# Inverter Testing for Verification of Hawaiian Electric Rule 14H

## Preprint

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# Inverter testing for verification of Hawaiian Electric Rule 14H

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***Abstract* — As utilities increasingly require inverters to perform grid-supportive functions, it is challenging to ensure that those functions are properly configured in the field. This paper presents details of inverter testing related to Hawaiian Electric's latest rule 14H interconnection requirements to validate that field installation procedures result in the intended advanced inverter behavior. The latest Volt-VAR, Volt-Watt, and frequency-Watt curves in Hawaiian Electric's Source Requirement Document (SRD) V1.1 for UL 1741 Supplement A were tested for two inverter manufacturers used in the utility territory. Both inverters were found to be largely compliant, though several discrepancies were identified and reported to the manufacturers. The results are presented and discussed here.**

***Keywords—Inverter testing, UL 1741 SA, IEEE 1547-2018, Hawaiian Electric, Rule 14H***

## I. INTRODUCTION

The IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE 1547-2018 [1], lists the technical specifications for interconnection and interoperability between utility electric power systems and distributed energy resources (DERs) such as photovoltaic (PV) generation. This standard [1] is a revision of the original IEEE 1547-2003 [2]. IEEE 1547-2018 requires DERs to be capable of various functions that help maintain reliable grid operations including Volt-VAR, Volt-Watt and frequency-Watt control.

Hawaiian Electric is one of the first U.S. utilities to require DER inverters to perform Volt-VAR, Volt-Watt, and frequency-Watt control. Hawaiian Electric Rule 14H [3] entails the advanced inverter functions be certified to Underwriters' Laboratories 1741 Supplement A (UL 1741 SA) [4]. Hawaiian Electric's Source Requirement Document (SRD) lists the specific ranges of inverter settings for certification with UL 1741 SA. An initial SRD V1.0 was published in March 2017 [5], and an updated SRD V1.1 was published in September 2017 [6]. Both SRDs are largely aligned with IEEE 1547-2018.

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To verify that SRD V1.1 functions were being properly deployed, two commercial inverters from different manufacturers used in Hawaiian Electric territory were tested at the Energy System Integrations Facility (ESIF) at the National Renewable Energy Laboratory (NREL). The tests were conducted in conjunction with a field pilot project [7]. The inverters settings were configured using the same methods used by installers in the field, as prescribed by the inverter manufacturers. The inverter systems under test were connected to a PV emulator and to a grid simulator, as shown in Fig. 1.

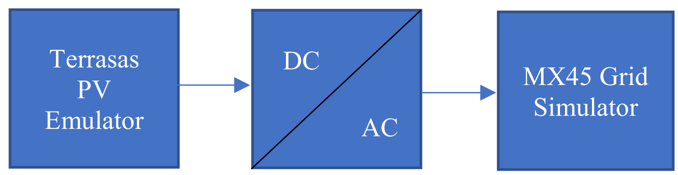


Fig. 1. Block diagram of the test setup

The grid simulator was used to change the voltage and frequency for the Volt-VAR, Volt-Watt, and frequency-Watt tests. The data acquisition was performed using a Yokogawa WT1800 power analyzer and DL850 digital oscilloscope. The programmed Volt-VAR, Volt-Watt, and frequency-Watt curves are discussed below along with comparison to experimental results. Observations from each test are compared with expected behavior from Rule 14H.

## II. VOLT-VAR TESTS

The Volt-VAR tests examine the response of the inverter to changes in grid voltage. The inverter should be capable of absorbing or injecting reactive power over the range of voltages from 0.88 p.u. to 1.1 p.u. The tests were conducted for verifying the default Volt-VAR curve included in SRD V1.1, shown in Fig. 2.

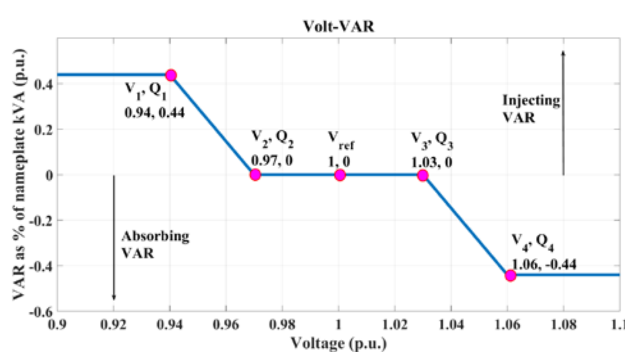


Fig. 2. Volt-VAR curve from Hawaiian Electric SRD V1.1

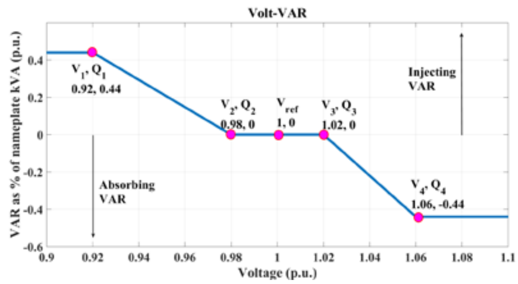


Fig. 3. Volt-VAR curve from Hawaiian Electric SRD V1.0

The curve shown in Fig. 2. is different from the default Volt-VAR curve in the SRD V1.0 shown in Fig. 3, which is no longer current. Table 1 shows the variation of reactive power with respect to voltages for both SRDs.

The Volt-VAR tests were conducted with voltage increasing in steps of 0.01 p.u. from 0.91 p.u. to 1.1 p.u. The time spent at each step was 180 seconds. The time step was chosen based on the maximum response time of 90 seconds for Volt-VAR tests provided in the SRD V1.1. The same experimental setup along with same voltage step sizes were used for Volt-Watt tests, which will be discussed in later sections. The Volt-VAR tests were conducted with available DC input power at 100% of the inverter's rating.

TABLE I
VOLT-VAR CHARACTERISTICS IN SRD V1.1 AND SRD V1.0

| Volt-VAR characteristics (SRD V1.1) | | Volt-VAR characteristics (SRD V1.0) | |
|---|---|---|---|
| Voltage (V/p.u.) | %VAMax | Voltage (V/p.u.) | %VAMax |
| 112.8V / 0.94 p.u. | 44% | 110.4V / 0.92 p.u. | 44% |
| 116.4V / 0.97 p.u. | 0% | 117.6V / 0.98 p.u. | 0% |
| 123.6V / 1.03 p.u. | 0% | 122.4V / 1.02 p.u. | 0% |
| 127.2V / 1.06 p.u. | -44% | 127.2V / 1.06 p.u. | -44% |

### *A. Results from Volt-VAR tests*

The voltages, currents, frequencies and powers (real, reactive, and apparent power) were acquired using the WT1800 system. The samples were acquired at a rate of 5 samples per second and then exported to MATLAB for processing, and relevant plots were obtained using MATLAB.

### *B. Observations from Volt-VAR tests*

The Volt-VAR experimental results of Inverter 1 show that

- Inverter 1's experimental Volt-VAR curve follows the SRD V1.1 curve, as shown in Fig.4. In fig. 4, inverter 1 shuts off at voltage of 1.1 p.u. due to overvoltage protection requirement in IEEE 1547-2018 [2].

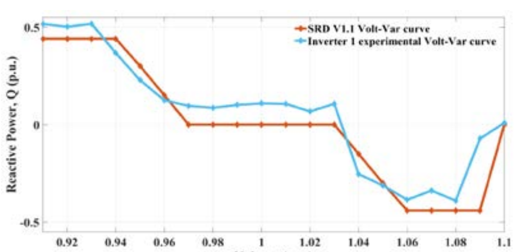


Fig. 4. Volt-VAR comparison of Inverter 1 experimental curve and default curve from SRD V1.1

- The step response time for change in reactive power, Q, with respect to step change in voltage, shown in Fig. 5. is somewhat longer than the 10-second default response time stated in SRD V1.1 but within the range of adjustability.

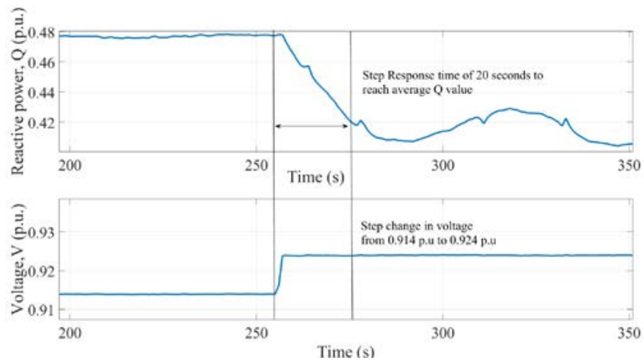


Fig. 5. Step response change in reactive power, Q for a step change in voltage for Inverter 2

The Volt-VAR experimental results for Inverter 2 show that

- Inverter 2's Volt-VAR curve, shown in Fig.6, follows the SRD V1.0 curve; the firmware should be updated to follow the SRD V1.1 curve

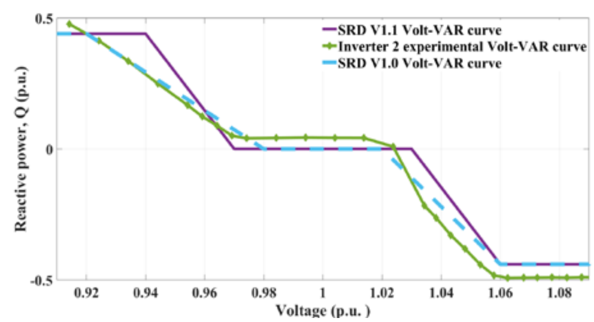


Fig. 6. Volt-VAR comparison of Inverter 2 experimental curve and default curve from SRD V1.1

- The step response time for change in reactive power with respect to step change in voltage, shown in Fig. 7, is faster than the 10-second default response time value specified in SRD V1.1 but within the range of adjustability.

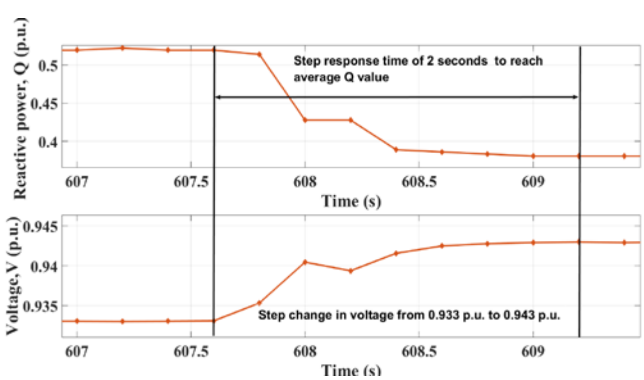


Fig. 7. Step response change in reactive power, Q, for a step change in voltage for Inverter 2

## III. VOLT-WATT TESTS

The Volt-Watt tests examine the response of inverter active power to changes in grid voltage. In this test, the inverter should limit its active maximum active power as a function of the voltage, shown in Fig.8. The tests were conducted using the default Volt-Watt curve from SRD V1.1.

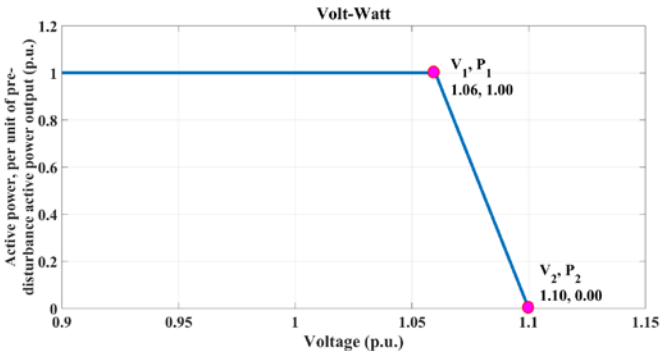


Fig. 8. Volt-Watt curve from the Hawaiian Electric SRD V1.1

### *A. Results from Volt-Watt tests*

The experiment was performed with available DC input power at 1.0 p.u. and 0.66 p.u. of the rated active power, depending on the test. The experiments compare the change of real power with respect to voltage using the Volt-Watt experimental data to the default Volt-Watt curve from SRD V1.1.

### *B. Observations from Volt-Watt tests*

The Inverter 1 experimental results for Volt-Watt show that:

- Inverter 1 follows the default SRD V1.1 curve Volt-Watt, as shown in Fig. 9. curve. At active power of 1 p.u., the real power starts reducing around voltage of 1.03 p.u. The region between voltage of 1.03 p.u. and 1.06 p.u. should not be confused as Volt-Watt activity. The real power curtails in this region due to both functions of Volt-VAR and Volt-Watt being active.

  The curtailing of real power occurs as to not exceed the total apparent power rating of the inverter. When the inverter hits its maximum apparent power rating, real power curtails to supply or absorb reactive power, due to VAR priority. At real power of 0.66 p.u., experimental Volt-Watt curve follows the SRD V1.1 Volt-Watt curve.

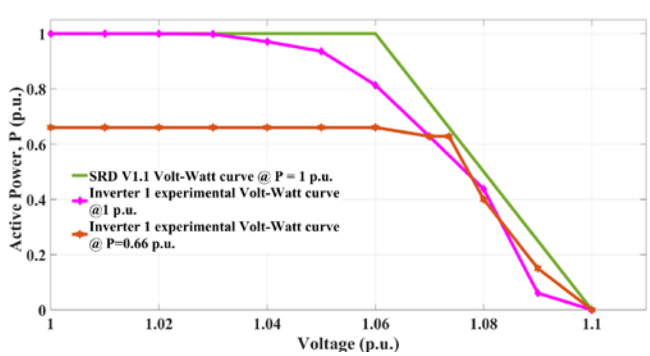


Fig. 9. Volt-Watt comparison of Inverter 1 experimental curve and default curve from SRD V1.1

- The step response time for change in active power, P, with respect to step change in voltage, shown in Fig. 10 is very close to the default response time of 10 seconds stated in the SRD V1.1.

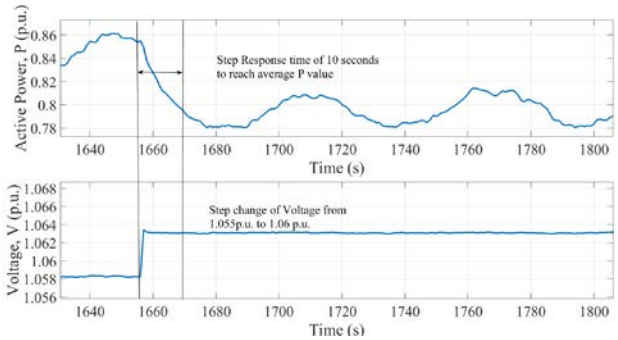


Fig. 10. Step response change in active power, P, for a step change in voltage for Inverter 1

- Fig. 11. shows the measured active and reactive power when both Volt-VAR and Volt-Watt are active. The active power gets curtailed due to the reactive power priority mode, as specified in SRD V1.1. From voltage of 1.03 p.u, it can be observed that active power curtails itself to not exceed the apparent power rating of the device.

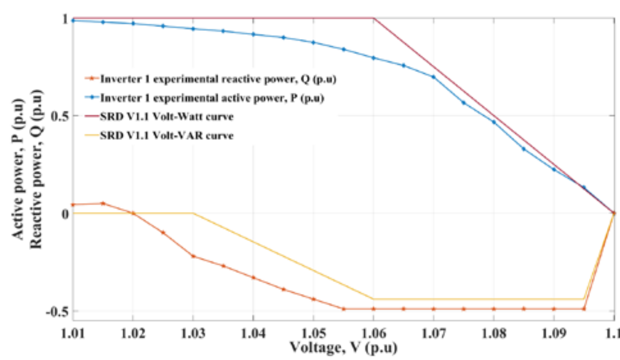


Fig. 11. Active power curtailment of Inverter 1 when both Volt-VAR and Volt-Watt are active

The Inverter 2 experimental Volt-Watt results show that

- The Inverter 2 Volt-Watt curve shown in Fig. 12 follows the default SRD V1.1 curve, but traces somewhat below the curve as active power is reduced due to reactive power production, which is permitted.

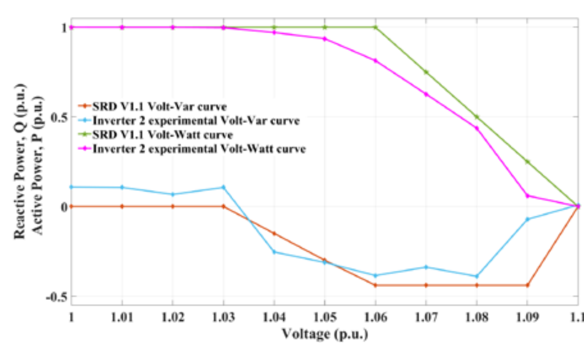


Fig. 12. Active power curtailment of Inverter 2 when both Volt-VAR and Volt-Watt are active

- The step response time for change in active power with respect to step change in voltage, shown in Fig. 13 is fairly close to default response time stated in the SRD V1.1.

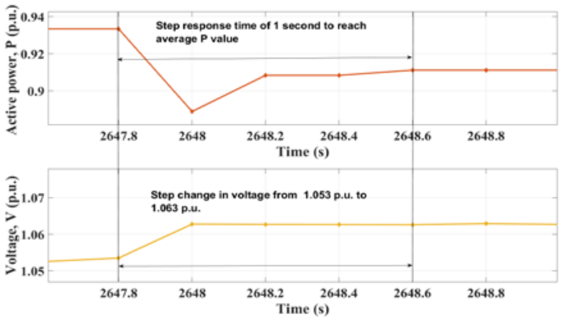


Fig. 13. Step response change in active power, P, for a step change in voltage for Inverter 2

## IV. Frequency-Watt tests

The frequency-Watt tests were conducted using the default curve from Hawaiian Electric SRD V1.1 shown in Fig. 14. This test verifies that inverters can modulate their active power based on the grid frequency, if the frequency exceeds specified dead band values.

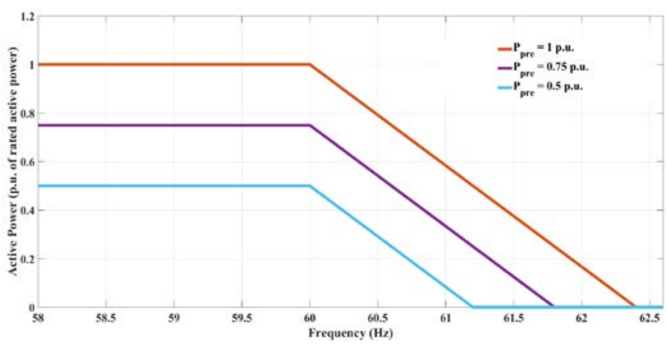


Fig. 14. Frequency-Watt curve from Hawaiian Electric SRD V1.1

In Fig. 14, the pre-disturbance power, *P_pre* is the active power at the time when frequency exceeds the frequency dead band. Once the frequency exceeds the dead band values, the pre-disturbance power should reduce 0.125 p.u. for every 0.3 Hz increase in grid frequency (a 4% droop coefficient). This means the inverter reduces its active power to zero at different frequency values based on the pre-disturbance power. The current version of Rule 14H only requires over-frequency response. The experiment was performed with a series of small frequency steps from 58 Hz to 63 Hz.

### *A. Results from frequency-Watt tests*

The experiment was performed at three conditions of available input DC power: 1.0 p.u. of the rated active power, 0.75 p.u. of the rated power, and 0.5 p.u. of the rated power.

### *B. Observations from frequency-Watt tests*

The experimental results of Inverter 1 and Inverter 2 for frequency-Watt, shown in Fig. 15 and Fig. 16, show that:

- The Inverter 1 and Inverter 2 experimental frequency-Watt curves closely follow the SRD V1.1 curve when the pre-disturbance power is 1.0 p.u. of rated active power.

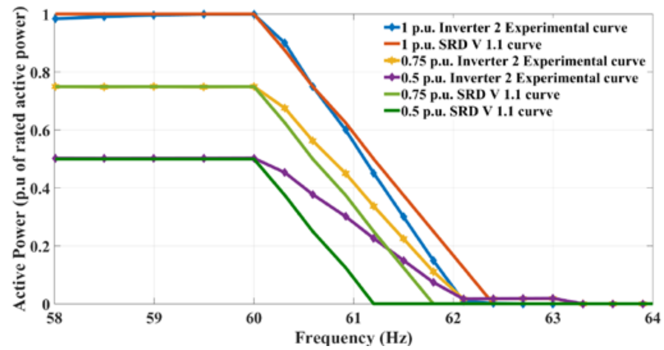


Fig. 15. Frequency-Watt comparison of Inverter 1 experimental curve and default curve from SRD V1.1

- Neither inverter follows the SRD V1.1 curve at 0.75 p.u. or 0.5 p.u. of rated active power. Instead, both inverters appear to be performing frequency-Watt following a specification where the power always reaches to zero by a specified frequency. This was acceptable on an interim basis per Rule 14H but is not in compliance with SRD 1.1 or IEEE 1547-2018, and will need to be updated.

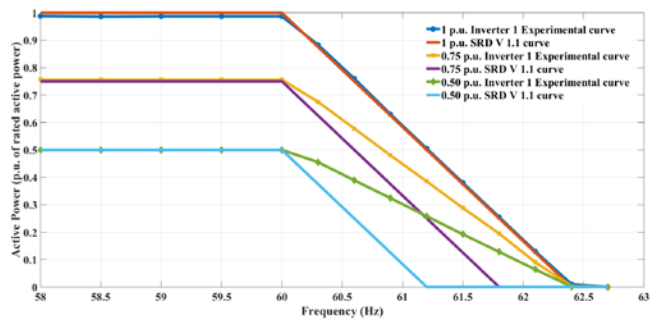


Fig. 16. Frequency-Watt comparison of Inverter 1 experimental curve and default curve from SRD V1.1

The time response of Inverter 1 for the frequency-Watt function appears to be about 4 seconds, shown in Fig. 17. This response time is within the allowed range of adjustability in SRD V1.1 but is not at the default value. This was permissible on an interim basis at the time of testing but should now be updated.

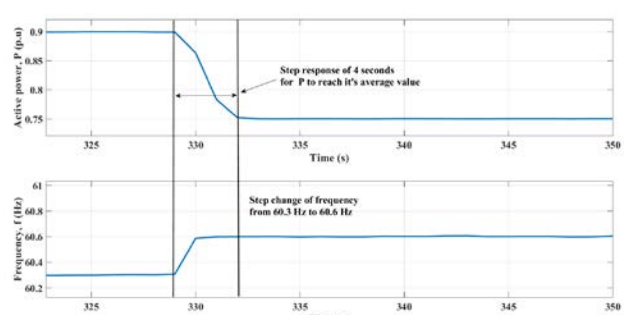


Fig. 17. Step response change in active power, P for a step change in frequency for inverter 1

- The time response of inverter 2, shown in Fig. 18, for frequency-Watt appears to be about 0.2 s. This is very close the default value of 0.5 seconds as specified in SRD V1.1.

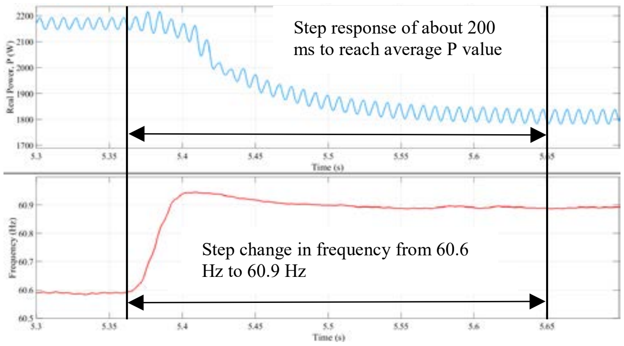


Fig. 18. Step response change in active power, P for a step change in frequency for inverter 2

## V. Conclusions

The two inverters tested were able to perform Volt-VAR, Volt-Watt, and frequency-Watt and were largely in compliance with Hawaiian Electric SRD V1.1 with some minor discrepancies as noted. In addition, some challenges were identified in programming the inverters and were communicated to the inverter manufacturers.

## References


[1] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, *IEEE Std 1547-2018*, April 2018.

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