

# Proposed test procedure for the laboratory characterisation of grid-connected micro-inverters.

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## Abstract

This paper describes a proposed setup and testing procedure for use in the characterisation of grid-connected micro-inverters within a laboratory environment. The procedure utilises a solar array simulator, external load and programmable ac power source. This arrangement allows for the determination of the operational characteristics as well as evaluation of performance of the unit under test. Parameters to be evaluated include inverter current and voltage operating range, input and output power and energy, conversion efficiency, maximum power point tracking range and accuracy for the static case, as well as MPPT utilization for dynamic cases. Total harmonic distortion for current and voltage, as well as disconnection behaviour under various utility conditions also forms part of the procedure. All tests are to be performed under a variety of irradiance, temperature and load conditions.

## 1. Introduction

The growth and development of grid-connected photovoltaic systems has been significant in recent years, with the possibility of South African consumers soon being able to sell any excess generated electrical energy back to the electrical utility authority. This makes grid connected systems greatly desirable to any consumers wishing to cut down on their energy costs. Although grid-tied systems can vary in size and form it has been noted that the use of multiple smaller micro-inverters may produce some advantages over the use of a single large inverter for a given array size under certain conditions, such as partial shading [1]. The use of micro-inverters for each individual module, or string of modules, allows for localized power point tracking, allowing for greater efficiency of the array as a whole, especially under shaded and partially shaded conditions. Thus the characterization of such inverters can be of significance to future developers. The objective of this study is to develop a setup and testing procedure for the evaluation and characterization of commercially available single phase grid connected micro-inverters up to 500W. The tests to be done are primarily intended for use in the characterization of the inverters under various irradiance and load conditions, although conformity to the relevant IEEE standards will also be considered.

## 2. Experimental setup

A schematic of the experimental setup is shown in figure 1, it consists of Agilent E4360A solar array simulator containing a E4361A 510W dc power source module, a resistive load bank and an Agilent 6813B 1750VA programmable ac power supply to act as grid simulator. The 6813B unit has a dual channel power analyser as an additional option. The dc current and dc voltage to the inverter is measured at the inverter's input terminals by means of the remote sensing capabilities of the solar array simulator module. Resistive losses due to connection wires are taken into account and compensated for as to not exceed the recommended maximum output current of the simulator. The ac output from the inverter is measured between the output terminals and the external load by means of the power analyser channel and an external shunt resistor supplied by the manufacturer. The power analyser measures ac current and voltage, dc current and voltage, power, frequency, phase and harmonic distortion. Measurements of the simulated grid are done at the output

terminals of the ac power supply, grid simulation parameters set at 230V at 50Hz, in accordance with the national standards.

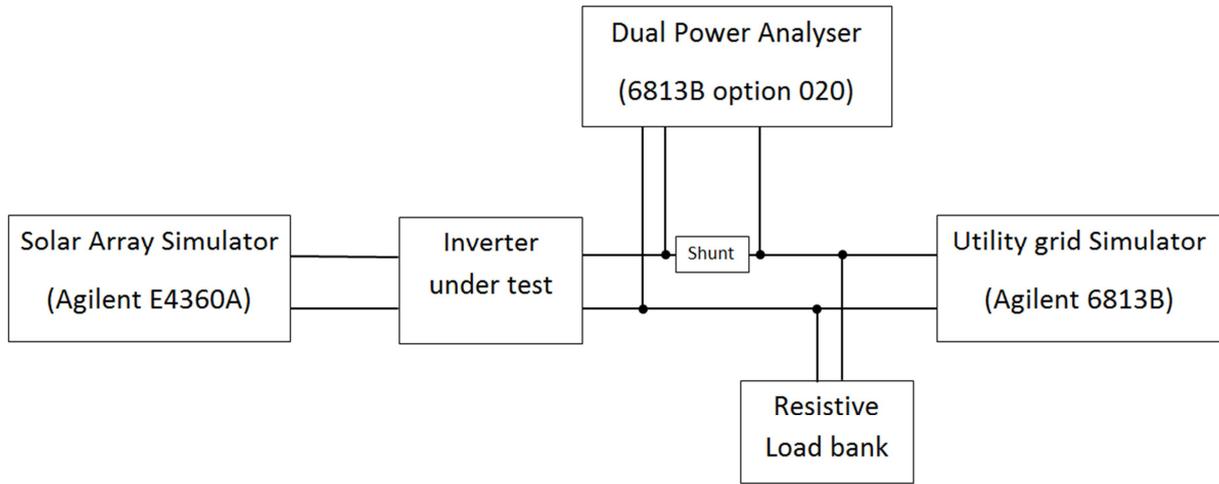


Figure 1: Schematic showing experimental setup

### 3. Experimental Procedure

Figure 2 shows a diagrammatic representation of the setup and points of measurement, defined as measurement zones A through C. The parameters measured in the procedure are listed below, together with a discussion on each and relevant definitions. The tests included in the procedure have no specific sequence and can be done in any order required.

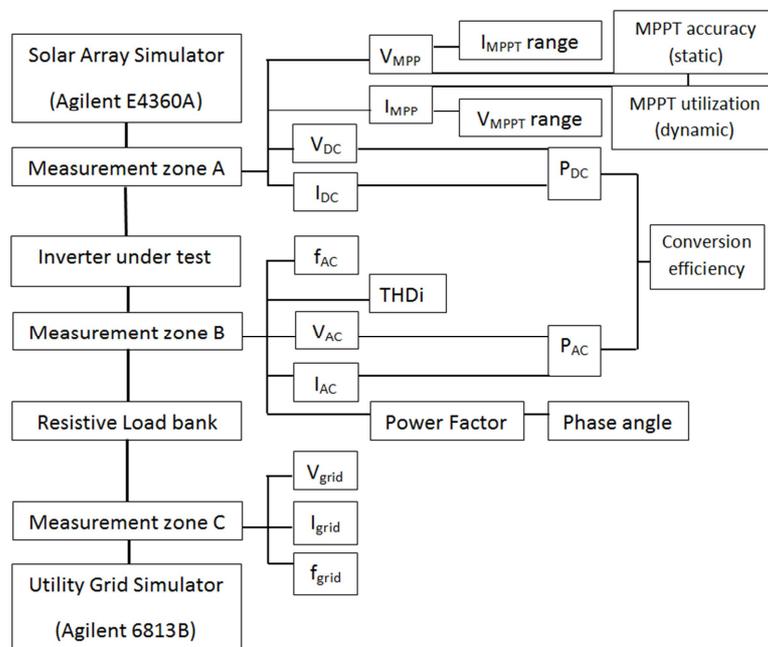


Figure 2: Diagrammatic flow chart of experimental procedure showing the various measurements and their locations.

**3.1 Power:** dc input current and voltage, defined as  $I_{DC}$  and  $V_{DC}$  respectively, is measured and used to calculate the total dc input power,  $P_{DC}$ , supplied to the inverter. The ac power output may be directly measured or calculated from the ac current and voltage,  $I_{AC}$  and  $V_{AC}$ . The maximum input and output power is recorded.

**3.2 Conversion Efficiency:** The efficiency, defined by the ratio of the dc input power to the ac output power[1]:

$$\eta = \frac{P_{AC}}{P_{DC}}$$

**Equation 1**

This is calculated for the inverter's entire specified operating power range. In addition the efficiency will also be calculated for various simulated irradiance, thermal and load conditions.

**3.3 Maximum Power Point Tracking (MPPT) range:**

- i. The MPPT voltage tracking range determines the operating limits of  $V_{DC}$  within which the MPPT can function. To evaluate the tracking range the array simulator is adjusted such that the maximum power point falls in the centre of the inverter's rated power operating range. The maximum power point voltage,  $V_{MPP}$  is then increased at a rate of no more than 5V per minute until inverter self-limits, while the maximum power point current,  $I_{MPP}$  is kept constant. This is noted as the upper limit of  $V_{MPP}$  [2]. The MPP is reset and the procedure repeated for decreasing  $V_{MPP}$ . The value at which the MPPT ceases to follow is noted as the lower limit of  $V_{MPP}$ .
- ii. The MPPT current tracking range defines the input current range across which the MPPT can function. To evaluate the range the inverter is operated with the maximum power point current near the centre of the inverter's rated operating current range.  $I_{MMP}$  is then increased at a rate of 0.02 of  $I_{max}$  per minute until the inverter self-limits, where  $I_{max}$  is defined as the maximum operating current of the inverter as specified by the manufacturer. This limit is noted as the upper limit of  $I_{MMP}$ . The procedure is repeated for decreasing  $I_{MPP}$  to find the lower limit of  $I_{MMP}$  [2].

**3.4 MPPT accuracy (steady state):** The MPP is set at the inverter's nominal rated output power and  $I_{DC}$  and  $V_{DC}$  measured and compared to the expected values for  $I_{MMP}$  and  $V_{MMP}$  from the IV-curve produced by the array simulator. The accuracy is defined as[3]:

$$MPPT \text{ accuracy} = 1 - \frac{|expected \ value - \ measured \ value|}{expected \ value}$$

**Equation 2**

The accuracy is calculated for  $V_{MMP}$ ,  $I_{MMP}$  and  $P_{MMP}$  as obtained under various simulated irradiance and thermal conditions.

**3.5 MPPT utilization (dynamic):** Used to evaluate MPPT response to changing weather conditions. Two tests are performed simulating different clouding effects, during these tests  $I_{AC}$ ,  $V_{AC}$  and  $P_{AC}$  are measured and compared to the corresponding expected output values. From these values the MPPT utilization is calculated as the ratio of the measured energy obtained from the array to the expected energy obtained from the simulator for each measurement point  $i$  [3]:

$$MPPT \text{ Utilization} = \frac{\sum_i P_{measured,i}}{\sum_i P_{MP \text{ expected},i}}$$

Equation 3

The two conditions are:

- i. Intermittent cloud cover: This simulates the effect of a large slow moving cloud passing in front of an array. The unit is allowed to equilibrate at ambient temperature and simulated 800W/m<sup>2</sup> irradiance. The simulated irradiance is then decreased linearly to 100W/m<sup>2</sup> in 5 seconds and the MPPT unit allowed to stabilize. Once stabilization has occurred the irradiance is increased to 800W/m<sup>2</sup> in 5 seconds. Time required for MPPT stabilization will be noted after each ramp. Power and time will be measured and used to calculate the energy produced by the inverter. This is compared to the expected energy production from the solar array simulator.
- ii. Partial clouding: This simulates the effect of several smaller, fast moving clouds passing in front of an array. The test will consist of a fast linear ramp from 800w/m<sup>2</sup> to 100W/m<sup>2</sup> and back to 800W/m<sup>2</sup> in 60 seconds. Repeated for 15 cycles. MPPT stabilization time and power is measured.

**3.6 Power factor:** The power factor is measured and plotted as a function of output power of the inverter[4].

$$PF = \frac{P_{AC}}{V_{rms} * I_{rms}}$$

Equation 4

**3.7 Harmonic distortion:** The total harmonic distortion (THD) is defined as the ratio of the root-mean-squared (rms) value of the sum of the squared individual harmonic amplitudes to the rms value of the fundamental frequency of a complex waveform[4];

$$THD = \frac{\sqrt{(I_2^2 + I_3^2 + I_4^2 + \dots)}}{I_1}$$

Equation 5

The THD will be measured, for the ac output current, up to the 40<sup>th</sup> harmonic at various levels of the inverter's rated output. The total harmonic current distortion, THDi, will be plotted as a function of output power and harmonic number.

**3.8 Steady state voltage range:** The inverter output voltage is adjusted to rated nominal voltage output of the inverter. The grid voltage is then increased stepwise in increments of 1V from the nominal voltage until the inverter shuts down due to overvoltage. Each voltage is maintained for 10s to allow the inverter to equilibrate. The last value at which the inverter was functioning is noted as the upper limit voltage of the inverter. The procedure is repeated for decreasing  $V_{grid}$  and the value at which the inverter last functioned, before disconnecting is noted as the lower limit voltage[3].

**3.9 Steady state frequency range:** The ac power supply output frequency,  $f_{grid}$ , is adjusted to the nominal grid frequency and varied in increments of 0.1Hz from nominal value, this is done until inverter shuts down due to under- or over-frequency. Each output frequency is maintained for 10s to allow the inverter to equilibrate. The lowest frequency at which the inverter was still functioning is recorded as the lower limit of f and the highest as the upper limit[3].

**3.10 Disconnection time due to voltage disturbances:** The inverter is operated at 50% of rated output power. In the case of a sudden deviation in the normal grid operating voltage the inverter is required to disconnect within a certain time. The following four tests are performed for voltage deviations, in each case the voltage will undergo a sudden deviation and time measured until inverter disconnection[2, 5]:

In each case the deviation is from nominal grid operating voltage to

- i. 49% of the nominal operating voltage
- ii. 87% of the nominal operating voltage.
- iii. 111% of the nominal operating voltage.
- iv. 138% of the nominal operating voltage.

The time for inverter to restart after disconnection will also be monitored.

**3.11 Disconnection time due to frequency disturbances:** The inverter is operated at 50% of rated output power. In the case of a deviation in the normal operating frequency of the grid, the inverter is required to disconnect if the deviation exceeds a certain range. The following two tests are performed for deviations in grid frequency[2, 5, 6]:

- i. The grid frequency is decreased from 50Hz to 49.6Hz at a rate of no more than 0.5Hz/s. The disconnect time is measured from the time the frequency reaches 49.7Hz.
- ii. The grid frequency is increased from 50Hz to 50.4Hz at a rate of no more than 0.5Hz/s. The disconnect time shall be measured from the time the frequency reaches 50.3Hz.

The Time for inverter to restart after disconnection will also be recorded.

**3.12 Disconnection time due to utility loss (Resistive loads):** The following tests are performed at the rated power output of the inverter, they form part of the anti-islanding tests specified for grid utilization[4, 6]

- i. The resistive load is adjusted such that the power output of the inverter and the power consumed by the load are matched.. The utility grid is disconnected and the time measured for the inverter to disconnect.
- ii. The resistive load is adjusted such that the inverter output power is 150% of the power consumed by the load bank. The utility grid is disconnected and the time measured for the inverter to disconnect.
- iii. The resistive load is adjusted such that the inverter output power is 50% of the power consumed by the load bank. The utility grid is disconnected and the time measured for the inverter to disconnect.

The time for inverter to restart after disconnection will also be recorded.

## **1. Conclusion**

Procedure outlined will allow for the evaluation of operational and behavioural characteristics of grid-connected inverter parameters such as the dc/ac conversion efficiency, power factor, maximum output power and operating voltage and current limitations. It also provides a way to measure MPPT range and accuracy under various solar conditions. The procedure also allows utility connection compatibility testing with regards to resistive loads, thus partially satisfying the procedure for full utility compatibility and anti-islanding testing. The procedure can however easily be expanded to incorporate the use of a reactive load which allow the user to perform the complete compatibility testing procedure, in accordance with the relevant

standard. The inverter behavioural testing under resistive loads will characterise the inverter behaviour with regards to utility voltage and frequency disturbances and harmonic disturbances as applicable to the AC current output.

## References

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