

**Nira Saadun^{1,*},
Ir. Dr. Sheikh
Kamar Sheikh
Abdullah²,
Mohd Khairun
Nizam Mohd
Sarmin³,
Muhamad
Tarmizi Azmi⁴,
Nik Sofizan Nik
Yusuf⁵**

J. Electrical Systems 13-3 (2017): 444-456



**Journal of
Electrical
Systems**

Regular paper

**Modelling and Implementation of
Intelligent Electronic Devices (IED) in
Real-Time Hardware-in-the-Loop (HIL)
Test System**

Modern power grid utilizes a sophisticated network of Intelligent Electronic Devices (IEDs). Proper coordination of IEDs is required to ensure safe, reliable and efficient of grid operations. This paper presents Real-Time Hardware-in-the-Loop (HIL) simulation test system modelled with RT-LAB real-time simulator for the design and testing of TNB Wide Area Defence Plan (WADP) scheme. The modelling of IEDs, which is one of the crucial components in this HIL test system, equipped with protection, control logics, metering and communication functions is developed. An overcurrent protection relay based on Inverse-Definite Minimum Time (IDMT) is modelled as key protection element function. Therefore, the capability of the modelled IEDs in this HIL test system is demonstrated towards the design and testing of TNB WADP scheme.

Keywords: Intelligent Electronic Device; Real-Time Simulation; Wide Area Defence Plan; Hardware-in-the-Loop; Inverse-Definite Minimum Time.

Article history: Received 19 March 2016, Accepted 17 June 2017

1. Introduction

The Hardware-in-the-Loop (HIL) testing is increasingly recognized as an effective approach in validating the power system model and design scheme. As traditional software-based simulation has the disadvantage of being unable to exactly replicate real operational condition, this HIL testing capable to increase the realism of the simulation and provides access to hardware features which are currently not available in software-only simulation model. Hence, this may reduce the risks of discovering an error in the very last stage of the on-the-field testing [1,8].

An Intelligent Electronic Device (IED) is a microprocessor-based controller of power system equipment. IED senses voltage and current, and capable of issuing control commands, such as tripping of circuit breaker. The extended functionality of an IED can be separated into the following groups such as protection, control, monitoring, metering and communication. In this paper, the HIL test system for TNB Wide Area Defence Plan (WADP) scheme developed by TNB Research Power System Group (TNBR-PSG) incorporates virtual IED model. The “virtual IED” term is referred to IED that modelled virtually in HIL test system instead of using physical IED. This is to minimize the number of physical IED in used since the TNB WADP scheme requires more than 80 IEDs for monitoring and control purposes. Therefore, it is practically impossible to connect those IEDs with the real-time simulator at a time.

* Corresponding author: Nira Saadun, Department of Power System, TNB Research Sdn. Bhd, Bangi, Selangor Darul Ehsan, Malaysia. E-mail: nira.saadun@tnb.com.my

^{1,2,3,4} Department of Power System, TNB Research Sdn. Bhd, Bangi, Selangor Darul Ehsan, Malaysia.

⁵ Department of Transmission, Tenaga Nasional Berhad, Bangunan Dua Sentral, Kuala Lumpur, Malaysia.

As wide range and interconnected power system network nowadays, protection relay such as Inverse-Definite Minimum Time (IDMT) overcurrent relays is crucial in the power system protection with its unique features that can be graded over a wide range of currents and operating times. This function is modelled in the virtual IED in order to replicates actual behaviour of protection element in the real TNB power grid when testing the TNB WADP scheme.

2. Notation

The notation used throughout the paper is stated below.

Constants:

- TMS Overcurrent relay time multiplier setting
- PMS Relay pickup setting
- I Measured load currents [Amps]
- I_r Plug setting multiplier

3. Material and Method

Generally, the HIL test system involves three-main software which is RT-LAB, ePHASORsim and MATLAB/Simulink. The following describes the software:

- i. RT-LAB is real-time simulation software that offers model-based design interacts with real-world environments.
- ii. ePHASORsim is a phasor-domain type power system dynamic simulation tool. It performs simulation at a typical time-step in range of milliseconds i.e. 10 ms time-step in this HIL test system, and provides phasor voltage and current information that enables simulation of large-scale of power grid within a real-time.
- iii. MATLAB/Simulink is a graphical programming environment for multi-domain simulation and model-based design. Integrated with RT-LAB enables MATLAB/Simulink model to interact with the real-world environment.

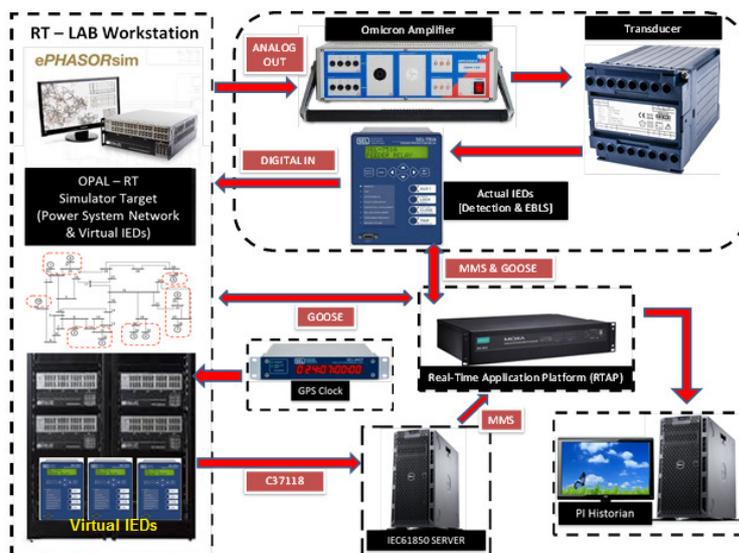


Fig. 1 Deployment diagram of HIL test system

As shown in Fig. 1 the HIL test system consists of real-time simulator and hardware under test. The real-time simulator includes its software i.e. RT-LAB, ePHASORSim and MATLAB/Simulink, and hardware i.e. real-time target, analog/digital input/output (I/O) modules etc. The hardware under test includes embedded system on Real-Time Application Platform (RTAP), Intelligent Electronic Devices (IED) and servers for data historian i.e. PI Historian, and IEC 61850 MMS server.

In this paper, the IEDs are modelled as a virtual component within MATLAB/Simulink environment. Basically, virtual IED model as shown in Fig. 2a and Fig. 2b replicates the function of physical IED and performing the following functions:

- Inverse-definite minimum (IDMT) 51P overcurrent protection element
- Bus frequency estimation
- Relay MW averaging
- Logical operations
- Communication protocol

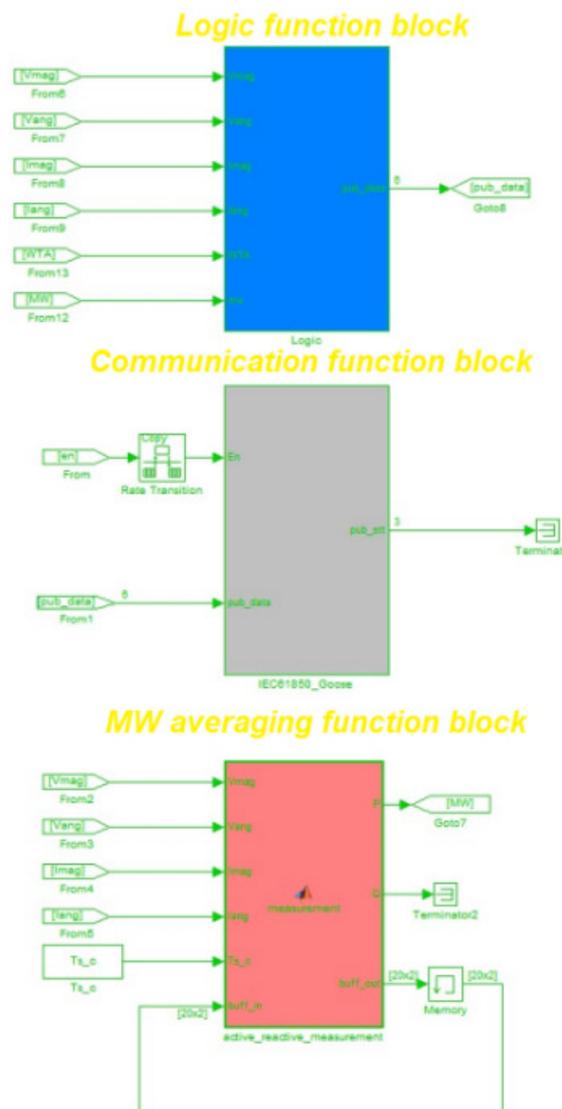


Fig. 2a Detailed model of virtual IED

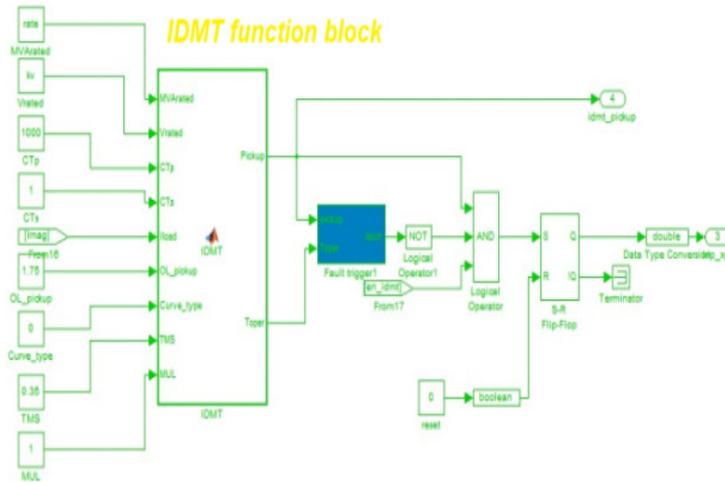


Fig. 2b Detailed model of IDMT

3.1 Inverse-Definite Minimum (IDMT) 51P Overcurrent Protection Element

The characteristics of an IDMT overcurrent relay is depending on the type of standard selected for the relay operation. The selected standard, IEC 60255 defines a number of standard characteristics as follows:

- Standard Inverse (SI)
- Very Inverse (VI)
- Extremely Inverse (EI)
- Long Inverse (LI)

Equations for relay a characteristic to IEC 60255 is define as follows:

$$t = TMS \times \frac{A}{(I_r^P) - 1} \tag{1}$$

$$I_r = \frac{I}{PMS \times \left(\frac{CT_{primary\ current}}{CT_{secondary\ current}} \right)} \tag{2}$$

where TMS is overcurrent relay time multiplier setting with range 0.01 to 10, I is measured load currents, I_r is plug setting multiplier, PMS is relay pickup setting, A and P is the coefficient based on relay characteristics.

TABLE I
DIFFERENT TYPES OF INVERSE CHARACTERISTICS CURVES

| Relay Characteristic | Coefficient | |
|------------------------|-------------|----------|
| | A | P |
| Standard Inverse (SI) | 0.14 | 0.02 |
| Very Inverse (VI) | 13.5 | 1 |
| Extremely Inverse (EI) | 80 | 2 |
| Long Inverse (LI) | 120 | 1 |

Any of the standards can be used to implement a characteristic curve for an overcurrent relay. An overcurrent relay has a minimum operating current, known as the current setting

of the relay. The current setting must be chosen so that the relay does not operate for the maximum load current in the circuit being protected, but does operate for a current equal or greater to the minimum expected fault current. Although by using a current setting that is only just above the maximum load current in the circuit a certain degree of protection against overloads as well as faults may be provided, the main function of overcurrent protection is to isolate primary system faults and not to provide overload protection. In general, the current setting will be selected to be above the maximum short time rated current of the circuit involved.

The IDMT 51P overcurrent protection element model in HIL test system for TNB WADP scheme is developed based on general IDMT equation as (1) and require input settings such as equipment apparent power rating, equipment voltage rating, current transformer primary and secondary current, measured load current, overload ratio for relay to start pickup, overcurrent relay actual plug setting, overcurrent relay time dial multiplier, and curve type of IDMT characteristic. Thus, the IDMT equation model is programmed with MATLAB code function block.

3.2 Bus Frequency Estimation Modelling

Since the frequency of the load buses cannot be obtained directly from the power system solver, a bus frequency estimation method is used to estimate the load bus frequency. Bus frequency is estimated from two samples of bus voltage phase angle thus the slip frequency (per-unit deviation of frequency from its nominal) at a respective bus is calculated.

With ePHASORsim, only generator bus frequency can be obtained directly from the solver based on the speed of the generator. Therefore, frequency obtained at generator bus is used as a benchmark. Based on IEEE 39-bus test system, a simulation has been performed to compare frequency obtained from the solver and the estimated one. The comparison results of frequency at different generator buses are shown in Fig. 3 and Fig. 4. From the figures, except during transient period i.e. within first 3 seconds after a disturbance, it is shown that the estimated frequency matches the actual frequency measured at the generator buses.

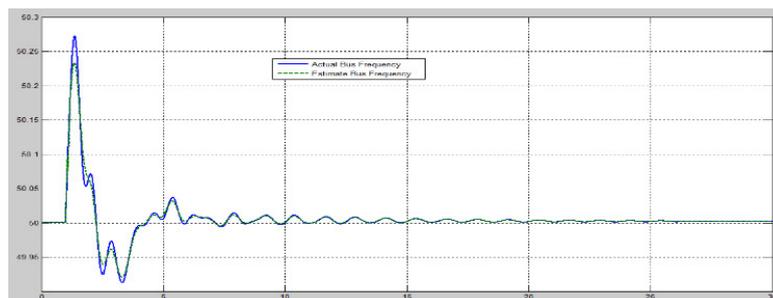


Fig. 3 Bus frequency at generator Bus 30

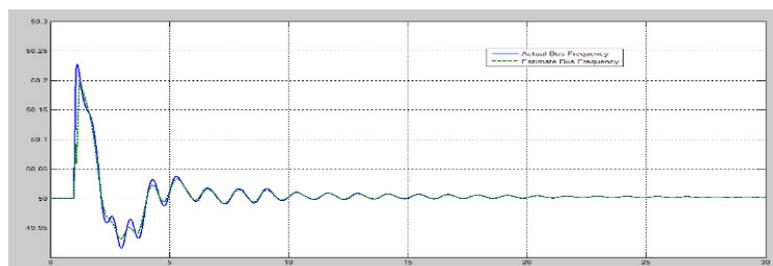


Fig. 4 Bus frequency at generator Bus 31

3.3 Relay MW Averaging Modelling

In the physical IED that is used in WADP system, the real power (MW) is not computed instantaneously however it is calculated within frame of 10 cycles. Thus, when the system frequency is at nominal i.e. 50 Hz, therefore the calculation of MW is within 200 ms. Since MW is an important measurement element in WADP system, hence the virtual IED have to replicate this characteristic as standard so that the HIL test system behaves like an actual system.

In HIL test system, MATLAB function block is used to perform MW calculation based on moving average of 10 windows. Fig. 5 and Fig. 6 shows the MW characteristics computed by virtual IED. From the figures, it is shown that the time taken for calculating the MW during ramp-up and ramp-down periods were around 200 ms.

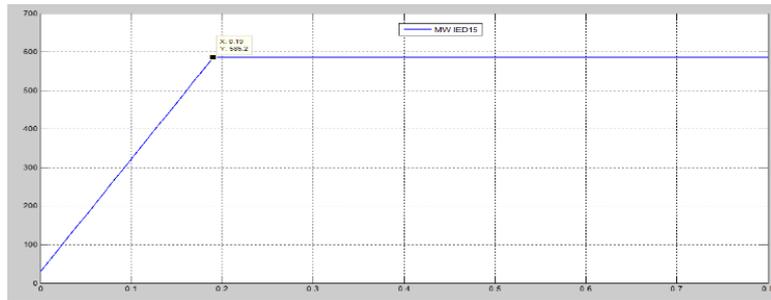


Fig. 5 IED15 MW during ramp-up period

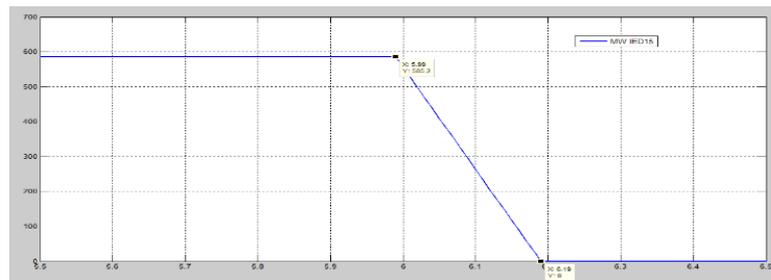


Fig. 6 IED15 MW during ramp-down period

3.4 Logical Operations Modelling

In WADP system, logical operations are used in physical IED for detecting line tripping, overloading etc. Depending on the function of the IED, logical function developed might be differ from one to another. Similarly, the logical operations developed in physical IED are replicated in virtual IED. The example of logical function modelled in virtual IED is shown in Fig. 7.

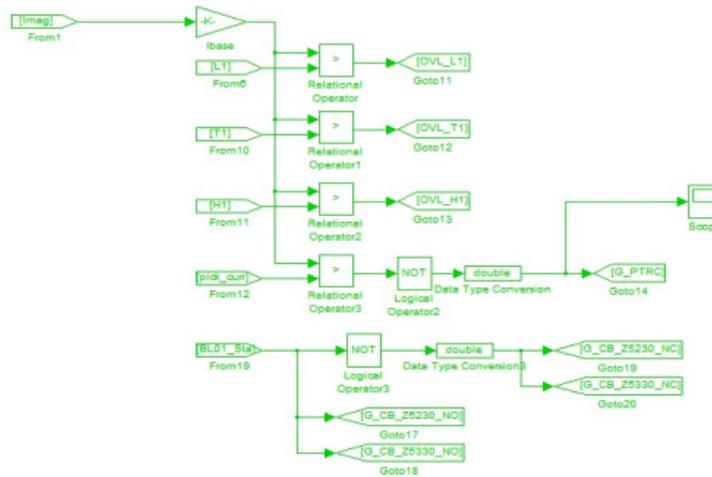


Fig. 7 Example of virtual IED logic diagram modelling

3.5 Communication Protocol Modelling

Communication protocol plays important role in WADP system. In this HIL test system communication protocol is used for exchanging data between IEDs e.g. between virtual IED and RTAP. The most common communication protocol uses in the HIL test system is IEC 61850 GOOSE and MMS. IEC 61850, the only international standard based on internet communication platform for the common parts of the substation automation systems (SAS), is widely practiced in recent years [2-6]. In [7] RTDS is utilized to simulate the power system network and platform MMS client is realized by a specialized tool of RTDS. As commercial external IEDs act as MMS server, by using this tool, all data exchange between MMS server and client can directly be fed to the simulation environment of RTDS. In this paper, only IEC 61850 GOOSE publisher and subscriber are being modelled in virtual IED since the real-time simulator is not supporting IEC 61850 MMS. Hence, the IEC 61850 MMS is treated differently i.e. with IEC 61850 MMS server developed outside of the real-time simulator. This requires IEEE C37.118 slave communication protocol for data exchange between the real-time simulator and the server. In this HIL test system, multiple of IEC 61850 MMS servers are virtually created in a physical hardware that acts as virtual IEDs. Fig. 8 shows an example of virtual IED communication protocol block i.e. IEC 61850 GOOSE publisher. Both IEC 61850 GOOSE and MMS communication protocols in virtual IED imports Configured IED Description (CID) files from the physical IEDs.

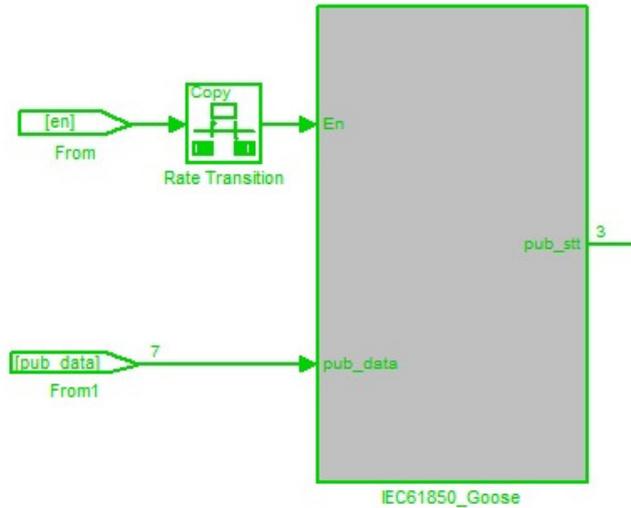


Fig. 8 Example of virtual IED communication protocol modelling

4. Result and Discussion

In order to validate the model, the virtual IEDs are tested with TNB power system in the real-time simulation environment. Overcurrent protection is one of the common protection functions available in TNB power grid. Since this protection element is believed to be highly influencing the WADP designed scheme, an IDMT 51P overcurrent protection element is modelled in the virtual IED to replicate protective function in order to simulate the actual power system responses. The following are the lists of virtual IED that are equipped with IDMT which has been tested in WADP scheme:

- XGT1 – IED25
- XGT2 – IED27
- XGT3 – IED29
- Tie-line L1 – MIED
- Tie-line L2 – MIED

The 51P overcurrent common settings were retrieved from the actual TNB CAPE (Protection Operation Setting) software. The details of the settings are as the following:

1) Tie-lines

- Rated MVA: 250 MVA
- Rated voltage: 230 kV
- CT primary rating: 1200 A
- CT secondary rating: 1 A
- Plug setting: 1.1 A
- Time dial multiplier (TMS): 0.2
- IDMT curve type: IEC standard inverse (SI)

2) XGT transformers

- Rated MVA: 750 MVA
- Rated voltage: 500 kV
- CT primary rating: 1000 A
- CT secondary rating: 1 A

- Plug setting: 1.5 A
- Time dial multiplier (TMS): 0.35
- IDMT curve type: IEC standard inverse (SI)

4.1 Validate Modelled IDMT with Actual Recorded Data

In order to validate the characteristic of the modelled IDMT, an actual recorded data from BEN disturbance recorder based on 19th of July 2016 events was used as a benchmark. The tie-line secondary RMS currents were computed based on the recorded three-phase data. Then, the tie-line yellow-phase RMS current was selected as a reference.

Fig. 9 shows the tie-line secondary current versus IDMT characteristics. Whereas Fig. 10 shows the IEC standard inverse (SI) curve starting from IDMT pickup until the tie-line tripped. It is shown that both IDMTs were pickup at the similar time and current i.e. 1.1 A secondary. Unlike the actual IDMT, the modelled IDMT was pickup several times at the beginning of the rising of current perhaps due to the fluctuation of current and there is no data filtering is modelled in the virtual IED. The tie-line was tripped at time 2.664 s, 2.5862 s after the IDMT was pickup. It is observed that the modelled IDMT operating time was slightly delayed, which was 4.215 s after IDMT was pickup. Therefore, if the secondary line current is maintained at 1.532 A i.e. the last operating current measured just before line was tripped, the modelled IDMT operating time is delayed by 1.6288 s. From the observation, the inconsistency of the operating time between these IDMTs perhaps due to:

- The actual relay may “seen” the secondary current differently since in this validation, the secondary RMS current were computed based on the recorded three-phase data from the disturbance recorder.
- Other actual relay settings/parameters such as breaker operation etc. were not being considered in the modelled IDMT.

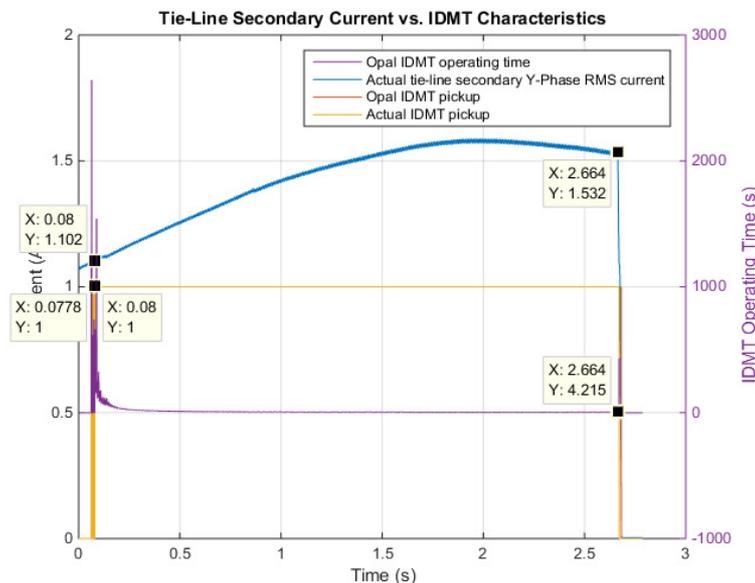


Fig. 9 Tie-line secondary current vs. IDMT characteristics

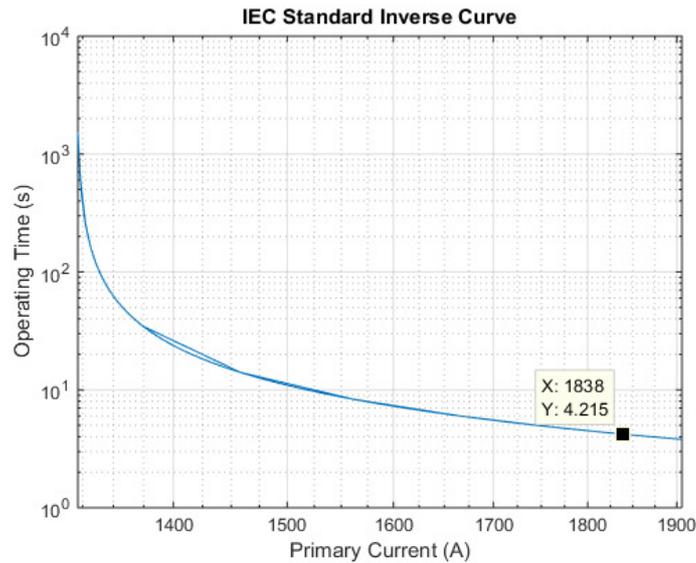


Fig. 10 IEC standard inverse curve based on actual recorded tie-line primary current

4.2 Validate Modelled IDMT with Real-Time Simulation

The IDMT characteristic was further assessed. Through the real-time simulation, the 19th of July 2016 events have been re-produced to validate the IDMT characteristic for tie-lines. The simulation sequence of events is as the following:

- @t = 0 s: Start simulation
- @t = 5 s: Trip TBIN_U4 and de-load JMJG_U2
- @t = 8 s: Apply runback of HVDC and hydro at local frequency 49.8 Hz
- @t = 10.3 s: Trip JMJG_U2
- @t = 20 s: Stop simulation

Fig. 11 shows the simulated tie-line secondary current versus IDMT characteristics. Whereas, Fig. 12 shows the IEC SI curve starting from IDMT pickup until tie-line tripped. It is observed that the IDMT was pickup at time 11.09 s with secondary current 1.102 A. The tie-line was tripped at 15.2 s, which was 4.083 s after the IDMT was pickup. The measured primary current before the tie-line tripped was 1858A.

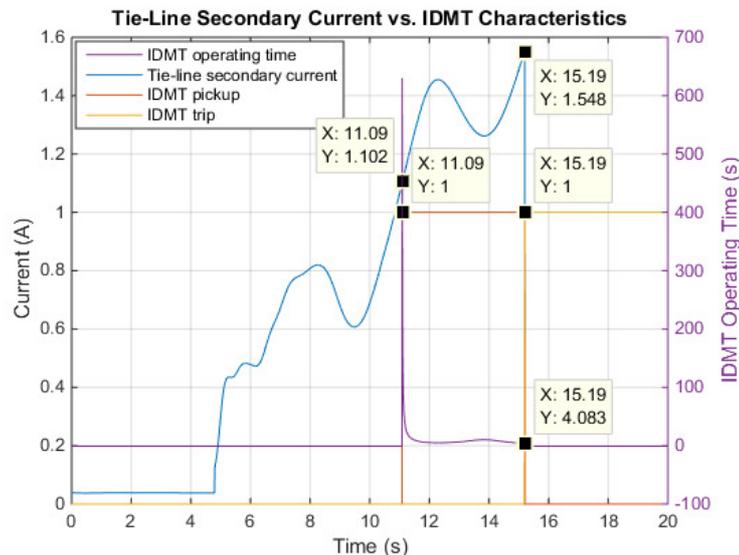


Fig. 11 Simulated tie-line secondary current vs IDMT characteristics

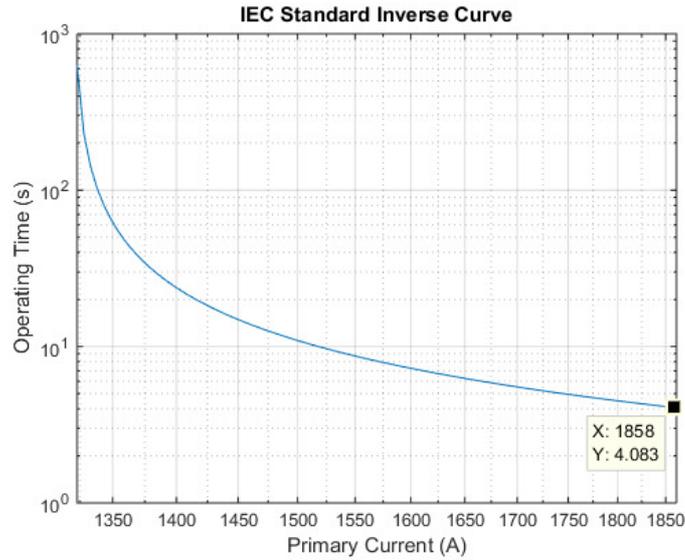


Fig. 12 IEC standard inverse curve based on simulated tie-line primary current

The second test scenario was created with the real-time simulator to validate the IDMT for XGT transformers. The simulation sequence of events is as the following:

- @t = 0 s: Start simulation
- @t = 5 s: Trip ATWR-BTRK 500 kV BL04 line
- @t = 10 s: Trip ATWR XGT1 and XGT2
- @t = 20 s: Stop simulation

Fig. 13 shows the simulated XGT3 secondary current versus IDMT characteristics. Whereas, Fig. 14 shows the IEC SI curve starting from IDMT pickup until transformer tripped. It is observed that the IDMT was pickup at time 10.13 s with secondary current 2.375 A. The XGT3 was tripped at 13.32 s, which was 3.183 s after the IDMT was pickup. The measured primary current before the XGT3 tripped was 3220 A.

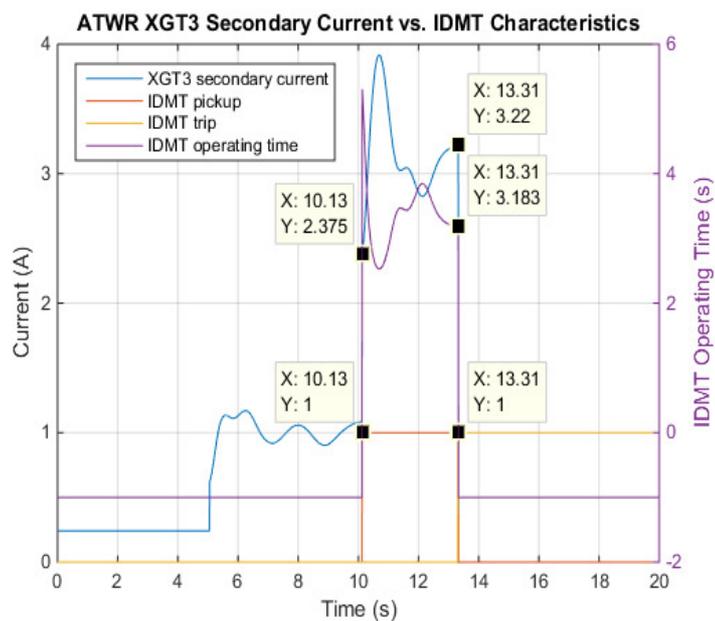


Fig. 13 Simulated XGT3 secondary current vs. IDMT characteristics

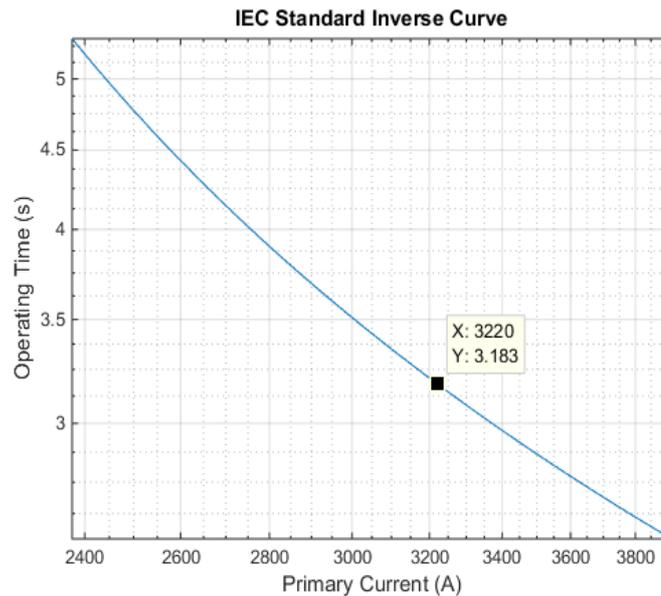


Fig. 14 IEC standard inverse curve based on simulated XGT3 primary current

5. Conclusion

This paper presents a comprehensive Intelligent Electronic Devices (IED) modelling in Hardware-in-the-Loop (HIL) simulation test system developed by TNB Research Power System Group (TNBR-PSG) for TNB Wide Area Defence Plan (WADP) scheme. The IEDs were virtually modelled in the HIL test system within MATLAB/Simulink environment. Thus, the model-based designs of HIL test system were successfully demonstrated in order to replicate actual behaviour of TNB power system towards the design and testing of WADP scheme. The communication protocols of the virtual IEDs were modelled and the IEC 61850 MMS servers were developed outside of the real-time simulator environment hence communications between IEDs are established. In summary, the contribution of this paper can be listed as follows:

- Real-time modelling and simulation for TNB WADP scheme.
- Demonstration of virtual IEDs including IDMT 51P overcurrent protection element modelling in real-time simulation.

Acknowledgment

The authors gratefully acknowledge the contribution of TNBR project members and TNB Transmission for their supports during the development works.

References

- [1] B. Lu, A. Monti, and R. Dougal, "Real-time hardware-in-the-loop testing during design of power electronics controls," in *Proc. IEEE IECON*, Nov. 2003, vol. 2, pp. 1840–1845.
- [2] IEC 61850-5: Communication networks and systems in substations – Part 5: Communication requirements for functions and device models State Grid Corporation of China, Q/GDW383 technical guides of intelligent substation[S]. 2003.
- [3] IEC 61850-9-1: Communication networks and systems in substations – Part 9-1: Specific communication service mapping (SCSM) – Sampled values over serial unidirectional multi-drop point to point link[S]. 2003.
- [4] IEC 61850-9-2: Communication networks and systems in substations – Part 9-2: Specific Communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3[S]. 2003.

- [5] Lars Andersson, Klaus-Peter Brand, Christoph Brunner and Wolfgang Wimmer. Reliability investigations for SA communication architectures based on IEC 61850[C]. Proceedings of IEEE Power Tech 2005: 604-612.
- [6] Skeie T, Johannessen S, Brunner C. Ethernet in substation automation [J]. IEEE Control System Magazine, 2002, 22(3):43-51
- [7] Pouya Jamborsalamati, Abhinav Sadu, Ferdinanda Ponci and Antonello Monti for A Flexible HIL Testing Platform for Performance Evaluation of IEC 61850-based Protection Schemes. IEEE Power and Energy Society General Meeting, 1944-9933. 2016
- [8] Lin Feng, Qing Zhong, Nanhua Yu, Kun Wang, Guojie Li, and Kan Chen for *Hardwareinthe loop Simulation Platform of Photovoltaic Grid Connected System*. TELKOMNIKA Indonesian Journal of Electrical Engineering Volume 12, No. 4, Pages 2465-2473. 2014