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Advanced Grid Integration Test Platform for Increased Distributed Renewable Energy Penetration in Smart Grids

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ABSTRACT Renewable energy-based generators are constantly being deployed to future grids. It is expected that their share in overall generation will increase in the future. These novel devices have unknown characteristics and cause novel issues in power system operation. Traditional distribution networks have been operated as passive networks. These devices, such as smart inverters, change this paradigm completely. Due to these considerations, grid operators insist on enforcing strict grid-integration requirements. These rules are developed to ensure the impact of the connected devices is minimized and their behavior can be accounted for, at least to some extent. Testing different devices for different grid codes is a daunting task. Since such tests are undertaken in lab environment with manual control and data collection, they are prone to errors, time-consuming and inefficient. A solution is required to standardize and automate such tests. This will provide consistent testing ability and minimize testing times and errors due to human-intervention. This article presents the design and implementation of an integrated testing platform. Steps of lab equipment integration and associated challenges are presented along with their solutions. Several smart inverter behavior tests are executed, and results are presented. The test durations are compared with traditional test durations and the benefits are reported. It is discovered that use of such platform can increase the system testing efficiency by 85 % while minimizing human-errors, inconsistencies and man-hours required to run the tests.

INDEX TERMS DER testing, certification, grid-support functions, renewable energy integration, distributed generators, power system planning, grid codes.

I. INTRODUCTION

Countries are becoming more aware of the environmental impacts of continued fossil fuel use. Consequently, there are initiatives to decrease their share in the generation portfolio and promote use of clean energy resources [1], [2]. These efforts stipulate a deadline before which countries should decrease their CO2 emissions below a certain limit [3]. Others, such as EU2020, mentions a certain amount of renewable energy that has to be connected to the grid [4]. All of these facts accelerate the transition to a more diverse generation portfolio which includes unprecedented amount of renewable energy-based generators [5], [6].

Unlike traditional generators that are based on rotating machines, these novel technologies are mostly inverter-interfaced. They do not take part in grid-forming activities such as supporting the operating voltage or frequency. When high number of inverter-interfaced generators are connected to the grid, the overall inertia of the systems decreases, and it becomes harder to set the voltage and the frequency in the system [7]. Therefore, grid operators have limited the permissible amount of renewable energy-based generators that can be connected to their infrastructure [8]. The idea behind that is clear: Due to negative impacts of inverters on the grid operation, they need to be kept below a certain threshold.

While these technical concerns can be understood from operator's point of view, they limit the amount of renewable generation that can be integrated. Without removing

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these, it is impossible to reach higher proportion of renewable generation in the generation mix, i.e. deep renewable energy penetration. In an effort to break this stalemate, smart inverters have been developed [9]. Unlike their conventional counterparts, these devices can provide auxiliary services, operate in four quadrants of the power plane and provide frequency and voltage support [10].

These devices can mitigate issues such as over-voltage due to excess power injection during peak solar radiation. However, smart inverters are highly active components that strongly influence to operating parameters of the system as well as the power flow in it. System operators insist on strict definition of their behavior and even stricter testing requirements [11], [12]. Only after these steps, do they allow these active components to be connected to distribution networks, which are traditionally designed as passive systems.

The capabilities of smart inverters have been well defined in IEC 61850-90-7 standard [13]. However, there is not a clear practical manual outlining how these need to be tested for validation. Currently, custom-made tests are performed by different labs around the world [14]–[17]. This is very costly, time-consuming and prone to errors. Furthermore, these custom approaches are not interoperable and, at times, not entirely repeatable [18]. Therefore, their reliability is questionable. Especially, when there are several devices that are tested for the same purpose.

The solution is to develop an automated and standardized testing platform that can repeat the exact steps for all devices and tests [19], [20]. While there have been efforts towards this goal [21], the experience has shown that development of such a platform and customizing it to the infrastructure present in the lab is not trivial.

The first action towards achieving this goal has been taken by SunSpec Alliance as California was spearheading the PV deployment projects. An integrated testing platform has been developed under the name of SunSpec System Validation Platform (SVP) [22]. This is a single test system that is developed as a starting point which leads the overall research direction. In order to achieve interoperability and standardized testing abilities, this platform needs to be implemented in different labs around the world. The customization steps for each lab shed light on what kind of investigations need to be run to reach a universal, one size fits all testing platform.

It is not an easy task to gather several test labs around the world to perform certain tests. Thankfully, Implementing Agreement for a Cooperative Program on Smart Grids (ISGAN) [26] under the auspices of International Energy Agency (IEA) has taken an interest in this field. The Smart Grid International Facility Network (SIRFN) [27], a group of test labs working on smartgrids, was formed from ISGAN members. These labs are commissioned with the task of customizing SVP to their lab equipment and report their findings. These experiences need to be documented so that other labs can benefit from this know-how and follow a similar procedure in their lab. Furthermore, if these efforts can help define what is required to customize SVP to a given lab structure, it will be preferable to automate those steps as well.

This article reports the findings when a standardized testing solution [22] was implemented in a different lab. Since each lab has a different set of devices, there is real effort and knowledge required to perform such transition. This article contributes to the current body of knowledge in several aspects: (i) by documenting the process of developing an automated testing platform for increased renewable energy in power systems, (ii) by reporting the issues encountered and the solution methods developed to overcome them, (iii) by developing solutions to customize certain testing scripts to suit a different lab setup, and (iv) by standardizing integration tests thereby increasing efficiency, minimizing human-errors and testing times.

Stakeholders will find it valuable in understanding automated testing, its implementation and configuration. As a result, more automated testing platforms can be developed to test active grid components before deployment. This will result in more trust in the equipment and increased renewable energy integration

Rest of the paper is organized as follows: The experimental set up in the lab and the specifications of the test equipment are presented in Section II. Some examples cases of non-automated (manual) tests are also given to act as benchmark. Section III gives the details of a generic automated testing platform developed by SunSpec. It continues to show the differences with FREA's test lab and what kind of issues are encountered. Detailed software and hardware issues along with the actions taken to solve them are presented. Section IV shows test results of automated testing platform developed in FREA. Results are compared and contrasted with manual testing results in terms of performance, timing and efficiency. Based on prior manual testing experiences, concrete time duration analysis is performed. Section V draws the conclusions and gives future research directions.

II. EXPERIMENTAL SETUP

This section explains the lab setup and the equipment used in automated test platform. Figure 1 shows the topology utilized for performing validation tests on a smart inverter [23], [24]. The setup consists of a grid simulator that is rated up to 500 kVA and can be utilized to create grid events or absorb the generated power. There are current and voltage transformers connected to grid simulator's terminals to monitor to power exchange with the device under test (DUT). A controller has the ability to set grid simulator's operating conditions as well as functions of DUT.

Since DUT is a battery inverter, a.k.a power conditioning system (PCS), for this case, it is coupled with a battery simulator that can be set to mimic the charge/discharge characteristics of different batteries. It is also possible to change the current state-of-charge instantly, instead of the need to *actually* charge or discharge, which is the case for tests performed with real battery banks. For other inverters, such as those used in PV modules, the inverter can be coupled

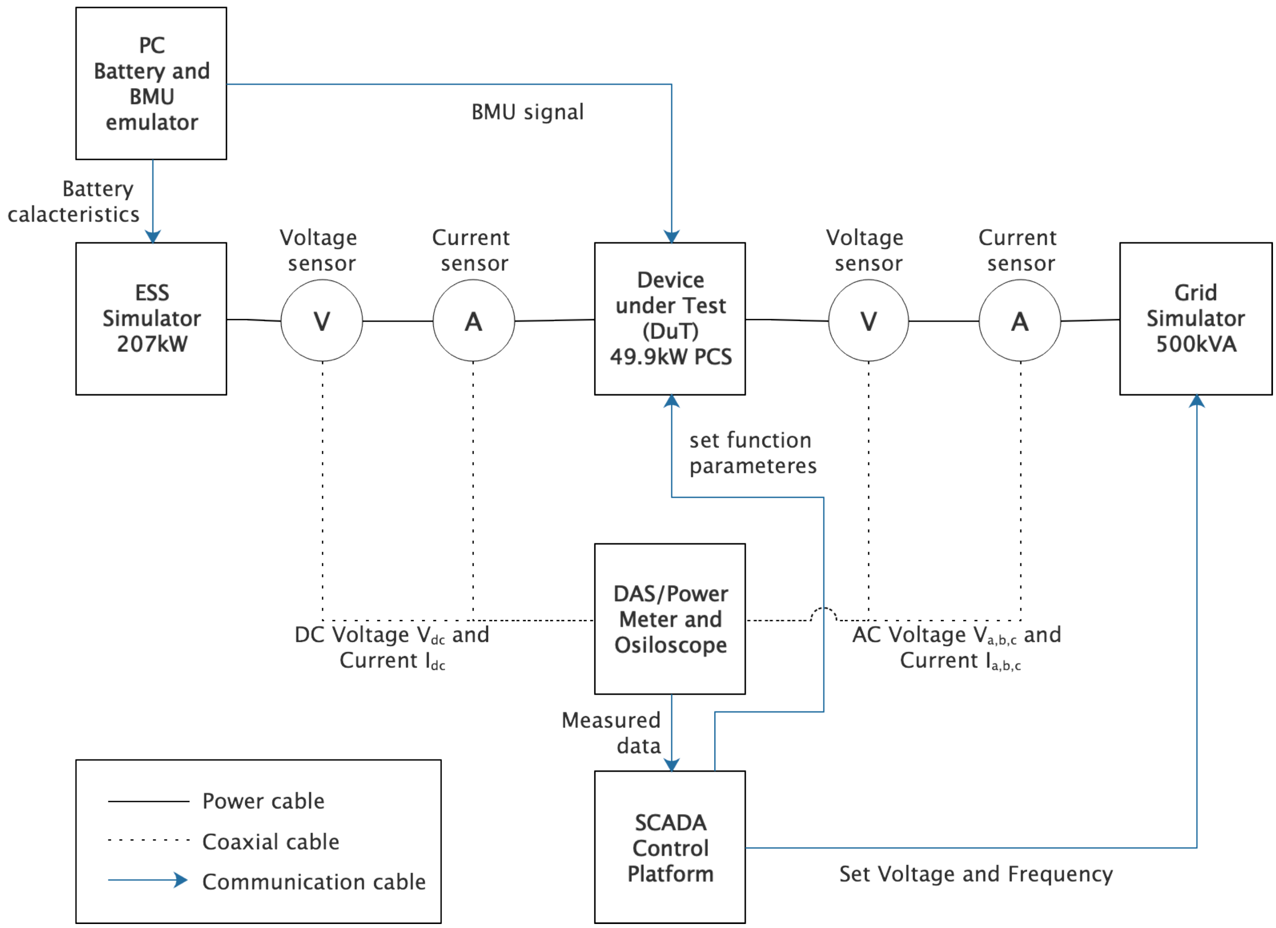


FIGURE 1. Lab test setup for inverter studies.

TABLE 1. Grid simulator back to back converter specifications.

AC Input-side converter	Capacity	590 kVA
	Voltage	420 V
	Acceptable Frequency range	50 Hz ± 3%
	Phase	3-Phase 3-wire
	Current Distortion	Total max. 5 %, Each phase max. 3 %
AC output-side converter (lab-side)	Capacity	500 kVA
	Voltage Range	0-576 V
	-Accuracy	±0.1 %
	-Resolution	0.1 V
	Frequency	45–66 Hz
	- Accuracy	0.01 z
	- Phase Range	0 – 360°
	Phase	3-Phase 3-wire

TABLE 2. Smart inverter specifications.

AC	Capacity	49.9 kW
	Voltage	200 V
	Frequency	50/60 Hz
	Phase	3-Phase 3-wire
DC	Nominal Voltage	540 V
	Voltage Range	330–750 V

TABLE 3. Battery simulator specifications.

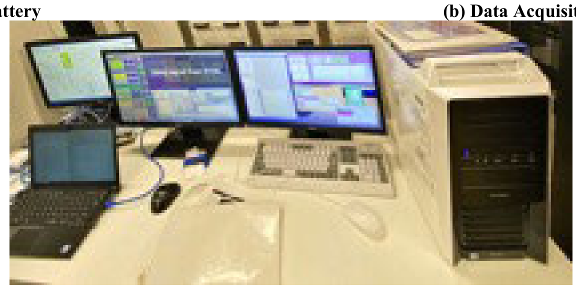
AC	Capacity	261 kVA
	Voltage	AC 200 Vrms ± 10%
	Max. Current	837 Arms
	Frequency	50/60 Hz
	Phase	3-Phase 3-wire
DC	Power setting range	± 208.8 kW
	Resolution	0.1 W
	Constant Power Accuracy	± 0.3%

with a DC simulator that represents the solar power input. Data Acquisition System (DAS) monitors the point of common coupling between the grid simulator and DUT. These readings are utilized by the controller to decide operating conditions. Figure 2 shows the overall view of lab equipment used during tests while Tables 1-3 list their electrical characteristics

Initially, this set up has been utilized to perform smart inverter capability tests. For these tests, everything is done manually. The control terminal (SCADA) shown in Figure 2 (c) is utilized to set operating conditions for

(a) Smart Inverter for Battery

(b) Data Acquisition and monitoring



(c) SCADA controller system

FIGURE 2. Different equipment used for inverter tests.

grid operator and select operating mode for the smart inverter. Once a test condition is configured, DAS shown in Figure 2 (b) is manually set to capture data points. These points are exported in.csv format and needs to be processed manually. Typically, this involves plotting voltage or frequency plots from these points and calculating the rate of change. Then, this rate is compared with the rates stipulated by the standard or grid code. The conclusions are derived based on these data curation, analysis and judgement steps.

Needless to say, such an approach is prone to human errors, very inefficient and expensive (in terms of time and money). Furthermore, the non-standard and non-automated testing procedures become really problematic when there are more than one devices to be approved or different grid-codes are involved. A systematic testing structure is vital in achieving a repeatable testing solution that follows the same steps precisely, caters for different devices thanks to interoperability and provides reliable results. It is also important to note that such an approach decreases the setup and testing times considerably. This, in turn, reduces to cost and complexity of these tests. Therefore, it is easier to subject devices to tests and repeat them for confirmation, if required.

With this set up, volt-var control (VV12) capability outlined in IEC 61850-90-7 [13] has been tested with manual procedures. Figure 3 shows the curve's definition in the standard. As shown in Table 4, this test requires implementation of two distinct volt-var curves for smart inverter control. This means before each test, smart inverter controller needs to be updated with these settings. Once this is done, the following test procedures is followed [25]:

TABLE 4. Utilized test curve characteristics.

Set Point (p.u.)	Curve 1 (V,Q)	Curve 2 (V,Q)
Set 1	(0.88, 0.5)	(0.88, 0.125)
Set 2	(0.97, 0.5)	(0.97, 0.125)
Set 3	(0.99, 0)	(0.99, 0)
Set 4	(1.01, 0)	(1.01, 0)
Set 5	(1.03, -0.5)	(1.03, -0.125)
Set 6	(1.12, -0.5)	(1.12, -0.125)

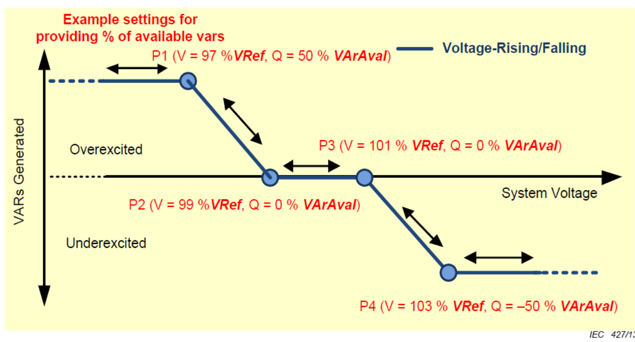


FIGURE 3. Volt-Var curve as defined in IEC 61850-90-7.

Volt-Var Test Procedure:

i) Grid Simulator parameters are set to meet EUT's ratings. Frequency is set and kept constant at the rated value. DUT's power output is set to Pmax.

ii) Start DUT, set Volt-Var mode ON.

iii) Grid Simulator voltage is set to a value larger than V4. Q4 value is observed (see Figure 3)

iv) *Time domain response of the DUT is recorded by manually stepping down Grid Simulator voltage. For each line in the curve, at least 3 data points are recorded. These are captured from DAS manually and saved in a separate file. Since Volt-Var curve has specific slopes and stipulated time range for response, the captured data needs to be plotted and these parameters need to be verified by the test engineer.*

v) *Step iv is repeated, except the voltage is stepped up, instead of down. Same data collection and analysis aspects still apply.*

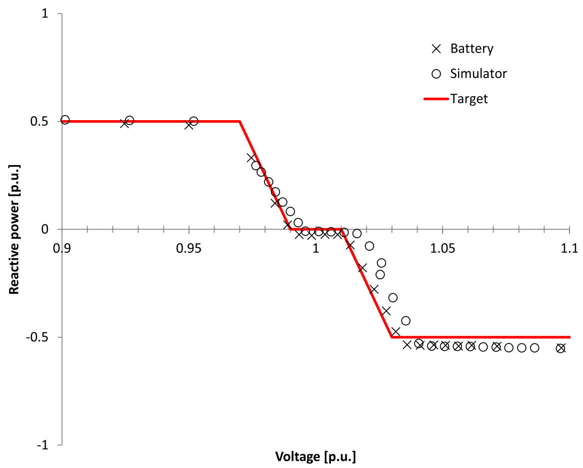


FIGURE 4. Volt-Var Test results with Curve 1.

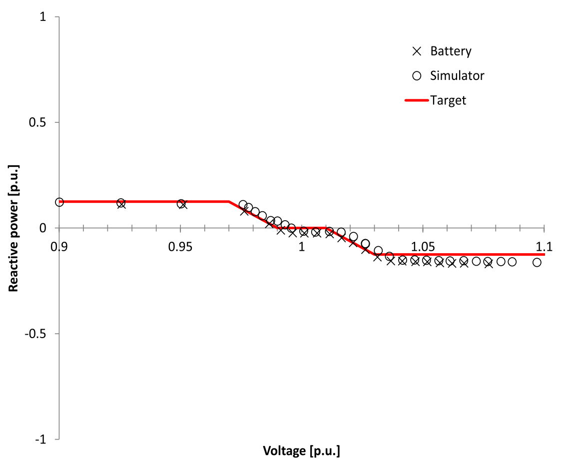


FIGURE 5. Volt-Var Test results with Curve 2.

These lab tests were performed with a battery bank and a battery simulator. As the results show in Figure 4 and 5, there is a visible discrepancy between the results, although all parameters are kept identical. Due to error-prone nature of the testing procedure outline above, it is not possible to conclude, definitively, that the discrepancy is cause by the different between battery bank and the battery simulator. Had this been a validation test performed in a certification lab, such small discrepancies may result in some electrical equipment failing the tests and not being able to enter a certain market. Manufacturers would complain about failing results, rightfully so, while grid operators would doubt the reliability of the tests where a certain product received certification.

In addition to these considerations, performing these tests in the lab was a great opportunity to observe how cumbersome these steps may become and how a careless move at an instant may render results of the entire test unreliable. Also, updating operating curves of the smart inverter, continuously changing grid simulator data and capturing measurements with DAS are very time-consuming and repetitive exercises.

In order to create a reliable testing environment, a solution is required where human error is reduced to minimum, repetitive actions are automated and performance evaluations based on value comparison are done in an automated way. In addition to this, to ensure different equipment can be utilized in the test, an interoperable approach needs to be taken so that any DUT can be seamlessly coupled to the test platform.

III. ISSUES ENCOUNTERED WHILE DEVELOPING THE INTEGRATED TESTING PLATFORM

This section presents the issues encountered during development of the integrated testing platform along with the actions taken to mitigate them. For easy reading, these issues are classified under three sub-headings which are (i) issues encountered during conversion of SVP to FREA's topology, (ii) issues related to Test Scripts and Libraries, (iii) issues related to software and hardware integration. These are discussed in detail below.

A. SVP CONVERSION TO FREA's TEST LAB

The generic design of the original SVP is shown in Figure 6. It is envisioned that the SVP will have the ability to exchange information with all three electrical components, i.e. grid simulator, DUT (smart inverter) and the DC source (PV or battery simulator). The data collection is done by DAS which has sampling devices connected to electrical connection between these devices. SVP receives these measurements through a direct communication link on the right. When this generic concept is compared with FREA's test structure shown in Figure 1, it is observed that there is not much difference. Consequently, it may be expected that the adaptation will be straightforward. However, this is not the case. Despite the similarity of the test lab in terms of electrical wiring, the communication lines and controllability of the devices are vastly different.

As shown in Figure 7, the main difference is the control access to the test equipment. Unlike the generic design where SVP is directly connected to these devices and has the ability to send instructions, in FREA's setup the dedicated controller software has to be utilized. This controller software is developed by the manufacturer of grid and PV simulators. It is later updated to add the ability to control smart inverter (DUT). Due to the test lab architecture, SVP cannot be directly connected to the test equipment. Instead,

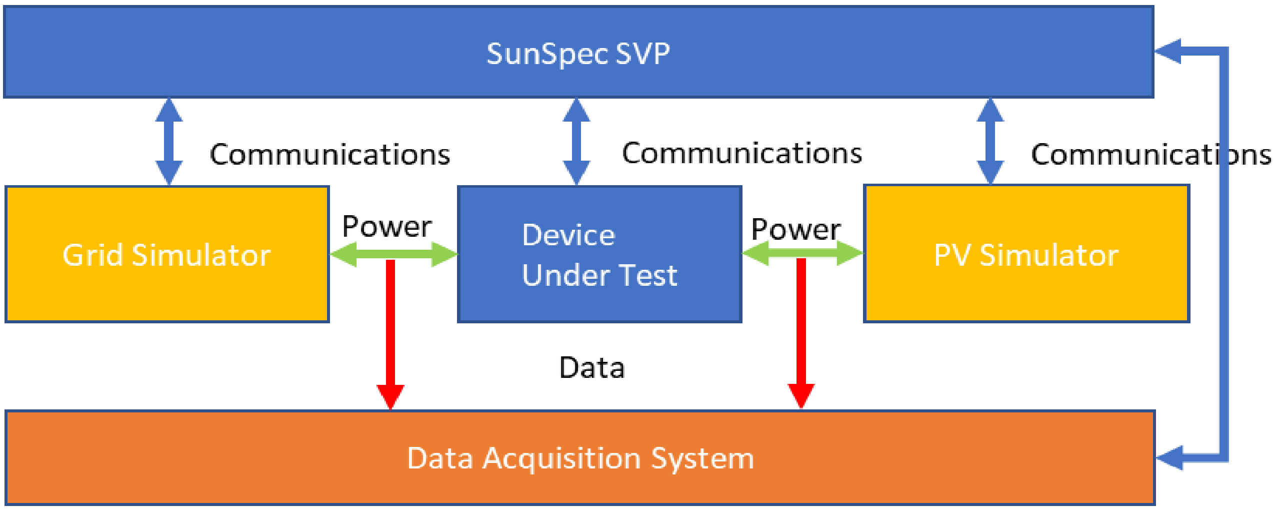


FIGURE 6. Generic design of SunSpec SVP platform.

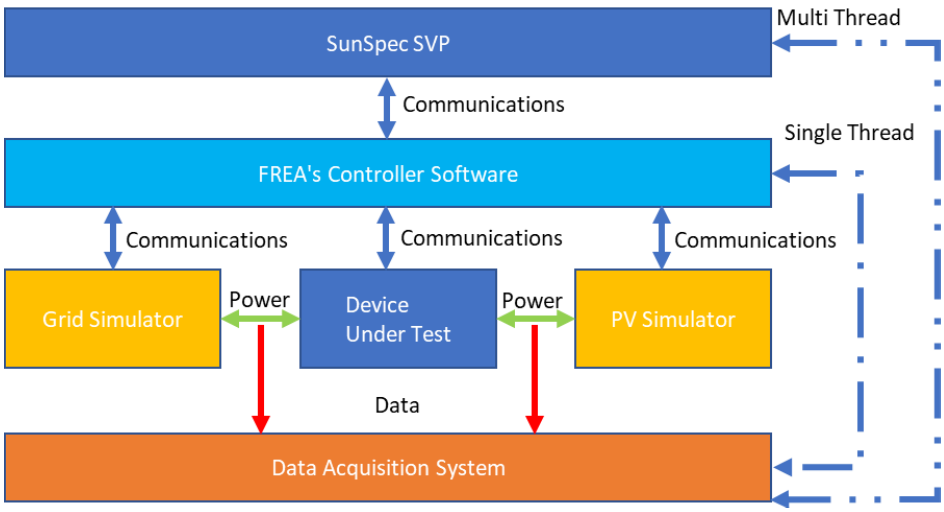


FIGURE 7. FREA platform with required modifications.

it needs to be modified in such a way that SVP sends its requests to the Controller Software which, in turn, instructs the test equipment accordingly. The problem with the former case is SVP acquiring all the necessary drivers to control the test equipment. In the latter case, on the other hand, the issue is integrating SVP with the Controller Software. Following sections talk about specific challenges encountered and the steps taken to resolve these issues.

DAS can be integrated to both SVP and Controller Software. If it is driven through Controller Software, it is the simpler as there is only one point of contact for SVP. However, lab's Controller Software can only handle single thread processing, and this would require slower data acquisition. Should DAS be couple with SVP, then data acquisition can be processed with multi threads. However, in this case, the customization needs to be performed in two steps. First, SVP needs to be customized to communicate with Controller Software for test equipment and, then, additional customization is required to receive data from DAS. In other lab architectures where different equipment is run with several controller software, this may prove to be problematic and time-consuming. This is discussed in a more detailed fashion, in the next section, where script development and library creation are presented.

B. ISSUES RELATED TO TEST SCRIPTS AND LIBRARIES

Figure 8 shows the operating principle of SVP which comes with a set of testing scripts that can be modified using SVP's graphic user interface (GUI). Once the test parameters and/or test equipment settings are entered through GUI, script creator creates script files that are written in Python. These scripts include the list of actions that need to be taken in a sequential manner, such as changing grid simulator's voltage value and recording DUT's reaction. In order to pass these

TABLE 5. Summary and classification of software-related issues.

#	Type	Issue	Action	Components
1	Software (Controller Software)	There must be one connection between SVP and Controller Software	The functions of DER Library and DAS Library are integrated into Grid Simulator Library for FREA. Along with consolidation, Python Script needs to support Library aggregation	・Python Scripts ・Grid Simulator Abstraction Layer ・FREA Environment Simulator Library
2	Software (Library)	The WT3000 Library provided by SVP was a VXI-11 protocol not supported in Japan	Created a brand-new script with FREA without using the provided library	・SVP GUI Front End ・Python Scripts ・FREA Environment Simulator Library
3	Software (SVP scripts)	When a new script is received from SunSpec, modifications are required due to the above problem	Analyze the new SunSpec and modify it to match the FREA environment	・Python Scripts
4	Software (FREA)	Graphs required by FREA are not automatically created	Added the function to create graphs using gnuplot The process itself is described in the FREA Environment Simulator Library	・Python Scripts ・FREA Environment Simulator Library
5	Software (Controller Software)	When implementing No4, when drawing a time-series graph, it is necessary to acquire data with multi-threads to the measurement device	Single thread is used for acquiring control data for script processing, and the other is used for acquiring graph data. Thread processing itself is described in FREA Environment Simulator Library	・Python Scripts ・FREA Environment Simulator Library

TABLE 6. Summary and classification of hardware-related issues.

#	Type	Issue	Action	Components
1	Hardware (Grid Simulator)	System voltage rises by about 1% to 202V	(Permanent measure) Value adjustment in the Controller Software. (Temporary measure) Adjustment in the Script	・SVP GUI Front End ・Python Scripts
2	Hardware (DUT)	At the end of Script, it is necessary to return DUT to initial state. If PF stays at last instruction PF = 0.85 remains and the DUT trips at the start of the test	Added processing to return DUT to the initial state in Python Script termination. The process is described in the FREA Environment Simulator Library	・Python Scripts ・FREA Environment Simulator Library
3	Hardware (DUT)	The input parameter of SVP is specified as an effective value, but DUT only accepts values as %	Added processing corresponding to functions specific to DUT in Library The process is described in the Library, but necessary to modify the script and add SVP parameters to pass the information to the Library	・SVP GUI Front End ・Python Scripts ・FREA Environment Simulator Library

instructions and settings to the actual devices, library files need to be created. These files, also can be considered as drivers, have the information about how a certain parameter or an action can be relayed from SVP. SVP manages this in two distinct steps where the abstraction layer is created first and, then, library files are built. As shown, in SVP's generic design, all these library files are created separately. SVP has the ability to talk to all the devices simultaneously.

This operation principle is modified significantly to cater for the architecture shown in Figure 7. While the automated testing approach stays intact, the internal dynamics of how this is achieved are very different. Figure 9 shows the script and library building steps used in FREA's lab. In order to accommodate for the single point connection architecture, SVP's script and library structure has been modified. As shown, developed scripts only call a single abstraction layer development which, in turn, creates a single library file. The reason behind this is the existence of FREA's dedicated Controller Software. It is possible to conceptualize this approach as creating a library for SVP to successfully communicate with FREA's Controller Software, instead of individual test equipment present in the lab.

There are two separate connections with the DAS. For tests that require low resolution data collection, such as volt-var tests, single-thread connection via Controller Software is preferred. In this case, a single point communication between SVP and Controller Software is sufficient. For tests that require faster sampling to document time-domain behavior, such as frequency response, multi-thread communication is utilized between SVP and DAS. In order to achieve this, FREA environment simulator library is modified. It is worthy to note here that all of Lab Abstraction Layer and the simulator library files needed to be re-developed. During this step, is imperative to have a thorough understanding of the

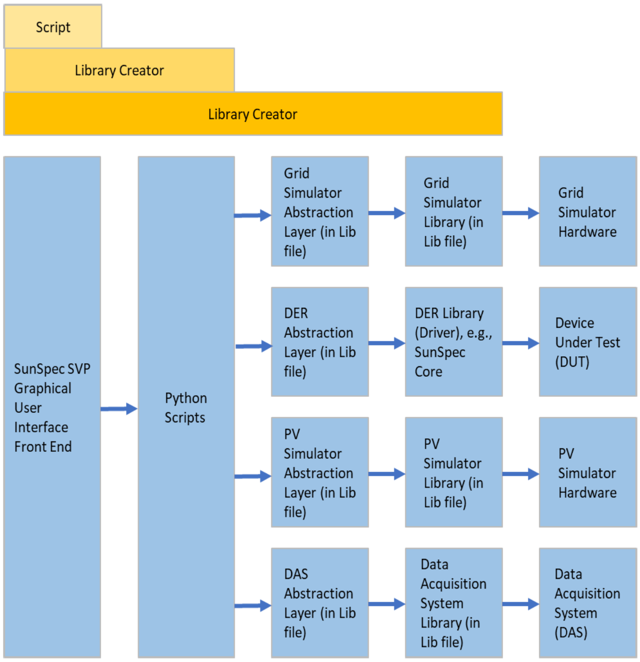


FIGURE 8. **Script and library creation steps for SunSpec SVP.**

test lab as well as specifications and capabilities of the test equipment.

For all test cases, regardless of the test lab utilized, script creator needs to have knowledge of how to interpret the test results obtained by DAS and how to judge whether DUT passes the performed certification tests. These comparisons and fail-pass judgements need to be set accurately through SVP GUI.

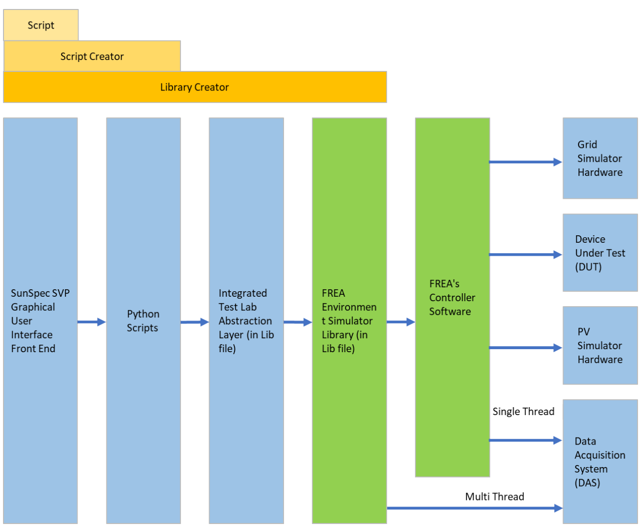


FIGURE 9. **Script and library creation steps, with necessary modifications for FREA.**

The modified operation is depicted in Figure 10. On the left most column, user enters the test desired parameters visa SVP GUI. These parameters are entered as absolute values, e.g. 40 kW, 100 V etc. Script generator takes these parameters and builds necessary processes that are needed to test a particular feature. For instance, in a volt-var test, the script generators creates (i) a process which will instruct the grid simulator to set the system voltage to a certain value, (ii) another process that will command DUT to set its operating conditions to tested mode and (iii) a final process that will ensure DAS is instructed properly to capture the results. One of the issues encountered in customization step is that DUT, i.e. smart inverter, in FREA's lab can only receive percentage values for setting active power, reactive power, output voltage and current. On the other hand, all the other layers utilized *absolute values* starting from SVP GUI. In order to tackle this issue, SVP's library pertaining to DUT needed to be modified so that any incoming absolute value is converted to *percentage value* that can be understood by DUT.

C. ISSUES RELATED TO SOFTWARE AND HARDWARE

Table 5 lists similar challenges related to software encountered during these tests along with the actions taken and the components that are affected by these actions. The majority of the issues are related to FREA's dedicated Controller Software, scripts or the library. These stem from the fact that different hardware used in the test lab require these software components to be customized. It is an important lesson for other test labs or researchers aiming at developing an interoperable testing platform. The first issue was about the single point contact requirement of the test lab's architecture. As indicated, this required modification of scripts, abstraction layer and the library so that SVP can send all the instructions via one connection. The second issue has to do with control of DAS devices and their compatibility. The devices used in the lab, WT3000, did not support the protocol used in SVP scripts. This required changing the SVP front end, scripts as well as the library. This is another important lesson about considering interoperable and standard communication when setting up test platforms.

The third issue has to do with following up on these changes, should the scripts be updated. If new standard scripts are received from third parties, these scripts need to be modified to fit the test lab's architecture, as discussed. The last two items have to do with automated plotting which is an integral part of reporting and certification. A new script is developed to plot required test results to achieve consistency in results. This also saves time, but the real motivation is achieving consistent reporting, especially when there are several devices that are tested. The last issue has to do with fixing scripts and library files to ensure both single and multi-thread processing can be utilized to acquire data from DAS.

Table 6 lists hardware related issues encountered. The first issue is related to voltage setting in grid simulator. When a certain amount is set in the script as grid simulator output, e.g. 200V, the voltage at DUT terminals is observed to be 1 % higher, i.e. 202V. This is due to the line impedance present between the grid simulator and DUT. The temporary measure was to insert value adjustment in the script to account for this

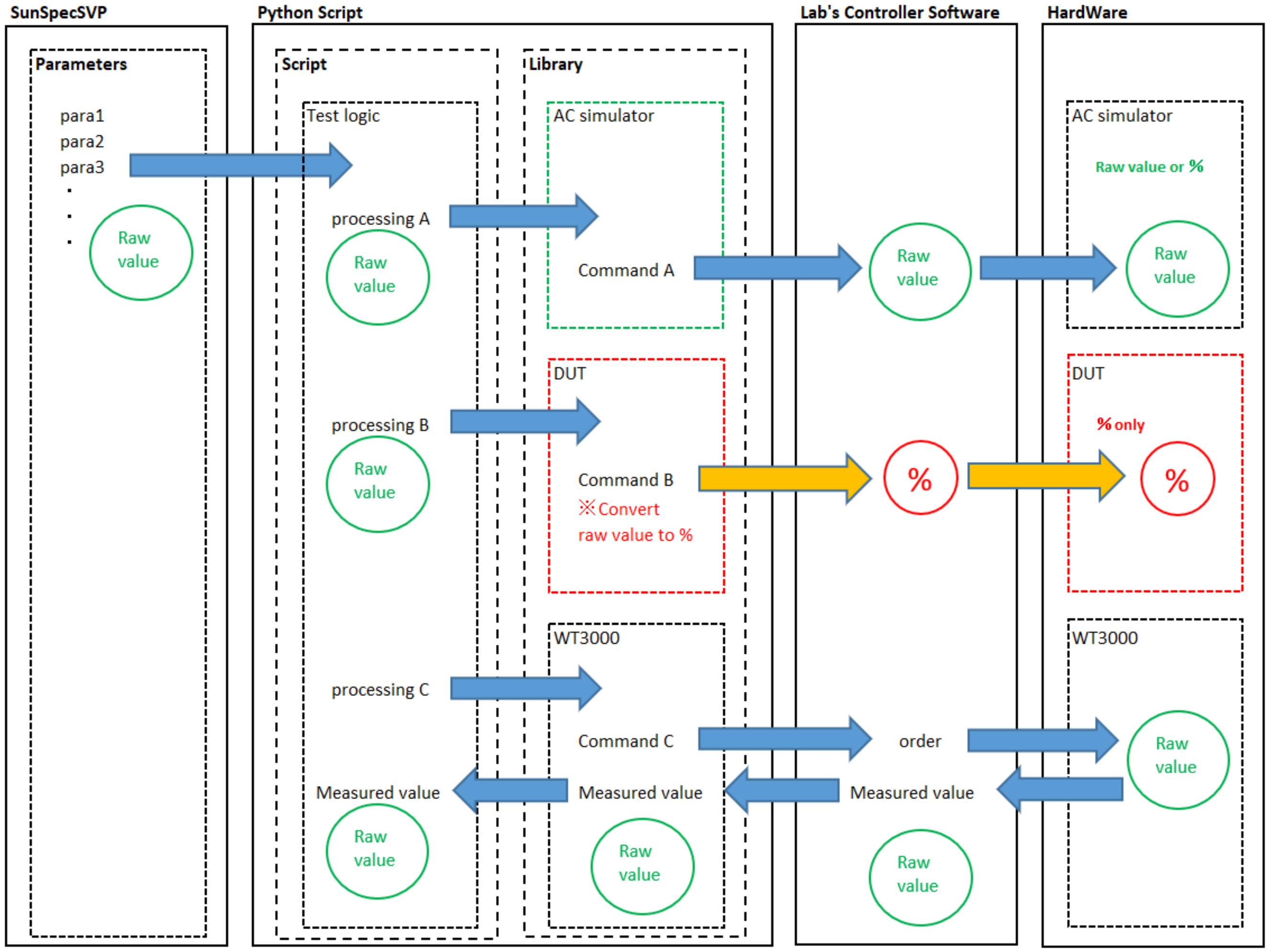


FIGURE 10. Script and library creation steps for SunSpec SVP.

1 % rise. The better solution is to perform this adjustment in the Controller Software. The measurement location can be changed to DUT's terminal in future.

The second issue is about ending the scripts as the last instructions may be kept in DUT and cause issues in subsequent tests. Both the scripts and the library information have been modified to make sure that parameters, such as power factor, are set to initial operating states when the tests are completed and the script returns. The final issue has been discussed earlier and has to do with DUT's inability to accept absolute value. SVP GUI, scripts and library files are all modified so that instructions are sent to DUT as percentage values.

The issues reported in this section are particular to the equipment and software present in FREA. When developing a different automated testing platform, identical or similar problems are likely to be encountered. Therefore, researchers and stakeholders in this field can benefit from (i) knowing such issues and (ii) possible solutions to mitigate them. These experiences will also help them develop their own solutions for unique issues encountered in their platforms.

IV. AUTOMATED TEST RESULTS AND DISCUSSIONS

The developed integrated testing platform is utilized to run a series of test on a smart inverter. These tests are required for certification before any inverter can be connected to utility grid and are as follows:

1. Low Voltage Ride Through (LVRT) & High Voltage Ride Through (HVRT)
2. Low Frequency Ride Through (LFRT) & High Frequency Ride Through (HFRT)
3. Ramp Rate (RR) & Soft Start Ramp Rate (SS)
4. Specified Power Factor (SPF)
5. Volt-Var (VV)
6. Frequency Watt (FW)
7. Volt Watt (VW)

Once the necessary electrical coupling is done in the lab, the entire testing has been done in an automated way using the developed integrated testing platform. This includes the testing procedures, data collection, data curation and reporting. Figure 11 and 12 show results for L/HVRT and L/HFRT tests. In these tests, three-phase three-wire split transformer method has been utilized. The power is always reduced from

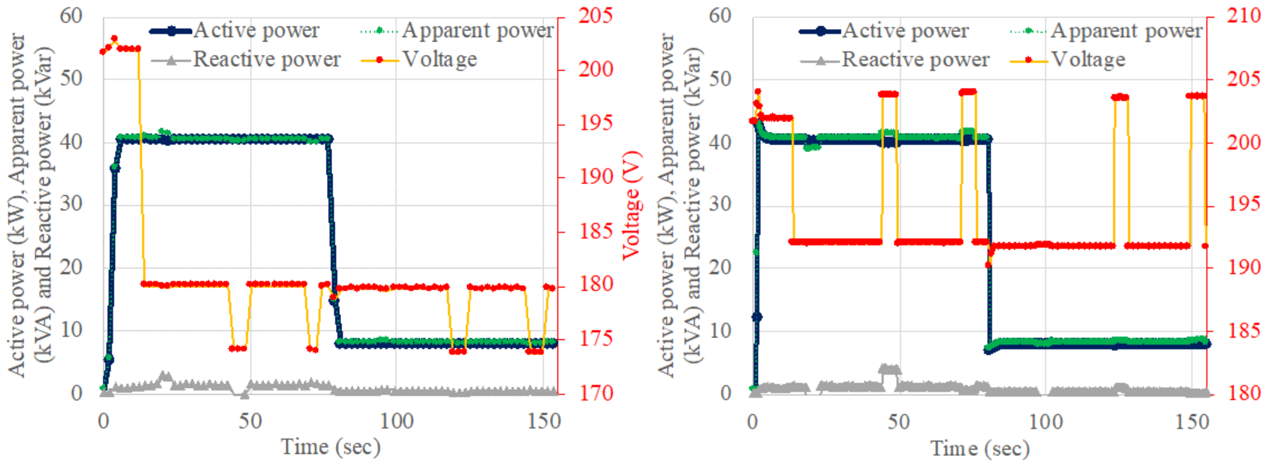


FIGURE 11. Low and high voltage ride through test results, LVRT (left), HVRT (right).

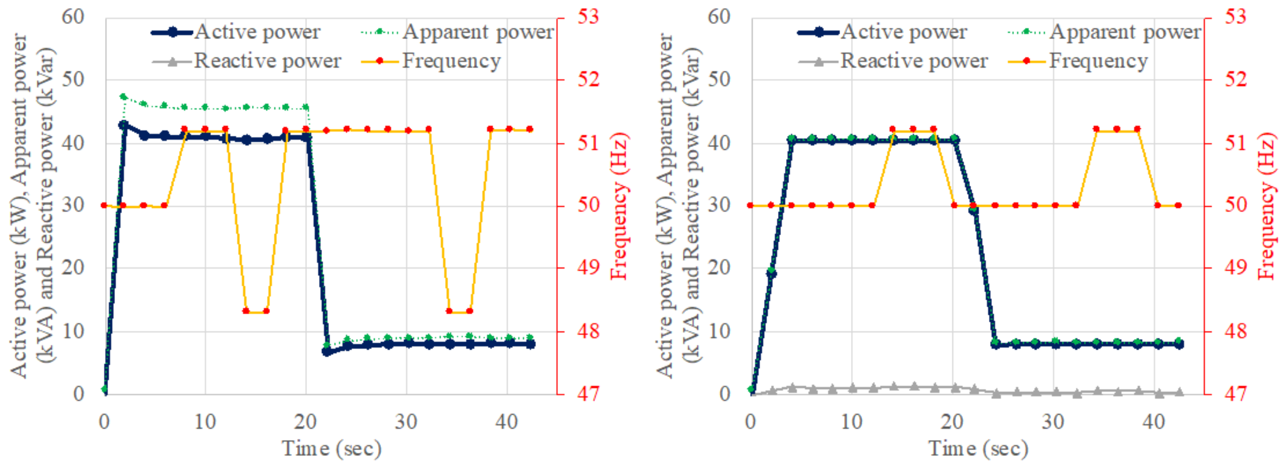


FIGURE 12. Low and high frequency ride through test results, LFRT (left), HFRT (right).

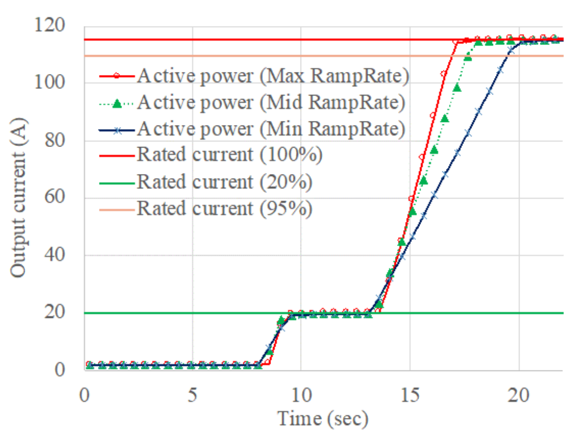


FIGURE 13. RR test results.

40 kW to 8 kW and the behavior is recorded for different modes.

Figure 13 shows the results of ramp rate tests. In this test, scripts set the output current value to 20 A initially. The inverter is expected to ramp up to 115 A which corresponds to 40 kW output, a limitation of the test setup. Minimum ramp rate the inverter is required to sustain is 10 A/sec. The script is run to sample the output periodically and check the ramp time. Results show that the inverter can achieve a higher ramp rate and passes the test.

SPF test is performed for two different cases minimum and medium, where the power factor should be 0.85 (min_ind) and 0.925 (mid_ind), respectively (-0.85 and -0.925 for capacitive cases, min_cap and mid_cap). WT3000 used in DAS shows the power factor variations as percentage values. For this reason, in Figure 15, 0.85 power factor value is shown as 15 % while -0.925 is shown as -7.5 %.

Volt-Var test is performed based on three volt-var curves, following international testing norms. These are average, least aggressive and most aggressive cases as shown in Figure 15. Scripts are run to change the grid simulator's voltage output and record DUT's reactive power output. The automated plots are obtained with the sampled data as shown.

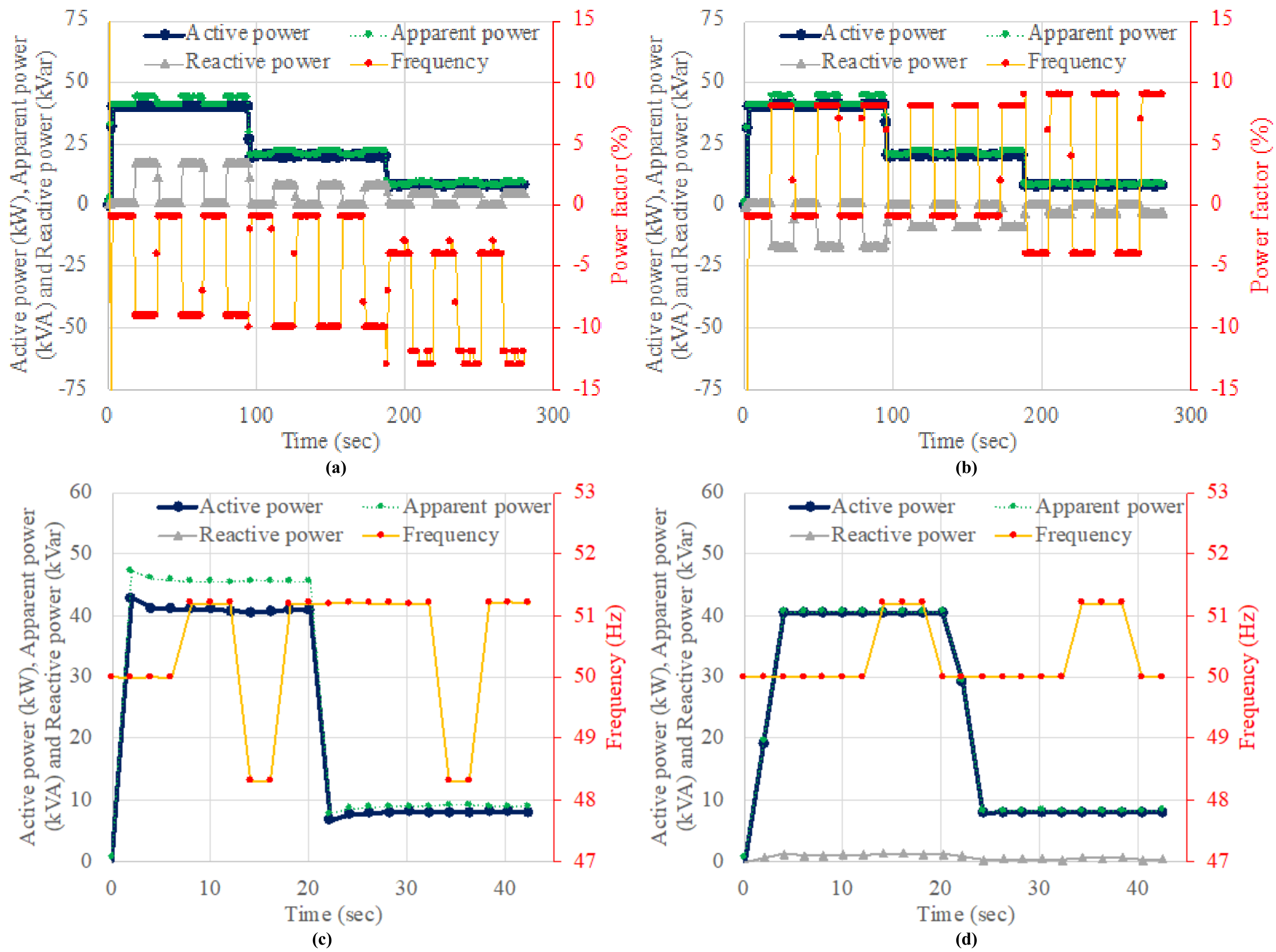


FIGURE 14. SPF Test Results, mid_cap (a) mid_ind (b), min_cap (c), min_ind (d).

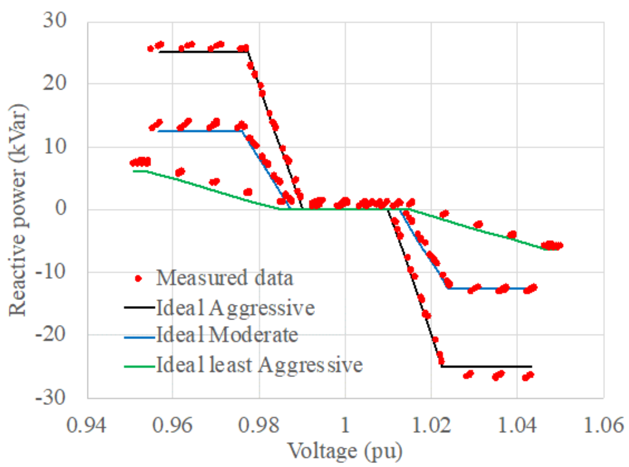


FIGURE 15. Volt-var test results.

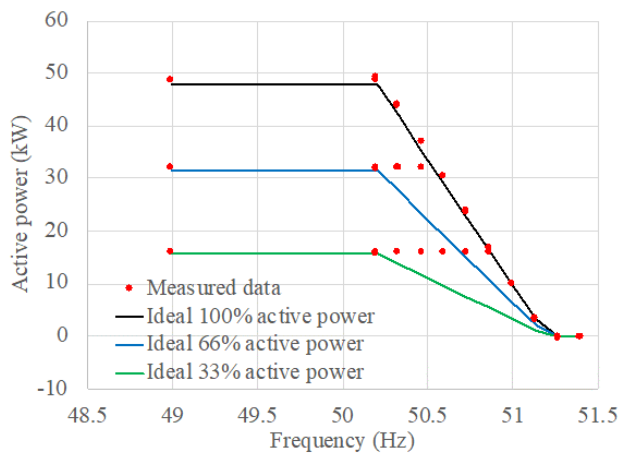


FIGURE 16. FW results, curve 1.

Last two tests are FW and VW. These tests are performed with two different characteristic curves, similar to volt-var tests. The active power output is set to 100 %, 66 % and 33 % when the frequency and voltage values (66 % is not required) are swept and the inverter behavior is recorded. As shown in Figures 17 and 18, the results are consistent with the ideal characteristic when active power output is 100 %. Significant variations are observed for other cases. Further

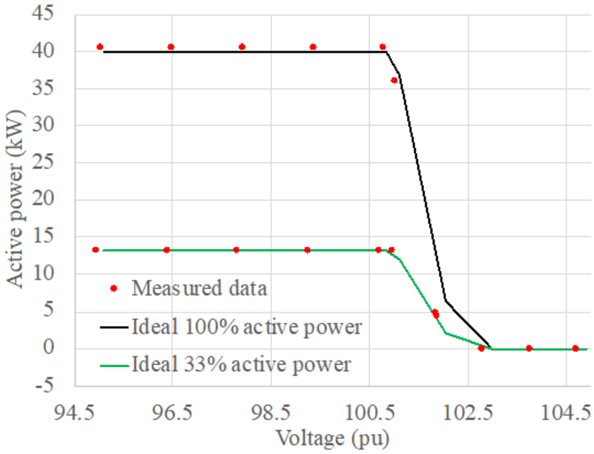


FIGURE 17. VW results, (a) 100 %, curve 1; (b) 33 %, curve 2.

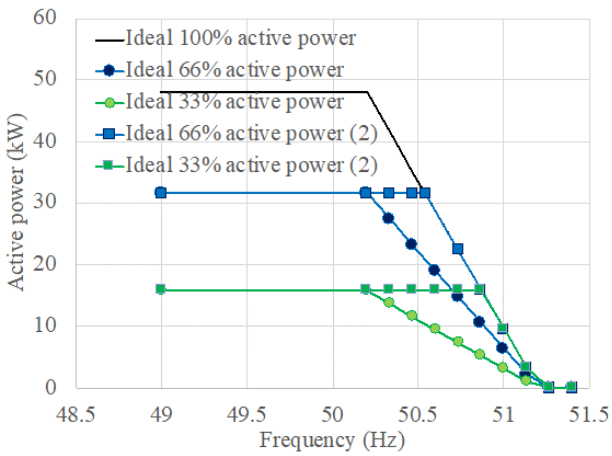


FIGURE 18. Different implementations of FW modes.

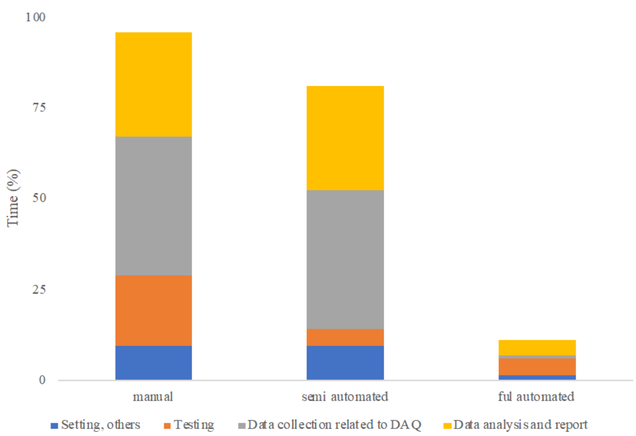


FIGURE 19. Time reduction with automated testing platform.

investigation into this matter clarified that the reason behind this is the difference in understanding of FW and VW implementations. The initial SIRFN draft on FW and VW modes have proposed two different implementations as shown in Figure 19. SVP scripts have adopted the implementation on the left while manufacturer of DUT opted for the one of the rights. It is a very important lesson that if there are issues open to different interpretations, automated testing platform (scripts and reporting) needs to be on the same page with the DUT.

When the tests are completed, the results are populated in a file and the report is prepared. Automated testing approach has many advantages such as consistency, interoperability and personnel safety. Reduced testing time is one of them. Table 7 shows the time required to perform each test. The overall duration to perform all these tests, including data collection and analysis, was a little over six hours. This is a huge improvement from manual lab tests that were performed earlier and presented in Section II. The past experience shows that these tests need something around 96 hours.

TABLE 7. Test durations.

	Test	Duration (min)
1	L/HVRT	55
2	L/HFRT	35
3	RR	18
4	SPF	38
5	VV	114
6	FW	39
7	VW	72
	Total	371 (6 hr. 11 mins)

Figure 19 shows times required for different test steps for manual testing and automated testing platform. Three steps; testing procedure, data collection, data analysis and reporting, are significantly reduced. The first component remains constant as it pertains to transportation of DUT and performing electrical wiring which cannot be automated. When this is factored in, fully automated testing requires only 13 hours whereas manual testing needs 96 hours. This is more than 85 % reduction. Moreover, since the tests are automated, there is no need for personnel to standby in the lab. The benefits can be maximized if the tests are run after office hours. In this case, tests will be performed overnight, and the results will be ready before the personnel come back the next day.

V. CONCLUSION

The will to increase renewable energy penetration has given rise to novel technologies such as SIs. These devices need extensive tests to understand their behavior and study their impact on the grid. There are procedure documents that give outlines for these tests. However, the interpretation of such tests is not singular. Furthermore, having consistent tests is vital for benchmarking studies as well as certification tests. This work develops an advanced integrated testing platform to address all of these issues. Conventional lab equipment is integrated over a platform. A central controller runs automated tests to run same tests with well-defined procedures. The integration steps required a lot of problem-solving and innovation which are documented above.

Use of such a platform increases the consistency and reliability of the tests. Other benefits are also received. Testing times are significantly reduced, from 96 hours conventional testing to 13 hours automated platform testing. In terms of efficiency, this is more than 85 % increase in number of devices tested in a fixed time period. Eliminating human intervention in the tests means that errors in parameter settings, data collection or reporting are brought to a minimum. In short, with the developed advanced integrated testing platform, a standard procedure is implemented to study SI behavior where the tests are run in an identical fashion and consistency is achieved. This would reflect itself as overall higher renewable energy penetration in future grids.

Future work should focus on collecting similar experiences from different platforms and utilizing them into developing a fully interoperable testing platform. Smart Inverters are becoming more popular thanks to their advanced capabilities. They can support the grid voltage and frequency. Of these, the voltage control is especially valuable for PV systems connected to low voltage networks. These networks tend to see more substantial voltage rises and smart inverter voltage support may be utilized to prevent these events. However, the optimal capacity for supporting the grid while injecting real power needs to be investigated.

Readers can look into automating their own test labs looking at the experiences, problems/challenges and solutions provided in this article. As the number of such testing platforms grow, it would be possible to compare performances and share best practices.

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