IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 23, 2020, accepted December 6, 2020, date of publication December 14, 2020, date of current version December 29, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3044327

Developing Power Hardware-in-the-Loop Based Testing Environment for Volt-Var and Frequency-Watt Functions of 500 kW Photovoltaic Smart Inverter

HIROSHI KIKUSATO[1], (Member, IEEE), TAHA SELIM USTUN[1], (Member, IEEE), JUN HASHIMOTO[1], (Member, IEEE), KENJI OTANI[1], TAKAYUKI NAGAKURA[2], YASUTOSHI YOSHIOKA[2], (Member, IEEE), RYO MAEDA[3], AND KENJIRO MORI[4]

[1]Fukushima Renewable Energy Institute (FREA), National Institute of Advanced Industrial Science and Technology (AIST), Fukushima 963-0298, Japan
[2]Fuji Electric Company Ltd., Kanagawa 210-9530, Japan
[3]TEPCO Power Grid, Incorporated, Tokyo 100-8560, Japan
[4]Tokyo Electric Power Company Holdings, Incorporated, Tokyo 100-8560, Japan

Corresponding author: Hiroshi Kikusato (hiroshi-kikusato@aist.go.jp)

This work was supported by the Project Subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

ABSTRACT The power hardware-in-the-loop (PHIL) simulation has become a popular testing approach due to the flexibility it provides and the high-fidelity of its results. It is expected to be utilized as an advanced laboratory testing scheme to validate the grid support functions of distributed energy resources (DERs) because it can evaluate the interaction between the power system and DERs. Despite the strong demand to utilize the PHIL simulation for such testing, the literature that elaborates on the practical design of PHIL simulation based testing (hereafter called ''PHIL testing'') environment including laboratory device setup, power system models, and test procedures is very limited. The simulation models, interfacing with the tested equipment, and data collection approaches are all different parameters that need to be fine-tuned for the successful execution of PHIL testing. It is vital for such successful test experiences to be shared to build universal knowledge around PHIL testing. In order to fill this knowledge gap, this paper presents such practical and essential techniques for the PHIL testing to share the knowledge for promotion of the PHIL simulation utilization. The development of PHIL testing environment to validate the smart inverter functions, i.e., volt-var function and frequency-watt function, is focused on in terms of laboratory setup, power system modeling, interfacing, and test procedure. The volt-var and frequency-watt functions of a 500 kW smart inverter of photovoltaic are validated on the basis of the presented techniques. Detailed test configurations, test procedures, and simulation models are presented along with obtained test results.

INDEX TERMS Distributed energy resource, IEC 61850-90-7, IEEE 1547, IEEE 1547.1, laboratory testing, power hardware-in-the-loop simulation, smart inverter, test procedure.

I. INTRODUCTION

Conventional power systems were not designed to accommodate active generation and storage at the distribution level [1]. Technologies and operational concepts for effective integration of distributed energy resources (DERs) into existing power systems continue to be further developed to realize additional benefits and to avoid adverse impacts on system reliability and safety. As the migration from traditional bulk power plants to numerous smaller DERs proceeds, the technical requirements of DERs also change. The notable changes include their response to voltage and frequency disturbances [2]. The test procedures to validate such sophisticated functions have been also amended [3].

In the power system where bulk generators are replaced by the DERs, the grid support functions of DERs become very important for power system stability. DER inverters with such functions, a.k.a smart inverter (SI) [4] monitor voltage and frequency of the grid and control their active and reactive power output. This, in turn, affects the grid voltage and

The associate editor coordinating the review of this manuscript and approving it for publication was Qiuhua Huang.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

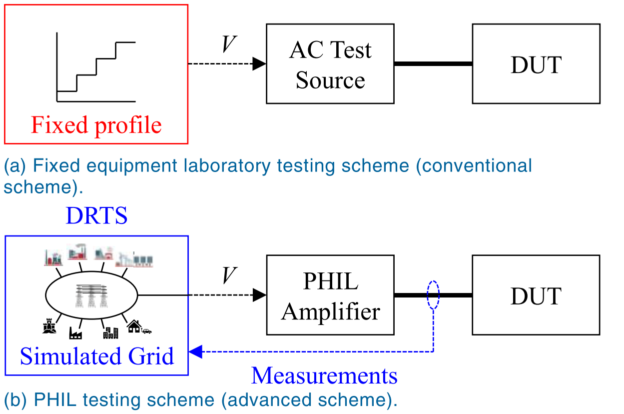


FIGURE 1. Comparison of testing schemes. In (a) conventional scheme, fixed profiles are set to AC test source. Open-loop response of DUT can be validated. In (b) PHIL testing, calculated values in DRTS are set to PHIL amplifier, and measurements of DUT output are fed back to DRTS. Interaction between the simulated grid and DUT can be validated.

frequency and the cycle continues. Therefore, it is necessary to understand the interaction between the power system and SIs to appropriately utilize the benefit and avoid the negative impact of the SIs on the power system [5]. Utility companies are sometimes conservative to install novel technologies to their grid from the perspective of the responsibility for stable power supply. However, proof that the benefits are obvious, but also that the negative effects are fully acceptable, can convince them to install such technologies. Although the current standardized testing includes the validations of SI's response to the voltage and frequency disturbances, it is not a scheme to be able to evaluate the interaction between power system and SIs. Hence, it cannot fully reveal the potential of SIs.

In order to address this knowledge gap, an advanced testing scheme has been developed with power hardware-in-the-loop (PHIL) simulation. An SI is generally tested to be connected to an alternative current (AC) test source, which is a bi-directional AC voltage source replicating a utility power source. Fig. 1 shows a comparison of the testing schemes. In the conventional testing for voltage and frequency support functions, the voltage and frequency of the AC test source are set to certain fixed values, and the outputs of the SI under the specified setting are evaluated [6]–[8], i.e. open loop responses of the SI are validated. On the other hand, in the PHIL simulation based testing (hereafter called ''PHIL testing''), a digital real-time simulation (DRTS) is incorporated and the SI is tested as if it is connected to the real grid [9]. The DRTS simulates the arbitrary power system, and the calculation results are sent to the AC test source. The AC test source amplifies and applies the voltage to the SI. The output of the SI is measured and fed back to the DRTS. This closed-loop simulation scheme can evaluate the interaction between the power system and SIs. Thus, in the PHIL testing, the AC test source acts as the power amplifier (hereafter called ''PHIL amplifier''). Another notable advantage of the PHIL testing is its flexibility, while the capability of conventional laboratory testing depends on the existing devices in the laboratory. Thanks to the incorporation of the DRTS, the PHIL testing can compensate for missing devices, scales the rating of a device under test (DUT), and validate the DUT in the different power systems even with critical conditions [10].

There have been some studies to test the grid support functions of DERs by PHIL testing. Above all, volt-var and frequency-watt functions in [2] are suitable to the PHIL testing because the performances of these functions are dependent on the interaction with grid. In these works, voltage and frequency responsive functions of DER inverters are tested by the PHIL testing [11], [12]. The simplified distribution system model is utilized to occur realistic voltage and frequency disturbances. The performances of the PV SIs' grid support functions are tested in the distribution system model based on the actual feeders [13], [14]. The PHIL testing is utilized to validate the multiple inverters connected to the simulated grid in parallel [15]. The utilization of the PHIL simulation for a certification test has been permitted in a limited test item, i.e. unintentional islanding test [3]. Thanks to the PHIL simulation, in this case, physical load banks are no longer needed. Furthermore, the advanced testing capability of PHIL testing is expected to encourage the smooth penetration of the SIs into the power system. This enhances international activities to promote the effective use of PHIL testing [16]–[18].

Although there is a strong demand for PHIL testing in power systems, there is a steep learning curve. The hardware configuration, interfacing between the DRTS and the DUT as well as the simulation model of power system are important components that need to be carefully developed. Research shows that the smooth integration of all these components is vital to the successful execution of PHIL testing [19]. Despite this need, there are few works that elaborate on practical test setup and procedures pertaining to PHIL testing of SIs. Instead of being given fixed voltage and frequency profiles to the AC test source in the conventional test, in the PHIL testing, realistic events that induce the arbitrary voltage and frequency disturbance should be designed. Besides, there is no case study focusing on the PHIL testing with the Japanese power system. To prevent the lost opportunity for the spread of advanced testing scheme using PHIL simulation, the practical knowledge should be appropriately and widely shared to increase and support researchers in this field.

To address this knowledge gap, this paper presents a practical setup and procedure of PHIL testing for validating grid support functions of SI, i.e. volt-var and frequency-watt functions. The main contribution of this paper is to elaborate on the development of the PHIL testing environment to validate the SI functions in terms of:

- Laboratory equipment setup,
- Interface of laboratory equipment and DRTS,
- Power system modeling in DRTS, and
- Test procedure.

A 500 kW PV inverter having SI functions is tested on the basis of the presented scheme with Japanese transmission system models.

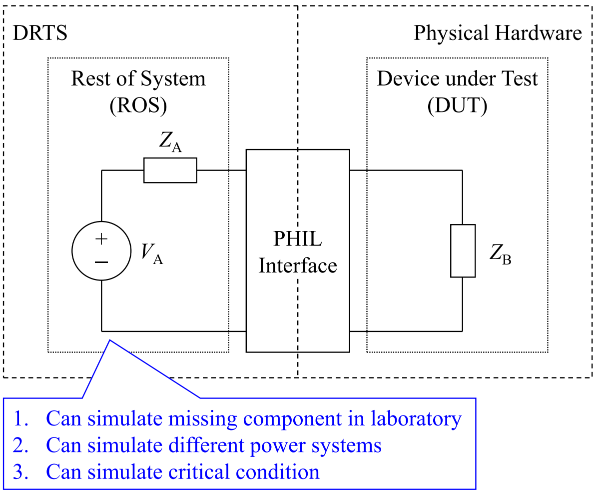


FIGURE 2. Schematic of PHIL testing implementation for single power device.

The rest of the paper is organized as follows. Section 2 explains the overview of the PHIL simulation. Section 3 elaborates on the test setup and techniques to run PHIL testing under stable conditions. The power system models, test procedures utilized in the test of grid support functions of SIs are described in Section 4 as well as the test results. Section 5 concludes the paper.

II. OVERVIEW OF PHIL TESTING

In the PHIL testing, a power device can be tested in an environment as if it is connected to the actual power system. Fig. 2 shows an example of the PHIL configuration. The DUT is connected to the DRTS via the PHIL interface. The DRTS simulates the rest of the power system to which DUT connects. Therefore, any power system that can be modeled and solved in real-time can be simulated in the DRTS. For example, it can simulate missing components in laboratories [10] as well as power systems in different countries. Thanks to the DRTS, the PHIL testing can scale the ratios of voltage and current between simulated power systems and DUTs. It can also test the DUT under various scenarios including critical faults. Since such scenarios are modeled in the simulation, they are reproducible and repeatable. This flexibility is a major advantage in the PHIL testing while these cannot be realized in the conventional testing scheme and actual power system.

The general PHIL interface includes filters, scaling gains, and voltage or current source in the simulation side and digital/analog (D/A) and A/D converters, voltage and current sensors, and a power amplifier, i.e. a grid simulator, in the hardware side. The PHIL interface utilized in the testing are explained in the next section.

III. PHIL TESTING ENVIRONMENT

This section introduces the PHIL testing environment composed for testing SI functions, i.e. volt-var and frequency-watt functions.

TABLE 1. Electric Specification of PV SI under Test.

Item name	Value
Rated capacity	500 kW
AC voltage range	0–750 V
Nominal voltage (three phase line-to-line)	200 V
Maximum power point tracking (MPPT) range	320–700 V
Rated current	1444 A
Nominal frequency	50 Hz

TABLE 2. Implemented Smart Inverter Functions.

No.	Value
1	Islanding Detection
2	Fault Ride Through
3	**Volt-var Control**
4	Ramp Rate, Soft Start
5	Constant Power Factor Control
6	Distributed Power Monitoring
7	Distributed Power Disconnection/Re-interconnection
8	Maximum Active Power Control
9	Active Power Control
10	Reactive Power Control
11	**Frequency-watt Control**
12	Volt-watt Control
13	Active Reactive Power Control
14	Scheduling Function

Volt-var control (No. 3) and frequency-watt control (No. 11) functions are tested in this paper.

A. LABORATORY SETUP

The PHIL testing was performed in a test facility for large scale DER inverters located in Fukushima Renewable Energy Institute, AIST (FREA) [20]. This facility has multiple units of AC test sources and direct current (DC) test sources with total capacities of 5.0 MVA and 3.3 MW, respectively. The DC test source is a programmable bi-directional DC voltage source that can mimic PV and battery I-V characteristics.

The laboratory setup for PHIL testing is shown in Fig. 3. A device under test is a PV SI with 500 kW developed by Fuji Electric. The electric specification of the inverter is shown in Table 1. The inverter implements advanced inverter functions based on Rule 21 [21]. The implemented functions are listed in Table 2 . In this paper, volt-var and frequency-watt functions (No. 3 and No. 11 in Table 2) are tested. The DUT is connected to the DC test source with 1.1 MW and AC test source with 1.67 MVA. The DC test source mimics the I-V characteristic of a PV panel. The AC test source, which is a bi-directional AC voltage source, is utilized as a power amplifier (PHIL amplifier). The PHIL amplifier is switching amplifier, with a maximum current of 2500 A and a maximum voltage of 576 V. Both simulators, made by SunRex, are regenerative power sources. Since they are connected to the same circuit as the facility load as shown in Fig. 3, the generated/consumed power in the testing system is utilized by the facility load. The DRTS is run by NovaCor

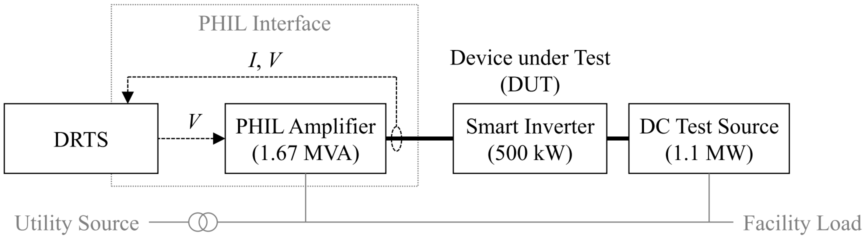


FIGURE 3. Implemented laboratory setup for PHIL testing.

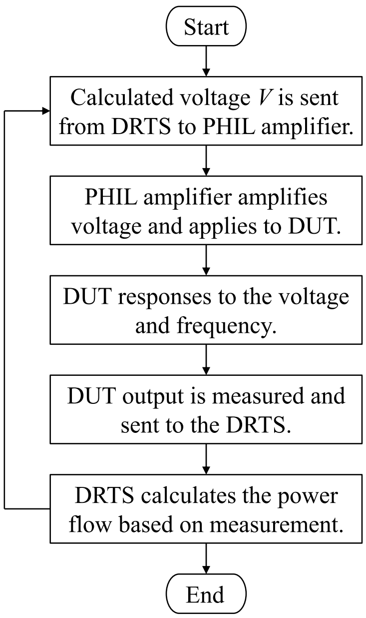


FIGURE 4. Closed loop flow of PHIL simulation.

and RSCAD of RTDS Technologies. The sampling time is set 50 μs. The power systems are modeled in the DRTS and calculation result of voltage at a certain bus is transmitted to the PHIL amplifier. The voltage is amplified by the PHIL amplifier and applied to the DUT. The DUT controls its output according to the voltage and frequency. The outputs of current and voltage from the DUT are fed back to the DRTS. This closed-loop flow is shown in Fig. 4.

B. PHIL INTERFACE

The PHIL interface, shown in Fig. 3, plays an important role in the accuracy and stability of PHIL testing [22], [23]. This part does not exist when the DUT is connected to the actual power system. Since the inserted interface causes the delay and noise which does not originally exist, the interface needs to be designed in a way that the characteristics and functions of DUT can be properly validated. Considering the SI functions verified in this paper, i.e. volt-var and frequency-watt functions, that response in seconds to tens of seconds after voltage/frequency disturbances occur, the higher frequency components are not of interest for evaluation purposes. Hence, the interface is designed more conservatively with a priority towards stability.

The PHIL interface implemented in this paper is shown in Fig. 5. The left and right sides of the dotted line show the DRTS domain and the hardware domain. The rated capacity and nominal voltage of the DUT in DRTS domain are S_1 and V_1, respectively, and those in the hardware domain are S_2 and V_2, respectively. In DRTS domain, the DUT is simulated by "Dynamic PQ Source" component and connected to the rest of power system circuit model. The Dynamic PQ Source is a current source component provided in RSCAD, which outputs current referencing set points of active power P and reactive power Q [19]. The closed-loop flow around the PHIL interface is shown in Fig. 6. The three-phase voltage $\mathbf{V}_1^{abc}$ at a point of common coupling (PCC) of DUT is measured and scaled so that the output of the PHIL amplifier is adjusted to the nominal voltage of hardware domain V_2. The scaled value is converted via the GTAO card, which is a digital/analog converter attached to NovaCor, and sent to the PHIL amplifier. The PHIL amplifier amplifies the voltage and applies to the DUT. The DUT responses to the terminal voltage and frequency variations that simulate the grid behavior. The three-phase current $\mathbf{I}_2^{abc}$ and voltage $\mathbf{V}_2^{abc}$ between the PHIL amplifier and the DUT are measured and sent to NovaCor. The measurements are converted via GTAI card, which is an analog/digital converter of NovaCor, and scaled so that the output of Dynamic PQ Source is adjusted to the rated capacity S_1 and nominal voltage V_1 of the DUT in DRTS domain. The scaled current and voltage are converted to active power P and reactive power Q by "3 Phase P&Q Meter" component in RSCAD. P and Q are filtered by the moving average and low-pass filter (LPF). Here, the sampling time of simulation is set 50 μs. The time window of moving average is set 10 ms, and gain K and time constant T of LPF are set 1 and 1 ms, respectively. The filtered values become the setpoint of the Dynamic PQ Source.

Note that the total delay, including D/A conversion, voltage amplification, voltage and current measurement, and A/D conversion, is about 0.1 ms in static condition. That in step response is about 1.5 ms.

C. INITIALIZATION OF PHIL TESTING

Although Fig. 5 shows the closed-loop condition after the DRTS and hardware domains are appropriately coupled, the initialization procedure is needed to reach such stable condition [24]. Fig. 7 shows the flow of the initialization procedure. First, the DRTS domain is run without feedback

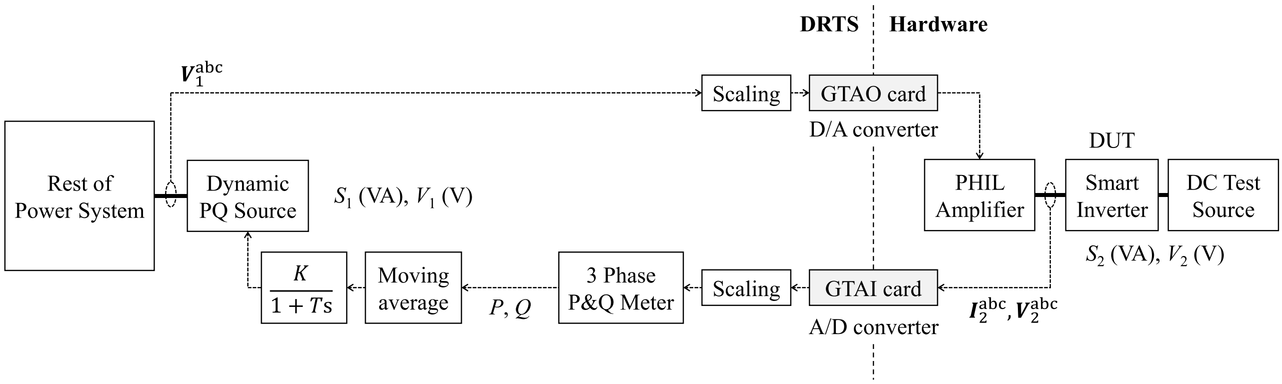


FIGURE 5. **Implemented PHIL Interface.**

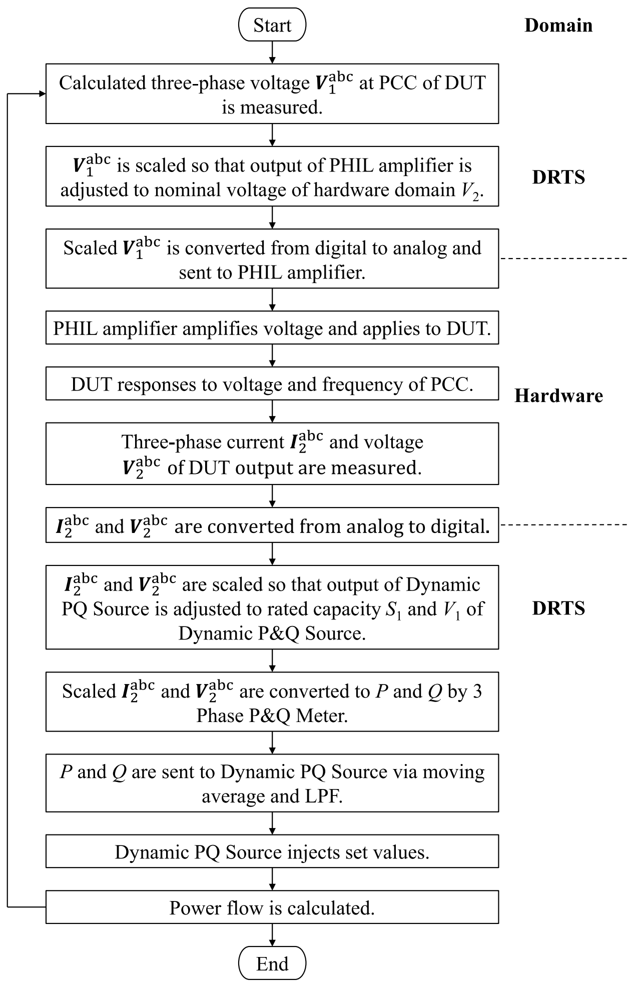


FIGURE 6. **Closed-loop flow around PHIL interface.**

from the DUT. The Dynamic PQ Source is designed that its set values, P_{set} and Q_{set}, can be selected from either value set in DRTS or from the DUT (see Fig. 8). In this step, the values set in DRTS, which should reflect an initial condition of a testing to be performed, is selected and the simulation is stabilized. Then, the hardware domain is started up in order. In our process, the signal from DRTS to the PHIL amplifier

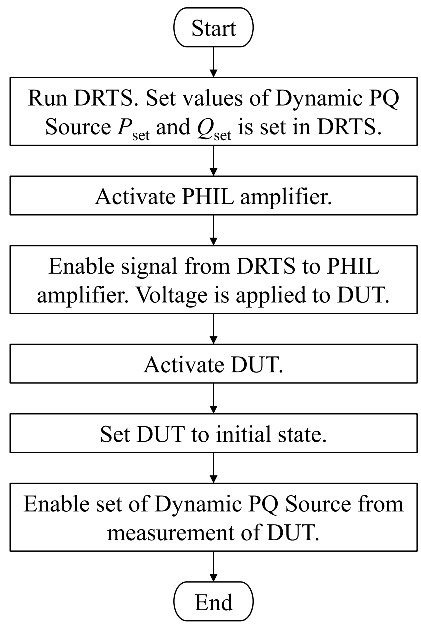


FIGURE 7. **Flow of initialization procedure for stable PHIL testing.**

is enabled. Since the voltage is applied to the DUT, it can be activated. The output of the DUT should be also set the initial state. Finally, the scaled and filtered measurements from DUT are enabled in DRTS by changing the selector in Fig. 8. The PHIL initialization is completed when the closed-loop condition becomes stable.

IV. PHIL TESTING TO VALIDATE GRID SUPPORT FUNCTIONS OF PV SMART INVERTER

This paper focuses on the PHIL testing for volt-var and frequency-watt functions of the SI. In the conventional testing scheme, the certain shape profiles for validating each function are given to the PHIL amplifier. While, in the PHIL testing, the arbitrary power system is modeled and the profiles of voltage and frequency disturbances that occur in the simulated power system are given to the PHIL amplifier. The disturbances are caused by specific events in the power system. This means the given profiles in the PHIL testing

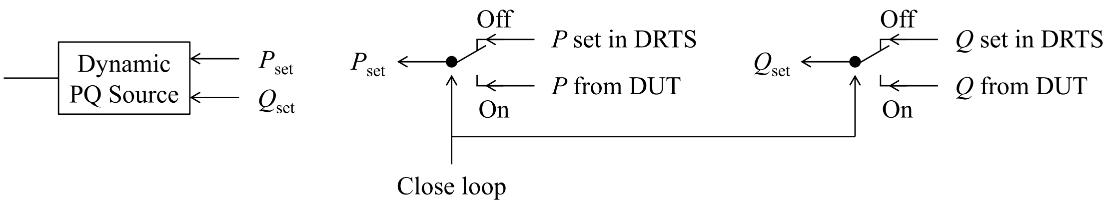


FIGURE 8. Design of Dynamic PQ Source to select set values for initialization of PHIL testing.

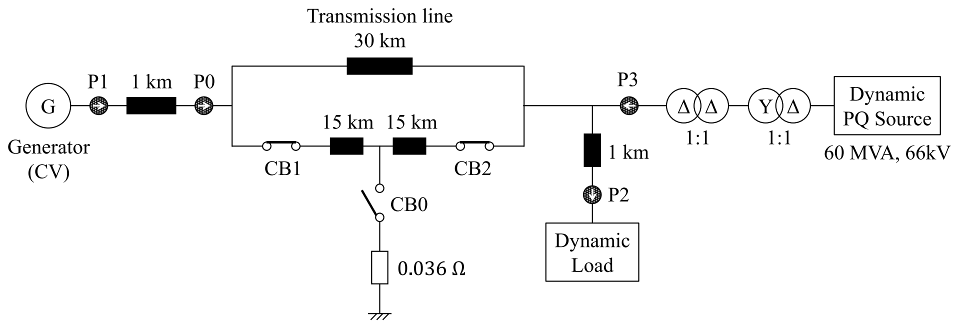


FIGURE 9. Power system model to test volt-var function.

are generated on the basis of the same mechanism as the actual power system. Consequently, events that can cause intentional but natural voltage and frequency disturbances in the power system model needs to be considered. Additionally, the power system needs to be modeled to satisfy it.

In this paper, two grid disturbances, which are suitable for testing the target functions, are extracted from seven of those defined in IEC 62749 [25] and IEC 62786 [26]. Besides, two events that induce the disturbances are selected as well as the power systems are modeled considering them.

A. TEST FOR VOLT-VAR FUNCTION

The testing in this subsection focuses on volt-var function of the SI. The function is designed to regulate voltage by controlling reactive power output. This test verifies the voltage regulation performance of SI when voltage sag occurs. As an event to induce the voltage sag, a three-line-to-ground fault is selected and implemented in the power system model.

1) POWER SYSTEM MODEL AND TEST PROCEDURE

A transmission system model shown in Fig. 9 is built on the basis of a Japanese model [27]. The nominal frequency is 50 Hz. A generator and Dynamic PQ Source, which represents the DUT in DRTS domain (see Fig. 5), supply the power to a load. The generator is modeled by a constant voltage source. The load is modeled by a "Dynamic Load" component in RSCAD. The rated capacity S_1 and nominal voltage V_1 of the DUT in DRTS domain are 60 kVA and 66 kV, respectively. There are two transformers between grid and Dynamic PQ Source. In this testing, since the nominal voltage of Dynamic PQ Source is set 66 kV, both transformer ratios set 1:1. The three line-to-ground fault is implemented in the

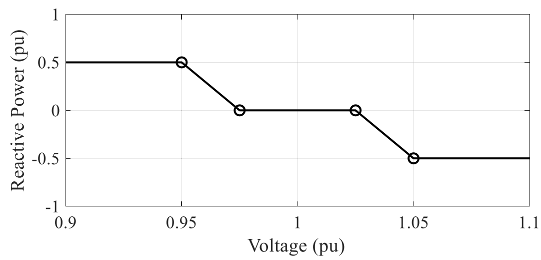
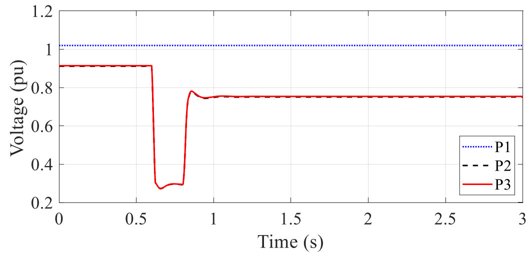


FIGURE 10. Volt-var curve setting.

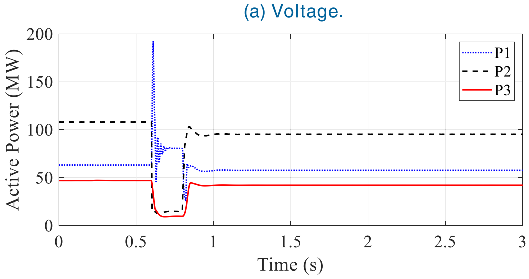
middle of one of the parallel transmission lines. P0–P3 show measurement points, which are for frequency measurement, generator output, load, and DUT output. The volt-var curve implemented in the SI is shown in Fig. 10. The horizontal axis is monitoring voltage and the vertical axis is reactive power output. This is on the basis of the definition in IEEE 1547-2018 [3]. The setting indicates that the inverter starts to inject reactive power when the voltage is below 0.975 and the output is fixed at 0.5 when the voltage is below 0.95. The reactive power injection is applicable within the voltage ride-through operation region. The same is true for high voltage.

As initial conditions, the active power output of SI is set 80% of rated capacity (48 MW) in order to guarantee a margin of reactive power output. The active power and reactive power of load are set 108 MW and 15.43 MVar, whose power factor is 0.98, respectively. Circuit breaker (CB) 0 is open and CBs 1 and 2 are closed. The test is carried out as follows:

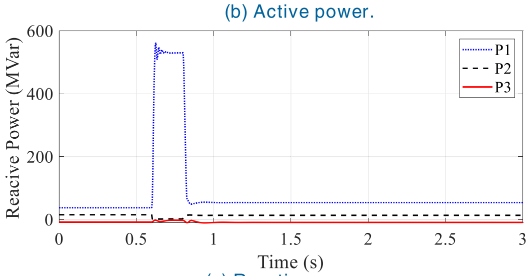
1) Set all parameters to certain initial conditions.
2) Close CB 0 and generate a three-line-to-ground fault.
3) Open CBs 1 and 2 to remove the fault location after 200 ms of fault detection.



(a) Voltage.

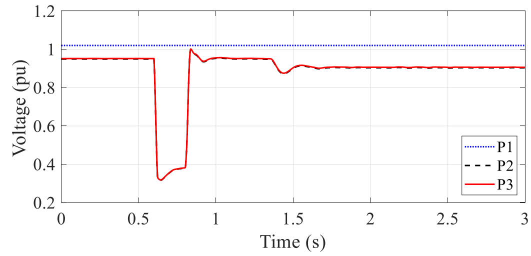


(b) Active power.

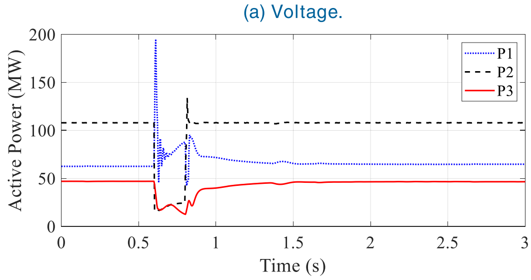


(c) Reactive power.

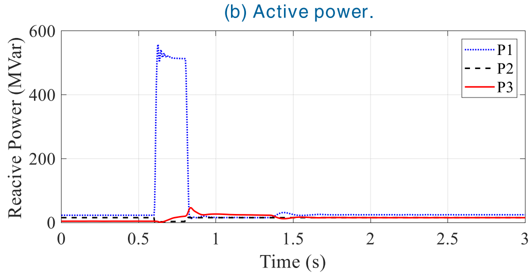
FIGURE 11. Test result without volt-var function.



(a) Voltage.



(b) Active power.



(c) Reactive power.

FIGURE 12. Test result with volt-var function.

2) TEST RESULT

The tests are carried out with and without volt-var function of the SI shown in Figs. 11 and 12. Fig. 11 (a) shows the voltage behavior without volt-var function. The voltage at P3 starts at 0.91 pu. The voltage sag occurs after the fault occurs at 0.6 s.

The inverter can ride through voltage deviation. The voltage drops to 0.27 pu after the fault occurs. Then, it is recovered to 0.75 pu and maintained after the fault is removed.

On the other hand, in the test result with volt-var function in Fig. 12 (a), the voltage at P3 starts at 0.95 pu. This is higher than the result in Fig. 11(a) because the inverter with volt-var function injects reactive power according to the volt-var curve setting. Similarly, the fault occurs at 0.6 s, and the voltage reaches 0.31 pu. It is found the voltage drop is smaller than the former. Besides, it can be observed that the voltage after the fault removal is recovered to 0.91 pu, which is much closer to the nominal one. Comparing the reactive power output in Figs. 11 (c) and 12 (c) at P3, the SI with volt-var function injects the reactive power to increase the voltage after the fault. These results suggest the volt-var function can compensate the voltage disturbance caused by the three-line-to-ground fault.

It is found the voltage ride through function is appropriately operated. The lower voltage ride-through setting is applied on the basis of the definition in [3], where the minimum ride-through time 0.16 when the voltage range (pu.) is $0.30 \leq V \leq 0.45$. As shown in Fig. 12, the tested inverter continues to operate when the voltage is in this range over 0.16 s.

Furthermore, the inverter operation to avoid overcurrent is observed in the Figs. 11(b) and 12(b). These figures show much higher active power is provided at P1 than the rating of the inverter, which is 500 kVA in the hardware domain and 60 MVA in the simulation domain. This is provided by the generator modeled as a constant voltage source in this simulation, while the active power of the inverter at P3 reduces during the voltage drop. The result implies the inverter mitigates the active power to avoid overcurrent during the voltage drop.

B. TEST FOR FREQUENCY-WATT FUNCTION

The testing in this subsection focuses on frequency-watt function of the SI. The function is designed to regulate frequency by controlling active power output. This testing verifies the frequency control performance of SI when the frequency rise occurs. As an event to induce the frequency rise, a load trip is selected and implemented in the power system model

1) POWER SYSTEM MODEL AND TEST PROCEDURE

A transmission system model shown in Fig. 13 is also built on the basis of a Japanese model [27] as well as the model for volt-var model test in Fig. 9. The major differences from Fig. 9 are the load location and generator setting. The Dynamic Load component is connected closer to the

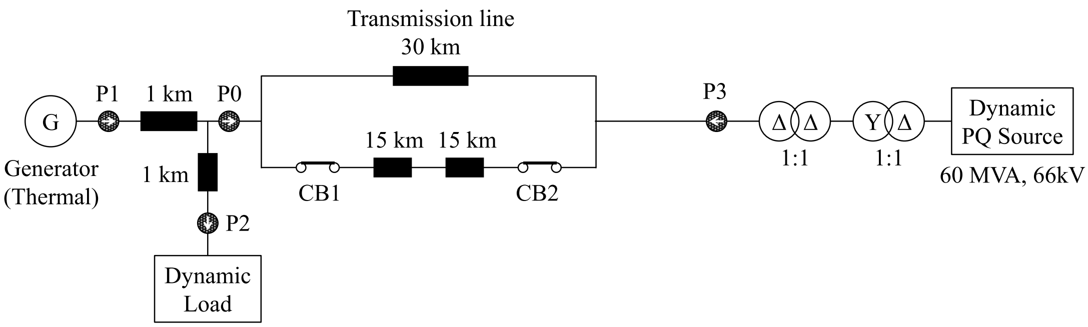


FIGURE 13. Power system model to test frequency-watt function.

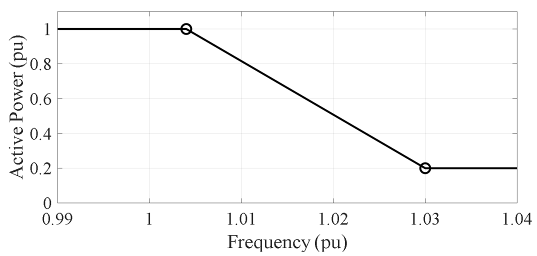
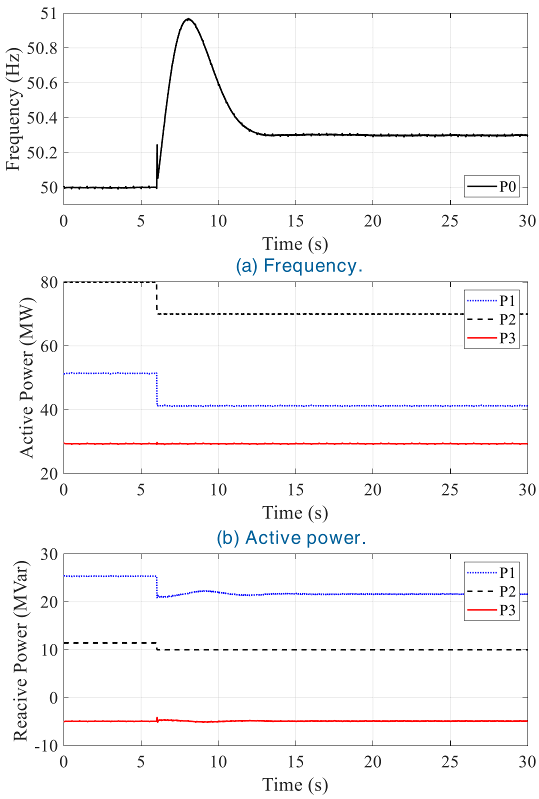


FIGURE 14. Frequency-watt curve setting.

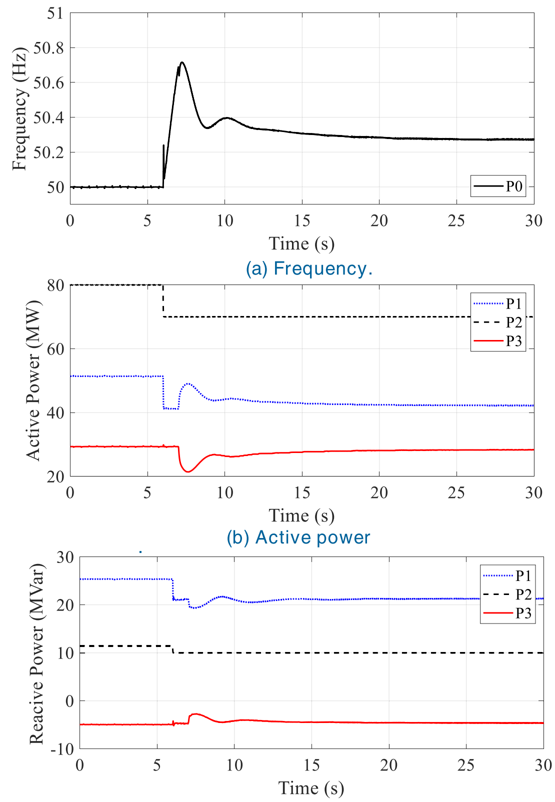


(a) Frequency.

(b) Active power.

(c) Reactive power.

FIGURE 15. Test result without frequency-watt function.



(a) Frequency.

(b) Active power

(c) Reactive power.

FIGURE 16. Test result with frequency-watt function.

generator. The synchronous generator is modeled as a thermal plant with 80 MVA. The governor and automatic voltage regulator (AVR) is implemented on the basis of the standard model in [27]. Whereas, the load frequency control is not implemented to clarify the evaluation of frequency-watt function. The frequency-watt curve implemented in the SI is shown in Fig. 14. The horizontal axis is monitoring frequency and the vertical axis is active power output. This is also on the basis of the definition in IEEE 1547-2018 [3]. The frequency-watt setting indicated that the inverter starts to reduce active power from maximum power point tracking (MPPT) output when the frequency is over 50.2 and the output becomes zero when the frequency is over 51.5.

As initial conditions, the active power output of SI is set 50% of rated capacity (30 MW) in order to guarantee a margin of active power output. The active power and reactive power of load are set 80 MW and 11.43 MVar, whose power factor is 0.98, respectively. CBs 0–2 are closed. The test is carried out as follows:

1) Set all parameters to certain initial conditions.
2) Step the output of Dynamic Load component from 80 MW to 70 MW, while the power factor is constant at 0.98.

2) TEST RESULT

The tests are carried out with and without frequency-watt function of the SI shown in Figs. 15 and 16. Fig. 15 (a) shows the frequency at P0 behavior without frequency-watt function. The frequency starts at 50 Hz. It increases to 50.97 Hz after the load decrease. Then, it is recovered to 50.30 Hz and maintained. In this case, only the generator contributes to the frequency stabilization, not the inverter.

On the other hand, in the test result with frequency-watt function in Fig. 16 (a), the frequency increase is smaller than the former, where it reaches 50.72 Hz after the load decrease. Besides, it can be observed that the frequency is recovered to 50.27 Hz, which is much closer to the nominal one. It remains over 50.4 Hz in 1.74 s, which is much shorter than the case without frequency-watt function of 4.59 s. Comparing the active power output in Figs 15 (b) and 16 (b), the SI with frequency-watt function controls the active power output to maintain the frequency when frequency swing occurs. These results suggest the frequency-watt function can compensate the frequency disturbance caused by the load variation.

V. CONCLUSION

This paper presents the essential information to build the PHIL testing environment for validating the volt-var and frequency-watt functions of SI. The PHIL testing contributes to promoting an understanding of the benefits and negative impacts of SIs on the power system. Although the suitability of the PHIL testing to validate the SI functions, the techniques to appropriately perform the PHIL testing have been limited. This paper gives details of the laboratory setup and method to run the PHIL testing under stable conditions. Additionally, the power system model and the events to induce the arbitrary voltage and frequency disturbances are implemented. The paper described the PHIL testing can provide a more realistic test condition than the conventional test scheme, which generally set the fixed voltage and frequency profiles to the PHIL amplifier and evaluate the open-loop response of the SIs. The tests of volt-var and frequency-watt functions of the SI are performed in the presented PHIL testing environment. The test results showed the PHIL testing is applicable in order to validate the grid support functions to mitigate voltage and frequency disturbances implemented in the actual SI.

The knowledge presented fills an important knowledge gap towards wide-scale use of PHIL testing in power systems. Best practices and positive use cases need to be shared for the main body of knowledge in this field. Researchers and practitioners can benefit from the test procedures presented herein while developing their test setups. This is very important in wide-scale acceptance and use of PHIL testing for power system integration and impact studies.

In this paper, the PHIL interface is designed to appropriately validate the SI functions. Future work should include designing it toward the validation of DUTs with the faster response time.

REFERENCES

[1] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar./Apr. 2017, doi: 10.1109/MPE.2016.2637122.

[2] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018 (Revision of IEEE Std 1547-2003), 2018.

[3] *IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources With Electric Power Systems and Associated Interfaces*, IEEE Standard 1547.1-2020, May 2020, pp. 1–282, doi: 10.1109/IEEESTD.2020.9097534.

[4] *Common Functions for Smart Inverters, Version 4*, Electr. Power Res. Inst., Palo Alto, CA, USA, 2016.

[5] T. S. Ustun and Y. Aoto, "Analysis of smart inverter's impact on the distribution network operation," *IEEE Access*, vol. 7, pp. 9790–9804, 2019, doi: 10.1109/ACCESS.2019.2891241.

[6] A. Hoke, S. Chakraborty, and T. Basso, "Testing advanced photovoltaic inverters conforming to IEEE standard 1547–Amendment 1," in *Proc. IEEE 40th Photovoltaic Spec. Conf. (PVSC)*, Denver, CO, USA, Jun. 2014, pp. 1014–1021, doi: 10.1109/PVSC.2014.6925086.

[7] N. Ninad, E. Apablaza-Arancibia, M. Bui, J. Johnson, S. Gonzalez, W. Son, C. Cho, J. Hashimoto, K. Otani, R. Bründlinger, R. Ablinger, C. Messner, C. Seitl, Z. Miletic, I. V. Temez, F. P. Baumgartner, F. Carigiet, B. Fox, S. Kumar, and J. Kumar, "Development and evaluation of open-source IEEE 1547.1 test scripts for improved solar integration," in *Proc. 36th Eur. Photovoltaic Sol. Energy Conf. Exhib.*, 2019, pp. 952–957.

[8] J. Hashimoto, T. S. Ustun, and K. Otani, "Smart inverter functionality testing for battery energy storage systems," *Smart Grid Renew. Energy*, vol. 8, no. 11, pp. 337–350, 2017, doi: 10.4236/sgre.2017.811022.

[9] G. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider, and J. Langston, "Characteristics and design of power hardware-in-the-loop simulations for electrical power systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 406–417, Jan. 2016, doi: 10.1109/TIE.2015.2464308.

[10] H. Kikusato, T. S. Ustun, M. Suzuki, S. Sugahara, J. Hashimoto, K. Otani, K. Shirakawa, R. Yabuki, K. Watanabe, and T. Shimizu, "Microgrid controller testing using power hardware-in-the-loop," *Energies*, vol. 13, no. 8, p. 2044, Apr. 2020, doi: 10.3390/EN13082044.

[11] A. Hoke, S. Chakraborty, and T. Basso, "A power hardware-in-the-loop framework for advanced grid-interactive inverter testing," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Washington, DC, USA, Feb. 2015, pp. 1–5, doi: 10.1109/ISGT.2015.7131817.

[12] N. Mizuta, S. Kamo, H. Toda, Y. Susuki, Y. Ota, and A. Ishigame, "A hardware-in-the-loop test on the multi-objective ancillary service by in-vehicle batteries: Primary frequency control and distribution voltage support," *IEEE Access*, vol. 7, pp. 161246–161254, 2019, doi: 10.1109/ACCESS.2019.2951748.

[13] J. Langston, K. Schoder, M. Steurer, O. Faruque, J. Hauer, F. Bogdan, R. Bravo, B. Mather, and F. Katiraei, "Power hardware-in-the-loop testing of a 500 kW photovoltaic array inverter," in *Proc. 38th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Montreal, QC, Canada, Oct. 2012, pp. 4797–4802, doi: 10.1109/IECON.2012.6389595.

[14] A. Nelson, K. Prabakar, A. Nagarajan, S. Nepal, A. Hoke, M. Asano, R. Ueda, and E. Ifuku, "Power hardware-in-the-loop evaluation of PV inverter grid support on Hawaiian electric feeders," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Washington, DC, USA, Apr. 2017, pp. 1–5, doi: 10.1109/ISGT.2017.8085982.

[15] A. F. Hoke, A. Nelson, S. Chakraborty, F. Bell, and M. McCarty, "An islanding detection test platform for multi-inverter islands using power HIL," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 7944–7953, Oct. 2018, doi: 10.1109/TIE.2018.2801855.

[16] J. Montoya *et al.*, "Advanced laboratory testing methods using real-time simulation and hardware-in-the-loop techniques: A survey of smart grid international research facility network activities," *Energies*, vol. 13, no. 12, p. 3267, Jun. 2020, doi: 10.3390/en13123267.

[17] *P2004—Hardware-in-the-Loop (HIL) Simulation Based Testing of Electric Power Apparatus and Controls*. Accessed: Sep. 29, 2020. [Online]. Available: https://standards-stg.ieee.org/project/2004.html

[18] T. Strasser, E. C. W. de Jong, and M. Sosnina, *European Guide to Power System Testing The ERIGrid Holistic Approach for Evaluating Complex Smart Grid Configurations*. Cham, Switzerland: Springer, 2020.

[19] T. S. Ustun, J. Hashimoto, and K. Otani, "Using RSCAD's simplified inverter components to model smart inverters in power systems," in *Proc. IEEE Workshop Complex. Eng. (COMPENG)*, Florence, Italy, Oct. 2018, pp. 1–6, doi: 10.1109/CompEng.2018.8536238.

[20] T. S. Ustun, H. Konishi, J. Hashimoto, and K. Otani, "Hardware-in-the-loop simulation based testing of power conditioning systems," in *Proc. IEEE Int. Conf. Ind. Electron. for Sustain. Energy Syst. (IESES)*, Hamilton, New Zealand, Jan. 2018, pp. 546–551, doi: 10.1109/IESES.2018.8349936.

[21] *Rule 21 Interconnection*. Accessed: Sep. 1, 2020. [Online]. Available: https://www.cpuc.ca.gov/Rule21/

[22] W. Ren, M. Steurer, and T. L. Baldwin, "Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms," *IEEE Trans. Ind. Appl.*, vol. 44, no. 4, pp. 1286–1294, Jul. 2008, doi: 10.1109/TIA.2008.926240.

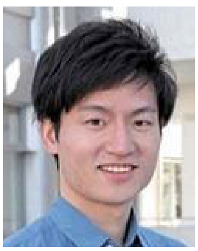
[23] G. Lauss, F. Lehfuss, A. Viehweider, and T. Strasser, "Power hardware in the loop simulation with feedback current filtering for electric systems," in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Melbourne, VIC, Australia, Nov. 2011, pp. 3725–3730, doi: 10.1109/IECON.2011.6119915.

[24] E. Guillo-Sansano, M. H. Syed, A. J. Roscoe, and G. M. Burt, "Initialization and synchronization of power hardware-in-the-loop simulations: A great Britain network case study," *Energies*, vol. 11, no. 5, p. 1087, Apr. 2018, doi: 10.3390/en11051087.

[25] *Assessment of Power Quality—Characteristics of Electricity Supplied by Public Networks*, Standard IEC TS 62749, 2020.

[26] *Distributed Energy Resources Connection With the Grid*, Standard IEC TS 62786, p. 2017.

[27] *Standard Power System Model*, Inst. Elect. Eng. Japan, Tokyo, Japan, 1999, vol. 754, doi: 10.11501/3237579.



HIROSHI KIKUSATO (Member, IEEE) received the Ph.D. degree in electrical engineering from Waseda University, Tokyo, Japan, in 2018. He is currently a Research Scientist with the Fukushima Renewable Energy Institute, AIST (FREA). His research interests include power system control and management, demand-side energy management using electric vehicles, and hardware-in-the-loop testing of distributed energy resources and microgrid.

TAHA SELIM USTUN (Member, IEEE) received the Ph.D. degree in electrical engineering from Victoria University, Melbourne, VIC, Australia. He was a Faculty Member with the School of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA. He is currently a Researcher with the Fukushima Renewable Energy Institute, AIST (FREA), where he also leads the Smart Grid Cybersecurity Laboratory. His current research interests include power systems protection, communication in power networks, distributed generation, microgrids, electric vehicle integration, and cybersecurity in smart grids. He serves in Editorial Board of IEEE Access, IEEE Transactions on Industrial Informatics, *Energies*, *Electronics*, *Electricity*, *World Electric Vehicle*, and *Information* journals. He is a member of the IEEE 2004 and 2800, IEC Renewable Energy Management WG 8 and IEC TC 57 WG17. He has been invited to run specialist courses in Africa, India, and China. He has delivered talks for the Qatar Foundation, the World Energy Council, the Waterloo Global Science Initiative, and the European Union Energy Initiative (EUEI). His research has attracted funding from prestigious programs in Japan, Australia, EU, and North America.

JUN HASHIMOTO (Member, IEEE) has joined AIST in 2017 and contributed to PV research, especially PV system performance testing and characterization. More recently, he has expanded his research to study smart grid systems, especially smart inverter interoperability and impact assessment of grid forming inverter.

KENJI OTANI currently leads the Energy Network Team of the Renewable Energy Research Center, Fukushima Renewable Energy Institute, AIST. He has researched the system integration technologies of PV and hybrid power systems.

TAKAYUKI NAGAKURA is currently involved in research on power electronics technology and a Smart Inverter with Corporate Research and Development Headquarter, Fuji Electric Company Ltd.

YASUTOSHI YOSHIOKA (Member, IEEE) received the Ph.D. degree in electrical engineering from the Kyushu Institute of Technology, Kitakyushyu, Japan, in 2006. Since 1993, he has been working with Fuji Electric Company Ltd., where he is currently working with Research and Development on EMC, power quality, and grid connection for distributed energy resources. He was a Visiting Scientist with the University of Toronto from 1999 to 2002 and Tokyo City University in 2009. Since 2016, he has been a Visiting Research with AIST. Since 2008, he has been involved in the international standardization under IEC and received IEC 1906 Award in 2014.

RYO MAEDA was a primarily involved in research on PV output control technology, such as DER management system and a Smart Inverter with the TEPCO Research Institute, TEPCO Holdings. Since July 2019, he has been working for the overseas consulting and survey in the Distribution Department of TEPCO PG.

KENJIRO MORI is currently the Project Manager with the TEPCO Research Institute. He tackles technical challenges related to the installation of large amounts of renewable energy.