion (signal conditioning) and data collection virtual instrument (VI). Bench-mark for sample application evaluation is provided by the entirely software driven (NI-DarlSIM) simulation. NI-DarlSIM simulation includes all of the above components in a modified form, excluding the Tricon v9. The following will describe further differences between the HIL platform and the NI-DarlSIM platform.

2.1 HIL vs bench-mark software simulation platform

The methods of communication between each of the components within the HIL loop is illustrated in Figure 1. The arrows represent signal transmission from the sensing devices to the decision-making unit and the return path to the actuating devices.

Conversely, Figure 2 presents a fully software simulation (NI-DarlSIM) environment. Here, the NI workstation acts only as a process variable monitor and does not provide any communication path between physical control system components as they remain software driven.

2.2 Darlington NPP simulator (DarlSIM)

DarlSIM emulates the operation of the Darlington NPP and controllers within the NPP. DarSIM main components include modules, a module table, configurations and restore points. These components are described below.

Modules are responsible for the execution of DarlSIM and exist for specific processes within the NPP. The module for the control loop being evaluated is replaced by a communication module. This module is executed within the module table of the loaded configuration. NI-DarlSIM and HIL simulations require communication modules for different purposes as demonstrated in Figure 1 and Figure 2. During HIL simulation, the communication module is used to transmit and receive process variables through ethernet via UDP/IP to and from the VI on the NI Workstation (NI-VI). However, during NI-DarlSIM, the communication module is used solely as a tool for monitoring process variables. The modules provide access to the common database (CDB) of DarlSIM. The CDB is a memory bank where process variables are stored during runtime.

A given module table specifies a list of module names, execution intervals and execution phases. For example, SDS1 Ch-D, E and F trip computers (three independent modules) are scheduled to execute during the 100ms phase of the 200ms execution interval. During HIL simulation the modules related to the control system being evaluated are disabled within the module table (Figure 1: Control logic) and replace with the communication module to allow external hardware to take control of the process.

There are three DarlSIM configurations within the following evaluations. Each configuration corresponds to a unique module table. This first is customized specifically for validation of the HIL simulation platform. The second corresponds to the benchmark simulation of the sample application. The third is necessary for simulation of the sample application on the HIL platform. These configurations will be discussed in more detail. Section 3 regarding validation and Section 4 regarding the sample application.

DarlSIM restore points provide access to common reactor operation modes and common scenario related instances. These points facilitate repetitive simulation. For the purpose of these evaluations, a single restore point is created. This restore point reflects full power operation of the plant and includes the instantiation of a design basis accident (DBA) for the purpose of the sample application.

2.3 NI workstation and VI

An NI PCI-6704 DAQ card is used within the HIL simulation platform to provide electrical connection between the external hardware (Tricon v9) and the LabVIEW VI. This card provides 16 voltage outputs, 16 current outputs and eight (5V TTL/CMOS) digital I/O lines. To communicate through UDP/IP with DarlSIM, an ethernet connection is used. This connection is established in a crossover point to point topology.

The process of the LabVIEW VI in the two simulation environments is illustrated in Figure 3. The connection to

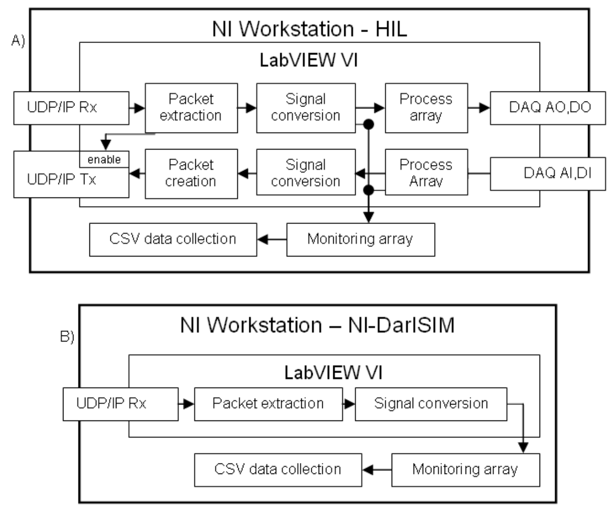

Figure 3: LabVIEW virtual instrument process A)HIL and B)NI-DarlSIM.

DarlSIM to receive and transmit UDP/IP packets remains the same between HIL and NI-DarlSIM. However, the NI-DarlSIM method does not interface to the PCI-6704 DAQ card. Further, data collection of the trip signal is modified according to the active simulation as logical definitions (TRUE/FALSE) of Tricon v9 and DarlSIM are different.

Within the VI, UDP/IP packets are extracted to a string using standard LabVIEW communication blocks. The string is segmented into process variable, identifying integer, multiplier, and signal value. The signal values are converted using the accompanying multiplier (Figure 3: Signal conversion) and inserted into the correct index within either the process variable array or process monitoring array. The monitoring array is stored into a database (CSV) for post-processing. The process variable array is output to the PCI-6704 DAQ card. Tricon v9 receives these signals (4-20mA) accordingly.

The same process occurs when signals are returned to DarlSIM from Tricon v9. However, the transmission of a UDP/IP packet back to DarlSIM must be requested by DarlSIM using a unique identifier. This allows DarlSIM to control the entire sequence of process variable transmission. Following the execution of the decision-making unit, signals from Tricon v9 enter the PCI-6703 DAQ card and are converted to SI unit process variables or DarlSIM compatible logical values. These process variables are then transmitted through UDP/IP to DarlSIM when a request packet has been received.

2.4 Tricon v9 PLC

The external hardware implemented in this evaluation is the Tricon v9 triple modular redundant (TMR) PLC. Tricon v9 has been certified by the US Nuclear Regulatory Commission (USNRC) [4] to meet IEEE Class 1E and 603-1991 standards and was recently selected for the replacement of SDS1 controllers at Point Lepreau NPP in New Brunswick. Tricon v9 provides complete triple redundancy from the input to the output terminals.

The Tricon v9 PLC within the HIL simulation and validation environment includes; triplicated 3008 Tricon enhanced main processors; a 4351 Tricon communication module; 32 points 3503/E discrete input 24V; 32 points 3604/E discrete output 24V; 32 points 3700/A analog input 5V; and 8 points 3805/E analog output 4-20mA [5]. Tricon v9 can be configured to execute over a range of intervals, however the requirements of the control loops within this paper require only a 25ms execution interval.

Tricon v9 control logic for all simulations are identical. The logic used is a simplified replication of SDS1 control logic and will be described briefly with regards to HIL validation and in more detail during the sample application evaluation in Section 4.

3 Performance Validation of the Hardware-in-the-loop Platform

Results from a previous study [6] revealed discrepancies in the received process variables from DarlSIM and the analog signals received from Tricon v9. The identified delay within process variable transmission may not impact operational evaluation of a process. The system may in fact appear to respond as expected. However, without accurate, reliable process variable communication between the simulator and the external hardware, the credibility of the HIL simulation environment as a basis for controller selection is diminished.

To best resolve the identified delays, a simple control loop is implemented. Tricon v9 is programmed with simple level low trip control logic similar to that employed in a shutdown system. When one of four analog input values drops below a specified threshold value the Tricon v9 will produce a trip signal. For validation purposes, the analog input signal is altered from a non-trip state to a trip state or from a trip state to a non-trip state in every execution interval (200ms) within DarlSIM. Contrary to shutdown system control logic, when the analog input signal rises above a specified hysteresis threshold, the trip signal is removed. This process is repeated several times to establish a set of data for evaluating the performance of the HIL platform.

3.1 Validating communication module

A generalized communication module layout is used for all simulations including sample applications and validation. The module includes five functions, 1) open UDP connection, 2) process variable transfer, 3) monitored variable transfer, 4) time transfer/write enable, and 5) close UDP/IP connection. The open and close UDP/IP connection modules are placed in the initialization (INIT) and termination (TERM) execution intervals of the module tables.

In validating the simulator platform, all five of the above function are used. The process variable generated within DarlSIM must be transmitted to the NI-VI exactly as it would if an application were being implemented. To accomplish this task, the execution order of the communication module within DarlSIM is as follows:

1. Process variable transfer
   (a) process variables are retrieved from the CDB
   (b) process variables overwritten by alternating validation signal
   (c) process variables transmitted to the NI-VI
   (d) sleep (1,10,50msec) (wait for Tricon v9)
   (e) process variable receive request packet transmitted
   (f) sleep (10msec) (wait for NI-VI to transmit process variable)
   (g) receive validation process variable (1μ sec, 1msec) (timeout)
   (h) validation process variable written to the CDB
2. Monitored variable transfer
   (a) validation monitored variable retrieved from the CDB to assure transmission
   (b) validation monitored variable transmitted to the NI-VI
3. DarlSIM time variable transmitted (initializes NI-VI CSV write)

The communication module invokes all events within the HIL platform, except for the timing of the Tricon v9 execution interval. This is beneficial as the NI-VI executes on demand, and is therefore synchronized with the DarlSIM execution intervals. To account for the execution of the Tricon v9 control logic a delay is introduced within the communication module.

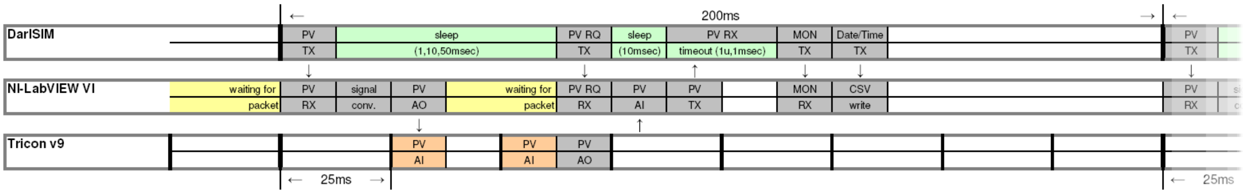

Figure 4: HIL simulation timing diagram.

As demonstrated in Figure 4, the Tricon v9 control logic execution interval is 25ms. Figure 4 includes two (PV/AI) blocks in the Tricon v9 timing diagram to demonstrate that the delay (sleep) within DarlSIM should be configurable as Tricon v9 is not synchronized with DarlSIM. Both of the analog input blocks (PV/AI) execute, however the early block may not receive the appropriate data for the execution cycle. In this case, the following Tricon v9 execution interval would respond. If the DarlSIM communication module includes a reduced sleep delay, the Tricon v9 may not have adequate time to execute appropriately and an inconsistent trip signal may be returned. To determine the best practice for delay within the DarlSIM communication module, multiple delay configurations are examined.

3.2 Expected response

Following Tricon v9 execution, the validation trip signal is available at the analog output of the Tricon v9 controller. It is necessary that this boolean signal is stored within the CDB of DarlSIM as immediately as possible. More specifically, the boolean signal should be stored in the CDB during the execution interval where the analog process signal drops below the defined threshold. This is performed by capturing the Tricon v9 digital output signal, while at the same time writing this signal to the CDB and transmitting the retrieved CDB validation value back to the NI-VI for monitoring and post-processing.

3.3 Assumptions for HIL validation

DarlSIM has a minimum execution interval of 50ms, where the SDS1 execution interval is 200ms. Therefore, for HIL validation purposes, an execution interval of 200ms is implemented. It is assumed that the dynamics of the evaluated process variable within DarlSIM do not vary during this interval. Further, the execution of the Tricon v9 controller logic is expected within two times of its specified execution interval. For example, for a 25ms execution interval, within 50ms the control logic should complete at least one execution. Known overhead exists due to the retransmission of monitored variables for post-processing analysis. These delays are assumed to be negligible as they can be eliminated during actual controller logic verification.

4 Evaluation of a Sample Application

In CANDU NPP, 28 neutron absorbing (cadmium) shut-off rods are suspended above the reactor core by energized clutch mechanisms. The rods drop into the core when de-energized. The primary shutdown system (SDS1) initiates the release of shut-off rods into the reactor core to stop the nuclear chain reaction.

CANDU SDS1 includes three redundant trip channels (D,E,F), each composed of two programmable digital comparators (PDCs). PDC1 and PDC2 are responsible for decision-making regarding a subset of the defined shutdown process parameters within a given channel. The parameter subsets for each PDC are identical across each of the three channels [7].

DarlSIM includes separate modules for the three SDS channels (D,E,F). Though each PDC cannot be independently disabled, an entire channel can. During HIL simulation, the Ch-D trip computer module is disabled (Figure 1: SDS1 Ch-D) to allow Tricon v9 to take control of the SDS1 process.

4.1 Design basis accident scenario

The DBA scenario selected for the current study is the spurious closure of feed-water valves. SDS1 DBA scenarios are developed according to individual trip parameters in Figure 5. The Spurious Closure of Feed-Water valves (SCFW) initiates a loss of secondary side heat removal [8]. This directly affects the SG level. Upon instantiating SCFW within the feed-water system of any of the four SGs, the corresponding SG level will decrease to an unsafe level.

For this investigation, the sole cause of SDS1 CH-D trip is the spurious closure of level control valve 101

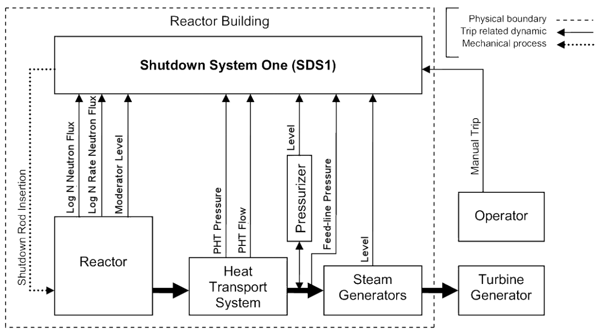

Figure 5: CANDU SDS1 parameters and process flow.

(LCV101) as illustrated in Figure 6. LCV101, 102 and 103 control flow of coolant to the North-West (NW) SG (Figure 6: NW BOILER) from the feed-water heat exchanger (Figure 6: HX5A). When a single spurious closure is detected, the SG level controller (SGLC) opens the parallel LCV103. If this redundant valve (LCV103) fails, the NPP will enter the DBA. This is performed by restricting LCV103 to fail partially opened. With the SG feed-water flow below sustainable level, LCV102 could be opened. However, the redundancy of the system has been compromised, therefore repair procedures are initiated.

The restore point associated with this DBA restores DarlSIM to the instant that the SCFW occurs. This procedure is repeated to verify the proper operation of the HIL platform.

4.2 Simulation scenario

Execution of the DBA is performed over 50 instances for NI-DarlSIM and HIL environments. For each of the simulations, the appropriate configuration is loaded into DarlSIM and the simulator is restored to full power operation with DBA pending. For proper identification of Ch-D HIL trip, the Ch-E SG level low threshold has been modified with an add-bias to override the value within DarlSIM (-0.15m). The Ch-F SG level low trip condition has also been modified (biased $+1.00$m) as it will not play a role in the 2oo3 trips required for SDS1 shutdown initialization. These biases are applied for both the NI-DarlSIM and the HIL evaluations.

During the HIL simulation, the Tricon v9 controller is placed in 'RUN' mode, this is not the case for NI-DarlSIM analysis. With DarlSIM in 'RUN' mode and the Tricon v9 controller in 'RUN' mode the NI-VI is executed. The two DBA initiating events are performed immediately. The NI-VI captures the dynamics of the system process variables and stores the data for post processing in a database (CSV).

4.3 SDS1 control logic

SDS1 reference logic is an emulation of the currently used code within the PDCs at Darlington NPP. Identical FORTRAN code is executed within DarlSIM. The logic is translated from FORTRAN source to block schematic diagrams and English description to enable replication in the new programming environment.

SDS1 logic implementation on Tricon v9 is performed using function block diagrams and Tristation 1131 Developer's Workbench (1131DW). The logic is configured to execute on a 25ms interval. Though Tricon v9 supports ladder logic diagrams; structured text; and cause and effect programming language editor (CEMPLE); function block diagrams (FBDs) are preferred for the following reasons:

- Tricon v9 SDS1 logic at Point Lepreau NPP will incorporate this method;
- proven performance of Wolsong 2, 3 and 4 and Qinshan 1 and 2 NPPs which utilize a similar graphical engineering software approach (Integrated Approach (IA)) and;
- similarities in concepts and functions between existing IA function block language and the available IEC61131-3 FBDs [9].

Execution of the SDS1 logic on the HIL platform, as in Figure 1, requires a path for input and output variables. In actual SDS, the decision-making unit is directly wired to sensors and actuators. The analog and digital input signals that are received by Tricon v9 analog and digital input modules are conditioned to produce similar analog and digital signals that would be present within the actual NPP.

Simplified SDS1 logic is implemented on Tricon v9 for this evaluation. Logic does not include compensated average power conditioning, manual SG level low conditioning or log N rate neutronic power conditioning. The process of determining SG level low trip is otherwise identical, with modified thresholds for observational purposes.

4.4 Communication modules

Two configurations (sds1_HIL_config and sds1_SIM_config) exist for evaluating SDS1 applications. The communication modules and module tables within each of these configurations differ slightly. They both include an initializing and a terminating function.

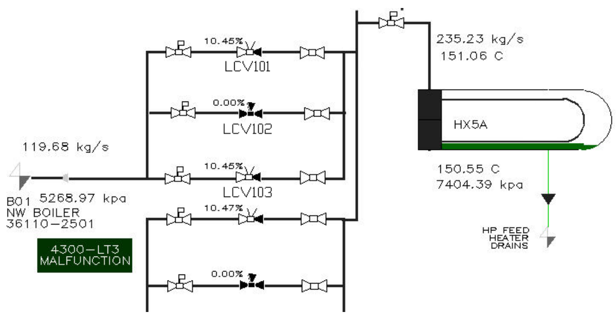

Figure 6: Steam generator feed-water system.

Tricon v9 delay	UDP/IP timeout	proper transfers (%)	signal correlation (%)
1ms	1us	98.7432	0.132
10ms	1us	99.7825	0.192
50ms	1us	99.9846	99.593
1ms	1ms	99.0994	0.102
10ms	1ms	99.8943	0.119
50ms	1ms	99.8716	99.453

Table 1: HIL platform process variable transfer and correlation characteristics

These functions open and close the UDP/IP ports when the simulator is loaded and unloaded. They both also include the process variable transmit and monitor variable transmit routines. However, the process variable transmit routine does not include the transmission of a return process variable request for the NI-DarlSIM configuration (sds1_SIM_config). Therefore, the NI-VI does not return the Tricon v9 generated trip signal, as specified. Additionally, both functions include a data capture function which, exactly as the validation procedure, triggers the NI-VI to save data to the CSV database.

The timing within the HIL communication module is exactly as specified in the validation evaluation. This timing configuration allows for excellent transfer of process variables between the DarlSIM and the external hardware. The sleep delay within DarlSIM for Tricon v9 execution is 50msec and the timeout for UDP/IP packet receive is 1msec.

4.5 Expected response of SDS1

The failure of the two valves will not immediately trigger shutdown. The level in the NW-SG begins decreasing at an increasing rate. Once the SG level drops below the SG level low threshold, Ch-D will trip on NW-SG level low. At this time, on the condition that neither Channel E nor F (Ch-E, Ch-F) have tripped, the reactor remains at full power and the shut-off rods remain outside the reactor core. Once either of the other two channels meets the trip condition, the shut-off rods will be dropped into the reactor core and the reactor remains in this safe state.

5 Results and Analysis

5.1 Performance analysis of the HIL platform

Validation of the HIL platform was performed over six configurations. The delay associated with DarlSIM waiting for the Tricon v9 controller to execute (Tricon v9 delay) along with the timeout for UDP/IP packet receipt (UPD/IP timeout) at DarlSIM were modified. The results of the six configurations are summarized in Table 1. Each of the configurations in Table 1 were performed for over 7000 iterations. The result is a very strong basis of the performance of the HIL platform. The proper transfer column represents the percentage of iterations where the trip signal produced by Tricon v9 was accurately stored within the DarlSIM CDB. The trip signal is alternated once per execution interval subsequent iterations should contain unique values. The Tricon v9 trip signal and the monitored trip signal variable are compared and the result is a percentage of iterations which appropriately transfer the trip signal.

It is apparent that the transfer between the Tricon v9 and the CDB performs adequately through the entire evaluation. There are only slight reductions in performance due to the decreased Tricon v9 waiting period. Further, a comparison between the 1us and 1ms UDP/IP timeout results indicates no significant deviation in performance. It can therefore be assumed that the communication between the Tricon v9 and DarlSIM is adequate over all configurations, with a slight peak in performance during 50ms Tricon v9 delay and 1us UDP/IP timeout.

Further investigation into the performance of the entire HIL loop is necessary. The signal correlation percentages in Table 1 provide this additional performance criteria. The Tricon v9 delay results have demonstrated that the signal received from Tricon v9 transfer adequately, however the correlation between the Tricon v9 generated trip signals and the expected trip signal must be investigated. Signal correlation represents the number of iterations where the SG level process variable value compared with the trip threshold (2.00m) corresponds with the returned Tricon v9 trip signal. For example, if the SG level is recorded as 1.5m, the Tricon v9 should produce a trip signal. If the SG level is recorded as 2.5m, the Tricon v9 should produce a non-trip signal. This comparison is performed over all iterations.

As the Tricon v9 execution interval is 25ms, any Tricon v9 delay less than 25ms would not have enough time to receive the appropriate corresponding variable. This is strongly supported by the high percentage in the correlation columns of the delays below 25msec. In fact, investigation of the raw recorded data indicates that the trip signal variables are delayed by one execution interval if the Tricon v9 delay is not of adequate length. A result which corresponds with observations of previous studies.

5.2 Analysis of the sample application

The DBA is first performed in the NI-DarlSIM environment as a bench-mark. Figure 7 reflects the dynamics of the entire SCFW DBA process. Prior to the simulation Ch-D, E and F SG level low thresholds are configured to (2.05m). The spontaneous closure of LCV101 (~18sec) causes the North-West (NW) SG level to begin decreasing as the feed-water flow has been reduced from ~308kg/s to 0kg/s. After 20-30 seconds, the redundant valve (LCV103) opens. The backup valve fails at 2.43%, representing a 97.57% blockage or a defective valve (~60sec). As feed-water requirements cannot be achieved, the NW-SG level continues decreasing. Auxiliary systems respond to the reduction in feed-water supply as indicated by the slowly decreasing reactor thermal power. The NW-SG level continues decreasing towards the pre-set threshold where the thermal power begins decreasing at a linear rate (Figure 7: 90-110sec). When the NW-SG level drops below the Ch-D SG level threshold, Ch-D, E, and F trip simultaneously. After a brief delay, the reactor thermal power decreases rapidly indicating proper shutdown operation. The brief delay following the trip corresponds to the shutdown rod insertion process. Though the rods are released almost immediately once the trip condition is detected, the process of insertion and the absorption require additional time.

An overview of the HIL response to the SCFW DBA is illustrated in Figure 8. For proper identification of Ch-D HIL trip, the Ch-F SG level low threshold has been modified with an add-bias override within DarlSIM. The Ch-F SG level low trip condition does not occur during the investigation as the included bias adds 1m to the detected Ch-F SG level. The spontaneous closure of LCV101 (~18sec) and a partial blockage at LCV103 (~225sec) produce the exact same dynamics as observed in NI-DarlSIM. However, upon Ch-E DarlSIM trip, the reactor thermal power reduction rate remains constant. The Ch-E trip mechanism has not failed, as it is clear that

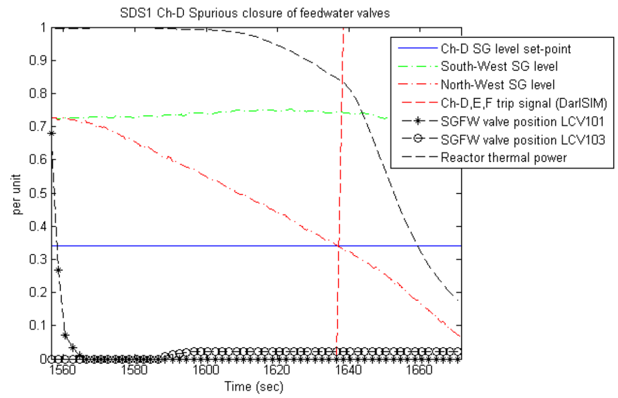

Figure 7: Spurious closure of feed-water valve process (NI-DarlSIM).

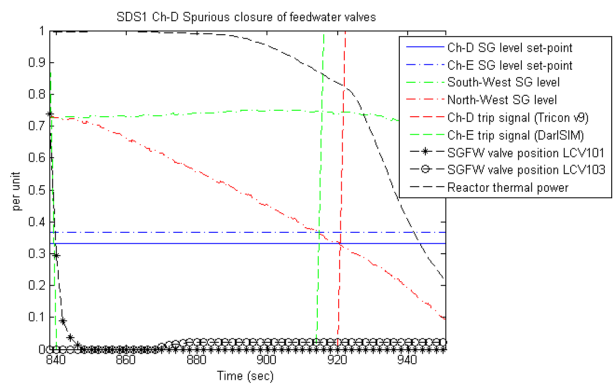

Figure 8: Spurious closure of feed-water valve process (HIL).

the channel tripped properly given the indicated threshold (2.20m), the SG level, and the Ch-E trip signal. The NW-SG level continues decreasing and drops below the Ch-D SG level threshold. When Tricon v9 receives the NW-SG level at the analog input card, the SDS1 logic executes and the trip signal is returned to DarlSIM. The response of DarlSIM following the Tricon v9 induced HIL signal resembles exactly the shutdown process following the bench-mark evaluation.

These two operational demonstrations were presented in [6] where the process reacted appropriately and the shutdown system initialized as expected. Further investigation into the HIL platform environment will provide details of the discrepancies encountered within [6] and the enhancements achieved in recent HIL platform developments.

5.3 Detailed simulation response

In investigating the monitoring capabilities of the NI-DarlSIM benchmark configuration, Figure 9, a comparison between captured trip dynamics is made. As reported in [6], the previous NI-DarlSIM results present discrepancies in the correlation between SG level and the indicated Ch-D trip signal (DarlSIM). NI-DarlSIM trip signal is a post-process signal which indicates when any SG level is less than or equal to 2.05m. The cause of the discrepancies in [6] are the result of errors in these post-process calculations. For example, the transfer of SG level is represented as a process variable. When the signal is quantized (internal to DarlSIM) the actual value corresponding to the SG level threshold is calculated as 2.05m (byte value: 2130). However, the resolution of the emulated analog to digital conversion within DarlSIM rounds values less than 2.0508 to 2.05. The discrepancies were produced as a result of the exact post-processed threshold of 2.05 for the NI-DarlSIM trip signal. The issue of quantization rounding has been accounted for in collected data within this study and will be accounted for in future studies.

5.4 Detailed sample application HIL simulation response

The detailed performance of the HIL platform in SDS1 application is demonstrated in Figure 10. The previous HIL results (Figure 10:A) are those reported in [6]. It is apparent from these results that the transfer of Ch-D trip signal to DarlSIM is not performed until the execution interval following the actual trip condition. This results in delayed process variable communication, a problem which may not be apparent when examining many applications. However, for processes requiring real-time decision-making capabilities the elimination of this one execution interval delay is essential. It is difficult to predict the possible scenarios given the inclusion of the communication delay, however the maximum execution interval within DarlSIM is two seconds, therefore a delay of two seconds could be induced.

The refinement of the HIL platform using the characteristics revealed during the validation of the HIL platform have eliminated this delay. This is apparent when observing the resulting response (Figure 10:B). This response is as expected. The trip signal transfers to the CDB within DarlSIM within the execution interval which the trip condition occurs. Exactly as would be simulated by DarlSIM. Note, the SG level set-point values have been modified to include the quantization rounding revealed previously in the study.

6 Conclusions and Recommendations

In summary, two simulation roles have been observed; the role of the NI-VI to monitor the entirely software DarlSIM simulator during a DBA and the role of the NI-VI and the communication module within DarlSIM to provide simulation capabilities on an HIL platform. Further, the performance of the HIL platform has been enhanced through validating a) the proper transfer of signals from the Tricon v9 to the CDB within DarlSIM and b) the correlation of the signal returned from Tricon v9 with the process variables of the current execution interval.

After refining the communication module within DarlSIM, the HIL platform has been validated. A DarlSIM generated trip condition to Tricon v9 trip signal correlation of 99.593% was established. This indicates that within 10000 iterations, or execution intervals, the corresponding trip signal may deviate from the expected value only 41 times.

The proposed validation method for HIL platforms must be studied further as the scalability of the communication module for larger more involved control loops has not been proven. It would be valuable to determine the limit of the capabilities of the HIL platform with regards to control loop intricacy. Further, the delays may be optimized for future HIL simulations. It is also recommended that validation be performed prior to any modified HIL simulations and that the HIL simulation be performed on a similar platform to that proposed in this paper.

The bench-mark NI-DarlSIM simulation provides an accurate illustration of the proper operation of SDS1 during SCFW. Upon further investigation, the discrepancies between DarlSIM and NI-VI process variables are identified as post-processing errors. These discrepancies were removed by accounting for quantization rounding within the post-processed trip signal calculations. Though the discrepancy does not affect the performance of HIL simulations, it will affect the verification of external hardware decisions.

A NPP shutdown scenario was illustrated where Ch-D SG level low trip was induced by the Tricon v9 controller. The HIL simulation environment is therefore integrated appropriately for evaluation of NPP processes. Upon closer inspection the Ch-D trip signal acquired by DarlSIM through the HIL platform is acquired within the same execution cycle as when DarlSIM is executing independently. To clarify, the Ch-D trip signal returned from Tricon v9 is stored in the CDB of DarlSIM during the same execution interval that the DarlSIM initiated SG low level condition occurs. The 200ms delay that existed in the HIL platform has been eliminated through the implementation of an enhanced communication module. Further, the communication module was validated and appropriate delays for proper functionality were identified.

The implementation of the simplified SDS1 control loop on the HIL platform is a preliminary implementation. The entire SDS1 control logic are to be implemented within the Tricon v9 controller, and the simulation environment expanded to include all three SDS1 channels.

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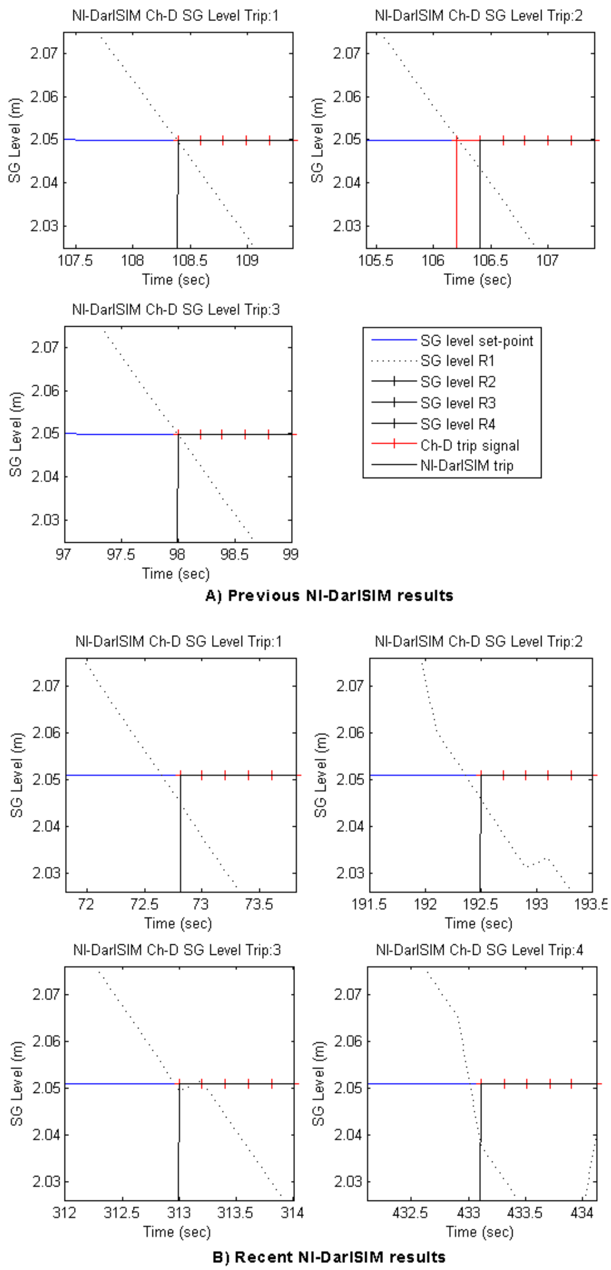

Figure 9: NI-DarlSIM signals.

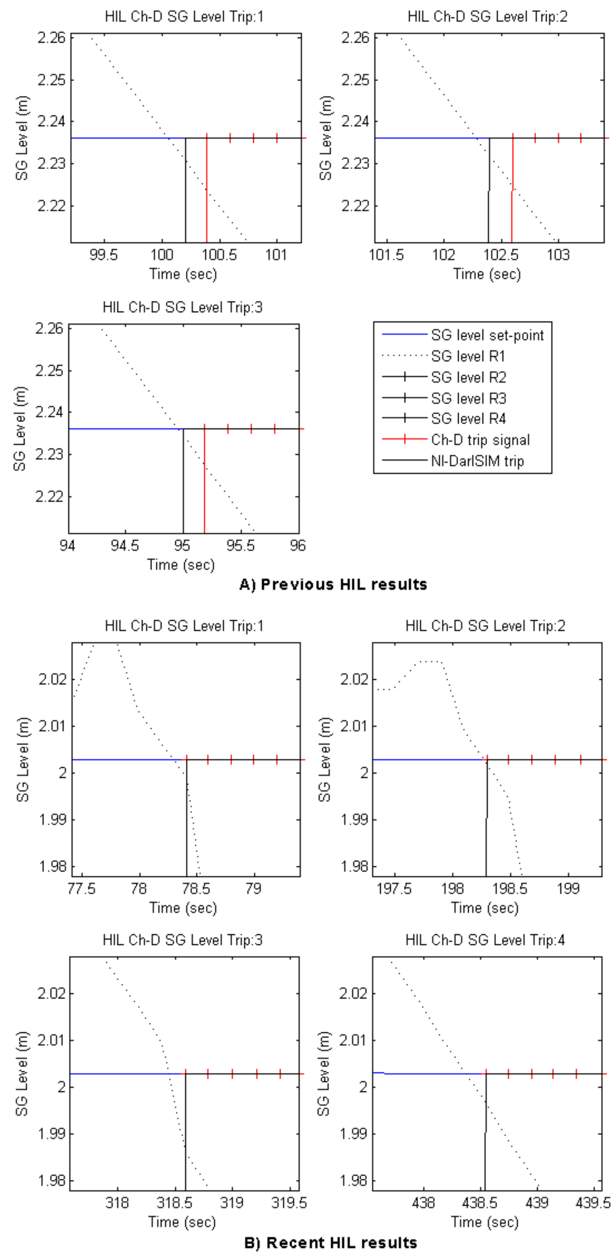

Figure 10: HIL signals.