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Building a Hardware-In-the-Loop Testing Setup for Evaluating Relays Impacted by High Penetration of Inverter-Based Resources

Y. HU[1*], H. CHAO[1], J. HOLBACH[1], Z. CHENG[1], S. NARAYANAN[1]
T. NGUYEN[2], E. L. SEITER[3], M. RAZANOUSKY[4]
Quanta Technology, LLC[1], New York Power Authority[2], National Grid (US)[3],
New York State Energy Research & Development Agency[4]
USA

SUMMARY

The Climate Act of New York State (NYS) in the US stipulates that 70% of the State's electricity will be generated by renewable energy by 2030 and 100% zero-emissions electricity by 2040. As a result, the penetration level of inverter-based resources (IBR) in the NYS control area has been increasing steadily. It has been well recognized that high penetration of IBRs (Hi-IBRs) reduces the fault current and changes negative and zero sequence fault current contributions, which could negatively impact protective relays commonly used today to protect NYS's transmission grid. To evaluate the true impact of the Hi-IBRs, these relays should be tested under realistic future low-carbon or carbon-neutral power system conditions in a Hardware-In-the-Loop (HIL) setup. This paper is to report the development of a HIL testing setup for a projected 2030 system condition in northern NYS with Hi-IBRs that is used to evaluate selected relays commonly used today to protect the northern NYS transmission grid. The paper is organized to provide readers with an awareness of many challenges that need to be overcome to develop such a testing setup for evaluating the true IBR impact on relays in a more realistic future system condition with Hi-IBRs. The first section of the paper presents the anticipated New York State (NYS) IBR penetrations and the likely NYS power system scenario by 2030, an overview of fault response characteristics of IBRs, and the motivation to evaluate the impact and the need to develop the HIL testing setup. The second section discusses the current practices of testing protective relays in a HIL testing setup and the HIL testing setup that is created for assessing the Hi-IBRs' impact on selected transmission relays commonly used for protecting the northern NYS transmission grid. The third section describes real-time electromagnetic transient (EMT) system models with and without Hi-IBRs for northern NYS power system that are developed for HIL testing setup to evaluate the impact of Hi-IBRs on the selected relays and the developed mitigation solutions. The Hi-IBRs EMT system model used a self-developed IBR EMT model that closely matches the dynamic and transient performance of a vendor-developed IBR EMT model.

KEYWORDS

Inverter-Based Resources (IBR), Real-Time Digital Simulation, Hardware-In-the-Loop (HIL), Grid Protection, Electromagnetic Transient (EMT), Battery Energy Storage System (BESS), Solar, Wind.

YHu@quanta-technology.com

INTRODUCTION

The increasing penetration of renewable energy resources such as solar, wind, and battery energy storage systems (BESS) as IBRs in NYS is starting to change electric power grid dynamics and create new challenges to grid planning, operation, and protection. It has been well recognized by the industry [1][2] that the fault response characteristics of IBRs are different from that of large rotating generators which could negatively impact the proper operation of existing protective relays. Many investigations have been conducted to evaluate the impact for protective relays and to develop mitigation solutions, such as the one in [3] that used a small four-bus five-line system model for the investigation. Similar small system protection study using a HIL simulation setup to test real relays has been done in [4]. However, how to properly evaluate the impact of Hi-IBRs on real relays under a realistic power system condition of a complex interconnected transmission grid using a HIL testing setup remains a major challenge.

This paper reports the successful development of a HIL testing setup that enables the proper evaluation of the impact of Hi-IBRs on real relays under realistic power system conditions. This work is done as part of a research study project funded by the New York State Energy Research & Development Agency (NYSERDA). The study, led by Quanta Technology and supported by New York Power Authority (NYPA) and National Grid US (NGrid), aimed to evaluate the impact of Hi-IBRs on commonly used relays, and develop and validate mitigation solutions if any issues are found. This section of the paper provides an overview of the existing and projected 2030 IBR penetration in NYS, the fault response characteristics of IBRs, and the motivation of the study that necessitates the development of such a HIL testing setup. The second section discusses the current practices of testing protective relays in a HIL testing setup and the HIL testing setup that is created for assessing the Hi-IBRs' impact on selected transmission relays commonly used for protecting the northern NYS transmission grid. The third section describes real-time electromagnetic transient (EMT) system models with and without Hi-IBRs for northern NYS power system that are developed for HIL testing setup to evaluate the impact of Hi-IBRs on the selected relays and the developed mitigation solutions. The Hi-IBRs EMT system model used a self-developed IBR EMT model that closely matches the dynamic and transient performance of a vendor-developed IBR EMT model.

New York State's March Toward A Zero-Emissions Electricity Future

Since its Climate Act was signed into the law on July 18, 2019, NYS has witnessed a rapid increase in wind, solar, and battery energy storage system (BESS) projects being proposed and put into service. The data in the New York Independent System Operator's (NYISO) annual Gold Book of 2021 and 2023 [6][7] have shown that the total nameplate capacity of in-service wind, solar, and BESS (all considered as IBRs) has grown more than 34% in just two years.

Table 1 shows existing and proposed wind, solar, and BESS projects to be in-service by 2030 in each load zone (Figure 1) based on data from the 2021 NYISO Gold Book [6] and the proposed project queue in 2021 [8]. In Table 1, (1) the Total Existing is the total generation capacity including the existing wind and solar; (2) the Total New is the total capacity of proposed wind, solar, and BESS projects to be in-service by 2030; (3) the IBR Total is the sum of Existing Wind/Solar and the Total New; and (4) the Total Gen is the sum of Total Existing and Total New. The table shows that for the NYS control area, the capacity of total IBRs could reach close to 60% with some load zones (e.g., zone E and K) having a much higher penetration level than other load zones. The correct operation of relays in areas with high penetration of IBRs could be negatively impacted due to the fault response characteristics of IBRs.

Table 1 New York State Existing and Proposed IBR Capacities by 2030

Load Zones	Existing Capacity (MW)			IBR Level (%)	Proposed New IBR Capacity (MW)				IBR Total / Total Gen (%)
	Wind	Solar	Total Existing		Wind	Solar	Battery	Total New	
A	179	0	3,376	5%	566	2,565	530	3,660	51%
B	0	0	765	0%	200	965	21	1,186	60%
C	518	0	6,381	8%	940	3,482	784	5,206	46%
D	678	0	1,921	35%	847	727	20	1,594	64%
E	442	0	1,004	44%	1,135	3,180	28	4,342	89%
F	0	0	4,492	0%	-	1,565	-	1,565	26%
G	0	0	4,790	0%	-	20	897	917	0%
H	0	0	1,088	0%	-	-	1,300	1,300	0%
I	0	0	-	#N/A	-	-	400	400	#N/A
J	0	0	9,618	0%	8,848	-	3,536	12,384	48%
K	0	32	5,236	0%	18,498	59	388	18,945	78%
Total	**1818**	**32**	**38,670**	**5%**	**31,034**	**12,562**	**7,904**	**51,499**	59%

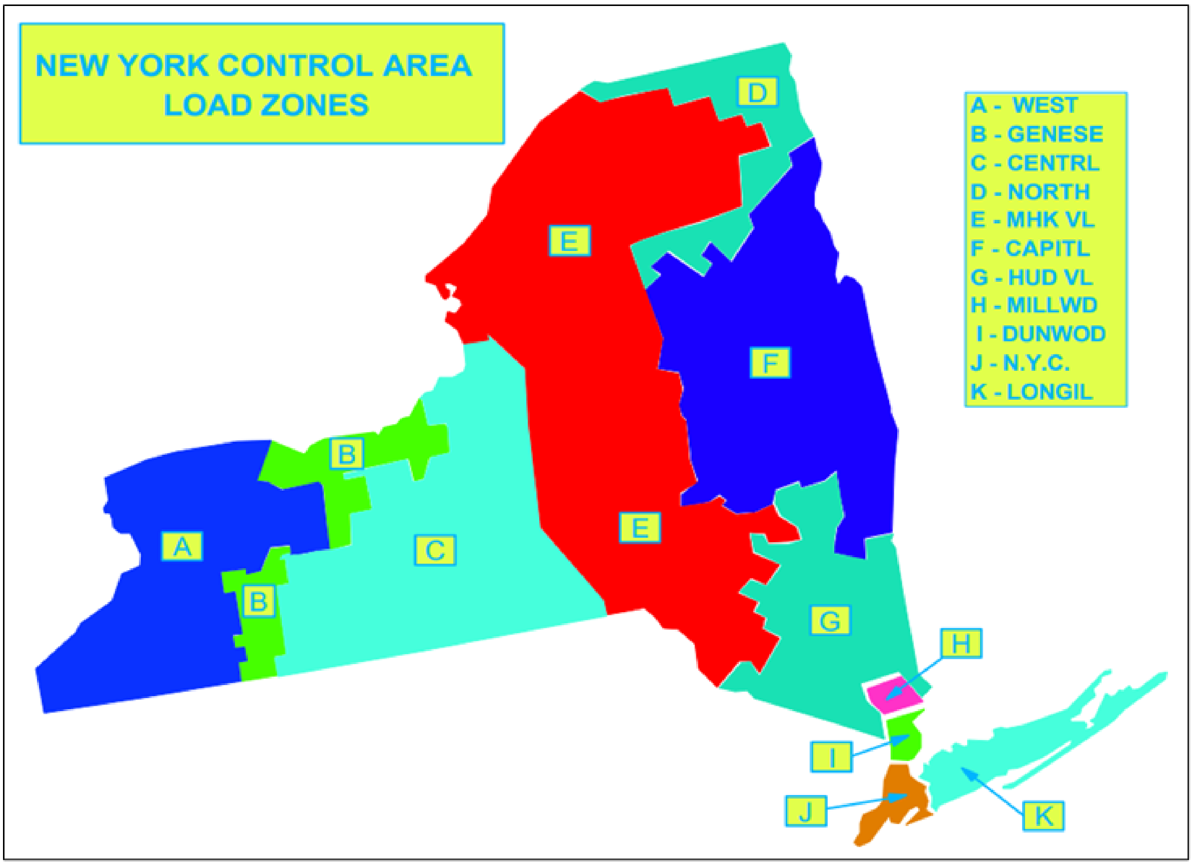

Figure 1 New York State Control Area Load Zones (Source: https://www.nyiso.com/documents/20142/1397960/nyca_zonemaps.pdf)

Fault Response Characteristics of Inverter-Based Resources

The common IBRs include Type-IV wind generators with full ac-dc-ac inverters, photovoltaic (PV) generation resources with dc-ac inverters, and BESS generation resources when in generation mode with dc-ac inverters. The cost considerations have led to the IBRs designed with limited overload capacity (typically <2.3 times the rated output current immediately after a fault and < 1.5 about 3 cycles after the fault [5]). This means IBRs will produce a much lower fault current output than that of the large rotating generation resources which could temporarily reach 10 times or higher of their rated output current. An IBR may only output a fault current higher than the rated output current when the IBR can "see" that there is a fault, i.e., the voltage magnitude at IBRs dips well below 0.9 pu of the rated voltage [5]. For many IBRs further away from the fault location, these IBRs may only contribute a maximum of the rated output current if the fault voltage magnitude at their connection points is above 0.9 pu.

Depending on the type of output current control scheme used, an IBR may or may not contribute negative sequence fault current. An IBR with coupled sequence control (CSC) scheme always output three-phase balanced current regardless if it is in the normal operation state or under an external fault condition. Thus the IBR with CSC scheme will not contribute any negative sequence fault current, but an IBR with decoupled sequence control (DSC) scheme will [5]. CSC scheme may be a common scheme used in many already installed IBRs, but DSC scheme has been adopted by recent commissioned IBRs which may become the dominant one when use of DSC scheme is mandated by the grid code or IBR interconnection requirement.

IBRs, when connected to the transmission grid through step-up transformers, in general, are unable to contribute any zero-sequence fault current to the grid regardless of the type of output current control schemes used. This is because these step-up transformers are all delta-wye configured. However, if step-up transformer windings on the point-of-interconnection side are wye-grounded, it will provide an additional path for zero sequence fault current of any fault involving the ground.

One aspect of a future zero-emissions electricity scenario in NYS is that its renewable energy resources will not be 100% IBRs. NYS has large amounts of existing hydro generation plants (5.3 GW) [6][7] and pumped storage generation plants (1.4 GW) [6][7] which are non-IBR renewable energy resources consisting of large rotating generators. These non-IBR renewable energy resources will be part of the overall zero-emissions portfolio and operate side-by-side with IBR renewable energy resources. The existence of hydro and pumped storage generation resources may help to lessen the level of fault current reduction and negative sequence fault current reduction but may or may not be sufficient to counter the full impact of Hi-IBRs.

Motivation to Take Action Now

Protective relays have been used to protect lines and equipment such as transformers of power systems from damage by faults and other abnormal conditions. The fundamental requirement for protective relays is that they must be highly dependable, meaning they must be able to take the required actions whenever needed, and secure, meaning they should never take any unnecessary actions. To meet this requirement, it typically takes a few years or more from developing a new relay or a new relay function to deploying it in the field for resolving a relay misoperation issue. The process typically involves the identification of the root cause of the relay misoperation issue, the development of a mitigation solution, the development of a new relay or a new relay function if needed, rigorous factory and field testing processes, and a full deployment or replacement process.

Waiting until the misoperation issues emerge when the IBR penetration reaches a critical level and then reacting to address them will have many unintended consequences, particularly when the identified issues require the development of new protective relaying functions or methods to properly mitigate them. If the appropriate mitigation solutions are not ready when needed, operating the future power system at the full IBR penetration level could subject the system to more relay misoperations, which may necessitate to operate the system at a lower IBR penetration level and/or delay the retirement of generators burning fossil fuels to avoid relay misoperation issues.

This NYSERDA funded study was motivated by the need to take proactive actions to identify and mitigate any potential issues well before their emergence. The study is to evaluate the impact of Hi-IBRs on commonly used protective relays under a realistic 2030 system scenario and to develop appropriate solutions to mitigate any identified relay misoperation issues. Developing a suitable HIL relay testing setup is a critical first step of this study.

HARDWARE-IN-THE-LOOP TESTING OF RELAYS

Performing closed-loop testing of relays under realistic power system conditions is an effective way to evaluate relay true performance in real situations. However, it is impractical and could be very dangerous to perform such tests in a real electric power grid. In addition, it is not possible to evaluate the performance of a relay for future electric power grid conditions in an existing grid. Testing relays in a HIL testing setup is practical and efficient but with some unique challenges.

HIL Testing of Relays

Early HIL testing of relays was performed on purpose-built physical model power systems with scaled-down physical components, such as small generators, small transformers, resistors, reactors, capacitors, switches, controllable switches, measurement devices, and control devices. Today, HIL testing of relays uses real-time digital simulators, such as RTDS and Opel-RT, exclusively as real-time digital simulators cost much less and are much easier to setup and use than using the physical model power systems.

HIL Relay Testing Using Real-Time Digital Simulators

Figure 2 shows the typical HIL setup using a real-time digital simulator for relay testing. The real-time digital simulator is used to simulate a real-time EMT power system model and various types of faults at different fault locations to generate output voltage and current signals at the proper measurement points for inputting into the relays under test. The output voltage and current signals could be in analog or digital format depending on the available relay input interfaces. The digital relay trip signals can be sent back into the real-time digital simulator to trip the desired breakers in the simulated power system model.

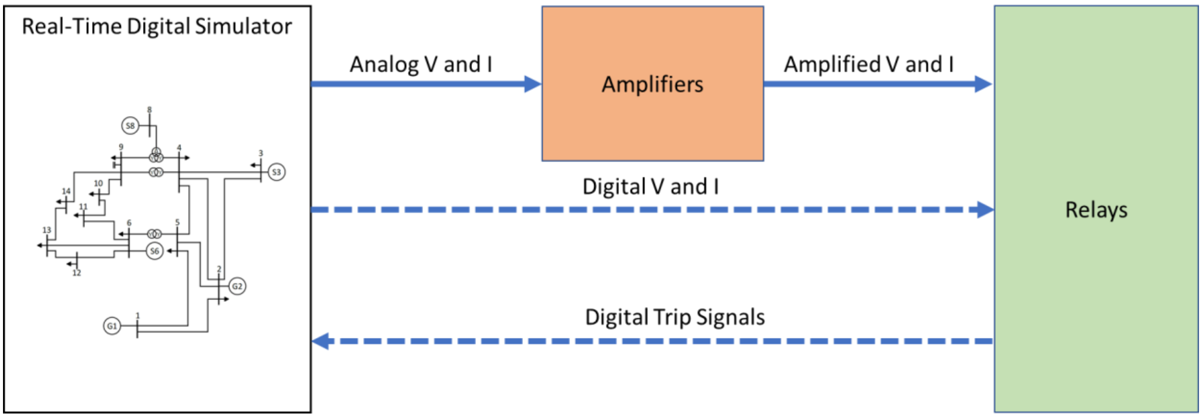

Figure 2 Typical HIL setup using a real-time digital simulator for relay testing

When using real-time digital simulators for HIL testing setup, developing digital power system models that are true representation of the physical systems, i.e., the digital models are true digital twins, has been a main challenge. The developed digital power system models must be rigorously validated to ensure that it is a true representation of the physical systems.

For HIL relay testing using real-time digital simulators, the development and validation of the real-time EMT power system models for intended testing generally require substantial efforts if needed system models are not readily available, the simulator is missing needed component models (e.g., IBR models for real IBR products), and/or modeling a large size electric power system is involved.

The HIL Setup Used in This Study

For HIL setup used in this study, the following relays and equipment are used that include:

- Nine relays undergoing testing for evaluating Hi-IBRs impact on these relays
  - Six relays for three different relay models, i.e., two relays for each relay model, for testing current differential, overcurrent, directional, fault type selection, and distance relaying functions or elements.
  - Three relays for three relay models, i.e., one relay for each relay model, for testing overcurrent, directional, fault type selection, and distance relaying functions or element
- RTDS:
  - Three NovaCor chassis to simulate the EMT power system models including the base system model and the Hi-IBR system model
  - Two giga-transceiver analog output (GTAO) cards to provide analog output from the RTDS simulation to amplifiers
  - One GTNETx2 card to provide IEC 61850 communication protocol
- Voltage and current amplifiers to provide a suitable input for the protection relays:
  - Eight AETECHRON as the voltage amplifier
  - One Doble F6300e as the current amplifier
- Ethernet switch for network communication
- DC power supply

The HIL testing setup for this study was assembled and validated at the Advanced Grid Innovation Laboratory for Energy (AGILe) of NYPA. The development and validation of the needed digital electric power system models for this HIL relay testing setup are presented in the next section.

CREATE REAL-TIME EMT SYSTEM MODELS IN RTDS FOR EVALUATING RELAYS

Evaluating the impact of Hi-IBRs on relays requires the creation of several real-time EMT system models. A base system model representing the current electric power system is needed to serve as a benchmark system. The base system model is used to confirm all relays that will be tested have the correct settings for current electric power system conditions. This will establish a baseline for evaluating the impact of Hi-IBRs. These relays should operate correctly under all internal and external fault conditions with the correct settings. A Hi-IBRs system model representing a 2030 electric power system condition is also needed to evaluate the relay performance under Hi-IBRs conditions. In this Hi-IBRs system model, the IBR models should be highly representative of the actual IBRs and all IBRs should be placed at the correct locations in the system model to create a realistic system condition for evaluating the performance of relays that may be impacted by the Hi-IBRs conditions. Variations of the Hi-IBRs system model were also created for evaluating relay performance under certain changed Hi-IBRs system conditions.

Selected Focus Area

As shown in Table 1, the projected IBR penetration level in NYS by 2030 varies widely from one load zone to the other. Selecting an area where IBRs will reach a high level (e.g., >60%) would be highly representative of 2030 and beyond NYS power system conditions since the average IBR penetration level in NYS should be somewhere between 50%-55% to reach the 70% target when hydro and pumped storage capacities are included. In this study, the North Country economic region of NYS, which encompasses load zone D and the northern part of load zone E, was selected. The region has a major hydro generation station (>500 MW), and the load zones D and E will have projected IBR penetration of 64% and 89% respectively. Load zones D and E also have a relatively high number of weaker buses than other load zones in the base system model. Hi-IBRs will impact relays more in a weaker part of a system. An analysis of all buses above 100 kV (1236 buses) in NYS based on their short-circuit MVA shows that load zones D and E have 17.2% (10 out of 58 buses) and 26% (39 out of 150 buses) weaker buses of the top 10% (124 out of 1236 buses) in NYS.

The Base EMT System Model for RTDS

The original EMT system model for North Country of NYS in AGILe's RTDS was developed through a separate effort prior to this study. The original model was developed based on PSS/E and Aspen system models for the area. The transmission lines have voltage levels of 765 kV, 230 kV, 115 kV, 34.5 kV, and 13.8 kV. There are 142 lines, 252 buses, 117 loads, and 57 generators modeled in this original RTDS EMT system model. There are 11 existing wind plants modeled in the system model, which are not Type-IV wind generators, i.e., not IBRs.

The fault current levels at various buses of the original RTDS EMT system model had large difference compared to fault current levels at the same locations in a corresponding Aspen system model, which was used to calculate the relay settings. It was identified that the main source of large fault current differences is due primarily to the differences in wind generator modeling between the two software. Differences in external system equivalencing and zero impedance values in some lines also contributed to the large fault current differences. Updates were made to bring the difference of fault current levels at various buses to be within an acceptable margin when all existing wind generators are turned off in both software. The updates included some adjustments to external system equivalencing and matching zero impedance values between the two system models. The updated RTDS EMT system model was used in this study as the base RTDS EMT system model.

Modeling IBR for RTDS

Our assessment of the availability of suitable RTDS IBR EMT models at the beginning of the study concluded that (1) The RTDS product at the time only provides generic IBR models that do not include required protection and control functions (e.g., high/low voltage ride-through, over-voltage tripping, etc.); (2) No vendor-developed RTDS IBR EMT models were found available; (3) No other suitable RTDS IBR EMT models were found based on our search. Developing a suitable RTDS IBR EMT model from the ground up became the only option for this study. However, the main challenge of this option is how to develop an RTDS IBR EMT model that can be validated to match closely with a real IBR. Getting a real IBR for validating the developed RTDS IBR EMT model is an impractical approach.

As was known to us, some United States Independent System Operators (ISOs) and Transmission Owners (TOs) already have mandatory requirements for vendors or developers to provide vendor-developed IBR EMT models for interconnection studies related to their interconnection requests. This has resulted in the availability of vendors-developed IBR EMT models for more detailed EMT studies in PSCAD – A non-real-time EMT simulation software. Some PSCAD IBR EMT models even included the actual vendor's IBR controller code as a Blackbox module. Thus, if a vendor-developed PSCAD IBR EMT model could be obtained, it could be used to validate if the model we developed matches with the vendor-developed model. After reaching out to many vendors and developers, we were able to obtain one such model for this study.

Based on the relevant information collected, we have developed an RTDS IBR EMT model consisting of a neutral-point-clamped (NPC) converter and an IBR controller (Figure 3). The self-developed RTDS IBR controller model was fine-tuned against the vendor-developed PSCAD IBR controller model through multiple iterations, with the self-developed IBR EMT model running on RTDS and the vendor-developed IBR EMT model running on PSCAD. After a close match had been achieved, a further validation was performed using the RTDS-PSCAD co-simulation method, which had just become available in the beta version before the validation. An IEEE 14-bus system model in RTDS was used to perform this further validation. The self-developed RTDS IBR EMT model was connected to a selected bus in the 14-bus system and subjected to a set of sixteen system fault events and the dynamic responses of the self-developed model were captured and stored. Then for the vendor-developed PSCAD IBR controller model, it was simulated in PSCAD and connected to the NPC converter and the IEEE 14-bus system model in the RTDS at the same selected bus through the RTDS co-simulation mechanism. The same set of system fault events were simulated and the dynamic responses of the vendor-developed IBR controller were also captured and stored. The results were compared to further validate if a close match has been achieved. This co-simulation approach ensured that both self-developed and vendor-developed IBR controllers detect and respond to the same system fault events, thereby eliminating the errors introduced by the modeling differences between PSCAD and RTDS power system components. For the self-developed model, the overall Mean Absolute Error (MAE) of its dynamic responses compared to that of the vendor-developed model for the sixteen fault events is 0.0031 kA. Using pre-fault IBR output current magnitude as the basis, the maximum modeling error is less than 1.1%.

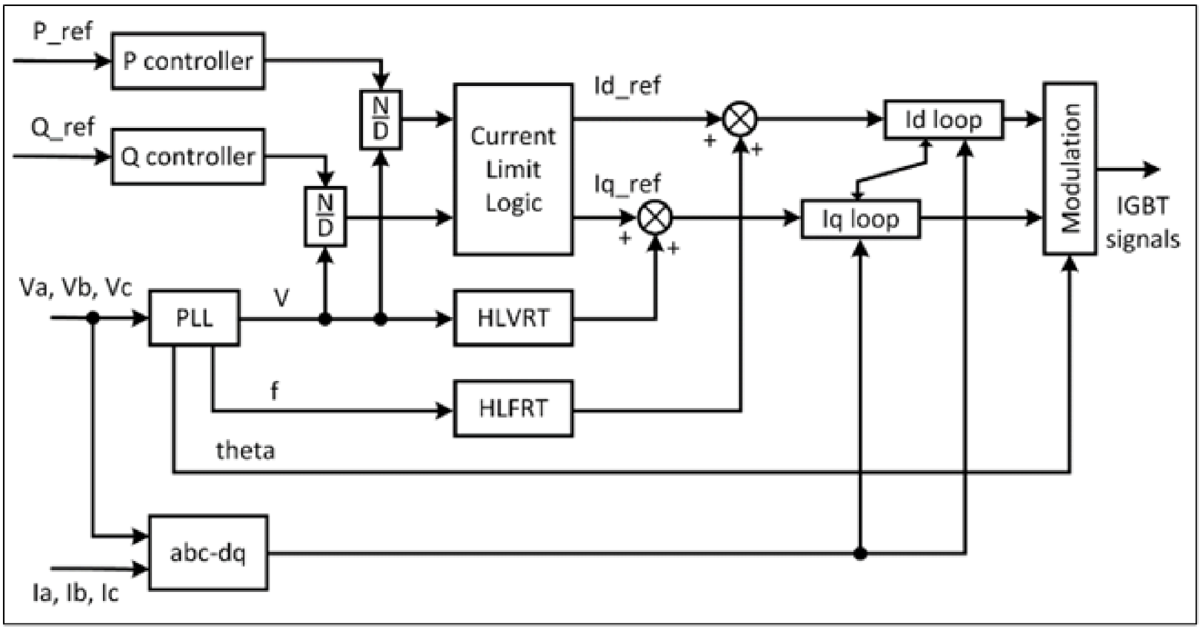

Figure 3 IBR Controller Bock Diagram

<u>The Hi-IBRs EMT System Model for RTDS</u>

The self-developed RTDS IBR EMT model is used to create an RTDS Hi-IBRs EMT system model from the base RTDS EMT system model. New IBRs are added to the RTDS base EMT system model using the developed RTDS IBR EMT model. The locations of new IBRs and their installed capacity information are based on the NYISO project queue. A total of 527 MW solar IBRs at four locations, 847 MW of wind IBRs at four locations, and 20 MW of BESS IBR are added. The power outputs of added new IBR plants are set to 41% for wind and 60% for solar and battery energy storage systems (BESS). All existing wind plant models are replaced with the new IBR EMT model assuming these wind plants will be upgraded to Type-IV by 2030. To rebalance the generation and load, 50% of the generators with 258 MW in a large hydro-generation plant are turned off, and a 315 MW combined-cycle generation station is retired. A weak equivalent boundary source is further weakened to make it a weaker connection (SCR=2.5, X/R < 5).

Various internal and external fault events are simulated in both the base EMT system model and Hi-IBRs EMT system models on one 115 kV and one 230 kV selected lines. The two lines are selected from the part of the system where a large number of existing and new IBR plants are located nearby and thus are considered that relays on these two lines could have been impacted by Hi-IBRs. We compared the changes in zero, positive, and negative sequence fault current components to assess whether high IBR penetration may have caused any major changes to these sequence fault current components. The results have shown that the 115 kV line is not a good choice as sequence fault current components at both ends of the line did not have major changes. Fault current contributions from the hydro generations still dominate the sequence fault current components for this line. The 230 kV line is impacted as major changes are seen in the negative and zero sequence fault current components. The extent of the impact, however, is not the same for the two ends of the line.

According to the simulation results, the fault currents at the end of the 230 kV line close to the large hydro generation plant show reductions but are still relatively high, whereas the other end of the line experienced a much large fault current reduction and a significantly decreased negative sequence fault current during unbalanced faults. The 230 kV line thus is used in the subsequent HIL testing of selected relays to evaluate the impact of high penetration of IBRs on the selected relays and to further evaluate several solutions developed to mitigate the identified issues in this study. The evaluation results of the relays and the developed mitigation solutions will be presented in separate follow-on papers.

CONCLUSION

In this paper, a hardware-in-the-loop testing setup was presented. The testing setup was developed for evaluating the impact of high penetration of inverter-based resources on transmission relays commonly used in the North Country region of the New York State for a projected system scenario by 2030. The core of the testing setup is a high-capacity RTDS real-time digital simulator with detailed modeling of every component of the transmission grid for the region along with existing and new IBRs using a detailed self-developed IBR EMT model that closely matches the behavior of a vendor-developed PSCAD IBR EMT model. The selected relays are connected to the RTDS through amplifiers and communication networks for performing the HIL testing.

Developing similar HIL testing setup is critically needed to support the energy transition towards a zero-emissions electricity future in NYS and elsewhere. Potential issues of commonly used relays due to the impact of Hi-IBRs must be identified, well understood, and properly mitigated well before the penetration of IBRs reaches a point when relays start to misoperate. Proactive actions are needed to ensure that there is ample time for us to go through the needed processes from the identification and confirmation of an issue to field rollout of the well-tested mitigation solution that typically takes several years at minimum, and much more years if new relaying algorithms/methods must be developed and validated to fully mitigate the identified issue.

Major challenges remain in developing the much-needed HIL testing setups for evaluating the impact of Hi-IBRs on real relays under realistic system conditions and for validating the developed mitigation solutions to identified issues. The lack of readily accessible vendor-developed IBR EMT models in general and specifically for real-time digital simulators would be the top challenge faced by any attempt to develop such a setup. In fact, at the beginning of this study, it was a major challenge across the industry to have access to such IBR EMT models for non-real-time studies as pointed out in [9]. While our team was able to successfully developed one RTDS IBR EMT model, it was a huge undertaking of the overall study. If a study area has multiple IBRs that are different from each other, the model development effort for these IBRs could be so cost prohibitive that it becomes a real obstacle to develop such testing setups. North American Electric Reliability Corporation (NERC) recently published a report [10] with recommended model requirements and verification practices for bulk power system-connected IBRs. This will help to make many vendor-developed and properly verified IBR models become available in the future. However, it remains to be seen if vendors may start to develop IBR EMT models for real-time digital simulators as most of their IBR EMT models developed so far are for non-real-time simulation software such as PSCAD and EMTP. Having access to a high-capacity real-time digital simulator is very important for studies similar to ours but could be a major challenge for many. Ensuring the developed system model on a real-time digital simulator is an accurate digital twin of the power system to be studied is an essential requirement to obtain credible evaluation results but could be a major challenge if the system models need to be developed from the ground up.

BIBLIOGRAPHY

[1] IEEE PES Report "Impact of Inverter-Based Generation on Bulk Power System Dynamics and Short-Circuit Performance," (IEEE PES, July 2018, Technical Report PES-TR68)

[2] Sandia National Lab Report, "Impact of Inverter-Based Resource Negative-Sequence Current Injection on Transmission System Protection", (Sandia National Lab, January 2020, SANDIA Report SAND2020-0265)

[3] R. Chowdhury, N. Fischer, "Transmission Line Protection for Systems With Inverter-Based Resources", (48th Annual Western Protective Relay Conference, October 2021, Conference Paper)

[4] Z. Cheng, S. Narayanan, J. Holbach, J. Stevens, M. Cummings, R. Rohde, et al., "Investigating Inverter-Based Resources Impacts on the Transmission Line Protection via Hardware-in-the-loop Simulation," (75th Annual Georgia Tech Protective Relaying Conference, May 2022, Conference Paper)

[5] IEEE PES Report "Protection Challenges and Practices for Interconnecting IBRs to Utility Transmission Systems," (IEEE PES, July 2020, Technical Report PES-TR-81)

[6] NYISO Report, "Load and Capacity Data Report," (NYISO, 2021, Gold Book 2021)

[7] NYISO Report, "Load and Capacity Data Report," (NYISO, 2023, Gold Book 2023)

[8] NYISO, "Interconnection Queue.xlsx," (NYISO, 2021, Public Interconnection Queue File)

[9] NERC Report, "BPS-Connected Inverter-Based Resource Modeling and Studies," (NERC, May 2020, Technical Report)

[10] NERC Reliability Guideline "Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources – Recommended Model Requirements and Verification Practices," (NERC, March 2023, Reliability Guideline).