School of Engineering and Information Technology

ENG470 - Engineering Honours Thesis

Development of a Stand Alone Inverter Efficiency Test Setup

"A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering"

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Abstract

Murdoch University's School of Engineering and Information Technology has a plan to develop the stand-alone inverter efficiency test setup for the laboratory exercise of the unit ENG421 Renewable Energy Systems Engineering. The laboratory exercise, which identified Inverters for Stand-Alone PV Systems, aims at helping students gain an understanding of the principles of operation, efficiencies and output current and voltage wave shapes at various loadings of two inverter types used in stand-alone PV systems.

This report focuses on the development of the previous setup of ENG421 laboratory at Building 190 on the Murdoch University Campus. The aim of the development is to work out some issues with the existing system including an ageing battery bank which is expensive to replace and the replacement of the inverters that they are expected to meet Australian Standards: AS5603 Stand-alone Inverters - Performance requirements and AS4763:2011 Safety of Portable Inverters. Moreover, the aim is to determine the uncertainty in measurement by undertaking the uncertainty analysis of the efficiency test results.

The stand-alone inverter efficiency test setup consists of power source, digital power analyzer, hall effect sensor circuit to supply isolated signals for viewing AC voltage and current, differential probe, oscilloscope, various load banks and two types of stand-alone inverters (sine wave inverter and modified square wave inverter) for comparing efficiency test results and output waveforms.

The design work and implementation of the development is complete now. The Agilent DC power supply (0-60V, 0-11A, 6.6kW) is used to replace the battery bank due to its good ability to simulate the batteries and high-quality performance during long period. Moreover, the Protek multimeters of previous setup are replaced by YOKOGAWA WT2030 digital power meter to achieve more accurate measurements. Two stand-alone inverters are selected and used in the new setup so far, they are Selectronic Sine Wave Inverter 350VA and Suntron Power Inverter 350VA (modified square wave inverter). However, all of these inverters were manufactured before 2011. To meet the requirement of AS4763:2011 Safety of Portable Inverters, a new stand-alone inverter manufactured after 2011 should be purchased for the setup in the future work.

In this project, several specific tasks were also carried out including the review of the previous work, redesign and implementation of the test setup, documentation and analysis of the stand-alone inverter efficiency test, and the determination of the uncertainty in

measurement. Also, the background information relating to the stand-alone inverter is provided and discussed. The maximum efficiency of Selectronic 350VA sine wave inverter is 88.8% when there is 104 watts loading. The maximum conversion efficiency of Suntron 350VA modified square wave inverter is higher which is 92.9% when there is approximately 150 watts loading. The final expanded uncertainty for measurement of the peak efficiency point of Suntron 350VA modified square wave inverter is 0.072%.

The work is completed now and ready to be used in the laboratory exercise of unit ENG421 Renewable Energy Systems Engineering. But the test setup requires new stand-alone inverters and improvement of measuring equipment for future work. The ultimate purpose of the test setup is to provide future students a safe, informative and reasonable experiment exercise.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisor Dr. Martina Calais who provided direction and continuous support for this thesis project. Her immense knowledge, motivation and patience were necessary for the completion of the project.

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- William Pettit and Horst Rechlin, Latronics Sunpower Pty Ltd, for providing quoted information of the Latronics LS series sine wave inverters.

- Dylan Connor, The 12 Volt Shop, for providing information about Latronics LS series sine wave inverters and answer about relevant standards.

At last, I would like to thank my family for patience and support on my study and project.

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Abbreviations

AC	Alternating Current
DC	Direct Current
GUM	Guide to the Expression of Uncertainty in Measurement
HF	High frequency
LF	Low frequency
MoU	Memorandum of Understanding
THD	Total harmonic distortion

1. Introduction

1.1 Project background

A stand-alone inverter efficiency measurement forms part of a laboratory exercise in the unit of ENG421 Renewable Energy Systems Engineering at Murdoch University. As one of the laboratory exercises, students measure the efficiency of a stand-alone inverter for variable load. This laboratory exercise helps students gain an understanding of inverters in stand-alone PV systems including the principles of operation, efficiencies and output current and voltage wave shapes at various loadings [1]. However, there are some issues with the existing system due to an ageing battery bank, which is expensive to replace (approx. $5700 for a 24V flooded, 714 Ah at C120 & 691 Ah at C100 rate of discharge battery bank) [2]. Secondly, the measurement instruments are expected to be replaced to achieve more accurate measurement results. Moreover, the stand-alone inverters of the existing system are expected to meet the requirement of the Australian Standards: AS 4763:2011 Safety of Portable Inverters section 8, which states:

“Inverters shall be constructed and enclosed so that there is adequate protection against accidental contact with hazardous live parts.” [3]

Therefore, there is scope to improve the existing setup for this laboratory.

1.2 Aims and Organisation of the report

The purpose of this project is to develop the setup for stand-alone inverter efficiency measurements, using a DC source at the Renewable Energy Building 190 at South Street Campus of Murdoch University. In order to complete the project successfully, the following specific tasks are necessary:

- A review of available equipment and standard test procedures according to the Australian standard: AS5603 Stand-alone Inverters - Performance Requirements.
- Familiarisation with the available equipment being used in the development of the setup.
- Redesign of the existing stand-alone inverter setups for ENG421 laboratories, possibly including the replacement of the batteries, measurement equipment and inverters.
- Consideration of safety issues and risk assessment.

- Implementation of the test setup with the help of the supervisor.
- Test and analyse the setup and investigate any technical issues.
- Analysis of the measurement uncertainty of the new setup.
- Present and document results and any methods which will assist to achieve more accurate measurements.

After the introduction to the project, the second chapter of the report starts with the background information about the previous test setup and stand-alone inverters. Moreover, the relevant Australian Standards are introduced.

The third chapter of the report provides details of redesign and implementation of the new setup including the risk assessment and safe experiment procedure for the future students.

The fourth chapter of the report documents and discusses the results of the stand-alone inverter efficiency test.

The fifth chapter of the report introduces the uncertainty in measurement and how to determine it in this project experiment.

Chapters 6, 7 and 8 contain the conclusion, future work and bibliography.

2. Background information

2.1 Review of previous setup

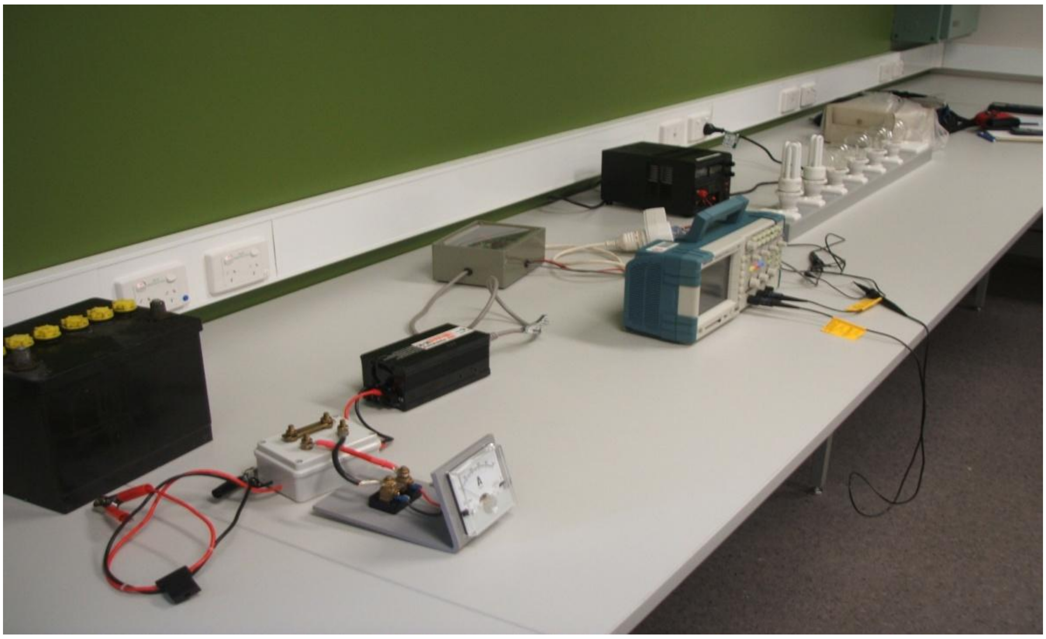


Figure 1: Photo of previous setup of ENG421 laboratory exercise

"Inverters for Stand-Alone PV Systems" [1], which is a laboratory exercise in the unit of ENG421 Renewable Energy Systems Engineering at Murdoch University, consists of two stand-alone systems. The one which will be developed for the thesis project is in Building 190. It mainly consists of two stand-alone inverters MI5062 and MI5082, 3x12 V HT12V40 batteries (120Ah total, C20 hour rate (2A)), battery charging facility and various loads. Due to the educational aim of the setup, measurement and monitoring equipment for AC and DC sides are also included.

Two standards are primarily referred to for the laboratory test setup including Australian standards: AS5603:2009 Stand-alone Inverters - Performance Requirements and AS4763:2011 Safety of Portable Inverters.

Specific tasks of the laboratory exercise contain the record and documentation of AC output voltage and current waveform under different load conditions, discussion of the difference, total harmonic distortion of the modified square wave inverter voltage, calculation of inverter efficiency and classification of the inverters according to AS5603 with respect to efficiency and output voltage THD [1].

2.2 Background on Stand-alone Inverters

Due to poor quality of grid supply such as low voltage, variable frequency and recurrent interruptions, much higher tariffs than the actual cost of supply, unfair impositions such as peak hour limits and unexpected load shedding, and unresponsive attitude of state electricity boards, stand-alone PV systems are designed for operating independently of the electric utility grid [4]. The aim of a stand-alone inverter is to allow the operation of large-scale different types of consumers and these ranges from rough manufacture technology to sensitive electronic devices [5]. A stand-alone inverter is used to regulate the AC voltage which will be supplied to the local loads. A very fast dynamic response of the inverter is required to keep stable operation of the system [6].

2.2.1 Transformerless Inverters

The following figures show the basic designs of different types of stand-alone inverters which are useful for understanding the principle of operation. Figure 2 shows a very typical design of single-phase transformerless inverters. The solar generator or battery bank provides DC input power, then the power is buffered in an input capacitor C1 and then supplied to a full bridge consist of the switches S1 - S4. These switches are turned on and off with a switching frequency of 5-20 kHz and a varying pulse width on the basis of the inverter controller's switching command. The rectangular output voltage is then fed to the inductors L1 and L2 that the pulses are smoothed to shape a sinusoidal output current. This kind of design has benefits such as simplicity, reliability and high efficiency. A significant drawback is that the input voltage must always be higher than the grid or load voltage. It can be overcome by setting up one or more DC to DC converters stages, as show in figure 3. However, the efficiency of overall will drop by 1 - 2% due to this additional power stage [6].

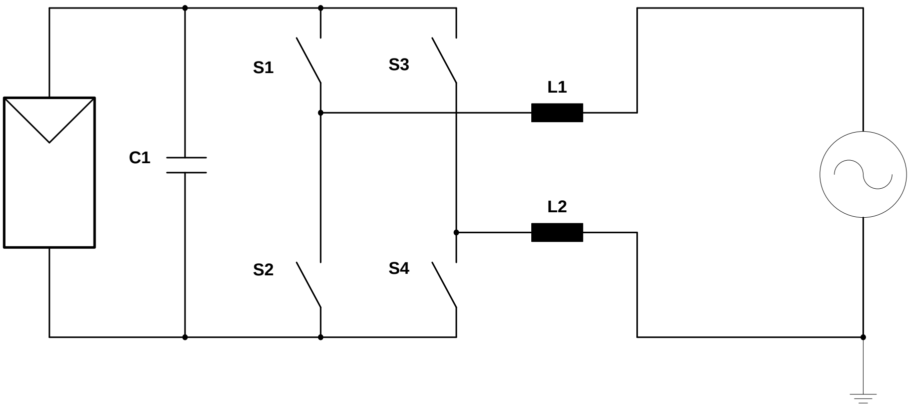


Figure 2: Basic transformerless inverter topology

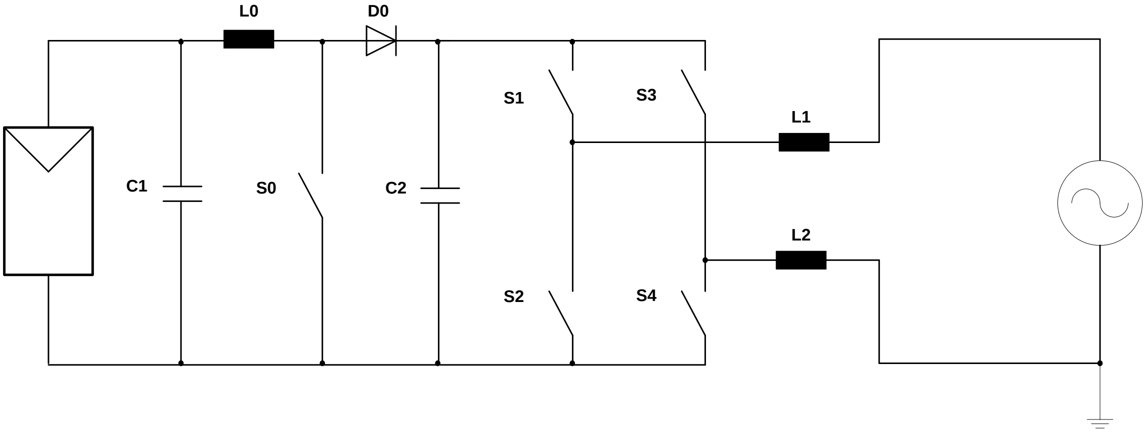


Figure 3: Basic transformerless inverter topology with input boost converter

2.2.2 Low-frequency (LF) transformer inverters

As shown in figure 4, the low-frequency inverter in principle contains a transformerless inverter and a downstream transformer operating at grid or local loads (for stand-alone inverter) efficiency. A galvanic isolation between AC and DC sides is offered by the transformer that it allows shifting of the solar generator potential in relation to earth potential [6]. Very low input voltages can still be utilised due to the turns ratio of the transformer [6]. The main disadvantages of the LF transformer inverters are that they are expensive, heavy (5 - 10 kg/kW), and have low efficiency due to the losses in the transformer [6].

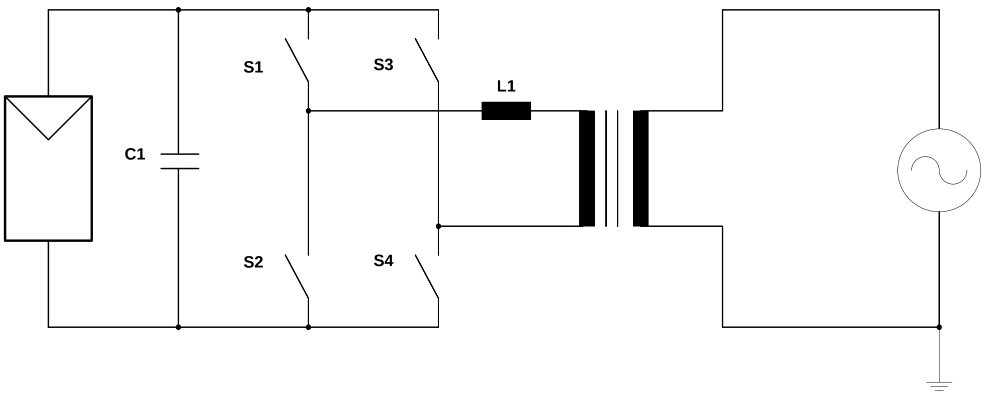


Figure 4: Basic design of a single-phase inverter with low-frequency transformer

2.2.3 High-frequency (HF) transformer inverters

Furthermore, the voltage conversion and the galvanic isolation can be carried out as well by a high frequency transformer. A common design of a high-frequency transformer inverter is shown in figure 5. Similar to the transformerless inverter, the input power is buffered by the capacitor C1 and then fed to the full bridge S1 - S4 which is locked with high frequency such as 16 kHz. Then the high frequency transformer Tr1 performs the galvanic isolation as well as the LF ones. The diodes D1 - D4 rectify the voltage. Then the voltage is fed via the inductor L1 into the DC voltage link capacitor C2. Due to the full bridge S5 - S8 and inductors L2 - L3, the constant intermediate voltage is converted into AC current [6].

As can be seen, to achieve the benefit of a low-weigh transformer an extra effort has to be spent on control and semiconductors. Lastly, the efficiency is around 2 - 4% lower compared with single stage - inverter due to the increase number of semiconductors the current has to pass through [6].

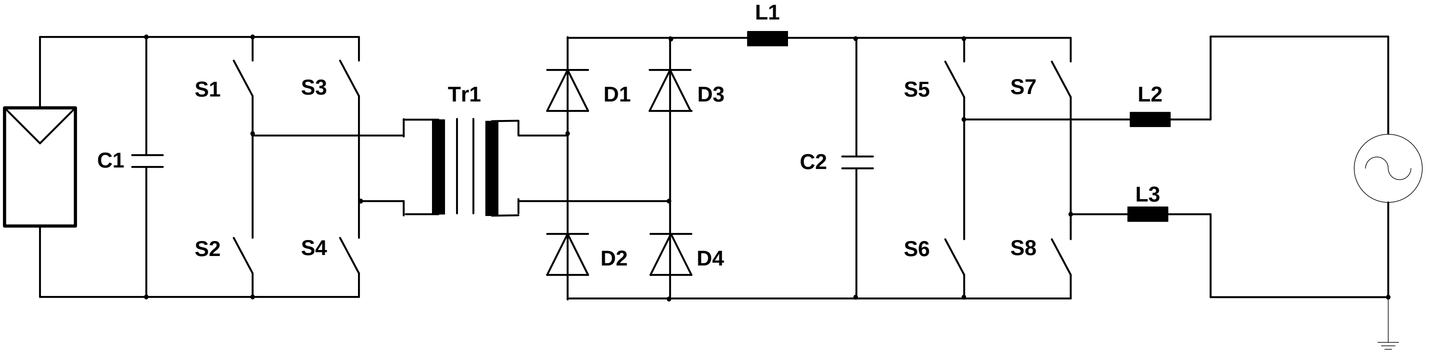


Figure 5: Basic design of a single-phase inverter with high-frequency transformer

2.3 Standards Australia

Standards are published documents that state specifications, requirements, and procedures designed to ensure that products, services and systems are safe, reliable and consistently perform the way they are proposed to do. They set up a common language that defines quality and safety criteria. Standards Australia is Australia's peak non government standards body which is recognized through a memorandum of understanding (MoU) with the Commonwealth Government of Australia [7]. "In consultation with government, business, industry, community, academia and consumers, Standards Australia develops internationally aligned Australian Standards and related publications to help ensure the safety, reliability and performance of a range of products, services and systems" [7].

For this project, AS5603:2009 Stand-alone Inverters - Performance Requirements and AS4763:2011 Safety of Portable Inverters, are the most relevant standards that the test setup should comply with to ensure safety and reliability. AS5603 provides manufacturers and test laboratories with a set of parameters, general and electrical requirements for assessing the performance of a stand-alone inverter. Also, the diagram of general test set-up in appendix 1 was referred to for the redesign of the test setup. AS4763 sets out manufacturers, designers, regulatory authorities, organisations, and testing laboratories with safety requirements. The safety requirements are designed for user's protection against hazards which might happen during operation of a portable inverter [8], [3].

3. Redesign and Implementation of the new test setup

In order to work out the issues mentioned in the project background, the development of the test setup will focus on the following aspects:

1. Replacement of the battery bank
2. Replacement of the measuring equipment
3. Replacement of the inverter
4. Review of risk assessment and safety procedures

3.1 Requirements of redesign

The measuring equipment should be easy to operate since it will be used as a teaching aid for students. The test setup should be able to record more accurate data than the existing system. More importantly, the system must be safe with no hazardous live parts accessible. All equipment and installation must comply with the relevant standards. Lastly, a longer operating life of the setup is required due to expensive replacement cost. The test setup is used for laboratory exercise only few times a year.

3.2 Equipment information

As one of the part of the project, available equipment checking is a basic step before redesigning and implementing the setup. With the help of Dr. Martina Calais, Simon Glenister and David Morrison, all relevant available equipment has been presented for the implementation of the design. Moreover, the technical manuals for the main components such as inverters, DC power supply and power analyzer are also necessary regarding safe and correct operation. The list of available equipment is documented in Appendix A.

3.3 Overview of the new test setup

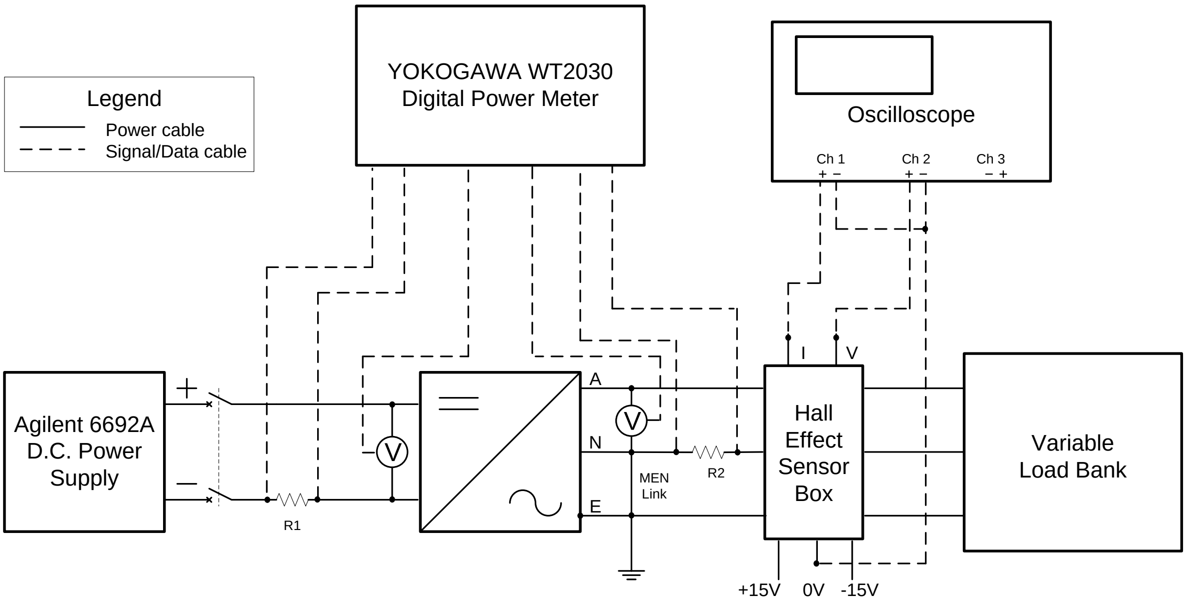


Figure 6: Diagram of the redesigned setup

Figure 6 shows the drawing of the redesigned test setup. First of all, the ageing battery bank of the existing setup should be replaced for the better performance of the laboratory exercise. However, the setup is used only for ENG421 students few times a year and the cost of replacement is expensive. Agilent 6692A DC power supply is used instead for its ability to simulate a battery that it can be operated stably for a long period under a large range of situations. Then the DC isolators are connected between the power supply and the inverter. Moreover, YOKOGAWA WT2030 Power Meter is selected for this setup because of its

powerful and comprehensive simulating functions. Two 100A shunts are connected to the neutral for the measurement of the AC and DC currents which can be calculated by the voltage across each shunt. A hall-effect sensor box with power supplies is connected into the circuit for the monitoring of the AC current and voltage waveforms. In the following test of the new setup, the waveform measurement of DC current waveform will be taken into consideration. Lastly, a variable three-phase load bank is used for this setup and in the future the load for testing will be varied using a slide rheostat, light emitting diode and motor.
Three stand-alone inverters are selected so far for the new setup for comparing the results of deferent types of stand-alone inverters.

3.4 Risk assessment and control

To ensure the safety and health during the project, risk assessment is one of the most important steps of designing a setup. A comprehensive risk assessment will help students and staffs identify kind of dangers during the implementation and the potential extent of damage it could cause to individuals or equipment. First of all, it is necessary to evaluate the hazards. Then list the risks and the level of each one. Also, the risk analysis and control of hazards should be documented in details in order to prevent and reduce harm if the accidents happen.

For this project, the risk assessment is separated into two parts estimating the risk when connecting the system and during the operation of setup.

3.4.1 Risks when connecting the setup

Table 1: Risk assessment when connecting the setup

What is the Hazard	**How might be harmed**	**The level of risk**	**Risk control**
Electrical shock	Students may suffer electrical shock and burn injuries from faulty electrical parts.	Low	Keep the power supply off and the isolators open during the connection. Do not modify circuit with power on.
Wrong connection of the shunt, isolator,	Setup and equipment may be damaged once the circuit is	Low	Review the previous setup of ENG421

inverter and power analyzer.	powered. Although this part is done with the assistance of the supervisor, students have to be aware of the correct connection due to the safety issues.		Laboratory 1. Get familiar with AS5033 (inverter testing part) and the manuals of equipment. Double check each connection with supervisor before powering the circuit.
Dangerous tools	Students may be hurt by the tools when connecting the circuit.	Very low	Ask help from supervisor when it is required to use dangerous tools such as an electric drill.
Heavy equipment	Students may suffer injures. Equipment may be dropped and damaged.	Low	Do not lift heavy stuffs (over 15kg) by own.
Trip hazards	Students may suffer injures if they trip over equipment on the ground.	Low	Wear safety shoes with a good grip. Be careful with the objects around.

3.4.2 Risks during the operation of setup

Table 2: Risk assessment during the operation of setup

What is the Hazard	**How might be harmed**	**The level of risk**	**Risk control**
Short circuit on DC side	Students may suffer electrical shock and burn injuries from faulty electrical parts since the rated current of supply is 110A which is a definitely dangerous current level. The power supply and the equipment connected in parallel may be damaged.	Low	Ensure all the wires installed are in good condition. Do not stack sockets on a single power source. Due to the overcurrent protection function of the DC power supply, the fuse is not essential for this setup but can be added for future work.
Short circuit on AC side	Both Selectronic Sine Wave Inverter 350VA and Suntron	Low	Ensure clean and tidy connections on the AC

	Power Inverter 350VA are able to shut down if the output current shorted beyond their capacities. However, they may also be damaged due to their old age.		side.
Overloading of inverter	Both inverters have overload protection function. However, they may be damaged if they are overloaded over 30 minutes.	High	Do not overload the inverters during the experiment. For the load bank, do not switch any 500W button on when varying the loads due to the 350VA rated power of the inverter.
Overheating of loads	It would cause heat and damage the load bank.	Low	The load bank used in this set up is designed to be ventilated due to its metal net on the surface. Shut down the load immediately if it is overheated.
Damage on the power analyzer	When a power disturbance falls outside operating limits, equipment may be disrupted or damaged. [9]	Very low	Ensure the accurate connection for the measurement.

3.5 Safety operation procedure

In order to make sure the students complete the laboratory exercise safely, there should be a document which explain the potential safety issues and provide a safety procedure for the operation. Such a document is provided in the Appendix B and can be added to the introduction of the laboratory exercise for future renewable energy students.

3.6 Implementation of design

With the help of Simon Glenister, the test of DC power supply, three stand-alone inverters, power analyzer and oscilloscope were completed. The new system was set up in Building 190 at Murdoch University. Figure 7 shows the redesigned setup including the DC power supply, oscilloscope, WT2030 Digital Power Meter, stand-alone inverters, LEM box, differential probe for measurement and variable load bank.

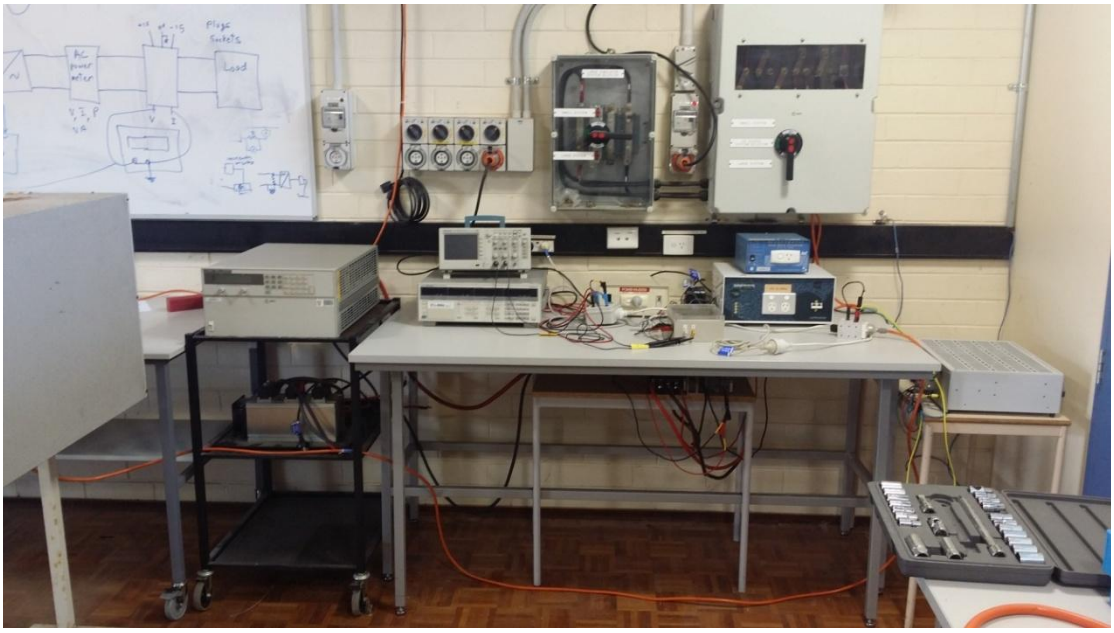


Figure 7: Redesigned setup in Building 190

Figure 8 shows the DC side connection including the shunt (see green circle), isolators and connection to DC power supply and each inverter. This part is set under the bench for the clean circuit of the setup which is easy to operate. Also, it is safe for the students that they do not have to modify the circuit during the laboratory exercise.

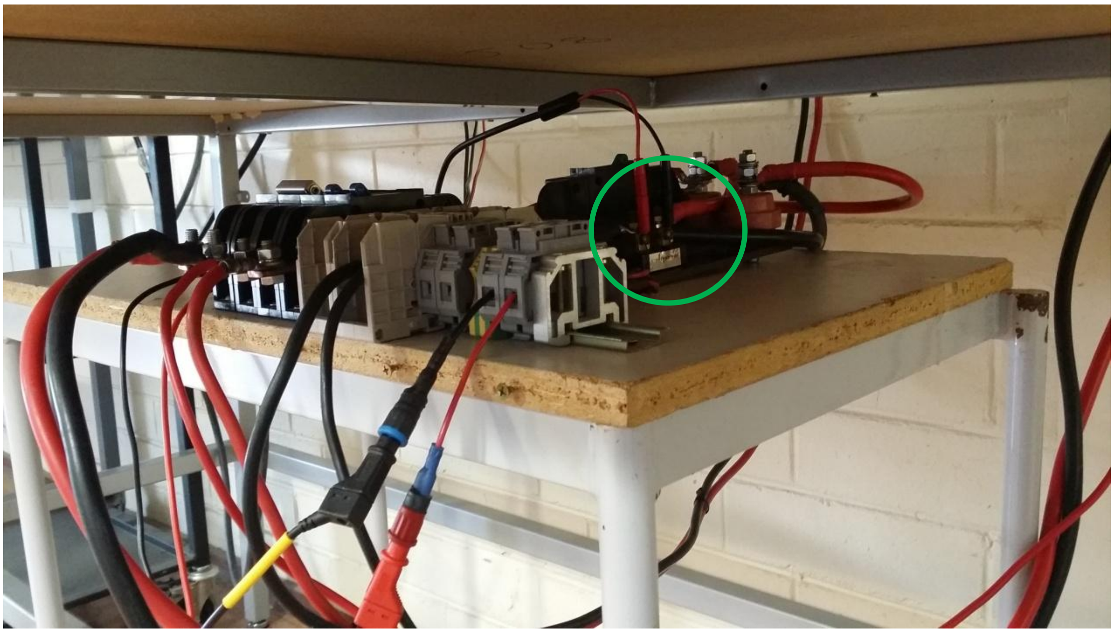


Figure 8: DC side and highlight of the shunt

Figure 9 demonstrates the connection between power supplies (for supplying the Hall-effect sensor circuit) and the LEM box. Two 5 ohms resistances (see blue circles) are used for meeting the rating of the Hall-effect sensor box.

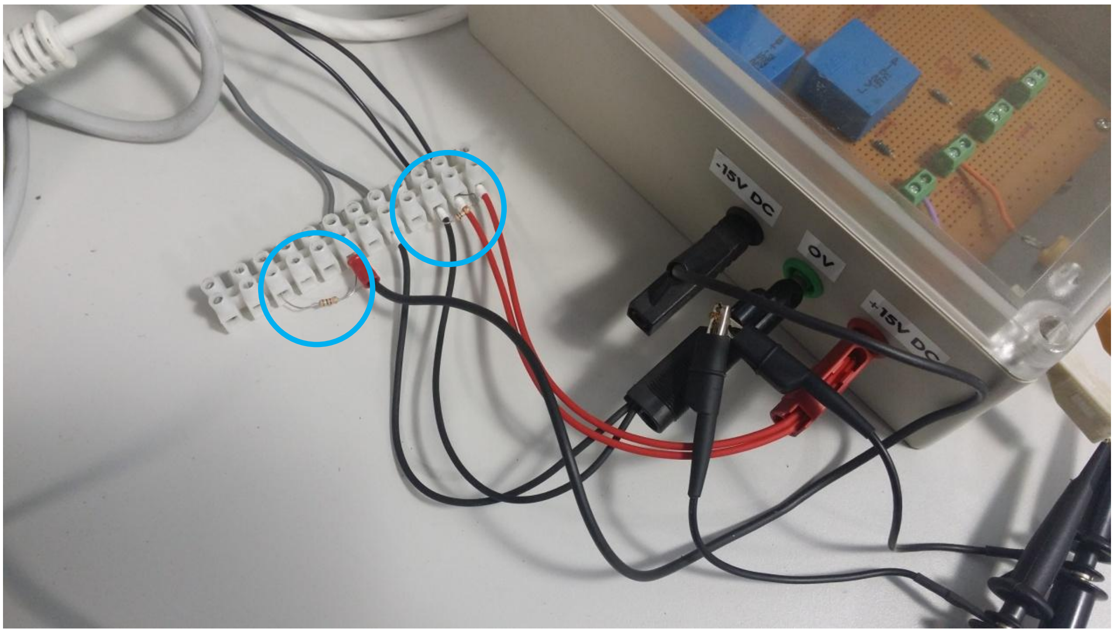


Figure 9: Partial connection of the hall-effect sensor box.

4. Efficiency test results

The aim of this part is to provide the results of the experiment to check the feasibility of the redesigned test setup and analyse it for any possible method of development and improvements. This part includes two inverters’ efficiency test data in order to achieve a good understanding of the experiment and comparable results. The setup was designed for testing multiple inverters. Two inverters, the Selectronic 350VA sine wave inverter and the Suntron 350VA modified square wave inverter, were connected into the circuit with an independent isolator for each one. It is convenient for renewable energy students during experiments that they can just plug in the inverter they want to use. Moreover, the waveform of each inverter testing and analysis are included in this part.

4.1 Overview of the experiment and results

4.1.1 Selectronic 350VA sine wave inverter

Table 3 shows the efficiency test result of Selectronic 350VA sine wave inverter. The data base on the measurement of DC and AC side including voltage, current, and power. In general, the efficiency is determined by dividing the AC power output from the inverter by the DC power input to the inverter. For this experiment, the measured efficiency is determined by the directly measured DC and AC power values, $eff_{(V_{DC},I_{DC},V_{AC},I_{AC})} = \frac{V_{AC} \times I_{AC}}{V_{DC} \times I_{DC,}}$. To compare with the measured efficiency, the calculated efficiency is included which is established by the calculated power that multiply the measured voltage by the current.

Table 3: Data of Selectronic 350VA sine wave inverter efficiency test

	DC (DC measurement mode)					**AC (RMS measurement mode)**					
Load (W)	Voltage(V)	Current(A)	Power(kW)	Power(W)	Power Cal.(W)	Voltage(V)	Current(A)	Power(W)	Power Cal.(W)	Eff(Pdc,Pac)	Eff(Vdc,Idc,Vac,Iac)
0	12.497	0.79	0.0098	9.8	9.9	242.87	0.0117	2.79	2.8	28.5%	28.8%
15	12.484	1.98	0.0247	24.7	24.7	242.86	0.0727	17.64	17.7	71.4%	71.4%
25	12.475	2.82	0.0352	35.2	35.2	242.98	0.1144	27.78	27.8	78.9%	79.0%
30	12.471	3.17	0.0394	39.4	39.5	242.93	0.1315	31.92	31.9	81.0%	80.8%
40	12.461	4.16	0.0516	51.6	51.8	242.86	0.1798	43.64	43.7	84.6%	84.2%
50	12.452	4.97	0.0619	61.9	61.9	242.89	0.2196	53.31	53.3	86.1%	86.2%
60	12.444	5.8	0.072	72	72.2	242.7	0.2592	62.91	62.9	87.4%	87.2%
80	12.426	7.51	0.0929	92.9	93.3	242.59	0.3391	82.21	82.3	88.5%	88.2%
100	12.408	9.54	0.1179	117.9	118.4	242.34	0.4323	104.8	104.8	88.9%	88.5%
125	12.384	11.82	0.1457	145.7	146.4	242.02	0.5342	129.25	129.3	88.7%	88.3%
150	12.358	14.21	0.1746	174.6	175.6	241.65	0.6385	154.28	154.3	88.4%	87.9%
180	12.326	17.03	0.2083	208.3	209.9	241.12	0.7567	182.43	182.5	87.6%	86.9%
200	12.303	19.12	0.2333	233.3	235.2	240.68	0.8437	203.04	203.1	87.0%	86.3%
225	12.275	21.67	0.2636	263.6	266.0	240.41	0.9449	227.1	227.2	86.2%	85.4%
250	12.243	24.34	0.2949	294.9	298.0	239.98	1.0483	251.48	251.6	85.3%	84.4%
275	12.211	27.59	0.3331	333.1	336.9	239.38	1.1706	280.22	280.2	84.1%	83.2%
300	12.183	30.77	0.3704	370.4	374.9	238.9	1.2879	307.68	307.7	83.1%	82.1%
325	12.154	33.86	0.406	406	411.5	238.1	1.3984	332.91	333.0	82.0%	80.9%
350	12.139	35.86	0.4294	429.4	435.3	237.09	1.4703	348.5	348.6	81.2%	80.1%

The efficiency curves of Selectronic 350VA sine wave inverter for both measured and calculated values lead to figure 10. The power versus efficiency curve shows that the inverter has relatively low conversion efficiency at low power. Then conversion efficiency is increasing as the inverter reaches its peak efficiency point. As power levels rise beyond the point of peak efficiency, conversion efficiency remains relatively linear, dropping only a few percent up to its rated power output [10]. The maximum efficiency is 88.8% when there is 104 watts loading. As shown in figure 10, the calculated efficiency is lower than the measured efficiency in average.

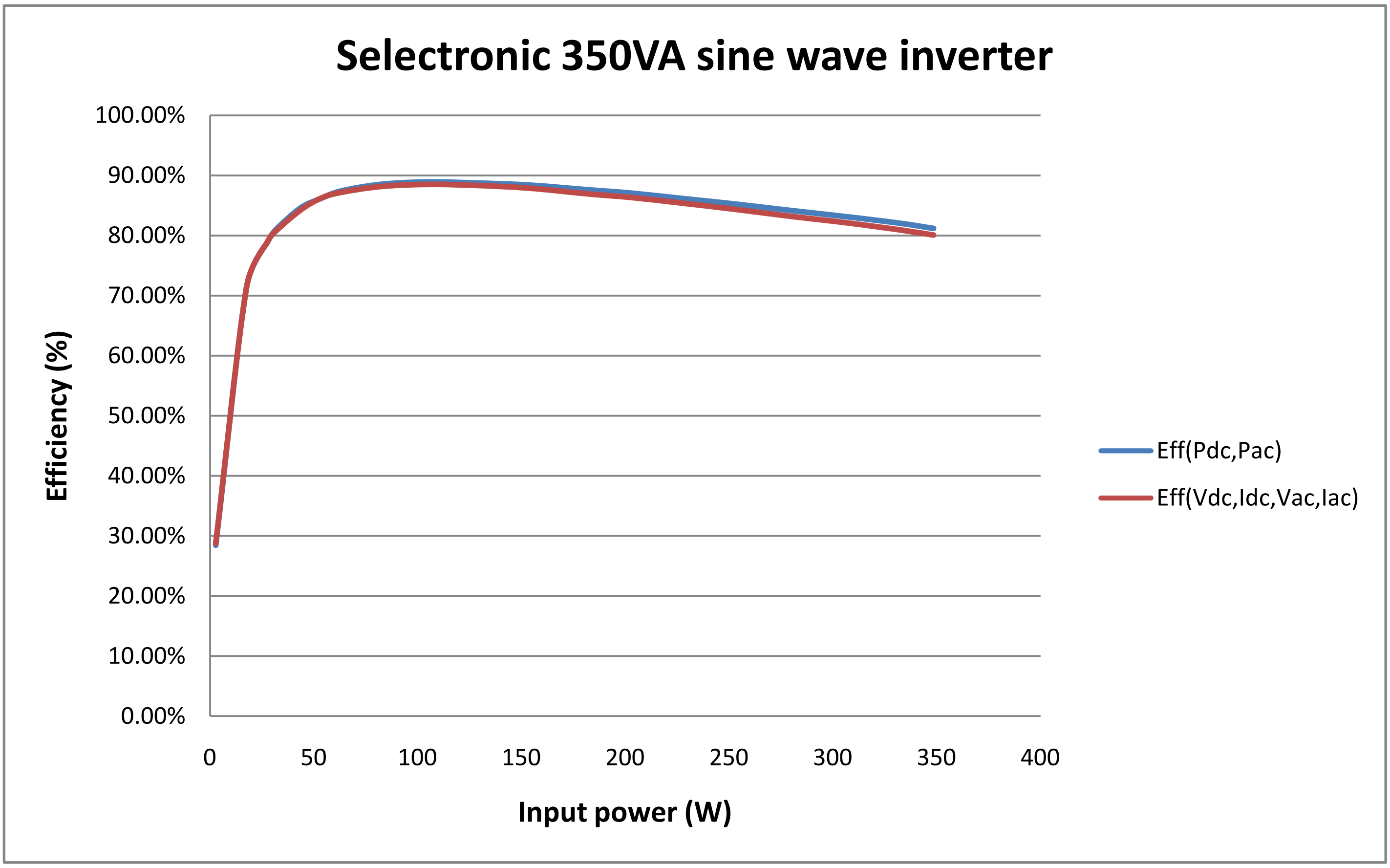


Figure 10: Figure 4: Efficiency versus power curves of Selectronic 350VA inverter

4.1.2 Suntron 350VA modified square wave inverter

Again, the test result of Suntron 350VA modified square wave inverter in the same condition leads to table 4.

Table 4: Data of Suntron 350VA modified sine wave inverter efficiency test

	DC (DC measurement mode)					**AC (RMS measurement mode)**					
Load (W)	Voltage(V)	Current(A)	Power(kW)	Power(W)	Power Cal.(W)	Voltage(V)	Current(A)	Power(W)	Power Cal.(W)	Eff(Pdc,Pac)	Eff(Vdc,Idc,Vac,Iac)
0	12.502	0.05	0.0006	0.6	0.6	33.17	0	0.05	0.0	8.3%	0.0%
15	12.486	1.7	0.021	21	21.2	243.29	0.0704	17.11	17.1	81.5%	80.7%
25	12.477	2.59	0.0321	32.1	32.3	243.84	0.1145	27.91	27.9	86.9%	86.4%
30	12.473	2.94	0.0363	36.3	36.7	243.87	0.132	32.17	32.2	88.6%	87.8%
40	12.465	3.93	0.0484	48.4	49.0	243.87	0.1803	43.97	44.0	90.8%	89.8%
50	12.457	4.73	0.0585	58.5	58.9	243.73	0.2201	53.61	53.6	91.6%	91.0%
60	12.448	5.56	0.0685	68.5	69.2	243.51	0.2598	63.25	63.3	92.3%	91.4%
80	12.432	7.23	0.089	89	89.9	243.11	0.3399	82.62	82.6	92.8%	91.9%
100	12.411	9.19	0.1129	112.9	114.1	242.53	0.4327	104.92	104.9	92.9%	92.0%
125	12.39	11.38	0.1396	139.6	141.0	241.84	0.5343	129.21	129.2	92.6%	91.6%
150	12.366	13.66	0.1669	166.9	168.9	241.13	0.638	153.83	153.8	92.2%	91.1%
180	12.337	16.3	0.1987	198.7	201.1	240.3	0.756	181.67	181.7	91.4%	90.3%
200	12.316	18.26	0.2222	222.2	224.9	239.7	0.8422	201.86	201.9	90.8%	89.8%
225	12.289	20.58	0.2497	249.7	252.9	239	0.9423	225.22	225.2	90.2%	89.0%
250	12.264	22.98	0.2782	278.2	281.8	238.3	1.0447	248.94	249.0	89.5%	88.3%
275	12.235	25.87	0.3123	312.3	316.5	237.48	1.1663	276.9	277.0	88.7%	87.5%
300	12.199	28.72	0.3457	345.7	350.4	236.71	1.282	303.4	303.5	87.8%	86.6%
325	12.174	31.47	0.3778	377.8	383.1	235.95	1.3916	328.3	328.3	86.9%	85.7%
350	12.149	33.36	0.3995	399.5	405.3	235.43	1.465	344.8	344.9	86.3%	85.1%

The efficiency curves of Suntron 350VA modified square wave inverter for both measured and calculated values lead to figure 11. Again, the conversion efficiency slightly declines after the peak efficiency point. The maximum conversion efficiency is higher which is 92.9% when there is approximately 105 watts loading.

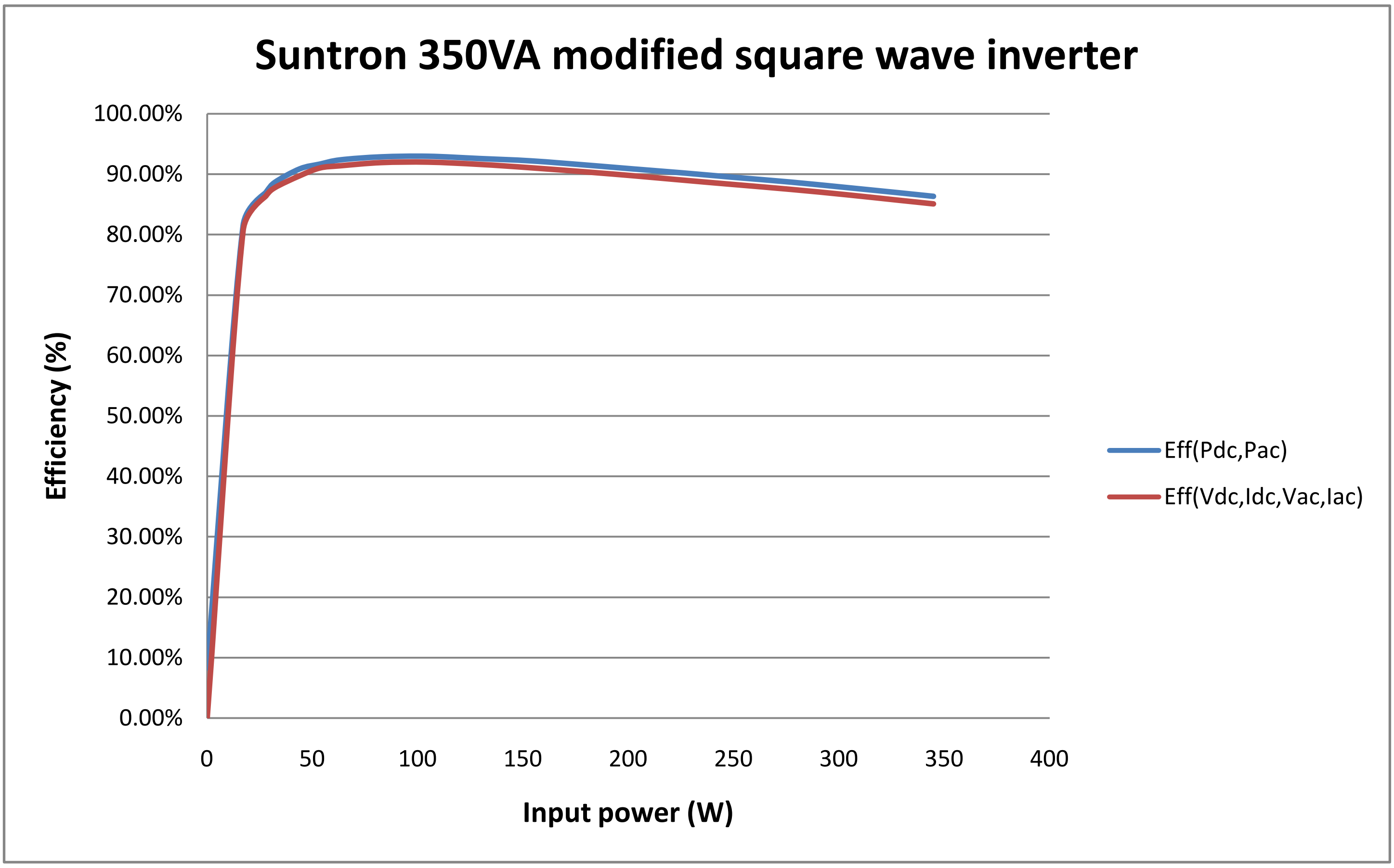
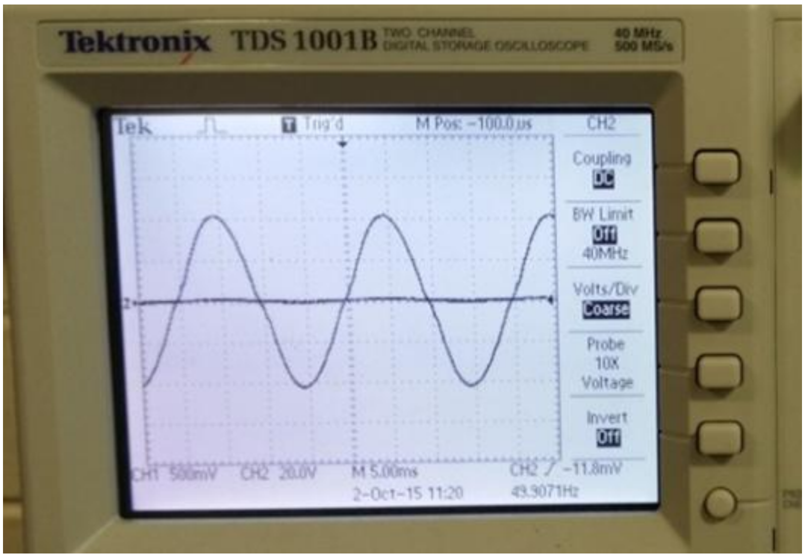


Figure 11: Efficiency versus power curves of Suntron 350VA inverter

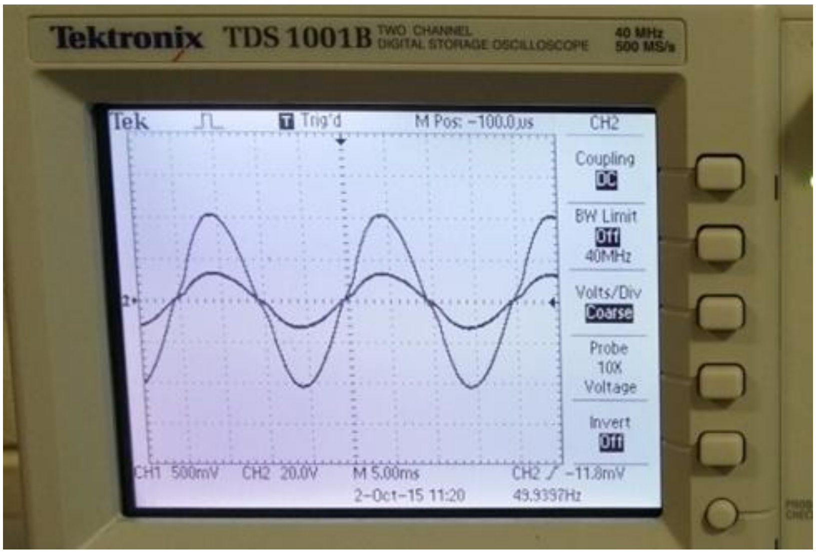
4.1.3 Waveform screenshots of Selectronic 350VA sine wave inverter

This section shows the waveform of Selectronic 350VA sine wave inverter and the discussion of them will be contained in 4.1.5.



M Pos: −100.0µs
CH2
Coupling DC
BW Limit Off 40MHz
Volts/Div Coarse
Probe 10X Voltage
Invert Off
CH1 500mV CH2 20.0V M 5.00ms CH2 ∫ −11.8mV
2−Oct−15 11:20 49.9071Hz

Figure 12: Output current and voltage wave forms with no loading



M Pos: −100.0µs
CH2
Coupling DC
BW Limit Off 40MHz
Volts/Div Coarse
Probe 10X Voltage
Invert Off
CH1 500mV CH2 20.0V M 5.00ms CH2 ∫ −11.8mV
2−Oct−15 11:20 49.9397Hz

Figure 13: Output current and voltage wave forms with 100W loading

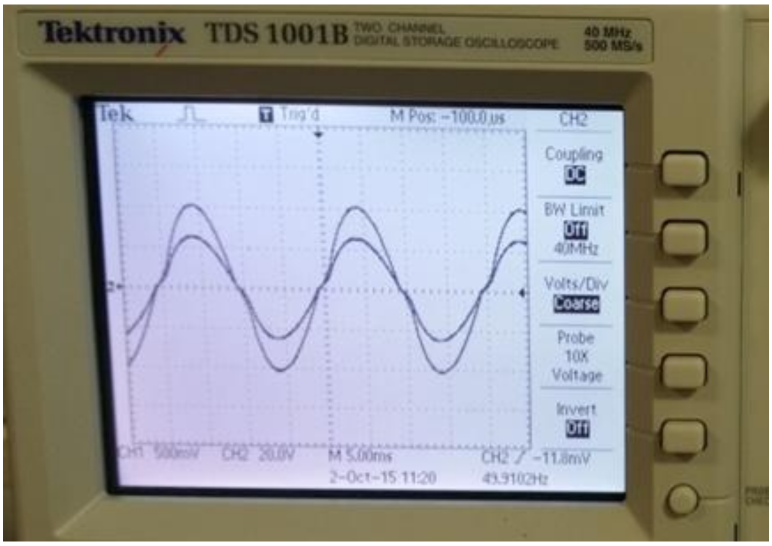


Figure 14: Output current and voltage wave forms with 200W loading

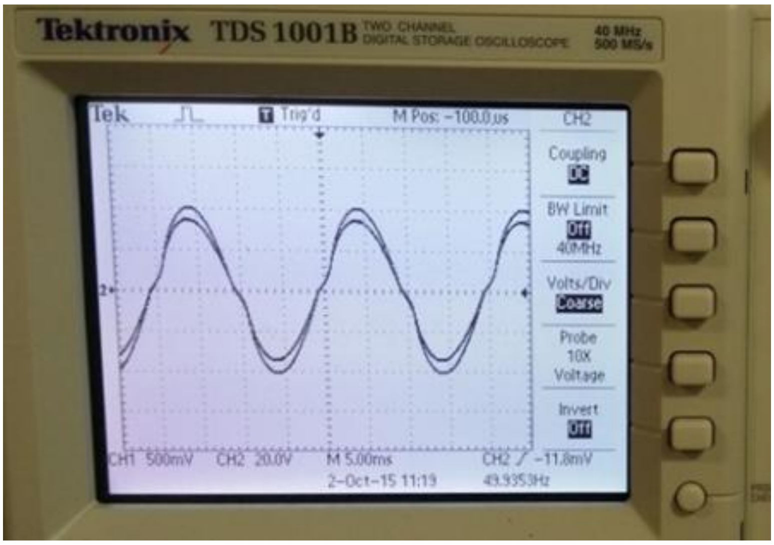


Figure 15: Output current and voltage wave forms with 300W loading

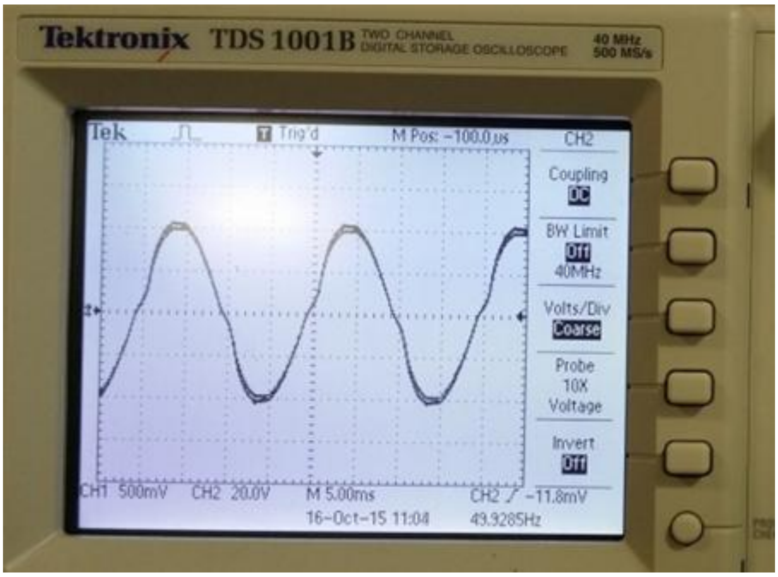


Figure 16: Output current and voltage wave forms with 350W loading

4.1.4 Waveform screenshots of Suntron 350VA modified square wave inverter

This section shows the waveform of Suntron 350VA modified square wave inverter and the discussion of them will be contained in 4.1.5.

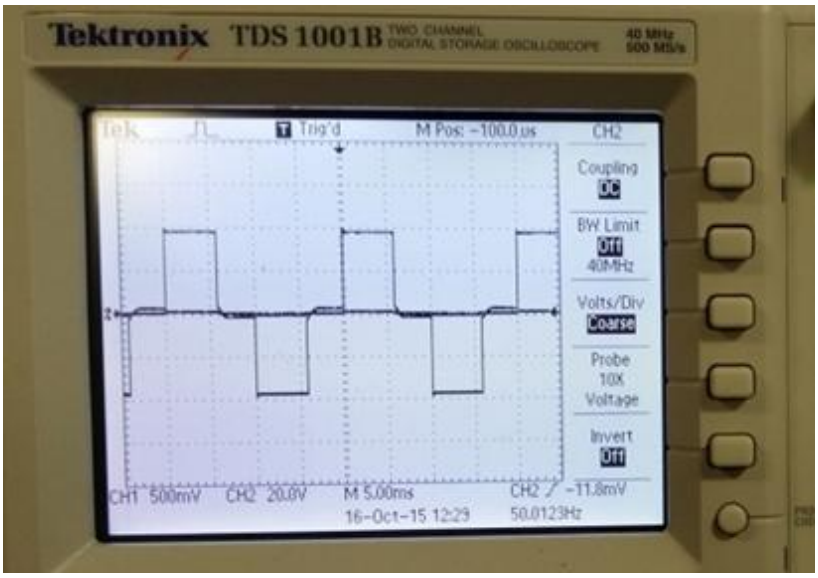


Figure 17: Output current and voltage wave forms with no loading

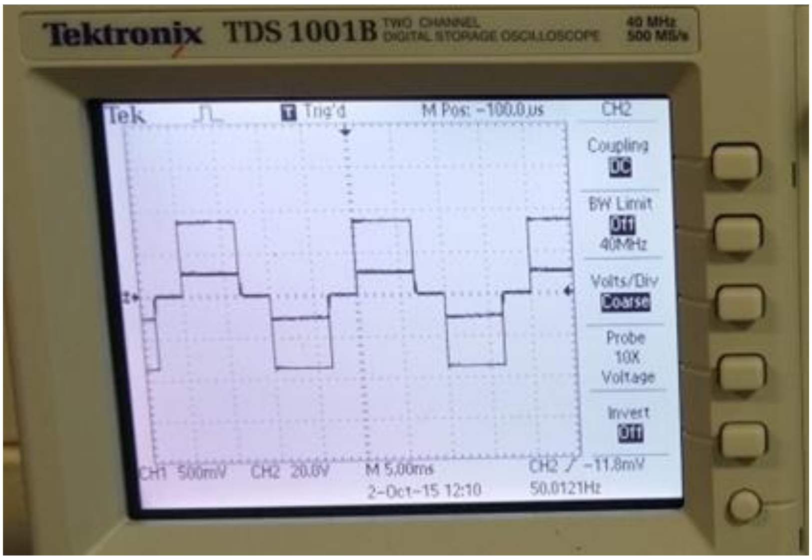


Figure 18: Output current and voltage wave forms with 100W loading

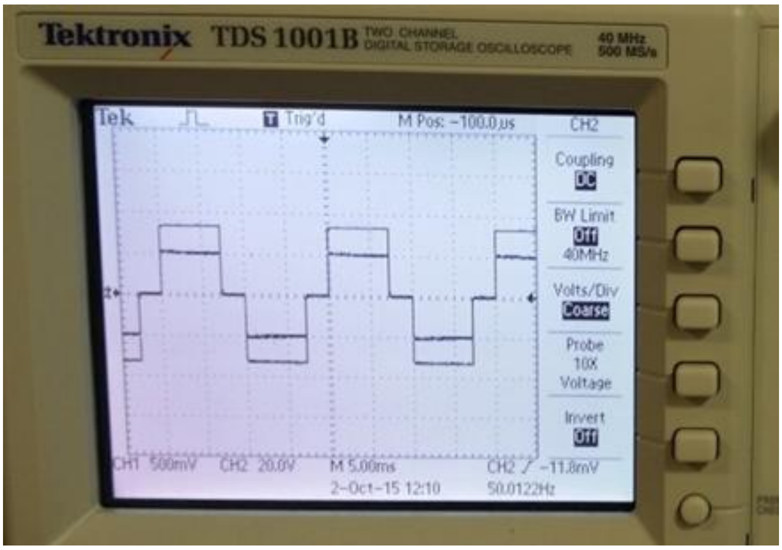


Figure 19: Output current and voltage wave forms with 200W loading

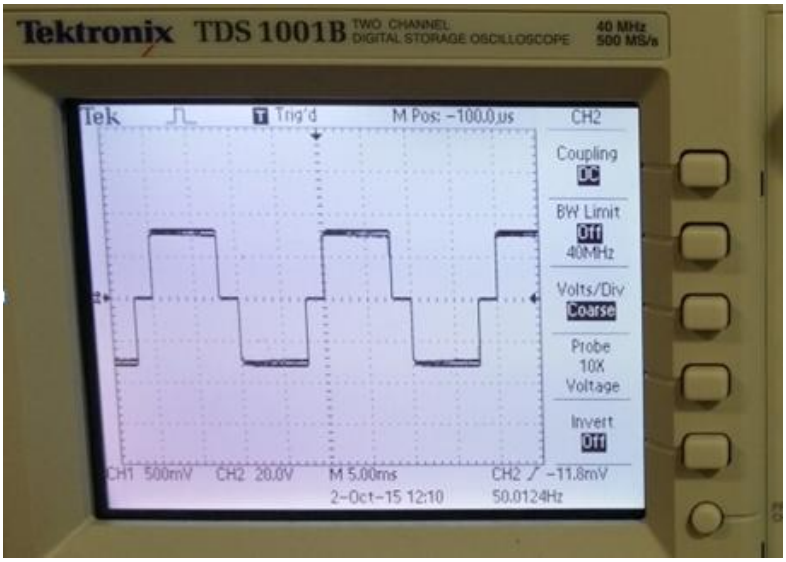


Figure 20: Output current and voltage wave forms with 300W loading

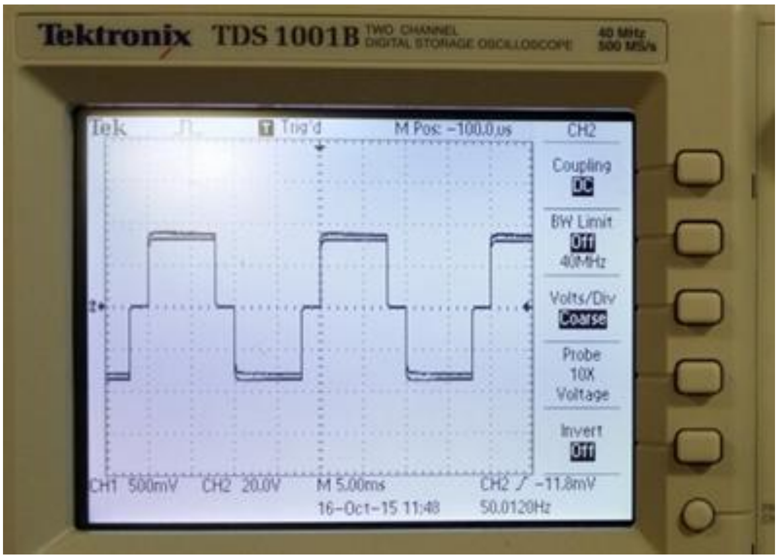


Figure 21: Output current and voltage wave forms with 350W loading

4.1.5 Discussion on waveform and THD measurement

According to the figures of waveform, shapes of the output currents shift with the increase of the load. Especially for the modified square wave inverter, the widening of the pulse is obvious as the inverter load increases. Furthermore, the distortion of the waveform occurs when the value of load increase. The THD measured for the modified square wave inverters is measured.

Table 5: Measurement of THD for Suntron modified square wave inverter

Load(W)	Voltage THD	Current THD
17.11	34.00%	34.30%
104.92	30.69%	30.71%
201.86	28.15%	28.19%
303.4	27.47%	27.50%
344.8	27.78%	27.82%

As shown in figure 22, the THD decreases with the increase of load then slightly increase after the lowest value. The THD values for the output voltage and the current are almost the same.

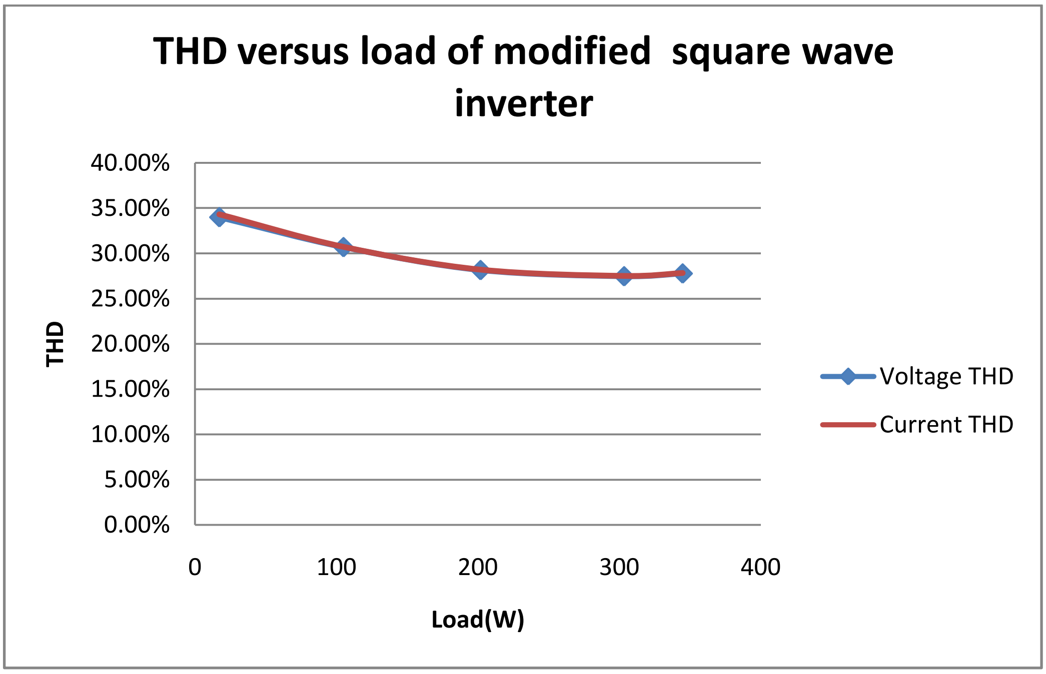


Figure 22: THD versus load of Suntron modified square wave inverter

4.2 Analysis and discussion of the results

On the basis of the comparison of both efficiency curves in figure 23, the average efficiency of Suntron 350VA modified square wave inverter is slightly higher than the Selectronic 350VA sine wave inverter. It proves that the Suntron 350VA modified square wave inverter has a better general performance in this little stand-alone system. In addition, the volume of conversion efficiency drop after peaking of the Suntron 350VA modified square wave inverter is lower, which is 6.6%.

For slow decline of the conversion efficiency after peaking, this is partially related to the temperature increases and resistive loses inside the inverter when it handles loads with more power [11].

According to the results so far, the efficiency curves, AC current and voltage wave forms are clear and typical. The operation of the system is safe and convenient for students. The functioning of measuring equipment is powerful and stable. These therefore show that the redesigned test setup is reliable and feasible to replace the previous one.

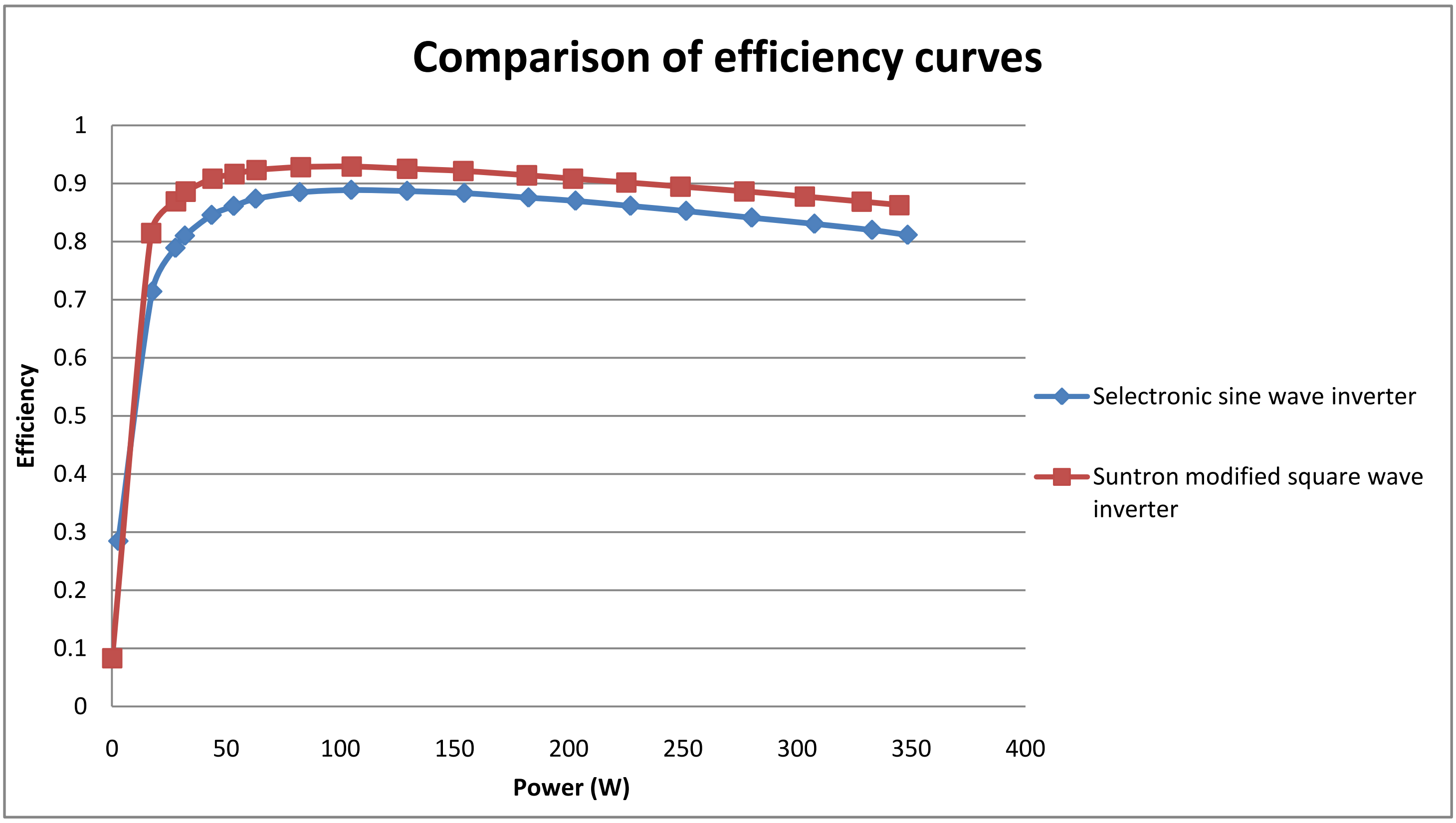


Figure 23: Comparison of efficiency curves

5. Uncertainty analysis

5.1 Introduction

Electrical measurement is used in various fields such as science, technology, and engineering. Experiment results, product quality, and financial decisions can all be impacted directly by errors introduced from uncertainty analysis. Despite the standards and established requirements, no measurement is able to be 100% exact. In other words, every measurement result includes an element of uncertainty. Every measurement can be affected by a wide range of errors which need to be translated into the values of uncertainty. Consequently, the uncertainty analysis is as important as the measurement.

For this project, calculations and results are based on various measurements during the experiment. In order to determine the value of uncertainty in measurement, the ISO GUM, which is Guide to the Expression of Uncertainty in Measurement is applied.

According to AS 5603:2009, there is a requirement of uncertainty in measurement for stand-alone inverter testing, that the uncertainties of measurement are shown in Table 6:

Table 6: Measurement uncertainties for general tests [8]

A.C. voltage	±0.5% of reading or better
A.C. current	±0.5% of reading or better
A.C. power	±0.5% of reading or better
A.C. power ≤ 20 W	±0.1 W or better
Reactive power	±0.7% of reading or better
Frequency	±0.05 Hz or better
D.C. voltage	±0.5% of reading or better
D.C. current	±0.5% of reading or better
D.C. power	±0.5% of reading or better
D.C. power ≤ 20 W	±0.1 W or better
Ambient temperature	±2°C or better
Surface temperature	±4°C or better

5.2 Background on the analysis method

The ISO Guide to the Expression of Uncertainty in Measurement, or GUM, manages terms and methods of estimating, combining and reporting uncertainties. The GUM discusses the statistical and mathematical principles in the process of the analysis of errors. Furthermore, it defines many of the terms to express uncertainty that have been used in the past. Most importantly, the GUM defines a method which is supposed to be accepted by all metrologists involved in high-quality measurement. The main process of the ISO GUM is to model the measurement, list all error sources, characterize all error components, determine components of standard uncertainty for the measurement, determine the combined standard uncertainty and the expanded uncertainty and state the result [12].

Uncertainty should not be referred to as random or methodical in order to avoid any ambiguity that the adjectives 'type A' and 'type B' should be applied instead. Therefore, uncertainties are classified as either type A or type B, terms that expresses the different methods of estimation. Type A uncertainties are those evaluated by statistical analysis; Type B uncertainties are evaluated by some other means because they are caused by an error source which has a methodical effect on that particular measurement, such as past experience, calibration, certificates, manufacturer's specifications, and published information [12].

5.3 Application of the ISO GUM

5.3.1 Model the measurement

First of all, a model or an equivalent of the measurement is obviously required in order to define the measurand and to enable its calculation from all the input statistics. Secondly, the sensitivity coefficient has to be introduced which allows the conversion of the raw data into their equivalents as components of uncertainty in the measurand. To determine the sensitivity coefficient which is usually represented by symbol $\mathrm{c_i}$, the following equation expressed in words can explain [12]:

$$sensitivity\ coefficient = \frac{resultant\ change\ in\ measurand}{small\ change\ in\ input\ quantity} \tag{5.1}$$

According to an example in the ISO GUM, an equation of the measurement is given by (5.2):

$$d=a+\frac{m}{v} \tag{5.2}$$

Where d is the measurand, the input data and the desired quantity are defined as symbol a, m, and v that they represent nothing as an example.

If a=100g/mL, m=200g and v=50ml. The value of d comes to 104.000g/mL

In order to achieve the sensitivity coefficient for v, assume a small change of 0.1mL in v from 50mL to 50.1mL. Recalculate and get value for d=103.9920g/mL. Thus, d had changed by -0.0080g/mL as a result of the 0.1mL change in v. According to equation (5.1):

$$\text{sensitivity coefficient for v} = \frac{-0.0080}{0.1} = -0.080\text{g/mL}^2$$

Therefore, to convert all uncertainties in v into components of uncertainty in the measurand d, multiply by 0.080g/mL^2(should use the absolute value).

Similarly, to calculate coefficients of other inputs analytically:

Sensitivity coefficient for a, $\mathrm{c_a} = \frac{\partial \mathrm{d}}{\partial \mathrm{a}} = 1$,

for m, $\mathrm{c_m} = \frac{\partial \mathrm{d}}{\partial \mathrm{m}} = \frac{1}{\mathrm{v}}$,

and for v, $\mathrm{c_v} = \frac{\partial \mathrm{d}}{\partial \mathrm{v}} = -\frac{\mathrm{m}}{\mathrm{v}^2}$.

For this project, the model of the measurement can be expressed by (5.3):

$$eff_{(V_{DC},I_{DC},V_{AC},I_{AC})} = \frac{V_{AC} \times I_{AC}}{V_{DC} \times I_{DC,}} \tag{5.3}$$

Where $\mathrm{eff}_{(\mathrm{V_{DC}},\mathrm{I_{DC}},\mathrm{V_{AC}},\mathrm{I_{AC}})}$ is the inverter efficiency calculated by the measured values $\mathrm{V_{DC}}$, $\mathrm{I_{DC}}$, $\mathrm{V_{AC}}$, and $\mathrm{I_{AC}}$ [12].

As we can see, there are four input qualities for this measurement and they are $\mathrm{V_{DC}}$, $\mathrm{I_{DC}}$, $\mathrm{V_{AC}}$, and $\mathrm{I_{AC}}$.

5.3.2 List all error sources

The sources of error that may affect the measurement are included in the section 5.3.7, that the uncertainty components of each input are listed such as calibration uncertainty, use, resolution, wiring, shunt calibration uncertainty, shunt use, and noise.

5.3.3 Characterise all error components

In this step, three values have to be identified for each error: U_i, k_i and v_i. U_i represents a raw estimate of uncertainty and it can be in any logical form. k_i is the coverage factor which can convert U_i to a standard deviation. v_i represents the degrees of freedom, as a means of expressing the quality of the components. The effect of each error must be evaluated as $\pm U_i$ from the row data and a reducing factor k_i chosen to allow its conversion to a standard deviation [12].
There are rules for selecting the values for k_i and v_i according to the ISO GUM.

There are usually five options for k_i:

- If a calibration correction is applied, k_i is the value of coverage factor stated in the calibration report, or k_i=2, if not stated;
- For type A estimates, k_i=1 because U_i is usually achieved as a standard deviation (standard uncertainty);
- k_i=1.73, if the error distribution is considered rectangular, e.g., instrumental resolution and rounding errors, or $\sqrt{2}$ for a U-distribution;
- k_i=3 for rough type B estimates;
- k_i=2, otherwise [12].

For degrees of freedom:

- Type A components

v_i=19, when the simplified method of getting U_i is adopted.

- Type B components are given in Table 7.

Table 7: Estimation of Type B vi

If the estimate is	v_i
rough	3
reasonable	10
good	30
excellent	100

5.3.4 Get components of standard uncertainty for the measurand

The standard uncertainty $u(x_i)$ is got from each raw estimate U_i as U_i/k_i. This value then needs to be converted into a standard uncertainty for the measurand using the sensitivity coefficient c_i for that input quantity that U_i directly affects. Which is:

$$u(x_i) = \frac{U_i}{k_i} \tag{5.4}$$

Where $u(x_i)$ is the standard uncertainty for the measurand;

U_i is the raw estimate of uncertainty;

k_i is the coverage factor [12].

5.3.5 The combined standard uncertainty

Combine all values of standard uncertainty to obtain the combine standard uncertainty, given the symbol u_c , where:

$$u_c{}^2 = \sum_{i=1}^{N} |c_i \times u(x_i)|^2$$

$$= |c_1 \times (x_1)|^2 + |c_2 \times u(x_2)|^2 + \cdots + |c_N \times u(x_N)|^2$$

Or

$$u_c = \sqrt{\textstyle\sum_{i=1}^{N} |c_i \times u(x_i)|^2} \tag{5.5}$$

Where u_c is the combined standard uncertainty [12].

5.3.6 The expanded uncertainty

Calculate the expanded uncertainty U, defined by:

$$U = ku_c \tag{5.6}$$

Which requires a value for the coverage factor k.

To determine the value of k, the Welch-Satterthwaite formula is applied to the paired values of $|c_i \times u(x_i)|$ and v_i to get:

$$\mathrm{v_{eff}} = \frac{\mathrm{u_c}^4}{\sum_{\mathrm{i=1}}^{\mathrm{N}} |\mathrm{c_i} \times \mathrm{u(x_i)}|^4/\mathrm{v_i}} \tag{5.7}$$

Where $\mathrm{v_{eff}}$ is the effective number of degrees of freedom [12].

5.3.7 State the result

For the uncertainty analysis of this project, the peak efficiency point of Suntron 350VA modified square wave inverter is used. The data measured is given in Table 8:

Table 8: Raw data for uncertainty analysis

	DC (DC measurement mode)			AC (RMS measurement mode)			
Load (W)	Voltage(V)	Current(A)	Power Cal.(W)	Voltage(V)	Current(A)	Power Cal.(W)	Efficiency
100	12.411	9.19	114.1	242.53	0.4327	104.9	92.0%

The values of the calculated power and efficiency (shown in table 8) were rounded according to *An introduction to Uncertainty in Measurement, chapter 2.3 rounding and significant figures* [13].

According to the example in section 5.3.1, the sensitivity coefficient of each input calculated is shown in Table 9.

Table 9: Sensitivity coefficient for each input

Input	Value	Sensitivity coefficient (ci)
$\mathrm{V_{DC}}$	12.411	-0.074146949
$\mathrm{I_{DC}}$	9.19	-0.10012662
$\mathrm{V_{AC}}$	242.53	2.126391266
$\mathrm{I_{AC}}$	0.4327	0.003793714

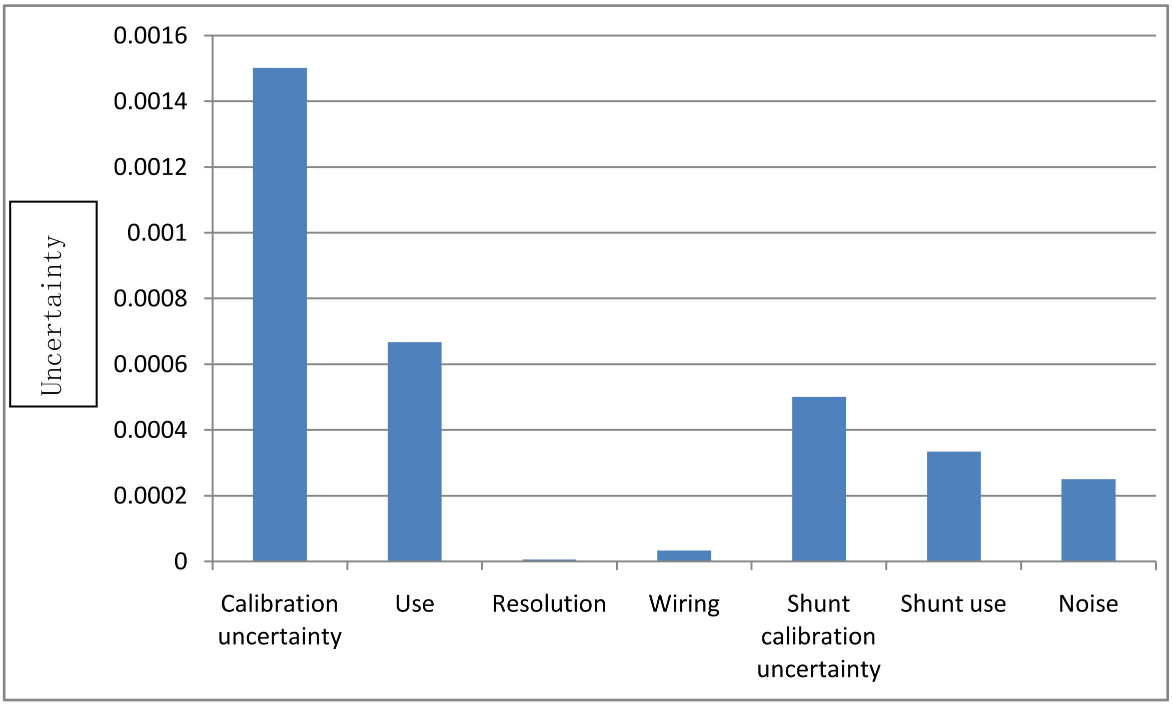


Figure 24: Uncertainty components distribution of DC current measurement.

Figure 24 shows the distribution of uncertainty components based on the measurement of the DC current. These results are estimated and calculated according to the application of the ISO GUM. As it can be seen, the calibration uncertainty contributes the most to the uncertainty in the DC current measurement. If we repeat the calculations for the other inputs, then we can achieve the final uncertainty analysis results shown in Table 10.

Table 10: Results of uncertainty analysis

u_c	0.03537978
$\mathrm{v}_{\mathrm{eff}}$	40.37715902
k	2.02107537
U(%)	0.071505202
After rounding(%)	0.072

Finally, the expanded uncertainty for measurement of the peak efficiency point of Suntron 350VA modified square wave inverter is 0.072%. The final uncertainty analysis calculation data sheet is provided in Appendix D.

6. Conclusion

The aim of this thesis project is developing the stand-alone inverter efficiency test setup, which is a laboratory exercise of Unit ENG421 Renewable Energy Systems Engineering of Murdoch University. The development includes the redesign and implementation of the test setup. To gain a good understanding of the topic, some information were provided including the project background, review of the previous test setup, and background on stand-alone inverters. Moreover, two Australian Standards AS5603 Stand-alone Inverters - Performance requirements and AS4763:2011 Safety of Portable Inverters were introduced as they are the most relevant to this project.

After completion of the redesign and the implementation work, the stand-alone efficiency test experiment on the new setup was carried out in order to ensure the reliability and safety of it. Two types of stand-alone inverters, Selectronic 350VA sine wave inverter and Suntron 350VA modified square wave inverter, were used in the experiment. The results included the measurement data of each one, discussion on efficiency curve and output waveforms, and comparison of these two inverters. The maximum efficiency of Selectronic 350VA sine wave inverter is 88.8% when there is 104 watts loading. The maximum conversion efficiency of Suntron 350VA modified square wave inverter is higher which is 92.9% when there is approximately 150 watts loading.

As the last part of the project, the uncertainty analysis of the result was performed due to its significance to determine the uncertainties in measurement. In other words, it is helpful to see how exact the measurement is. For this project, the uncertainty analysis is referred to the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The main steps in the application of the GUM contain modeling the measurement, listing all error sources, characterizing all error components, getting components of standard uncertainty for the measuring, the combining standard uncertainty, expanding uncertainty and stating the results. The final expanded uncertainty for measurement of the peak efficiency point of Suntron 350VA modified square wave inverter is 0.072%.

7. Future work

Although the implementation of the test setup was completed, there are some potential improvements that could be accomplished as future work.

First of all, the inverters used in this project were manufactured before 2011. To comply with the AS4763:2011 Safety of Portable Inverters, the new inverters manufactured after 2011 should be purchased to replace the previous ones.

Secondly, a color digital oscilloscope should be used in order to obtain waveforms in different colors. It helps student to distinguish the waveforms in a better way.

Lastly, the test setup can be used to measure the performance when there are multiple loads connected into the systems such as non-linear loads or motors. It assists to discuss and compare the results of different kinds of loads including the waveforms on the output side.

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9. Appendices

Appendix A Available equipment list

The existing available equipment at the Renewable Building 190 are listed below in order to review the equipment and set up the developed system.

Inverters:

- Latronics Sine Wave Power Inverter Mitro 1000 Series
- Selectronic Sine Wave Inverter 350VA
- Suntron Power Inverter 350VA

These three stand-alone inverters are selected so far for the new setup. However, there are safety issues since all these inverters were manufactured before 2011. To meet the requirement of AS4763:2011 Safety of Portable Inverters, a new stand-alone manufactured after 2011 needs to be purchased for the future work to replace the old ones.

Power supplies and batteries:

- Agilent DC source 0-60V 0-110A 6.6kW rating power [14]

Measurement equipment:

- Display cabinet with 100A, 75mV shunt (for inverter input current measurement)
- 2 Protek Multimeters
- Energy Meter System 2000-0400
- Hall effect sensor circuit to supply isolated signals for viewing AC voltage and current waveforms (current conversion factor: 0.5V/A, voltage conversion factor: 11.72mV/V)
- Power supplies (for supplying the Hall effect sensor circuit with 15 V)
- Tektronix Oscilloscope TDS 1000B series or equivalent and associated accessories (2 probes, training board)
- YOKOGAWA WT210 Digital Power Meter
- YOKOGAWA WT2030 Digital Power Meter
- Differential probe

Loads:

- Various loads bank

Appendix B Safety operation procedure

Start procedure

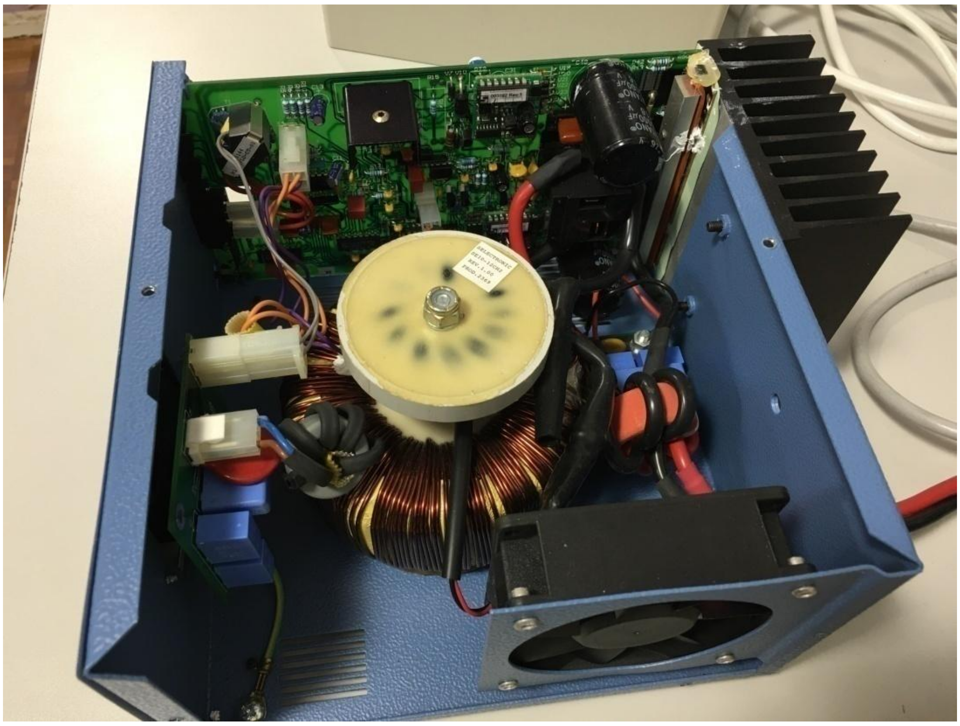
1. Power and switch on the measurement equipment
2. Switch on the power supply for LEM circuit
3. Switch on the DC power supply
4. Set the operating voltage and current for the circuit by clicking function (voltage and current) button
5. Power the circuit by clicking output on/off button
6. Select and plug in the inverter
7. Close the isolator for power supply
8. Close the isolator for inverter which is used
9. Switch on the inverter and load bank

Close procedure

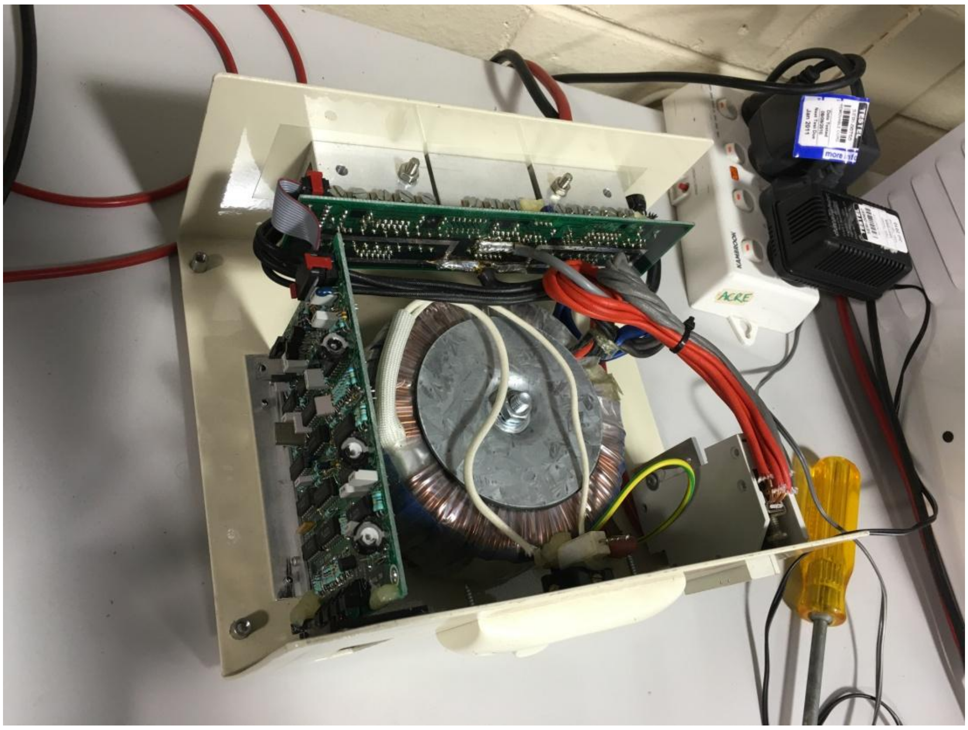
1. Switch off the load
2. Switch off the inverter
3. Open the isolators for inverter and power supply
4. Switch off the power supply
5. Switch off the measurement equipment

Appendix C Circuits of stand-alone inverters and Details of the DC connections

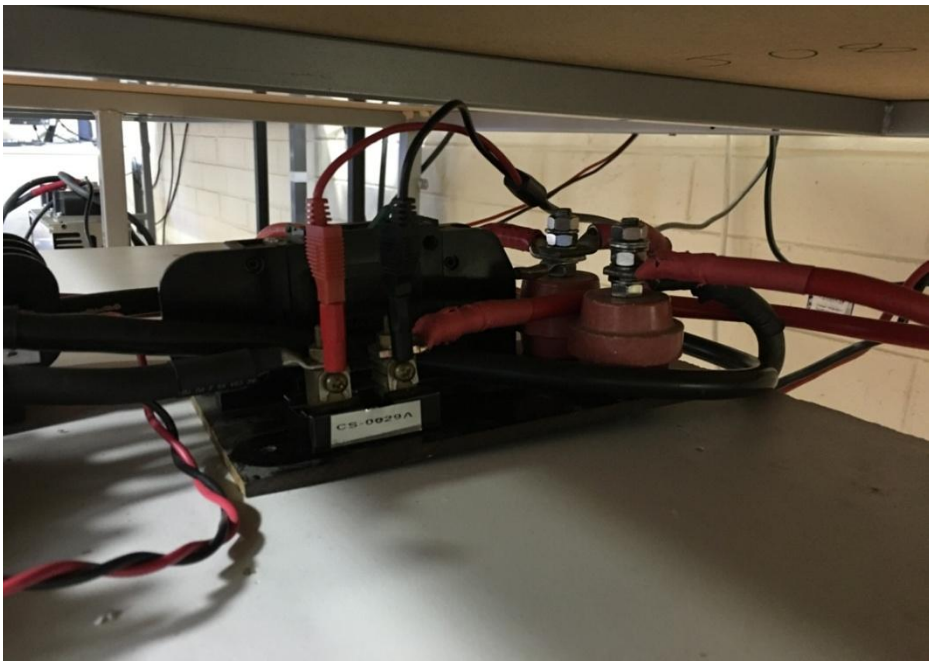
Suntron modified square wave inverter



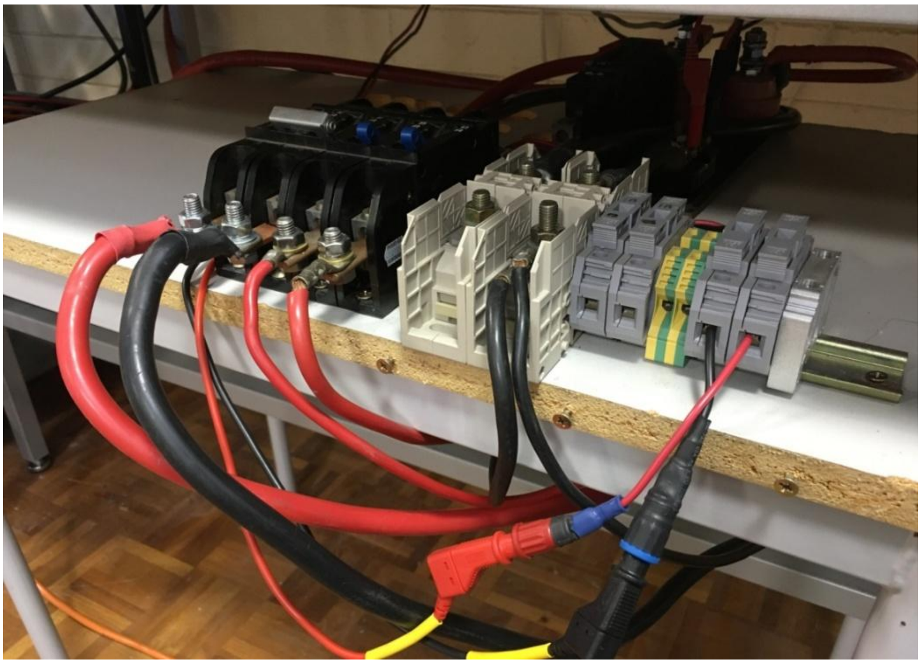
Selectronic sine wave inverter



Connection from the DC power supply and DC shunt



Inverters DC side connections



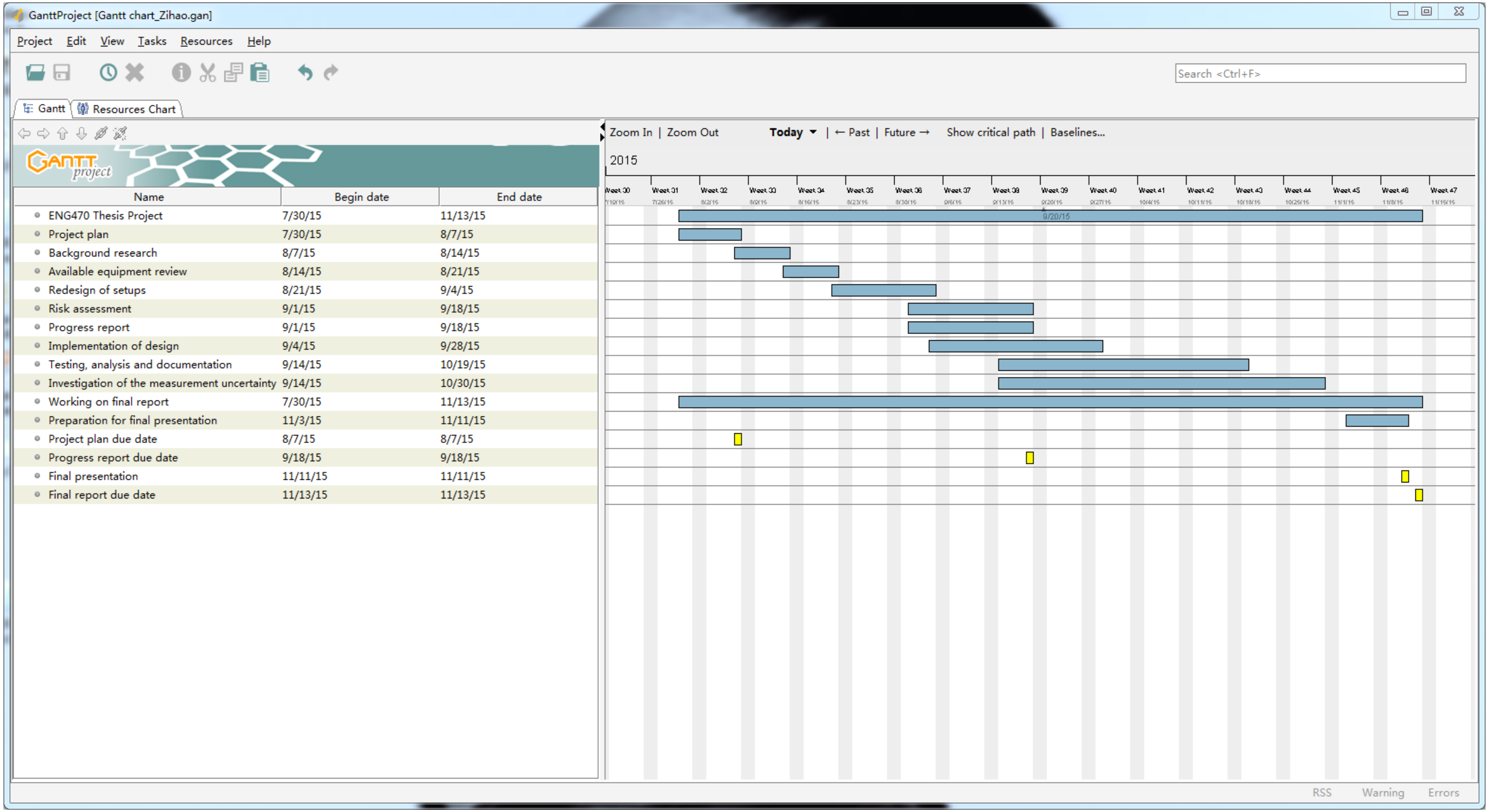
Appendix D Uncertainty analysis calculation data sheet

Table 11: Uncertainty analysis table

Component (i=1,2,…)		Type	expanded uncertainty Ui(%)	Reducing factor ki	Standard uncertainty u(xi)	Sensitivity coefficient ci	ciu(xi)	ciu(xi)^2	Degree of freedom Vi	[ciu(xi)]^4/Vi
DC voltage	Calibration uncertainty	B	0.03	2	0.015	-0.074146949	0.001112204	1.237E-06	30	5.10055E-14
	Use	B	0.02	3	0.006666667	-0.074146949	0.000494313	2.44345E-07	10	5.97046E-15
	Resolution	B	0.0001	1.73	5.78035E-05	-0.074146949	4.28595E-06	1.83694E-11	10	3.37434E-23
	Wiring	B	0.001	3	0.000333333	-0.074146949	2.47156E-05	6.10863E-10	3	1.24385E-19
	Noise	B	0.005	2	0.0025	-0.074146949	0.000185367	3.43611E-08	3	3.93561E-16
DC current	Calibration uncertainty	B	0.03	2	0.015	-0.10012662	0.001501899	2.2557E-06	30	1.69606E-13
	Use	B	0.02	3	0.006666667	-0.10012662	0.000667511	4.45571E-07	10	1.98533E-14
	Resolution	B	0.0001	1.73	5.78035E-05	-0.10012662	5.78767E-06	3.34971E-11	10	1.12205E-22
	Wiring	B	0.001	3	0.000333333	-0.10012662	3.33755E-05	1.11393E-09	3	4.13611E-19
	Shunt calibration uncertainty	B	0.015	3	0.005	-0.10012662	0.000500633	2.50634E-07	3	2.09391E-14
	Shunt use	B	0.01	3	0.003333333	-0.10012662	0.000333755	1.11393E-07	3	4.13611E-15
	Noise	B	0.005	2	0.0025	-0.10012662	0.000250317	6.26584E-08	3	1.30869E-15
AC voltage	Calibration uncertainty	B	0.03	2	0.015	2.126391266	0.031895869	0.001017346	30	3.44998E-08

	Use	B	0.02	3	0.006666667	2.126391266	0.014175942	0.000200957	10	4.03838E-09
	Resolution	B	0.0001	1.73	5.78035E-05	2.126391266	0.000122913	1.51076E-08	10	2.28238E-17
	Wiring	B	0.001	3	0.000333333	2.126391266	0.000708797	5.02393E-07	3	8.4133E-14
	Noise	B	0.005	2	0.0025	2.126391266	0.005315978	2.82596E-05	3	2.66202E-10
AC current	Calibration uncertainty	B	0.03	2	0.015	0.003793714	5.69057E-05	3.23826E-09	30	3.49544E-19
	Use	B	0.02	3	0.006666667	0.003793714	2.52914E-05	6.39656E-10	10	4.0916E-20
	Resolution	B	0.0001	1.73	5.78035E-05	0.003793714	2.1929E-07	4.8088E-14	10	2.31246E-28
	Wiring	B	0.001	3	0.000333333	0.003793714	1.26457E-06	1.59914E-12	3	8.52417E-25
	Shunt calibration uncertainty	B	0.015	3	0.005	0.003793714	1.89686E-05	3.59807E-10	3	4.31536E-20
	Shunt use	B	0.01	3	0.003333333	0.003793714	1.26457E-05	1.59914E-10	3	8.52417E-21
	Noise	B	0.005	2	0.0025	0.003793714	9.48429E-06	8.99517E-11	3	2.6971E-21

Appendix E Project Gantt chart



Name	Begin date	End date
ENG470 Thesis Project	7/30/15	11/13/15
Project plan	7/30/15	8/7/15
Background research	8/7/15	8/14/15
Available equipment review	8/14/15	8/21/15
Redesign of setups	8/21/15	9/4/15
Risk assessment	9/1/15	9/18/15
Progress report	9/1/15	9/18/15
Implementation of design	9/4/15	9/28/15
Testing, analysis and documentation	9/14/15	10/19/15
Investigation of the measurement uncertainty	9/14/15	10/30/15
Working on final report	7/30/15	11/13/15
Preparation for final presentation	11/3/15	11/11/15
Project plan due date	8/7/15	8/7/15
Progress report due date	9/18/15	9/18/15
Final presentation	11/11/15	11/11/15
Final report due date	11/13/15	11/13/15