SOLAR PV INVERTER CHARACTERIZATION IN INDOOR LABORATORY

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Abstract: A commercial 3ph 25 kW inverter is characterised at the Smart Grid Laboratory, CEA-INES in accordance with IEC/EN 61727 and EN50530. The minimum, nominal and maximum power point tracking power conversion efficiency for normalized power levels measured an average 96%, 97% and 97% respectively. The response time of tested inverter during over / under voltage and frequency conditions set with IEC/EN 61727 grid code parameters measured as expected. The ride through functionality test for Y and X1 type of voltage dips complied to the IEC/EN 61727 requirements. The total harmonic distortions for simulated clear and cloudy sky irradiance profiles measured distortions above the stipulated 5% in accordance with IEC/EN 61727 during early morning and late afternoon periods i.e., when inverter tends to turn ON and OFF. The cloudy sky irradiance profile measured higher distortions compared to clear sky. The exposure to real time inverter characterization at CEA-INES laboratory has enhanced the knowledge on inverter characterization process and increased the confidence in the inverter performance operating in low voltage network.

Keywords: PV inverter, characterization, voltage, frequency, current, IEC.

1. Introduction

Grid-tied PV systems are the fastest growing renewable energy source for power generation today and many consumers are switching to embedded generators due to increasing electricity tariffs. The quantity of the electricity produced from PV systems directly depend on the amount of solar irradiance striking the active PV area. Changes in weather conditions affect the output power from PV and one primary reason for variable output power is the cloud movement. Power fluctuations on a grid-tied low voltage network causes harmonic distortions in the current waveforms [1]. PV inverters are the main source of injecting current harmonics into the network. The injected harmonics can increase power losses in the system [2]. There is a motivation worldwide to conduct power quality analysis as more embedded generators particularly solar PV systems are connected to low voltage utility grid. Power quality analysis includes harmonic distortions, reverse power flow, voltage fluctuations and power fluctuations and these parameters must comply with the governing standards to ensure the safe operation of connected loads and cleanliness of the supply. The Council for Scientific and Industrial Research Energy Centre (CSIR EC) solar photovoltaic (PV) team capabilities include characterization of solar PV modules in indoor and outdoor conditions for the ever-growing renewable energy industry. There is a strong emphasis to increase localization content for PV components in the country and CSIR being a parastatal company supports the growth of local industry in all the respective sectors. The Utility has also raised concerns about the un-safe inverter operations during maintenance periods and injection of harmonics by high frequency switching devices in the low voltage network. High penetration of intermittent PV can also cause voltage fluctuations in grid, voltage rise and reverse power flow, power fluctuations in grid, variation in frequency and grounding issues. PV penetration in low voltage distribution network also causes harmonic distortion in current and voltage waveforms [3]. The filters in the inverter may also absorb some of the harmonics in the network. Inverter characterization in indoor laboratory reveals the actual performance against its intended requirements. The lack of inverter characterization infrastructure in the Republic of South Africa motivated to submit a proposal to access the ERI Grid Trans-national Access (TA) program fully sponsored under Horizon 2020 program. The proposal focused on characterization the PV inverter in terms of over / under voltage and frequency trip time, voltage ride through test and perform efficiency related measurements at CEA-INES France in accordance with IEC/EN 61727 [4] and EN50530 [5]. The objective is mainly to increase the knowledge in the space of inverter characterization and gain confidence in the inverter operations.

2. Method

The Device under Test (DuT) is a commercially available 25 kW solar PV inverter. As the prime objective is to understand the technicalities involved during inverter characterization, IEC/EN 50530 and IEC/EN 61727 standards widely used for design qualification and certification is considered to determine the test sequence, criterions and evaluate the measured results.

2.1 Characterization tests

2.1.1 Power Conversion Efficiency test:

- Note the minimum (Umppmin), nominal (Umppnom) and maximum voltage (Umppmax) values at maximum power point (MPP) from the inverter rating label.

- For each MPP voltage level, power conversion efficiency parameters are measured at eight power levels (5%, 10%, 20%, 25%, 30%, 50%, 75% and 100%) normalized to the rated power.
- Prepare a solar irradiance (W/m^2) profile using calculated current, Idc for each of the MPP voltages (Umppmin, Umppnom and Umppmax).
- Load it to PV simulator using PRISMES software and wait until the inverter synchronizes with the grid.
- A measurement dwell period of 10 minutes programmed for each of the power levels with 5 minutes interval between the measurements.
- Monitor the entire system for steady operations during the test period.
- Record the measured values of Udc, Idc, Uac and Iac at an interval of every second.
- Calculate the power conversion efficiency (η_{conv}) from the i, simultaneous measurements of Udc, Idc, Uac and Iac over a period ΔT per the equation (1).

    - $$\eta\text{conv} = \frac{\int_0^{Tm} Pac\ (t)}{\int_0^{Tm} Pdc\ (t)} = \frac{\sum_i Uac,i\ Iac,i\ \Delta T}{\sum_i Udc,i\ Idc,i\ \Delta T} \qquad (1)$$

- The European power conversion efficiency (η_{conv}EUR) and Californian power conversion efficiency (η_{conv}CEC) is calculated using the equations (2) and (3).

    - η_{conv}EUR = 0.03ηconv,5% + 0.06ηconv,10% + 0.13ηconv,20% + 0.1ηconv,30% + 0.48ηconv,50% + 0.2 ηconv,100% (2)

    - ηconvCEC = 0.04ηconv,5% + 0.05ηconv,10% + 0.12ηconv,20% + 0.21ηconv,30% + 0.53ηconv,50% + 0.05 ηconv,100% (3)

2.1.2 Over / Under Voltage and Frequency test:

- To test the inverter for IEC/EN 61727 Metropolitan Electricity Authority (MEA) requirements: Manually adjust the Rotary switch A to position B and Rotary switch B to position 8 on the inverter underneath the LCD display board as specified in the user manual.
- Design a logic diagram using Simulink tool on MATLAB to run the test in steps.
- Program the test steps for the voltage levels $V < 50\%$, $50\% \le V < 85\%$, $85\% \le V \le 110\%$, $110\% < V < 135\%$, $V \ge 135\%$ and frequency levels, <49Hz and >50Hz as stipulated in the IEC 61727.
- Allow sufficient time in-between for the inverter to turn ON post dis-connection from the grid.
- Apply stable DC input from the PV simulator. Control the grid simulator and perform the required simulations using OPAL-RT real time simulation software.
- Allow time for the inverter to synchronize with the grid parameters and turn ON.
- Monitor the entire system for steady operations during the test period.
- Record the real time voltage and current for all the 3 phases and frequency values at every 50µS time intervals and analyse the measured values.
- Determine the response/trip time.

2.1.3 Ride through functionality test:

- Design a logic diagram using Simulink tool on MATLAB to run the test in steps.
- Program the test steps for the Y type voltage dips type $10\% \le V \le 15\%$ for 2000mS, $15\% \le V \le 20\%$ for 600mS, $20\% \le V \le 30\%$ for 150mS and X1 type voltage dip type $30\% \le V \le 40\%$ for 150mS as stipulated in IEC 61727.
- Allow sufficient time for the inverter to turn ON post dis-connections from the grid if any.
- Apply stable DC input from the PV simulator. Control the grid simulator and perform the required simulations using OPAL-RT real time simulation software.
- Allow time for the inverter to synchronize with the grid parameters and turn ON.
- Monitor the entire system for steady operations during the test period.
- Record the real time voltage and current for all the 3 phases and frequency values at every 50µS time intervals and analyse the measured values.
- Verify the ride through functionality.

2.1.4 Harmonic measurements:

- Perform measurement of Harmonic distortions in the current waveform for a full clear and cloudy sky day profile. This test is conducted with controllable electronic load (RLC) in the circuit.
- Design a logic diagram using Simulink tool on MATLAB to run the test continuously and load it to the grid simulator.
- Install a power quality analyser and connect the voltage and current measurement probes of the Power Analyser (PA) to the inverter output terminations.

  Prepare solar irradiance profile for clear and cloudy sky conditions consisting of 30 sec interval data for a full day and program the PV simulator to feed the DC power continuously based on the irradiance.
- Keep the per phase AC power output limited to 4000W totalling to 12000W feeding to the grid.
- Calculate the Resistance (R), Inductance (L) and Capacitance (C) values for the RLC load bank using below equations and apply it to the load bank.
    - $R = V^2_{RMS} / P$ (4)
    - $L = V^2_{RMS} / 2\pi fPQf$ (5)
    - $C = PQ_f / 2\pi fV^2_{RMS}$ (6)

    Where $Q_f = R\sqrt{C/L} = 1$
- Apply programmed DC voltage and current inputs based on solar irradiance data from the PV simulator.

- Control the grid simulator and perform the required simulations using OPAL-RT real time simulation software.
- Monitor the entire system for steady operations during the test period.
- Record the voltage, current, frequency and harmonic emissions up to 50th order (3 kHz) at every second interval.
- Analyze and calculate the Total Harmonic Distortions (THDi) and Odd/Even harmonics for multiple orders for the current using the equation (7)

$$\mathrm{THDi} = \frac{\sqrt{\sum_{n=2}^{\infty} \mathrm{THDi}_n^2}}{\mathrm{THDi}_1} \quad (7)$$

- Verify the measured values against the limits stipulated in IEC / EN 61727.

2.2 Test set-up(s)

The following equipment are used to perform the characterization tests mentioned in 2.1.1 to 2.1.4:

2.2.1 DC power supply Elektro Automatic PSI 91500-30 with PRISMES software

- Technical specs: 15 kW max each, PV simulator function included (possibility to simulate irradiance fluctuation), 1500 VDC max, 30 A DC max.
- PRISMES software is used to configure, remote monitoring, control, and data acquisition purposes for PSI. Additional PSI's are looped together to supply power to multiple MPPT's at the same time where the test conditions demanded for full load conditions.

2.2.2 400V 3 ph+N Grid simulator

- Technical specs: 45 kVA generation (from simulator to equipment under test [EUT]), 15 kVA absorption (from EUT to simulator), the simulator can be autonomous or driven by an OPAL RT system, Voltage AC range: from 120V to 690V, Frequency range: from 0 to 2500 Hz, Possibility to inject voltage harmonics.
- OPAL-RT simulation software that provides powerful, real-time simulation solutions for electrical conversion, enabling customers to conduct precise and exhaustive testing more quickly on all controls is used to drive the grid simulator and conduct the tests.

2.2.3 Device under Test (DUT)

- The device under test is a commercially available 3 phase 25 kW power output solar PV inverter with two (2) maximum power point tracking inputs.

2.2.4 Electronic Load (RLC)

- Technical specs: 30 kVA, 40 ARMS, consumption of AC 3-phase or 1-phase current, 100% configurable power factor, inductive and capacitive, configurable harmonics, Operation modes: CC, CP and CI, Automatic test from Excel file.
- An Ethernet communication interface with protocol MODBUS/TCP is used to configure, monitor, and operate the electronic load. By using HMI software application provided by CINERGIA, uploading of excel files is also possible.

2.2.5 Power Analyzer

- Technical specs: TRMS AC+DC voltage up to 1,000 V, TRMS AC+DC current: 5 mA to 10 kA depending on the sensors, Frequency, Power values: W, VA, VAR, VAD, PF, DPF, cos φ, tan φ, Energy values: Wh, VARh, VAh, VADh, BTU, toe, Joule, Harmonics from 0 to the 50th order, phase Transients: up to 210, Inrush with waveform over a period > 10 minutes, True Inrush function, Recording of a selection of parameters at the maximum sampling rate for several days to several weeks Alarms: 10,000 of 40 different types, Peak detection Vectorial representation, IEC 61000-4-30 Class B

2.3 Monitoring

- The operation of all the equipment and functioning of the DuT is physically monitored on a real time. For the harmonic measurement test that is for full day solar irradiance profile and for different conditions, the operation of the equipment is remotely monitored. All the DC data including voltage and current is acquired by PRISMES software and the AC data parts including voltage, current, frequency, power factor with other key electrical parameters are acquired by OPAL-RT software.

2.4 Data Management and Processing

2.4.1 Power conversion efficiency test:

- Solar irradiance data with the Udc, Idc and Pdc are averaged to every minute interval from their measured data at every 30 seconds interval in the first step.
- In the next step, the Uac and Iac for all the 3 phases are averaged to every minute interval from their measured data at every second interval.
- Based on the data sets and time stamp match, the measured DC data is aligned with the measured AC data on a Microsoft spreadsheet.
- The power conversion efficiency is calculated from the sum of AC and DC power values as per the Eq. (1) for minimum, rated and maximum MPPT voltages. The European and Californian efficiency are also calculated as per Eq. (2) and (3).

2.4.2 Over / under voltage and frequency, ride through functionality tests:

- In this test, the Uac, Iac, Hz are the critical parameters to determine the trip time of an inverter. These parameters are monitored at 50 µS interval for all the 3 phases.
- The acquired data is processed using MATLAB software and simple scripts to plot the Uac, Iac and Hz for the same time frame.

- Measured Iac is used as common metric against varying voltage and frequency to determine the trip time.
- The measured Uac is plotted followed by Iac for the same time frame and similarly measured Hz followed by Iac.
- The time taken to trip or override the different set of conditions is calculated from the Iac curve.

2.4.3 Harmonics measurements test:

- Solar irradiance data with the measured Udc, Idc and Pdc are averaged to every minute interval in the first step.
- The data stored on the Power analyzer memory space is downloaded to Microsoft spreadsheet.
- Based on the datasets and time stamp match, the irradiance, Uac, Iac, Pac are averaged to 1 minute interval using pivot table for all the 3 phases.
- The harmonic emissions in each phase for the range of orders mentioned in the IEC standard is calculated on an hourly basis as per the equation (7).

3. Test Results and discussion

3.1 Power conversion efficiency test

The power conversion efficiency (Ƞconv) measurement is carried out as per the methodology briefed in section 2.1.1.

Figure 1 shows the calculated power conversion efficiency (Ƞconv) for the Umppmin, Umppnom and Umppmax at 5%, 10%, 20%, 25%, 30%, 50%, 75% and 100% normalized inverter power.

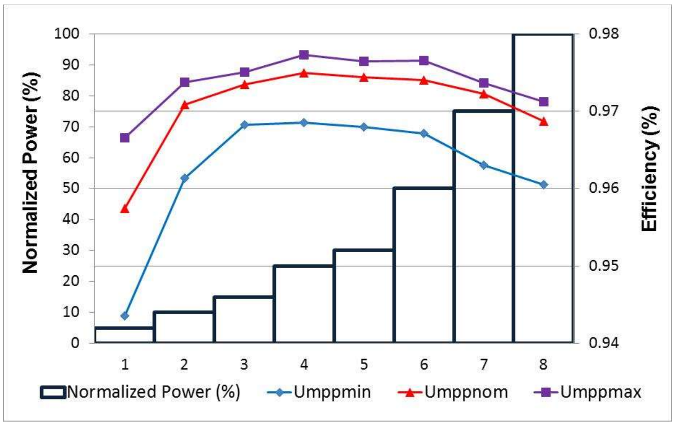

Figure 1: Measured Power conversion efficiency (Ƞconv)

Marginal increase in efficiencies were recorded for the inverter with 30% to 75% rated power across the three voltage ranges. The calculated average efficiency for Umppmin, Umppnom and Umppmax values is 96%, 97% and 97%, respectively . The calculated European power conversion efficiency (ȠconvEUR) results is 96% at 390 V, 97% at 600V and 97% at 800V. Similarly, the calculated Californian power conversion efficiency (ȠconvCEC) results is 97%, 97% and 97% at the same min, nom and max MPPT voltages.

3.2 Over / Under voltage and frequency test

The response time of the inverter in a case of over / under voltage and frequency is measured as per the methodology briefed in section 2.1.2.

Figure 2 presents the scenario of decreasing the V_{RMS} to <50% (231V to 113V in 200 milli-secs) for all the three phases in top graph with simultaneous output current measurements in bottom graph. The inverter response time to shut its output power in this scenario is 0.086 secs (300.0203 to 300.1063 seconds) and is well within 0.1 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 132.60 secs (not shown in graph).

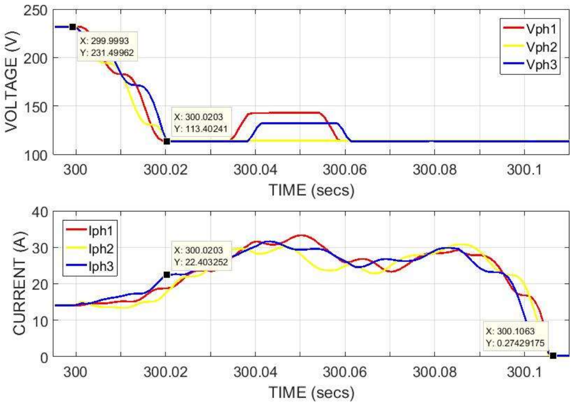

Figure 2: Response time during <50% of the VRMS

Figure 3 presents the scenario of decreasing the V_{RMS} to <85% (231V to 194V in 27 milli-secs) with simultaneous output current measurements. The inverter response time to shut its output power in this scenario is 1.998 secs and is well within the 2.0 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 135.71 secs.

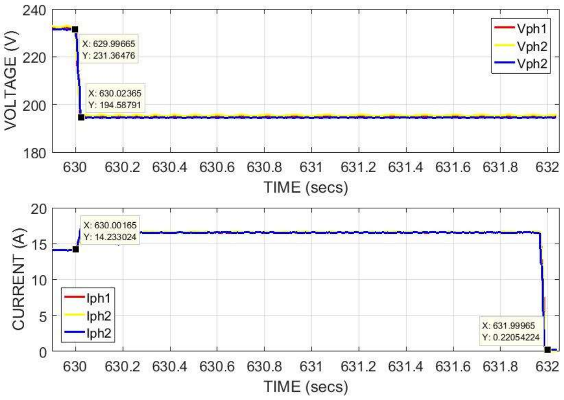

Figure 3: Response time during <85% of VRMS

Figure 4 presents the scenario of varying the voltage between 85% to 110% of the rated V_{RMS} (85% ≤ V ≤ 110%) with simultaneous current measurements across the three phases. The voltage is initially dropped (231V to 197V in 88 secs) and then increased to (197V to 255V in 163 secs) before returning to normal operating voltage. The tested inverter demonstrated continuous operations during the test duration as per the requirement stipulated in IEC 61727.

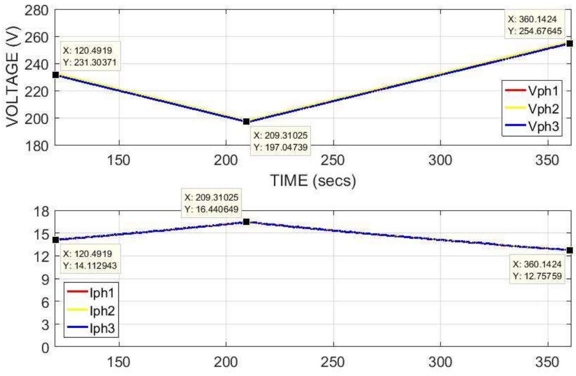

Figure 4: Continuous operation during 85% ≤ V ≤ 110%

Figure 5 presents the scenario of increasing the V_{RMS} to >110% (232V to 257V in 24 milli-secs) with continuous output current monitoring. The inverter response time to shut its output power in this scenario is measured at 1.963 secs and is well within the 2.0 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 132.04 secs.

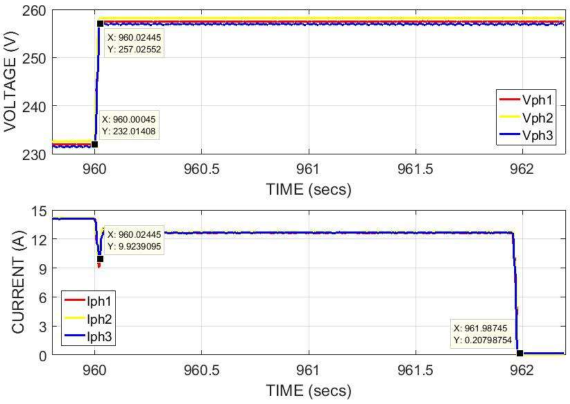

Figure 5: Response time during >110% of the VRMS

Figure 6 presents the scenario of increasing the V_{RMS} to >135% (232V to 292V in 20 milli-secs) with continuous output current monitoring. The inverter response time to shut its output power in this scenario is measured at 0.05 secs and is within the 0.05 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 135.89 secs.

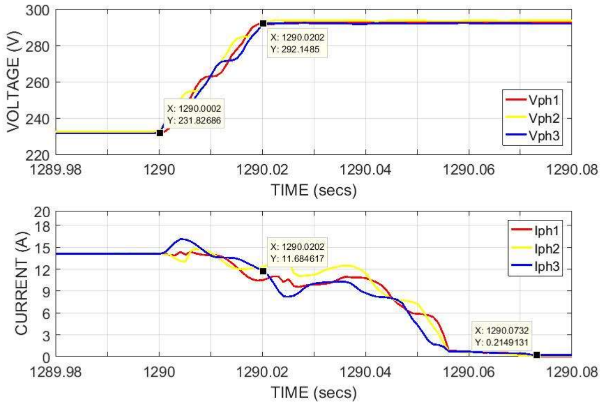

Figure 6: Response time during >135% of the VRMS

Figure 7 presents the scenario of decreasing the frequency to <49% (50Hz to 49Hz in 92 milli-secs) with continuous output current monitoring. The inverter response time to shut its output power in this scenario is measured at 0.006 secs and is well within the 0.2 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 134.76 secs.

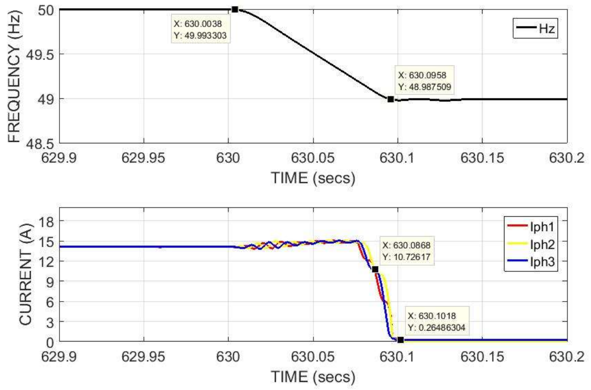

Figure 7: Response time during frequency <49Hz

Figure 8 presents the scenario of increasing the frequency to <51% (50Hz to 51Hz in 90 milli-secs) with continuous output current monitoring. The inverter response time to shut its output power in this scenario is measured at 0.011 secs and is well within the 0.2 secs criteria stipulated in IEC 61727. The measured re-connection time post trip upon returning of voltage to normalcy is 132.68 secs.

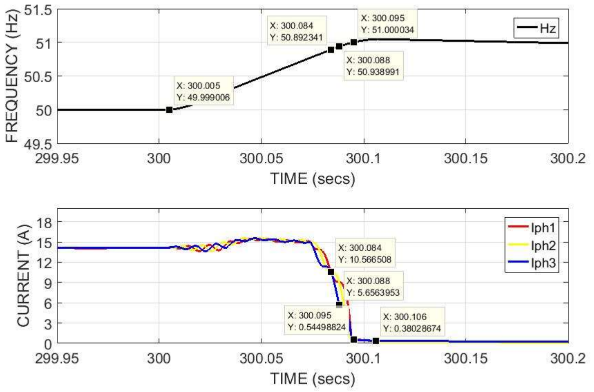

Figure 8: Response time during frequency >51Hz

3.3 Ride through functionality test

The ride through functionality of the inverter during short-term voltage dips is tested as per the methodology briefed in section 2.1.4. Figure 9, 10, 11 and 12 presents all the four scenarios constituting Y type voltage dips (10% ≤ V ≤ 15% for 2000 mS, 15% ≤ V ≤ 20% for 600 mS, 20% ≤ V ≤ 30% for 150 mS) and X1 type voltage dip (30% ≤ V ≤ 40%). The top graph in each figure shows the voltage dips of the Y and X1 (231V to 197V, 231V to 185V, 231V to 162V and 231V to 139V) for the prescribed test duration with the simultaneous current measurements at the same time frame in below graph. The tested inverter ride through all the four scenarios of voltage dips without dip in measured current throughout the test period.

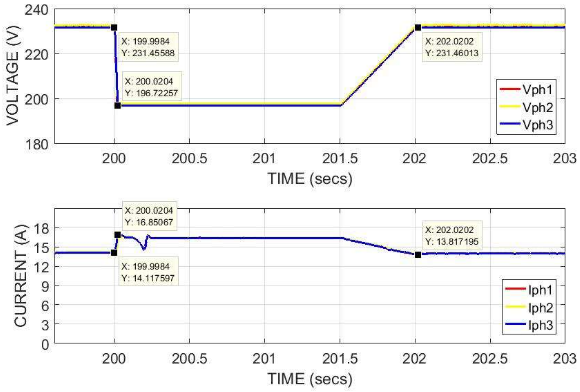

Figure 9: Ride through functionality during Y type 10% ≤ V ≤ 15% voltage dip for 2000mS

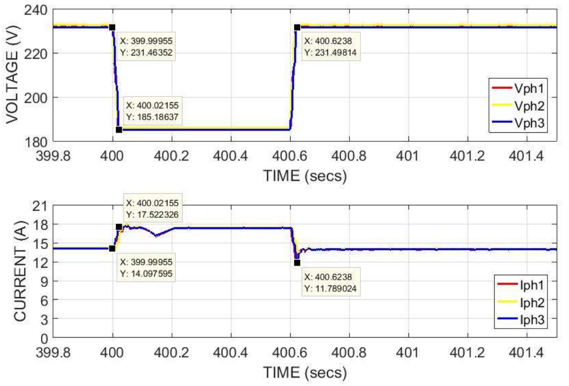

Figure 10: Ride through functionality during Y type 15% ≤ V ≤ 20% voltage dip for 600mS

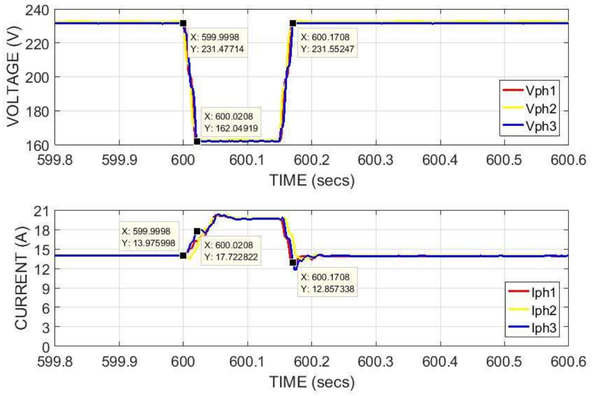

Figure 11: Ride through functionality during Y type 20% ≤ V ≤ 30% voltage dip for 150mS

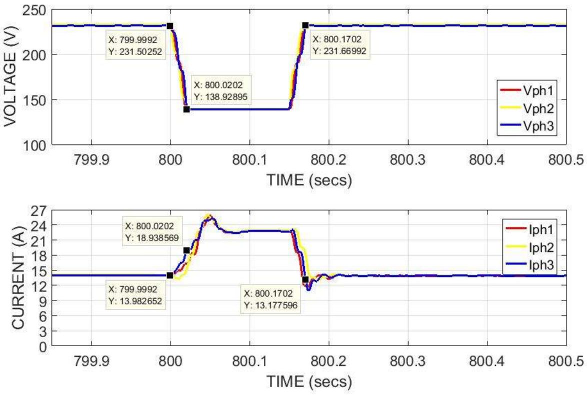

Figure 12: Ride through functionality during X1 type 30% ≤ V ≤ 40% voltage dip for 150mS

3.4 Harmonic measurements:

The total harmonic distortions measurement is carried out as per the steps briefed in section 2.1.5. A good overlay of the measured 3 phase fundamental AC current profiles over irradiance profile in Figure 13 indicate no outliers in the measurement thus permitting to co-relate the distortions either to irradiance profile or inverter operations.

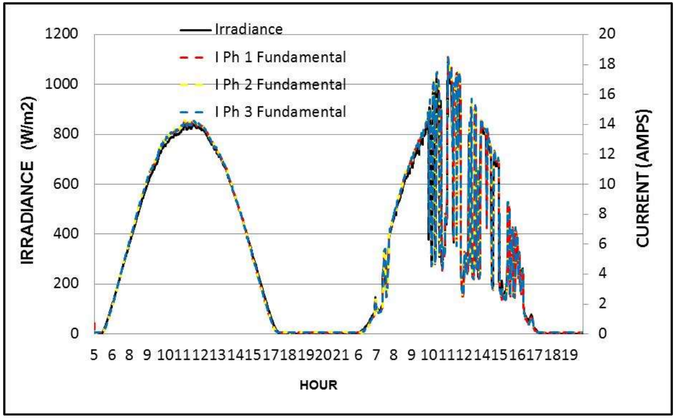

Figure 13: Overlay of measured fundamental current over clear and cloudy irradiance profiles

Figure 14 presents the measured total harmonic distortions for a clear (bold columns) and cloudy sky (striped columns) irradiance profiles. The red, yellow, and blue columns depict the total distortions in phase 1, 2 & 3 respectively for both the clear and cloudy sky profiles. Early morning and late afternoon periods measured higher distortions where inverter tends to turn ON and OFF irrespective of clear or cloudy sky profile. The total distortion during these periods is found to be well above the acceptable limit of 5% in accordance with IEC/EN 61727. Higher distortions were measured whenever the irradiance fluctuated (cloudy sky profile) compared to clear sky profile. It is observed that the filters in the inverter absorb some of the harmonics in the network during its operations.

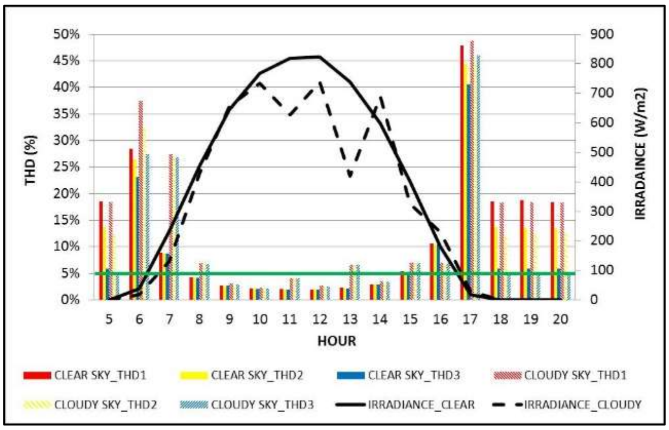

Figure 14: THD measured for a clear and cloudy day irradiance profile

4. Conclusion

A commercially available inverter is characterized to gain hands on experience determining power conversion efficiency, measure inverter response time during over / under voltage and frequency situations, ride through functionality during short period voltage dips and measure harmonic distortions of inverter connected to controlled load conditions for simulated clear and cloudy sky profiles. The minimum, nominal and maximum power point tracking power conversion efficiency test carried out in accordance with EN50530 for normalized power levels measured an average 96%, 97% and 97% respectively. The calculated European and Californian power conversion efficiency measured 97% at nominal maximum power point. The inverter response time during over / under voltage and frequency scenarios set with IEC/EN 61727 grid code parameters is observed to be within the permitted values. The ride through functionality test for Y and X1 type of voltage dips measured as required i.e., inverter riding through those short period voltage dips without shutting the output power. The total harmonic distortions in current for clear and cloudy sky profiles in accordance with IEC/EN 61727 measured above the stipulated 5% during certain periods of the day particularly in the morning and evening periods. The cloudy sky irradiance profile measured higher distortions compared to clear sky. The knowledge developed in the inverter characterization space is beneficial to advise or set up inverter testing infrastructure in African sub-continent including Republic of South Africa where such facility is non-existent. Establishing such test infrastructure will provide a platform for local manufacturers to test their prototype's and perform compliance testing to respective grid code parameters.

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