An Investigation into Arc Detection and Fire Safety Aspects of Photovoltaic Installations

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

The number of PV systems around the world is increasing and the systems are aging with little to no inspections and maintenance. Exposed to UV, the weather and rodents cables, connection points and other components can degrade to the point where there is a break in the circuit and over this gap the current from the PV array can continue to flow causing an arc. The heat and electrical energy from the arc can ignite nearby materials and start a fire which could cause further damage. When an arc starts there is no off switch to easily cut the power from the PV array so the arcing situation can continue. A number of systems have been developed to detect these arcs in order to identify and eliminate them early before they start a fire. One of these devices was tested to determine if it was effective in detecting arcs. The Texas Instruments SolarMagic RD-195 DC Arc Detection Evaluation Board detected all the arcs created and did not give any false positives. The devices available on the market today are effective at detecting arcs and some have been integrated into the inverters of PV systems along with devices to extinguish any arcs. The integration of these and other features into PV systems makes PV systems safer and reduces the potential for damage to people the system and surrounds.

Disclaimer

I declare the following to be our own work, unless otherwise referenced, as defined by the University’s policy on plagiarism.

Signed:

Date:

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1. Introduction

Photovoltaic modules can create electrical power from the sun. Generating units can be small but powerful enough to fit on the roof of a house and significantly reduce a household's net power consumption from the grid. Large installations with many units can be used to supplement power created from more traditional plants to feed onto the grid. The number of photovoltaic (PV) installations to provide power is growing rapidly, as their popularity increases due to lower prices for installations and higher prices for electricity. Many homes and utilities around the world are installing PV systems to supply power to their loads. Traditionally power supply networks have been centralised with large power generators, a transmission and distribution network and decentralised loads. The generators and network infrastructure was monitored and controlled from a central station. With the high degree of monitoring of generators it was easy to detect problems such as an arc fault that could lead to a fire and quickly take action to control the situation. Now, with photovoltaic systems, generation has become more decentralised and less centrally controlled. With the large size of many utility scale systems and the distributed nature of household systems there is less direct oversight of individual modules and cable connections. In a large utility scale system a whole array or string may be monitored but perhaps not individual modules.

1.1 The Problem

Once an arc or fire starts, the photovoltaic modules can continue to feed power to the fire in daylight, even in cloudy conditions. A PV module is a current limited device, any fault currents that may occur are often close to normal operating currents. This makes some faults difficult to detect when compared with traditional power networks. Fault currents in traditional networks are often considerably higher than normal operating currents and over current devices can be used to aid in protection. When an AC arc occurs there is the zero crossing point in the waveform which enables protection devices to more easily discontinue arcs in the case of fault. In the case of a

DC arc there is no zero crossing point, so once established DC arcs can persist and protection devices need to be able to disconnect under load. In a PV installation of any size many joins between conductors need to be made and a series arc could happen at any one of them.

1.2 Project Aim

To investigate literature and conduct an experiment on devices and techniques which look at: reducing the potential of arcs and subsequent fires, suppressing an arc once it starts and detecting a fire and alerting people to control the situation.

It is hoped that, through literature review and testing, it can help the wider community to better understand the risks and improve fire safety in photovoltaic systems and reduce future harm to people and property.

1.3 Objectives

The main objectives to of this thesis are; to conduct a literature review summarising what is known in the literature about the topic and relevant standards and guidelines, to survey the technical solutions currently available on the market and ones in testing and perhaps development, to perform a series of tests and analyse selected devices that have arc detection capabilities and to document the findings of the research in a clear and understandable manner

2. DC arcs

In order to prevent, detect and eliminate arcs it is necessary to better understand arcs. Information on DC arcs in PV systems is available and relevant but there is a limited body of literature. Some important points to understand are the properties of arcs in general, the difference between AC and DC arcs, the specific properties and types of DC arcs and possibly how these properties can be used for arc detection.

2.1 Arcs in general

An arc, whether AC or DC, is the flow of current from one point to another through air or other medium that has been ionised. A voltage between two electrodes that is greater than the voltage required to ionise the air will create an arc and the ionised path can be sustained by the continued flow of sufficient electrons. A lightning strike overcomes the high voltage required to ionise the air from the clouds to the ground but is only sustained for a fraction of a second as there is not sufficient current flow to sustain it for longer. A more relevant example, as it is a man made power system, is the switching of AC power transmission. In an AC power transmission network there can be a large current flowing through a connection point and for one reason or another, the contacts are opened. The current flowing through the points continues to flow through the air as the contacts are pulled apart until the gap is too large and the arc extinguishes.

2.2 How does an AC arc differ from a DC arc?

The currents in an AC system ideally have a sinusoidal waveform at the grid frequency but in reality will be of some periodic waveform. Importantly the periodic waveform will have a point at which the current is zero as it crosses from flowing in one direction to the other. Protection devices in AC systems can detect this point at which the AC current is zero or close to it and open the contacts at this point to avoid arcing. DC current; however, flows in one direction and can be continuous, without a zero crossing point at which it is convenient and safer to open a switch. PV systems have a continuous flow of current from the PV modules which cannot be turned off at the source as the source is the sun. The amount of current is proportional to the intensity of the solar irradiation on the PV cells. So when there is a disconnection on the DC side of a PV system the current continuously flowing across the gap creates an arc, whether it arcs from a deliberate switching action or the breakdown of a connection or a cut in a wire.

2.3 Arc types

2.3.1 Series

A series arc forms in line with existing connections. The current continues to flow through the circuit, flowing through the added impedance of the arc (an example is shown in Fig 1). Series arcs can be formed by bad connections such as a broken or cut wire or a loose or corroded connection; they can also happen in switch or connect/disconnect devices. Systems can continue to operate as normal with a series arc just with less power as there is a voltage drop across the arc.

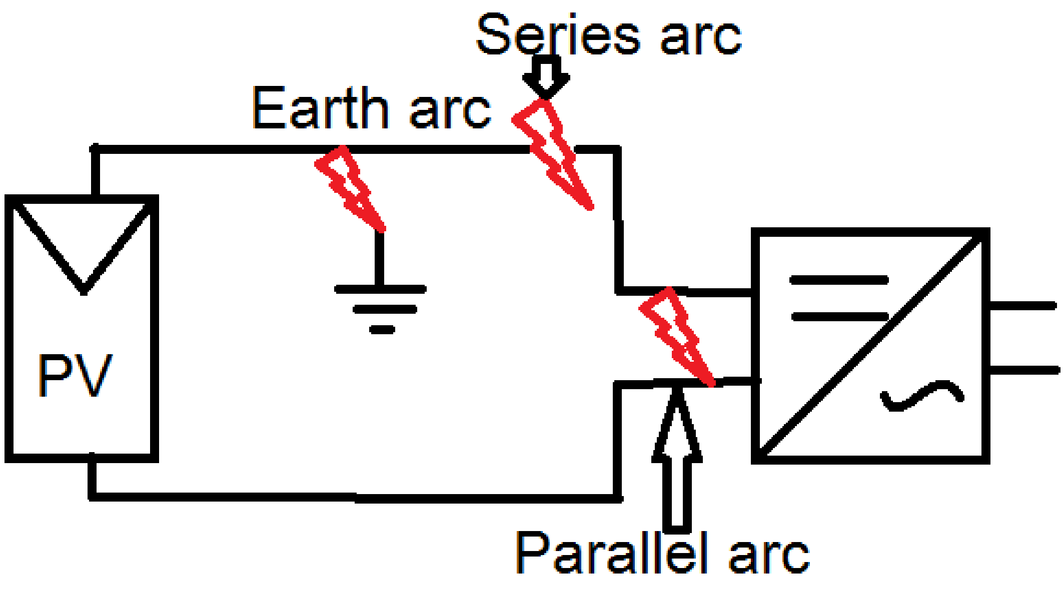

Figure 1 Series, Parallel and Earth arcs

2.3.2 Parallel

Parallel arcs create new pathways for the current to flow, pathways that were not designed in the system (an example is shown in Figure 2). These pathways often short circuit or bypass the inverter e.g. in grid connected PV systems and so can significantly reduce the power output of the DC side. Some pathways may go straight to ground and if there are two ground faults this can form a parallel loop.

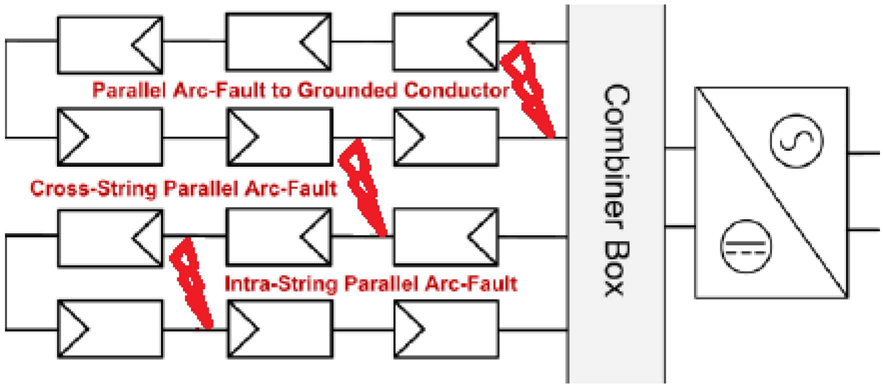

Figure 2 Different types of parallel arc fault

2.4 Characteristics of DC arcs

Both series and parallel arcs emit a high amount of electronic noise [1]. In grid connected PV systems in the case of a series arc there is a sudden change in voltage and impedance but current remains steady as the additional impedance of the arc is added to the circuit. When a parallel arc occurs there is a drop in current and voltage at the inverter. The current drop occurs because a portion of the current flows through the short circuit created by the parallel arc so less current goes to the inverter. The voltage drop is as a result of the short circuit, so the operating point of the PV array moves along the IV towards the higher current lower voltage end and the lower voltage at the array means a lower voltage at the inverter.

2.4.1 Noise signatures

Both series and parallel arcs show similar noise distributions over the range of frequencies from 0-100 kHz. The distributions are reasonable flat with lower levels of noise at higher frequencies.

The TI device can output the filtered noise signal after it has been converted from analogue to digital [2]. The filters on the device are designed to pass above 40 kHz and pass below 100 kHz to keep the circuit required for arc detection compact so the distribution found may not be true representations of the full noise spectrum.

3. Examples of fires caused by PV systems

This thesis is mainly concerned with the prevention of fires but it is useful to attempt to analyse the causes of incidents that have occurred in order to seek improvements that can be made to reduce risk or to find the real reasons why fires start and spread so they can be better prevented. PV systems have been around for a considerable amount of time, operating with little maintenance or supervision in harsh conditions. Even though this thesis has focused on the risks and what could potentially happen, there have been few actual fires or incidents of note that have been openly reported.

The most prominent example is the fire in Bürstadt, Germany in 2009 [3]. The 5 MW system caught fire and damaged 80 of 200 m^2 of modules. The probable cause for this fire was a bad connection in a junction box or an electrical connection within the modules, either of which generated hot spots which in turn triggered a fire.

On the 5th of April 2009 a row of solar panels caught fire on the roof of the Target building in Bakersfield California USA. An investigation revealed that one piece of conduit containing array cables from a group of panels had arced, but the exact cause was unknown [4]. The problem was that two ground faults had occurred. One small ground fault less than 10 amps had developed from a small string cable and not been detected by the older ground fault protection device on the large inverter, which had a lower detection limit of 10 A. At a later stage a second fault developed in a larger array cable creating a parallel fault. The ground fault protection operated and stopped the inverter operating and the higher current form the larger array cables fed into the prior smaller fault with smaller cables. The smaller cable and connections overheated with the larger current flowing through it and started the fire [5].

In Kent in the UK in 2011 a house was destroyed by fire from a rooftop PV system. The suspected cause of the fire was a faulty DC switch [6]. It is not known why the switch was faulty but it is possible that the device was an AC device that was not rated for DC and was perhaps installed because of lack of knowledge about the requirements for DC PV systems.

Currently the situation in Australia is concerned in response to other incident of PV fires to which the Clean Energy Council has responded, stating that Australia has suffered only three minor ‘incidents' from more than 300,000 solar panel installations nationwide, and no actual house fires. To put this into perspective, the Clean Energy Council chief executive Matthew Warren said "there are more than 20,000 fires caused by faulty electrical wiring in Australia each year." [7]

In reviewing these reported fire incidents it is not always known what exactly the cause of the fire was. With the increasing number of systems and aging systems more fires may happen. In the noted examples the faults were not detected until that fire had already started. Preventive measures could have been employed to avoid the faults and fire spread, with higher quality installation and components and regular inspection of the system or use of arc detection devices.

4. Fire fighting techniques associated with PV systems

One key objective in safety is to design and build a system which has less potential for destroying itself either through fire or equipment failure. The risk of a fire can be reduced by following good design practices [8] and utilizing the latest technologies that improve safety, combined with a high quality installation. However sometimes fires will still happen. The cause of a fire can be one of many things or a combination of factors. A fire can be caused by the PV system or a fire from another source may spread to include the PV system. When fires do occur, fire fighters have to deal with them and when the fire crews arrive at the scene of the incident they often do not immediately know if the cause was the PV system or another source. However they do know that a PV array can continue to produce power and continue to feed the fire and increases the electrical hazard of the area. This chapter looks at some of the methods and techniques used by fire fighters in dealing with fires where PV systems are involved. Fires with PV are still relatively uncommon and some crews are unfamiliar with fighting them [9] and are wary of using traditional techniques such as water. PV fire fighting techniques share many similarities and practices with fighting electrical fires. PV fires also have additional hazards associated with them which will be discussed such as poisonous gasses, and falling debris.

4.1 Leave and control spread

Without other equipment to isolate or control the voltage of an array, once the inverter is turned off to stop it exporting power the array will produce its open circuit voltage or something close to it depending on the damage to the equipment. The DC open circuit voltage can easily be at levels that make it dangerous to work on or near given that with a fire there could be exposed connections where insulation has melted off. For their own safety fire fighters may not approach a fire that involves a PV array [10] because even if it has been isolated at the inverter parts of the array or any metal structures in the building may be assumed to be live. So, not willing to risk their safety, the fire crew may decide that it is best to leave the fire to continue and to protect the areas surrounding the fire so that it does not spread. This technique is often used as part of a strategy to combat bush or forest fires in Australia whereby an area on fire cannot be combated directly with water because of its size. Hence fire breaks are made and monitored and the existing fire is left to burn out and fire fighters attempt to stop it spreading beyond the fire breaks.

4.2 Water

One common technique used to combat fires is to dowse them in water. This has the effect that it reduces the intensity of the fire and, by soaking unburned areas, it makes it harder for the fire to spread. Fire fighters are careful about using this technique with fires that involve electrical systems [11] as they firstly need to ensure their own safety. Fire fighters cannot help other people if they themselves are injured or in trouble. When using water, there is a risk that the stream of water will make a conducting path from the damaged electrical system through the stream of water and through the fire fighters and their equipment. It has been demonstrated that this risk can be lowered to a level such that water can be used to fight fires involving electrically live PV systems [12].So at first when a fire crew arrives at the scene of a fire, they will disconnect the mains or other power sources before using water. If they see a PV system, they may hesitate to use water. This puts them at more of a disadvantage when fighting against the fire, as water is often the most effective method. Using water is an effective method because large quantities can be used when there is a hydrant nearby, more water is available than can be carried in one or multiple vehicles. It is safer to fight fires when the electrical hazard has been removed from the situation but this cannot always be done. It is always possible to use water to extinguish fires [11] if appropriate safety procedures are followed. DC up to 1000V has a comparable risk to fire fighters as 230/400V AC, in the case of combating fires with live electrical lines.

The other methods used are to attempt to stop power and dangerous voltages being produced by the solar array before the fire fighters can move in and deal with the rest of the fire if it has spread.

4.3 Wait for night

As long as sunlight reaches the panels voltage will be produced so the simplest way to stop the dangerous voltage is to wait until night when there is no sunlight. With this technique the safety of the fire fighters is maintained as they do not need to go near the system and buildings it is attached to when it is potentially live. But it is not completely dark at night, there is moonlight and more importantly in these situations there is light used by the fire crews to illuminate the area and perhaps spotlights shining onto the array to keep a close eye on it. It was hypothesised that this artificial illumination could be enough to produce hazardous voltages but it was found experimentally that it was not a significant electrical hazard [12].

4.4 Blocking the light

It may not be possible to wait until nightfall so one other option that has been suggested is to cover the array in foam [10] to block out the light and thus stop the production of electricity by the panels. This is considered an option as well equipped fire crews can have access to multiple kinds of materials to extinguish fires such as foam or powder, for use when dealing with oil based or chemical fires that would otherwise react unfavourably to water. There are a few reasons why this may not be a preferred option. Firstly PV arrays are often sloped and so the foam or powder could simply slide off immediately or unexpectedly at some time later, secondly the foam or powder may not cover the whole array; there could be uncovered areas with some panels or parts of panels still producing electricity.

Instead of using foam or powder it is also possible to cover the array with polyethylene (PE) sheets [10] or other solid covering to block sunlight. The advantage of this method is that the coverings can be fixed on so they do not slip off and almost guarantee that no light will penetrate. However the significant issue, when using blankets to cover the array, is that you need to move in relatively close to a system that is potentially still live and dangerous.

4.5 Conclusion

Prevention is better than cure; it is better to design and build a system well, but when fires do occur, there are a variety of methods that can be used by fire fighters to extinguish fires involving PV systems. Water can be always used as an effective method. The fire can be contained in an area and left to burn out, it is possible to wait until night to reduce the electrical hazard from the array and the less preferred options to cover the array with foam or sheets.

5. Insurance

The objective of this thesis is to help identify arcs that may cause a fire, but it also attempts to discuss what happens when a fire starts and the consequences of a fire. Insurance can help protect a system owner from further financial loss in the event that a system is damaged. Insurance companies promote safer systems by specifying certain criteria before the system can be insured.

5.1 Overview of PV system insurance

There are two main forms of insurance available. There is building insurance and technological or electronic equipment insurance [13].In Australia household PV systems are generally covered under home and contents or building insurance policies [14]. Building insurance, also known as home and contents insurance, includes the PV system into the insurance of the building. The dangers covered by a policy typically include storm, hail, mains water leaks and fire caused from lightning, explosion or other sources of ignition. The area of cover is limited. It can be difficult to determine the level of compensation for a claim, given factors such as the building price index against the PV system price development.

Technological or electrical equipment insurance can cover all risks foreseeable making it the best coverage for a system, whereas building insurance is limited in its scope of coverage. The claim is settled independently of any claim for the building. The wider coverage of the insurance also includes the system's service interruption. Building insurance is more limited and includes the system with the building. Building insurance may not cover additional financial losses, for example due to downtime in electricity production. Settling a claim can be more difficult and complicated. Technological insurance focuses on the PV system; it is wider in its coverage of the risks and claims for system and building a settled independently. In Australia the relevant insurance company that insures the building needs to be informed when a PV system is retrofitted to a residential building and premiums are often increase by some small amount [15]. PV systems are considered part of the home as they are fixed to it.

5.2 Potential damage

In a review conducted by one insurance company it was found that of all damages 26% of expenditures are caused by fire damage. Fire damage accounts for only 2% of cases of damage [13].The addition of a PV system to a new or existing building is not considered to add additional risk to an insurance policy by insurers [13]. Insurers have little doubt as to the insurability of PV systems - they can be insured. The reason that insurers feel secure in this is that claims for damage due to PV systems are marginal and that there is strong regulation that is adequately maintained in terms of standards that apply to the systems and their installation. Although residential and commercial systems have been around for some time, the number of systems has been somewhat limited and as such insurers are unfamiliar with the potential risks and risk management strategies. The number of fires involving and particularly caused by PV systems has to date been small and so statistical analysis of risk and potential damage is difficult.

5.3 Specific risk factors

Most claims are as a result of overvoltage, storms and theft [13]. Overvoltage can come from a number of sources; the grid could fault in some manner such as a large load dropping off or an increase in local residential rooftop PV system production, the DC side of the system may produce higher voltage than anticipated, through a combination of factors that may include; a recent rain cleaning and cooling the panels followed by a period of highly intense sunshine and high cloud cover that does not obstruct the Sun or in winter there may be low ambient temperatures and high solar radiation. Storms cause multiple kinds of damage. Large areas of metal and conductive material high on a building that connect to ground through low resistance cables are likely places to be struck by lightning. High winds, hail or falling tree branches test the structural strength of the panel mountings and the toughness of the glass on the panels. A relevant standard for the solar panel frame mounting points is AS/NZS1170.2:2002 Structural design actions – wind actions). Mounting systems that are not parallel to the roof, so as to be more optimally angled act in certain wind directions to capture the wind and this places additional strain on the mounting structure. Any mounting structure will be rated to a certain wind speed but in severe or very unusual storms gusts of wind may exceed this rating and damage the structural integrity of the mounting system beyond a point where it can recover. The glass or other large parts of the panel can be fragile and a little torsion or twist can causes cracking and allow water into the cells and cause more damage. In a system fitted to an older building the mounting system of the new PV system may be more than up to the task of mounting the modules on the roof. However the additional weight and stress caused by the PV installation in addition to the age of the structure could cause damage to the roof as it was not designed or built with this consideration in mind or it may fail in some manner under more extreme conditions of a storm. Some installations are not mounted on top of a roof but are built integrated into it. Over time the seals may deteriorate and not be weather proof any more leading to ingress of water and the damage it can cause.

PV system themselves have caused few fires, instead PV systems may be damaged by a fire originating elsewhere in the building or structure [13]. Agricultural or farm building are good examples of this situation [16]. A large PV system may be placed on the large roof space of a shed or other structure. The shed may store a variety of; chemicals, fuels, flammable materials, machinery, electrical systems or other forms of ignition sources and fuels. In Australia ambient temperatures can reach more than 40°C and the PV system, shed or the machinery, if operating (such as a diesel generator could) induce much higher temperatures inside a structure. This creates a high risk situation whereby, if a fire were to occur, the entire structure and contents including the PV system could be destroyed. A fire may be ignited by any number of causes not related to the PV system.

Theft is not a high risk but it is one that still exists. PV systems have a low risk of theft as they are fixed to walls and rooftops. The component parts are large and bulky and the resale market is smaller and more specific than, say for a mobile phone. As the system is fixed to a structure, tools and more time are required to remove the parts, however the tools needed are often very common standard tools. The value of the parts, such as the inverter, is still high when new, since the size and price of an inverter may be equivalent to a new television. Thieves do not need to enter the premises in order to steal parts of the system and so do not need to bypass most existing security that protect the contents of a building. Although, for an individual criminal, it may not benefit them enough to steal a PV system, organised criminal gangs have used sophisticated methods to break into and steal new cars, motorbikes and ATMs. These large high value items can be stripped down to components and resold in other areas. The processes used by organised crimes could be targeted towards PV systems. Standard PV systems generally do not have any security that detects theft such as locks or other systems but products are available to increase the security of a system. Large commercial installations could be targeted as these may in remote locations with little security and little monitoring during night when not in operation. During the construction phase components and materials may be stolen when they are stored on the worksite before installation. Theft has been consistently mentioned as a concern by insurance brokers and underwriters [17].

5.4 System quality

On the few occasions where the PV system has caused a fire a few components appear to pose a higher risk than others. Junction boxes, connecters and inverters all have in the past been determined to be the cause of PV system fire in the past. Some key factors affecting the risk associated with components and connections is the quality of manufacture and installation, the higher the quality of parts and installation the more the risk is reduced. Some insurers add to the conditions of the policy that high quality parts be used and that accredited installers build the system. Additional steps to reduce risk due to aging of components could be to ensure maintenance and inspection is done regularly and accredited bodies update their regulations and offer training and refresher courses or seminars to installers. Much like the system for First Aid accreditation used in Australia whereby a longer initial course is undertaken and every 3rd year shorter refresher courses are required to keep qualified people qualified. These give the opportunity to teach any new methods or updated procedures to students. It is felt by insurers that, as long as the regulation is maintained, then no additional risk is incurred with insuring PV systems against damage. “Insurers feel that many claims for damage are avoidable” [13].By increasing the standard of installation quality and better designs that take into account more aspects of consideration, the risk of damage to system can be reduced. Sometimes known risk factors such as module and inverter quality are ignored in a systems design stage [13]. This could be for several reasons including reducing costs or simplifying considerations in order to reduce time spent on design.

5.5 Conclusion

PV systems are considered low risk causes of fire and damage. Some systems have been around for a long time and there have been a small number of claims. Insurance policies may cover the technology separately, potentially in the case of commercial projects or the policy may integrate the PV system into an existing home or building insurance (this is common for residential systems). Overvoltage, storms and theft are the main causes of claims. Overvoltage can be avoided by thorough electrical design. Storm damage is difficult to predict or protect against. Systems are often left unsecured with no anti theft mechanisms. Some component parts have a higher risk of causing fire such as junction boxes and connectors. The risk from these components can be reduced by increasing the quality of parts and installations and insurers are increasingly demanding higher quality systems and installations. Regularly updated and revised regulation increases the standard of system quality and installation and reduces the potential risks.

6. Arc Detector example TI SolarMagic RD-195 DC Arc Detection Evaluation Board

The device chosen to perform the experiments with was the Texas Instruments (TI) SolarMagic RD-195 DC Arc Detection Evaluation Board. This device was chosen as it is specifically designed to perform the task of arc detection in solar PV systems.

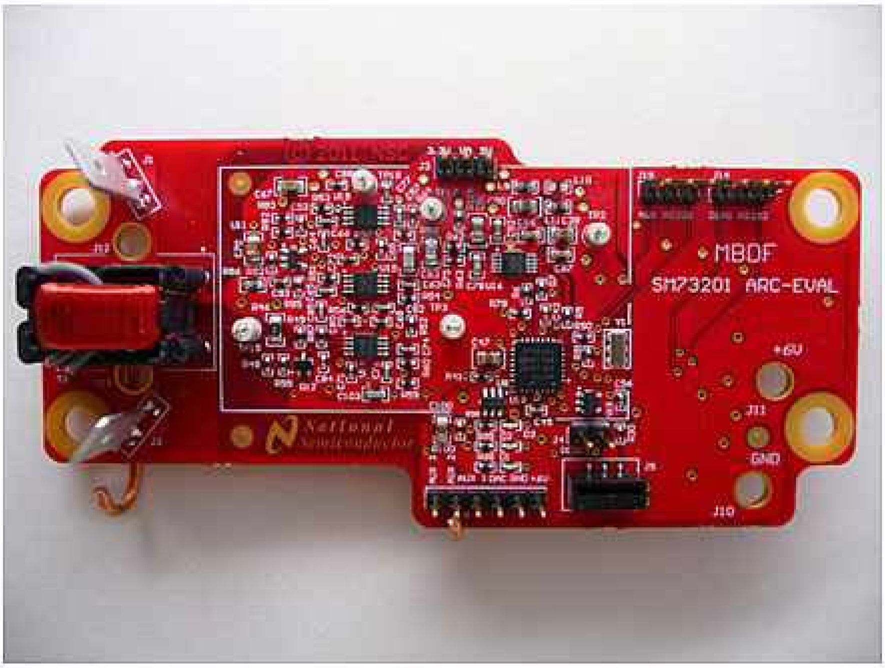

Figure 3 Texas Instruments SolarMagic RD-195 DC Arc Detection Evaluation Board

Other reasons why this product was chosen were: the price was in the range of the budget available and it was easily and immediately available through online purchase. Features of the device that are of interest are the 1000V DC isolation, maximum string current capability of 15A DC and a simple LED arc detection flag. Other devices considered will be discussed later (7. Other devices) but most were not available for a variety of reasons. Some were still in the testing development phase. Other devices were not readily available as an individual purchase but rather sold in larger numbers. Some other devices performed the arc detection as one of its functions and was only available as part of a complete system with inverter and other communication and networking devices and would not function independently.

6.1 Theory of operation

There are a number of different methods that can be used to detect arcs and these are discussed in conjunction with the other devices considered. The TI device detects the noise that an arc emits in the string current of an array.

It is simpler and cheaper in a technical product to try to detect an arc in a limited frequency band rather than over the whole spectrum. It is easier to select components in a design with a limited spectrum. For this device a band of frequencies was selected to be the area in which the device searched for arcs. Arc detection noise in the band of frequencies between 40 kHz and 100 kHz was chosen for this device by the manufacturers. The spectrum of the noise created by an arc has a Gaussian or Normal distribution that extends to several MHz [2]. This was demonstrated in the experiments performed and discussed later. Above 200 kHz the intensity of the noise current varies significantly with frequency between different systems. This is typically due to the arrangement of cabling in a PV system. The long cables and loops act as antenna boosting certain wavelengths depending on the cable layout. The effect of the cable impedance increases with frequency and length. In different systems with different cable length and arrangements the effect of the cables varies. Inverters used in PV system typically employ switch mode controllers on the DC which cause high levels of noise at the switching frequency on the PV array string wiring. The switching frequency of these controllers is below 50 kHz in most cases. The frequency band 40 kHz to 100 kHz avoids the significant problems of switching frequency noise below 50 kHz and the significant variability above 200 kHz. However other services such as maritime radio navigation and standards time services use frequencies from 50 kHz to 100 kHz, these signals are eliminated in this device after an analogue to digital conversion by digital processing by a microcontroller.

6.2 System implementation

A block diagram of the system is shown in Figure 4. The way that the arc detection system is implemented is that the string current is fed through the primary winding of an isolating current transformer, the secondary winding picks up the AC component of the all the noise. This is amplified and filtered and then fed to an analogue to digital converter (ADC). The digital signal is processed by a microcontroller which looks for the characteristics signal of an arc. The device has a rating of 1000 V DC and up to 15 A DC and the isolating transformer needed to be able to meet these requirements. A reasonably sized transformer that meets these requirements has a relatively low magnetisation inductance and this means that the noise signal at the secondary is relatively low which means that the amplification is needed. The analogue to digital conversion is performed by the SM73201 which is a 16 bit, 50 kSPS (Samples Per Second) to 250 kSPS sampling analogue to digital converter. [18]

Figure 4 System diagram

7. Other devices

Only one device was chosen to conduct the experiments with although other products were considered. However, with the others, there were problems primarily with availability or cost.

7.1 Methods of operation

DC arc detection/preventative devices can be broadly classified according to their method of operation and include; micro inverters, power optimisers and standalone devices.

7.1.1 Micro inverter

Micro inverters significantly reduce the risk of DC arcs occurring by housing a small inverter on the module and transferring power through AC cabling. This removes most of the DC cabling and so there is much less need for DC arc detection because the DC connections and cables which are at a high risk of arcing are removed. Micro inverters are currently less efficient than larger string inverters but they can operate a PV module at its maximum power point and DC cable losses are reduced.

7.1.2 Power optimiser

Power optimisers often are DC to DC converters which find the MPP of a module and then output power at a certain voltage so that the power from each individual module is maximised rather than the inverter using the MPP of the array as a whole. Some devices detect the sudden change in power caused by an arc and reduce the power output or the module to starve the arc of current and eliminate it. Reducing the power output of the modules will eliminate both series and parallel arcs as the current is reduced from the source in both cases.

7.1.3Stand alone device

The stand alone device is dedicated to arc detection and has the capability to generating a signal which can they be used to operate a disconnect switch or activate an alarm in the case that an arc is detected. These devices may be cheaper and easier to retrofit into an existing system.

Table 1 provides an overview on arc detection devices or products incorporating DC arc detection. Some more details of these products are provided following the table. If the devices do not specifically have an arc detection capability then they have some other mechanism that significantly reduces the risk of arcs.

Manufacturer	**Primary Purpose**	**Model**	**Market Launch**	**Arc Detection**	**Website**
AMPT	Power optimizer	V40-x	Launched	Yes	www.ampt.com accessed on 24th April 2013
Azuray Technologies	Power optimizer	AP260	Launched	No	www.azuraytech.com accessed on 24th April 2013
Ehw Research	Power optimizer	Smart Power Booster	Launched	Not specified	www.ehw-research.com accessed on 24th April 2013
SolarEdge	Power optimizer	OP250-LV	Launched	Yes	www.solaredge.com accessed on 24th April 2013
Newtos	Arc detector	ARC D01-06	Not launched	Yes	www.newtos.com accessed on 24th April 2013
SMA	Inverter	Sunny Boy 3000-US	Launched in USA	Yes	www.sma-america.com accessed on 24th April 2013
Enecsys	Micro inverter	SMI-S240W-60	Launched available in Australia	No	www.enecsys.com accessed on 24th April 2013
Altenergy Power System Inc.	Micro inverter	YC200-EU-SAA	Launched available in Australia	No	www.altenergy-power.com accessed on 24th April 2013
Texas Instruments	Arc detector	SM73201	Launched	Yes	www.ti.com accessed on 24th April 2013
Sunvision	Power optimizer	SPC Power Optimizer	Not launched	Not specified	www.sunvisionsrl.com accessed on 24th April 2013
Tigo Energy	Power	Module	Launched in	Yes	www.tigoenergy.com

	optimizer	Maximiser MM-2ES	USA		accessed on 24th April 2013
Dorfmuller	Micro inverter	DMI 350/35	Launched in Germany	No	www.dorfmueller-solaranlagen.de/de/ accessed on 24th April 2013
MidNite Solar	Charge controller	Classic 150	Available	Yes	http://www.midnitesolar.com accessed on 24th April 2013

Table 1 Arc detection devices

AMPT produces the V40-x which is an external add-on to the junction box on a single module. The device is programmable, when using a proprietary program and this is available as a package with a number of devices. The price for the software package was above the budget available of less than 1000 AUD.

The Azuray TechnologiesAP260 is a power optimizer fitted onto the junction box of individual modules and requires signals from an additional ACM300 Communications Gateway. This added increased complexity and increased the cost above an acceptable level for a simple system with only one power optimizer used for testing.

Ehw Research produces the Smart Power Booster. This is a single device with many individual inputs for single modules. The many other inputs would be wasted in an experiment using only one small array. The cost of the device is unknown and the device has not been released and is not available.

Available in the USA the SolarEdgeOP250-LV is a power optimiser that can be retrofitted to modules and is controlled by a communications gateway and an inverter. The device has arc detection and elimination and additional safety for installers and fire fighters, being able to control the output of individual modules to reduce their output during installation or a fire and then operate at maximum output when the system is working correctly. Though not available in a single device and the price of the system required for the devices to act with arc detection and elimination feature was too expensive.

ARC D01-06 by Newtos is a dedicated arc detection only unit in the final stages of development and entering further development to incorporate it into inverters.

SMA has released in the USA an inverter the Sunny Boy 3000-US with built in arc detection and DC disconnecting. Though not yet available in Australia the price would be too high to buy a whole inverter just for the arc detection experiment.

Enecsys sell a micro inverter, the YC200_EU_SAA. Micro inverters reduce the risks of arcs by significantly reducing the DC cabling in a PV system. This micro inverter is for sale in Australia for orders of large numbers. One micro inverter is installed on each module.

The Texas Instruments SM73201 is a dedicated arc detection unit. Within the price range as it is a standalone device with no need for additional communications or other equipment.

Tigo Energy sell in the USA a power optimiser called the Module Maximiser MM-2ES which connects to individual modules and is controlled by a central communications gateway device. The total cost of a system that would have arc detection and elimination capability would be too high.

Dorfmuller have released in Germany a micro inverter, the DMI 350/35. Micro inverters reduce the need for DC cabling and so reduce the risk of DC arcs.

Midnite Solar PV system battery charge controllers, one of which is the Classic 150 have the ability to detect and eliminate arcs integrated into the device. They can detect arcs without the need for other additional equipment and are available in Australia but prices are too high for the allocated budget of 1000 AUD.

8. Controlled arc creator

8.1 Introduction

A large part of this thesis project was concerned with testing the Texas Instruments SolarMagic RD-195 DC Arc Detection Evaluation Board and the associated experimental setup. In order to successfully carry out the experiments a setup for creating a safe and reliable arc was required. The device was required to have a point that acted as a normal low resistance contact to allow current to flow and then by some method to open that contact point creating a gap with the current continuing to flow creating an arc across the air gap. The first point of research in this area was to find publications which were based on experiments conducted with arcs and with DC arcs of particular interest. Through these publications ideas for designs and methods to implement arcs were collected. Three devices were found that were used to demonstrate DC arcs by other parties. The first one was used in a public demonstration and used with the TI device chosen for this experiment. The second was a part of a demonstration by SolarEdge with their PV system which included an arc detection feature. The last one was used in an experiment that looked at how long it takes for the arc to burn through the plastic cable sheath.

8.2 Chosen design idea

The preferred design idea for the arc creation device to be used in the experiment for this thesis is the screw-based design. This design was chosen because it allows for the greatest degree of control of the gap distance whilst still being easily adjustable and enclosed for safety. A reason it was chosen over the lever based device is that the screwing action allows the operator to be further away from the arc and to have more insulating objects between the operator and the arc, whereas the lever design only has one layer of insulation between the metal directly in contact with the arc and the operator. An example of the lever idea can be found at [19]. The lever system operates using a metal bar bolted at one end to a stand. The end of the lever is a handle used to adjust the position of the metal bar. On the stand there is a metal contact point that can touch the metal bar between the bolt and the handle. The bolt has enough friction to hold the bar steady when not being touched and also allows movement of the bar when pulled by an operator. The screw design also allows finer adjustment of the arc distance than the level method which would require increasingly longer levers to allow finer adjustments. With a lever rotating about a point as it is moved away from the connection point the distance the lever is moved does not have a linear relationship with the increase in gap distance. Also it is important to be able to fix the gap distance. A lever that is easy to adjust will be difficult hold in a specific spot. Alternatively a lever that is stiff and stays in the same position with be hard to make fine adjustments. When using a screw system one turn of the screw gives the same increase in gap distance every turn. The fixed gap design allows for easily repeatable experiment at the same gap distance but this was not a requirement of the experiment to be conducted. The fixed gap design shown in [20] initially requires a fine wire to be placed between the electrodes and when a current passes through it heats up and burns away and allows the arc to cross the gap, an issue with this is that the wire needs to be replaced every time after it burns up and there is a wide range of voltage and current levels that would melt the wire which would not be sufficient to sustain an arc. Once an arc has been established in the fixed gap design it cannot be extinguished by moving the electrodes apart which can be done by the level and screw designs. The screw design allows for more easily adjustable and repeatable gaps. For example, given the same power output of the DC supply, whether it be power supplies or PV array, when the electrodes are screwed apart a number of turns to the point where an arc cannot be sustained, to get the maximum arc length the next time the screw can be turned slightly less in total to get the largest arc in that situation. Overall the screw design offered higher safety with more insulation, accurate adjustable control of the arc gap distance and faster repeatability.

8.3 Development of controlled arc creator

The device went through a few stages of design (see figures 5, 6 & 7) with the initial plans based on the device shown in the SolarEdge demonstration [21]. The first plans try to replicate the demonstrated device with a clear glass shell housing the screw mechanism and moving electrodes. Glass was chosen at first because it would insulate against the potentially high voltage components, it is clear so the arc could be able to be observed. Also a suitable glass tube was available to be used. The disks in the middle would be made of wood or plastic as these materials could be easily shaped, were electrical insulators and had some resistance to heat build up in the electrodes. The original idea was to make the electrodes out of tungsten. Tungsten is often used in TIG welding electrodes, which is a similar situation in which a controlled arc is created. Tungsten would have been a better metal to use but in the actual build of the design copper was used. Tungsten has some properties that make it more desirable in this experiment than Copper. Tungsten also conducts electricity well and has a high melting point so it would not be severely eroded by the arc. Copper was available and easier to machine. Copper has good electrical conductivity and during the experiment proved that is was a suitable material. The copper electrodes were not severely eroded or damaged by the heat of the arc. The ends of the electrodes would be shaped, one would remain mostly flat and the other would be machined to more of a point but still with a small flat tip. When the electrodes were connected together the surface area of the joint would be approximately the same as the cross sectional area of the wires carrying the current in the system (around 2.5mm^2). This would help to simulate a break in the wire.

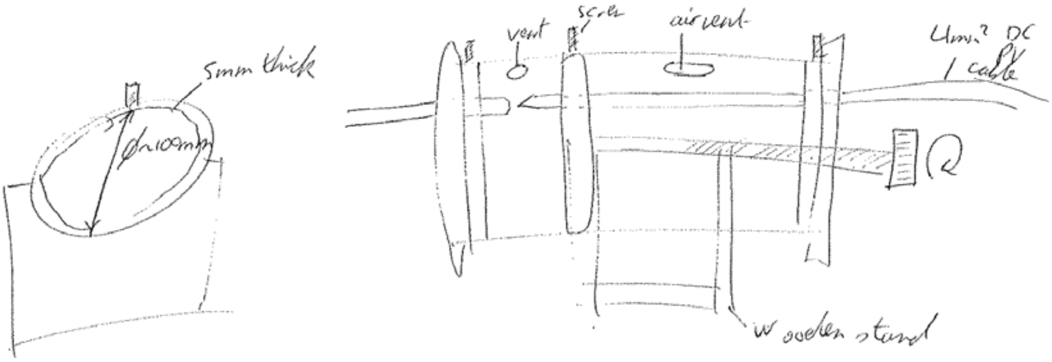

Figure 5 Initial drawing for controlled arc creator

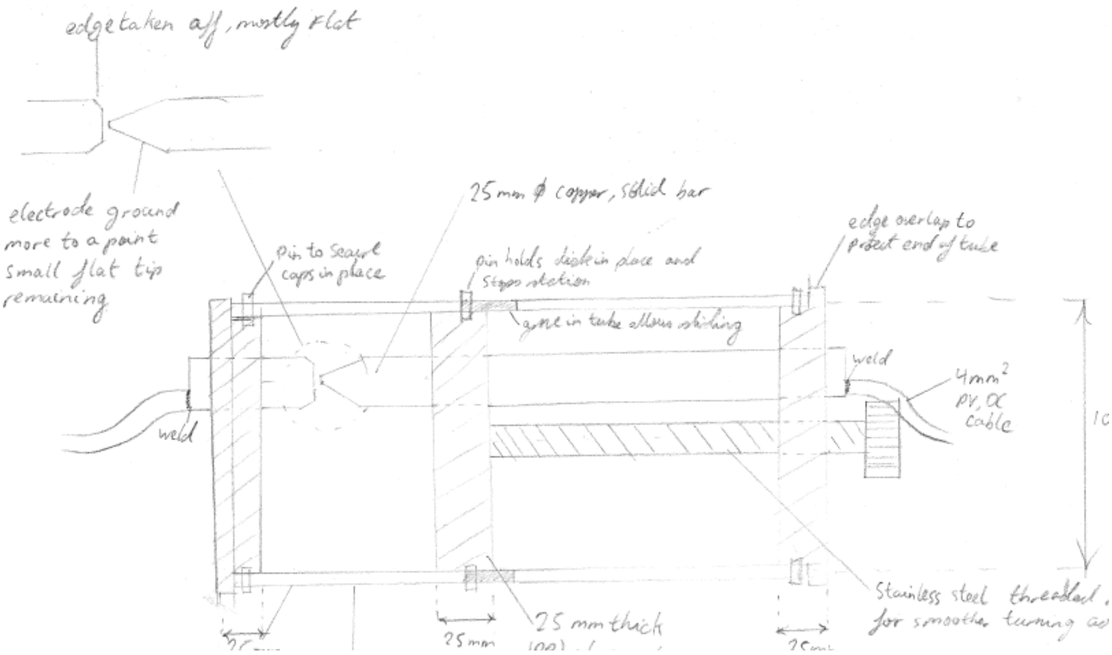

Figure 6 Refined drawing for a controlled arc creator

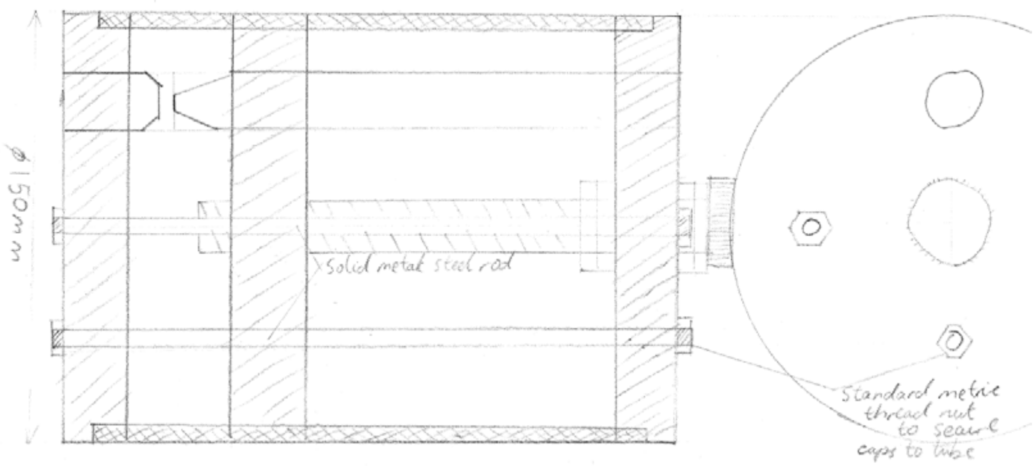

Figure 7 Simple drawing for controlled arc creator

The electrodes would be made of a solid copper rod much thicker than $2.5mm^2$. The rod was approximately $25mm^2$. This larger piece of metal would be able to absorb more heat from an arc so experiments could be run longer single runs, without the electrodes heating up to unacceptable temperatures where they might damage their mountings.

The arc creation device that was actually built was of a simpler design than originally planned (See figures 8, 9 & 10). The electrodes were mounted in a piece of insulating wood and mounted onto a vice for the screw movement action. Initially the electrodes and mounting were not enclosed in a glass tube and were open. The reasons for this are that there was concern that there would be gasses, smoke, molten metal slag and corrosive build-up on the electrodes caused by arcing and the open design allowed for easy maintenance, free flow of air and better passive cooling of the warming electrodes. There was a degree of slack as the vice was opened and closed, but small increases to the size of the gap could easily be made. Tapped bolt holes were drilled into the ends of the electrodes to enable easy connection of wires. Given the large diameter of the copper electrodes this meant there was a low residence between the arc and the probe, so that when high voltage probes were connected to the end of the electrodes it was possible to get accurate readings of voltages across the arc, without exposing the probes to the heat of the arc directly. High voltage probes were used to protect the oscilloscope. The voltages spikes expected during the transient phase of arc creation were likely to exceed the voltage ratings of the standard probes.

A PVC tube replaced the metal handle of the vice to better insulate the operator from the live electrodes. An enclosure was created to prevent accidental contact with any live parts and to block direct eye contact with the arc for other personnel in the area. A viewing port was added to the enclosure with a screen that partially filtered UV light in order to reduce the hazard from the arc light damaging the eye. The filter reduced the light seen but when the arc existed it was still easy to observe the arc with the naked eye and film and photograph the events.

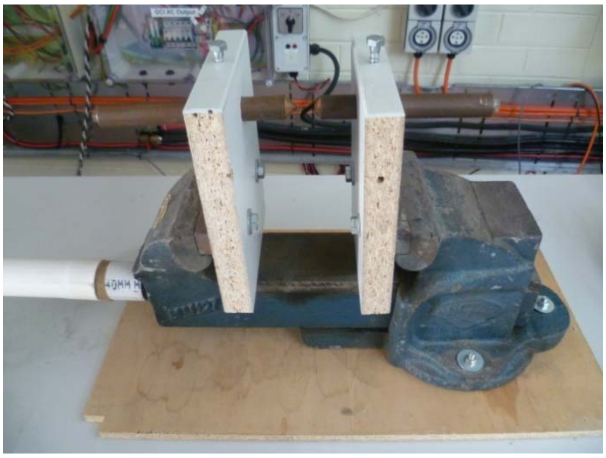

Figure 8 Simple open build of arc creation device

Figure 9 Arc creation device enclosed for additional safety

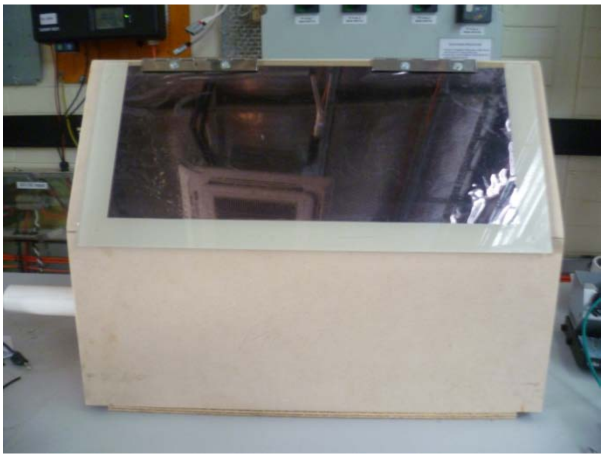

Figure 10 UV filtered viewing port added on to device enclosure

Improvements could be made to the device by reducing the overall weight and size to the point where the device may become portable. Weight could be reduced by replacing the bench top vice screw mechanism with another lighter small mechanism as large forces are not required to connect the two electrodes. A portable device could be more easily setup on the roof of the laboratory near the photovoltaic array to create an arc connected into the junction box on the roof. An arc in an area exposed to the elements would be a more realistic situation than having the arc some way along the array cable sheltered inside a building. With a longer cable from the arc to the detector the inductance of the cables acts as a low pass filter, reducing the magnitude of the noise created by the arc, making it more difficult to detect an arc. A longer cable acts a better antenna, picking up more unwanted background signals. With the arc close to the PV array and the minimum distance of cable to the inverter if the experiment were repeated this may produce results with less unwanted background noise and a clearer noise signal from the arc. This would also be more representative of a possible real situation where there are no additional loops of cable unnecessarily extending the distance between arc and inverter.

9. Testing

9.1 Introduction

Part of this thesis is concerned with arc detection, what methods can be used and how they are implemented into some systems. The experiments conducted focused on determining the capabilities of one device. The device was tested in a real and existing PV system. The experiment also tested whether the device could perform even when there were some factors present that could have adverse effects on its performance. Long cable lengths and noise from other sources most notably the inverter, these sources of interference may make the arcing noise more difficult to detect for the device.

The aim of the experiments were to test the stated capabilities of the TI arc detection device in terms of detecting DC series and parallel arcs in a real PV system.

The objectives of the experiments are:

- To artificially create a contained arc that could be controlled safely;
- To test the TI arc detection device to see if it does detect arcs; over long cable lengths, with noise from an inverter present;
- To test the TI arc detection device to see if it does detect both series and parallel arcs;
- To observe and record the oscilloscope FFT spectrums of series and parallel arcs.

The experiments comprised of three key parts. The first experiment used a low power setup that used DC power supplies to provide power to the arc. The second and third experiment used the PV array on the top of the laboratory building as a higher power source and to provide a setup closer to a real situation. The second experiment used a series arcing setup and the third experiment was a parallel arcing setup.

The aim of the first experiment was to test the arc creator device and to establish that an arc could be created using the device and to find the lowest voltage and current that could be used to create a sustainable arc. The emphasis on a lower energy arcing was there to increases safety and to decrease the potential damage that an arc could do by limiting the power available and using readily controllable power sources. The idea was that the DC power supplies could provide power more consistently and at a repeatable level of voltage and current. Rather than the PV array where the power output varied over the course of the day and minute by minute depending of clouds, wind gusts, shading from tress and other factors. It could also be shut down with an emergency switch if required.

Once it was established that arcs could be created using the arc creation device, the experimental setup was moved to Murdoch University's Engineering and Energy laboratory. The second experiment required using the configurable PV array on the roof of the building and the grid connected inverter to simulate a more realistic situation where an arc may occur. The third part was a simple reconfiguration of the second experiment to artificially create a parallel arc. The setup was moved to enable the other objectives of the experiment to be completed using long cable lengths from the roof to the inverter on the ground floor. By using a more powerful power source, arcs could more easily sustain a larger gap length.

9.2 List of equipment

- Texas Instruments SolarMagic RD-195 DC Arc Detection Evaluation Board
- BP Solar BP 275F x10 solar panels
- Dick Smith Electronics Q1770 30V 2.5A DC power supplies x3
- SMA 5000TL-20 grid connected inverter
- Arc creation device
- DC resistive load
- Tektronix TPS2012 oscilloscope
- High voltage oscilloscope probes P5122

- Protek 506 Multimeters
- Calibrated shunt resistance 1mΩ
- ~60m PV array cable
- Various cables and connecters

9.3 Method

9.3.1 First Experiment: Primary system testing with power supplies

The setup consisted of a series loop (as shown in Figure 12). In the loop were two series power supplies, the arc creation device, the TI arc detector, and the calibrated shunt resistance in series. High voltage oscilloscope probes were connected to the external ends of the arcing electrodes to measure the voltage across the arc, standard oscilloscope probes were connected across the shunt resistance to measure the current through the circuit and multimeter probes were also connected to the same points as the oscilloscope probe to display waveform shape and Fast Fourier Transform (FFT) data. Each power supply was at 30V to create a total of 60V being supplied. The TI device was powered by the third power supply set to 6V as recommended in the manual [2].

To create an arc the arcing electrodes were pulled apart, the power supplies turned on and then the electrodes were pushed together. Once current was flowing they were pulled apart again to create an arc. The arc was extinguished either when the gap was too wide or the power supplies were turned off.

9.3.2 Second Experiment: Series arc

The rooftop array was configured to have 10 modules in series. The setup is visualised in figures 11 &12. There were three runs of cables running alongside each other from the roof to the ground floor. They were approximately 10m for length each. The array was connected to the arc creation device from one run then the circuit continued back up to the roof where it was connected to the last run and came back down to the ground floor where it was connected to the arc detector and the inverter. This setup allowed the arc to be physically located as close to the array as possible whilst maintaining electrical separation. The apparatus was too bulky and heavy and it would have been dangerous to transport and set up on the roof. The extra runs of cables also allowed the tests to determine if the extra distance along the cables affected the performance of the arc detection circuit as it was further away from the arc electrically. The resistance and inductance of the cables could act as a low pass filter reducing the magnitude of the arcing noise that the device is trying to detect. Also a long cable length may act as an antenna magnifying unwanted background noise in the same frequency range as the device is searching for arcing noise. A reduction in the arcing signal and an increase in other interfering signals may make it more difficult for the device to detect arcs.

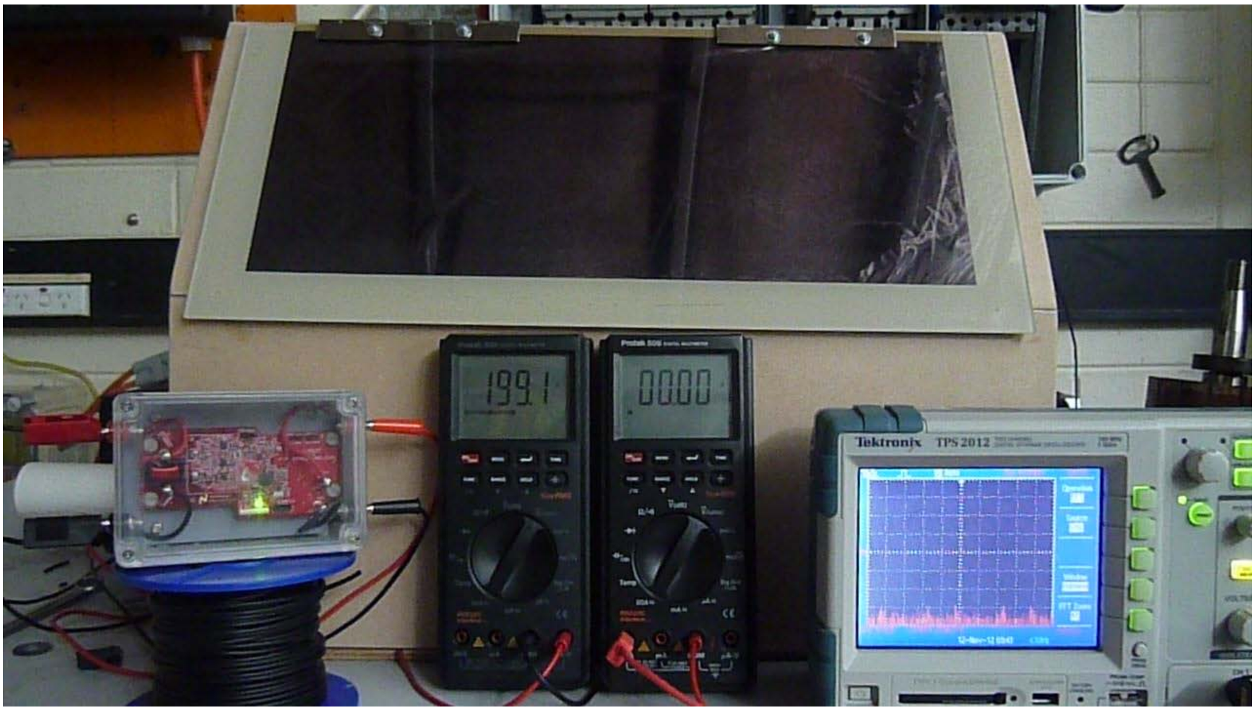

Figure 11 Setup showing data collection equipment

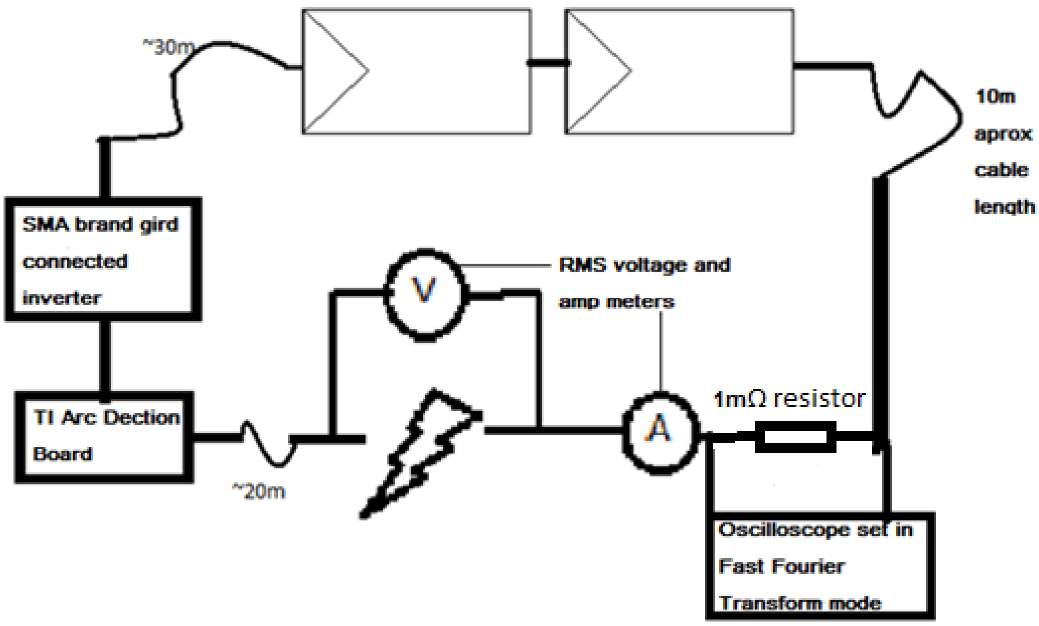

Figure 12 Sketch of series arc setup

9.3.3 Third Experiment: Parallel arc

To create a parallel arc, (for setup see figure 13) the wires on the ground floor were reconfigured so that they created a short circuit in the array cabling. The inverter and the arc detection device were still electrically separated from the arc by two runs of cable.

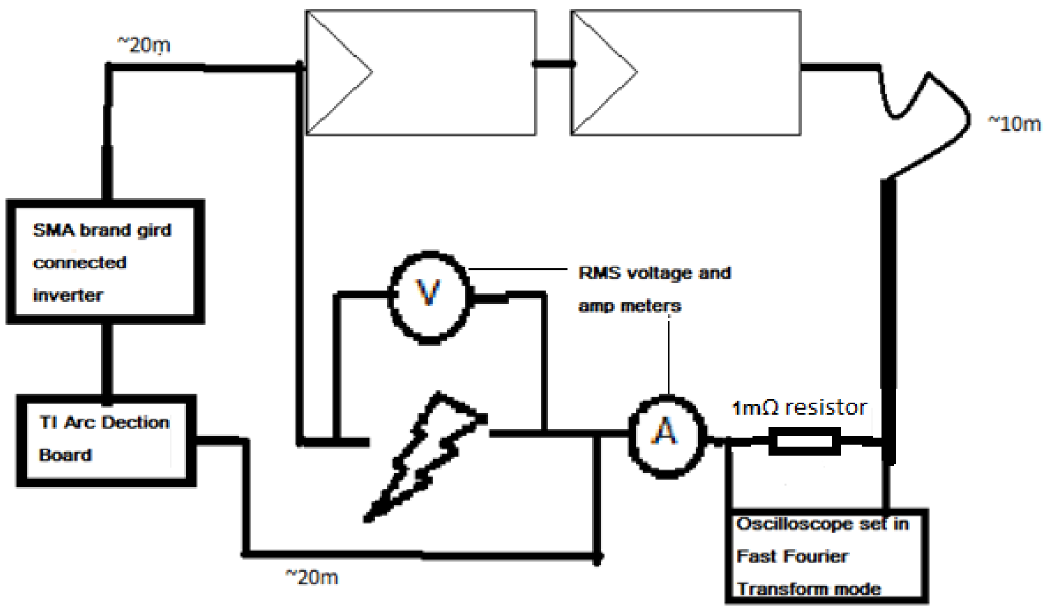

Figure 13 sketch of parallel arc setup

9.4 Results

The arcs were created safely in a contained environment with physical protection to the operator from shocks and a filter on the viewing port protecting the eyes of observers. The screw device operated consistently and as expected.

In all experiments whenever an arc was successfully created the TI arc detection device detected them. It detected both series and parallel arcs. Small arcs were detected before they were visible through the viewing port. It detected all arcs along the extended runs of cable and detected arcs when the inverter was operating. It did not produce any false positive results from picking up any other sources of noise such as the inverter. The situations tested were:

- DC power supplies with a series arc
- DC power supplies with a parallel arc
- Solar array with series arc
- Solar array with series arc and operating inverter
- Solar array with parallel arc

- Solar array with parallel arc and operating inverter

These screenshots (figures 14-17) were collected from the oscilloscope in Fast Fourier Transform mode. The figures show the current signal captured without an arc and with an arc. And the figures have a narrow range of frequencies and a wider range to show to spectral distribution of the noise. The setup used the solar array for power, it was a series arc, and it did not include an operational inverter. The other experiment setups produced very similar results.

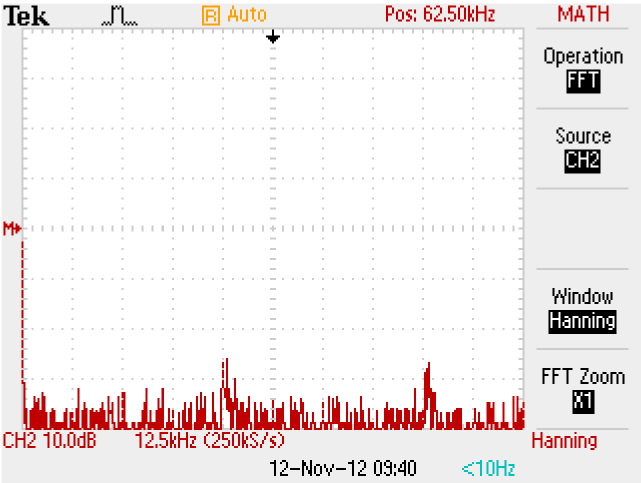

Figure 14 no arc narrow spectrum (12.5 kHz/div 0-125kHz)

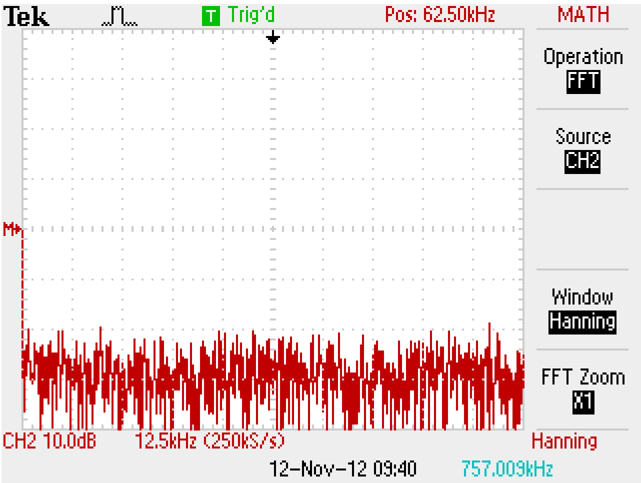

Figure 15 arcing narrow spectrum (12.5 kHz/div 0-125kHz)

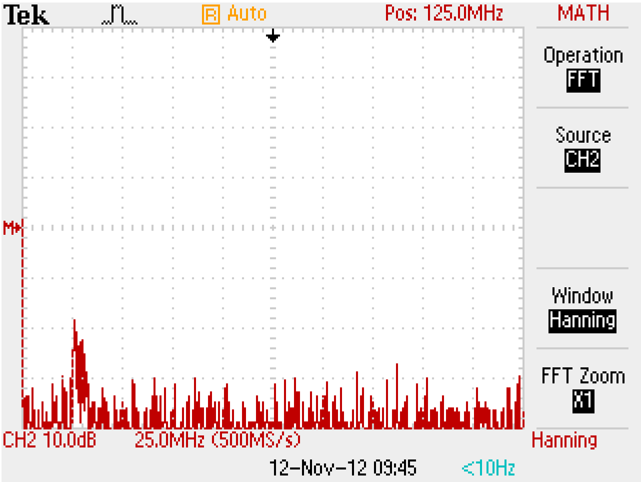

Figure 16 no arc wide spectrum (25 MHz/div 0-250 MHz)

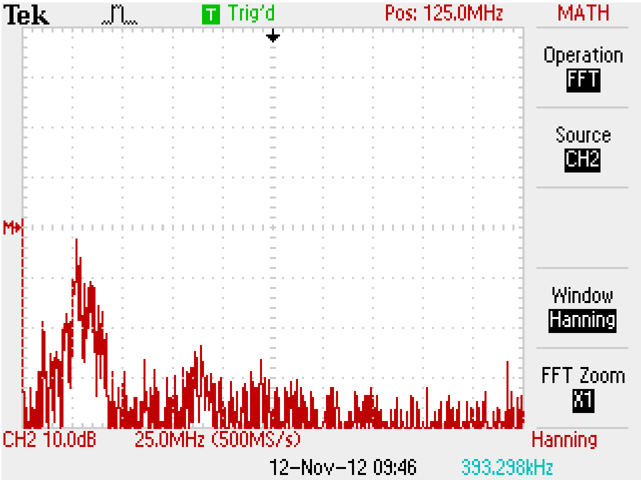

Figure 17 arcing wide spectrum (25 MHz/div 0-250 MHz)

The narrow spectrum results show the FFT over the frequency range 0-125 kHz and the wide spectrum results show from 0-250 MHz. Both no arcing images show the background noise being picked up from the cables acting as antenna. The narrow band arcing image shows increased amplitude of noise across the spectrum measured. The wide spectrum with arcing (Figure 17) shows an increase in noise at certain frequencies, it shows a likeness to a normal distribution for the main peak with subsequent smaller peaks at higher frequencies.

All arcs, the preliminary, series and parallel arcs appeared to be very similar to the results shown. The results presented in figures 14-17 are from the second experiment using the rooftop array and a series arc. Results could not be obtained from the preliminary tests with power supplies and with parallel arcs as the arcs could not be sustained for periods of time long enough for sufficient data to be gathered. The solar array could supply a maximum of 4.5A to 5A at times of peak solar radiation this current produced the most stable and largest arcs. At 2.5A the arcs could not be sustained for long and quickly extinguished as they were extended.

9.5 Discussion

The preliminary testing to identify what was required to create an arc and to get preliminary data as to the voltage and current across the arc, as well as the FFT of the arc current was perhaps the most informative. The DC power supplies were used to keep the experiment relatively safe, however, the power supplies used were designed to act as current limited voltage sources whereas a PV array acts more like a current source. When the series circuit was energised and short circuited the power supplies had the current limited by their own internal protection systems. When the gap was opened and an arc created, this changed the impedance of the circuit and the internal control of the power supplies reacted. The power supplies performed more as constant voltage source rather than constant current sources. The power supplies did not supply to same current continuously. For an arc to be sustained it is more important to have uninterrupted and sufficient current rather than voltage, so when the current output of the power supplies changed, this disrupted the arc and it extinguished very quickly. To partially overcome this problem, inductors were added in series to the circuit to help maintain the flow of current. This worked somewhat. Longer arcs could be sustained for more time but the thin wire of the inductors heated up quickly so arcs could not be run for more than a few seconds. Once an arc started there were approximately 20 volts across the arc and the arc voltage increased quickly with arc length and with two 30 volt power supplies in series producing 60 volts there was not sufficient voltage being produced by the power supplies to extend an arc. The DC power supplies were not powerful enough to create and sustain an arc for long and only produced a fraction of the DC power that could be reasonably expected to be produced in a small grid connected photovoltaic system. A small arc can be created with an arc voltage of 30V and a continuous current of 2.5A. All arcs in this experiment produced high temperatures at the point of the arc. Even in a small and relatively low power arc, the high arc temperature could melt cable insulation and start a fire. If the arc gap widened by a small amount there would not be enough power to sustain a larger arc, without sufficient current or voltage the arc will extinguish. More power supplies could have been added in series and parallel, this would have made the setup larger, more cumbersome. Additional power supplies were not available, the best way to increase power was to use the solar array.

The second part of the experiment produced more fruitful results. Series arcs could repeatedly be created and sustained long enough to collect good oscilloscope FFT readings. Ideally the arc would have been created on the roof near to the array as this is the most likely place for damage to cables and connections to occur where there are many connections and are exposed to the weather UV and possible rodent bites. The arc creation device was too heavy and cumbersome to place on the roof so it was setup within the laboratory. The open circuit output of the array was very close to 200V and the modules had a short circuit current of 4.75A (this was much greater than the 60V and 2.5A used in the preliminary experiments). The array produced much larger arcs and arcs that would have continued for some time without interference. In one video of the experiment, a reasonably sized arc is created and left to continue for 2 minutes. That arc would have continued but the experiment was stopped to ensure that damage was not done by overheating the electrodes.

During the design of the arc creation device there was a concern that carbon or oxide deposits would build up and create an insulating layer that prevented current from flowing and arcs from forming. After repeated use black deposit did appear on the tips of the electrodes and built up to the stage where when the electrodes were contacting there was a high resistance and minimal current flow, preventing arcs. The open design allowed for easy access to the electrode tips and the build-up was easily removed with steel wool and sandpaper. After repeated or prolonged experiments there would be a noticeable smell of ozone but the large viewing port allowed plenty of ventilation when it was opened so the build-up of hazardous ozone gas was not a problem.

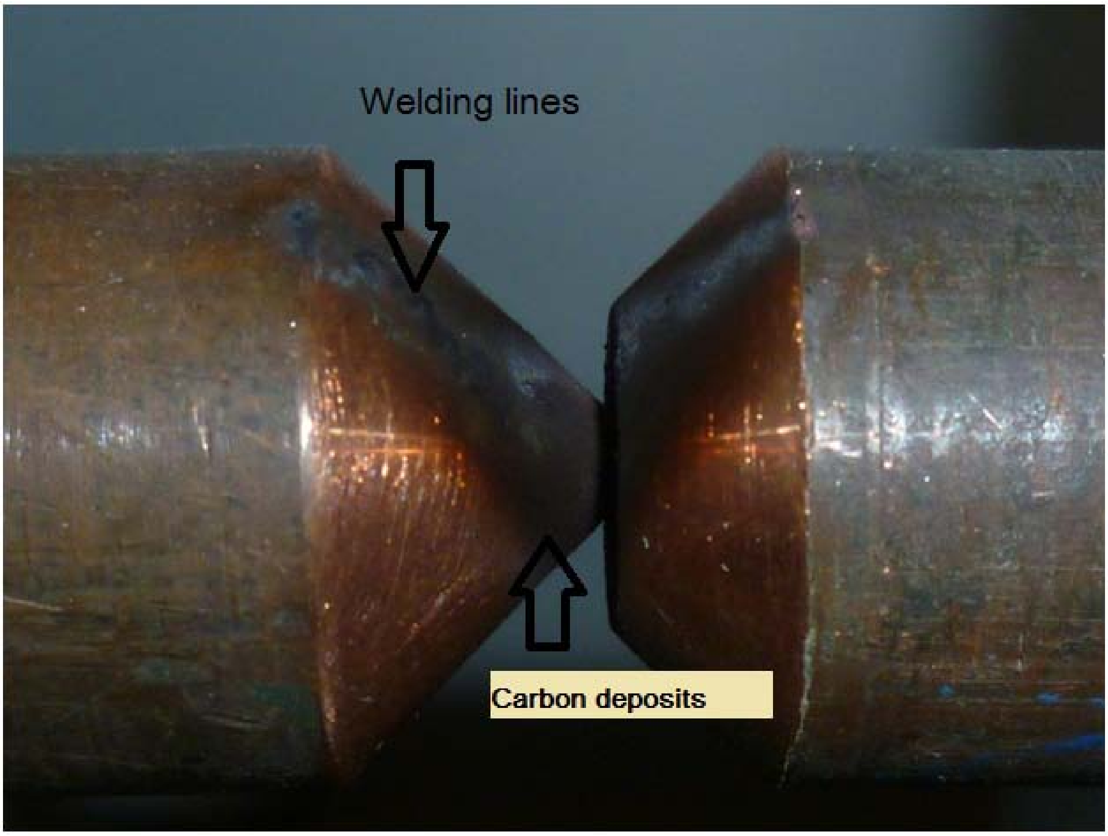

Figure 18 Close-up of electrodes showing deposits and welded lines from arcing

The arcs produced by the electrodes were green in colour (figure 19). It is believed that this is from ionised particles of copper. Along with the black deposits on the electrodes there were additional lines caused by the arc rising up. In an ideal situation the arc would follow a straight line of the shortest distance between two points, from images of the arc itself and visual inspection of the electrode it appears that the arc rises, somewhat like a flame. The effect is more pronounced as the arc gap becomes larger. One explanation for this is that the intense heat in the arc heats up the air and the air raises and as the ionised air rises the arc follows the path of least resistance which is not a direct line, but rather a curve through the ionised air which has moved upward. This could also act as a natural mechanism to extinguish the arc as it gets larger. As the arc gap increases and heats the air, the air flow forces the ionised air up and increases the distance the arc travels so making the arc more unstable and the flow of fresh air may thin out the ionised particles making a less suitable path for arcing so the arc extinguishes. As the arc gap was larger it appeared that the arc curved upward became larger and flickered as would a flame (figure 20) before extinguishing. Also noted was that, sometimes when the inverter was operating in series with the arc and exporting energy, the inverter would shut down if the arc got too large. A possible reason for this is that as the arc gap increases so too does the voltage across the arc which means that the voltage at the inverter is reduced as it has already had a significant drop over the arc. This additional voltage drop then reduces the voltage at the inverter to below the lower operational limit and it switches off due to under voltage on the DC input side. This could have been checked by measuring the DC voltage at the inputs of the inverter.

Figure 19 Green coloured arcs

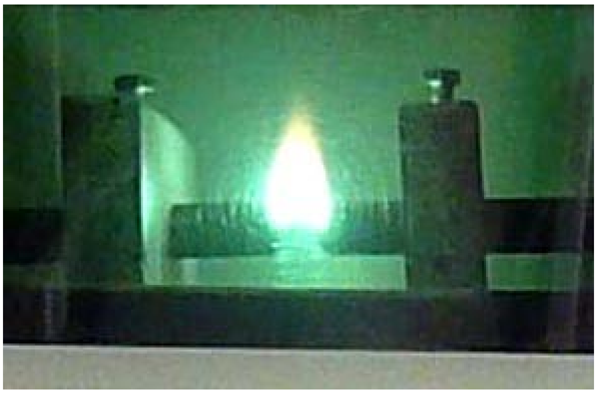

Figure 20 arc rising

The third experiment was concerned with parallel arcing in the array cables was also difficult to record results for. The idea of the setup was that the arc would be in parallel with the operating inverter. It was found that in the preliminary tests that to sustain an arc, a current of at least 2.5 amps was required. Any less and the arc quickly extinguished. The short circuit current of the single string of modules was 4.75A and once the short circuit was created to start the arc, there was insufficient current to the inverter and it shut down. And when the electrodes were pulled apart, the arc quickly extinguished as some current flowed to the inverter and there was not enough current supplied to the arc to sustain it.

The FFT produced from the arcs gave some positive results but were not entirely as expected, as they did not have some characteristics that were expected. The arc did significantly increase noise which was expected and confirmed. However the captured FFT in the narrow spectrum band from 0 to 125 kHz displayed a uniform increase in noise above the non arcing background noise across that frequency. In both the narrow band and wide band analysis switching noise from the inverter was also not evident but is it was expected. The transformerless inverter probably used utilizes a switching frequency below 50 kHz, this was in the range of the frequencies analysed. It is possible that the high quality SMA inverters do not produce much hard switching noise on the DC side as there may be filters that block this between the DC inputs and the switching devices. Information about the exact switching frequency and internal layout of this exact model of inverter is not readily available. The wide band FFT showed that the background noise was not uniform but had a peak around 25 MHz. The wide band arcing showed a peak noise around 25 MHz as well with an approximately normal distribution and a smaller peak around 82.5 MHz. Although the oscilloscope and probes used had the appropriate frequency ranges for these arc FFT's they did not have particularly good fidelity. The amount of background noise shown in the non-arcing FFT's could be in part due to the equipment used, that is not designed primarily for analysis a range of frequencies. It would have been better to use a spectrum analyser instead of an oscilloscope but the equipment was not available and a purchase was not justifiable for these experiments. Voltage probes over a resistance were used to obtain the arc FFT because the voltage probes had a larger frequency range than the current clamps available. The current clamps had an upper limit of 100 kHz which would not have been sufficient for the wide band FFT analysis.

9.6 Conclusion

A device was designed and built that safely and constantly created an arc. The TI arc detection device worked for all situations tested. It detected series and parallel arcs as well as detecting arcing over long cable lengths and with an operating inverter. The device did not give any false positive arcing messages. The FFT's confirmed what was expected in that arcing creates noise significantly above the background noise. What was seen was a uniform increase in noise in the narrow band frequency analysis not the expected distribution. There was an approximately normal distribution shown in the arcing noise in the wide band frequency analysis.

10. Future work

There are many different areas that this work could expand into or extend on. There is more literature on DC arcs and arcs in PV systems that could be analysed further and more in depth. The part that has most potential for more returns from further work would be the experimental part.

The functionality of the TI device was not fully explored in the experiment. One feature of the TI device that was not used in this experiment was the signal and data output via the RS232 terminals. The device can output a signal indicating the existence of an arc or no arc and this could perhaps be used to trigger a DC disconnect switch. The digital data from the ADC can be collected. The RS232 port can be used with any terminal program to communicate with the TI device. This was not done to collect the data in these experiments. The FFT data was collected from screen shots recorded on the oscilloscope. The device could, in effect be used to perform a spectrum analysis and the digitised spectrum could be compared to the FFT from the oscilloscope or from another spectrum analysis device. The TI device has limited frequency range of 40-100 kHz for spectrum analysis but still comparisons with other devices could be useful.

The arc testing setup could be expanded to include other arc detection devices, perhaps simultaneously for detection only devices. And for devices that eliminate arcs the trigger function of the oscilloscope could be used to see how long an arc exists until it is extinguished by the device.

To further investigate the effectiveness of the oscilloscope probes across a resistance, current clamps could be added and the data from the probes measuring the current from the voltage across a resistance could be compared to the data from current clamps. Although the maximum frequency of the current clamps is 100 kHz the frequency range of interest is 40-100 kHz so voltage probes and current clamps could be compared across this range.

It could also be modified into a laboratory experiment for students. The tasks could be to setup a series circuit with the arc creator and detector and to measure the voltage and current over and through the arc and to collect the digitised spectrum data from the TI device and compare it with the unfiltered and unmodified FFT of the current from the oscilloscope. As a demonstration the inverter could be connected and a situation where the inverter is operating and a small arc is created with the inverter still operating and exporting power but less than before. The power exported, the input voltage and current can be compared before and after the arc. Students will see from this that a small arc can be sustained for a long period of time and there will be a noticeable drop in AC power. This however is perhaps not large enough to be noticed unless the system was being watched and all the while an arc is burning and could spread and start a fire.

The primary part of the experiment using DC power supplies was very limited in power. The other parts of the experiment were conducted at 200V DC and ~4.5A but the roof top array is configurable. So the other experiments could be done with greater voltage or current to see if the magnitude of the arcing noise increases with a larger current, making it easier to detect arcing noise in higher current systems. There could be a setup of two strings created and an arc created in one. Crosstalk could be examined, with the cables next to each other from the roof to the ground floor; an arc could be created on one cable circuit and a test to see if the arc can be picked up by the TI device in the other cables not directly carrying the arcing noise current. With more current, parallel arcs could be explored further and a setup created whereby there is enough current to feed a parallel arc and still have the inverter operating but exporting less power. It was difficult to sustain parallel arcs, work could be done to longer sustain a parallel arc and more collect FFT screenshots and data. With more samples of parallel and series arc FFT screenshots they could be used to compare the arc noise distributions of series and parallel arcs.

With the rooftop configurable array, the experiment can be expanded to test other scenarios of series and parallel arcs and to collect data on the distribution of arcing noise in the 40-100 kHz spectrum or test other arc detection and elimination devices. The current or suggested expansion of the experiment could be modified to be a laboratory or demonstration for 3rd or 4th year students.

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12. Annotated bibliography

H. Haeberlin, M.R., *Arc Detector for Remote Detection of Dangerous Arcs on the DC Side of PV Plants*, in *22nd European Photovoltaic Solar Energy Conference*. 2007: Milano, Italy.

This article gives examples of fires that have occurred. It describes the operating principles of one early arc detection device, results of field tests and suggests improvements.

Andrea, J., Schweitzer P., and Martel J. *Arc Fault Model of Conductance. Application to the UL1699 Tests Modeling*. in *Electrical Contacts (Holm), 2011 IEEE 57th Holm Conference on*. 2011.

This paper describes a theoretical model for arcs. It also gives details and results of an experiment where electrodes are pulled apart much like the arc generator device I have chosen to construct.

Strobl, C. and P. Meckler. *Arc Faults in Photovoltaic Systems*.in*Electrical Contacts (HOLM), 2010 Proceedings of the 56th IEEE Holm Conference on*. 2010.

This work focused on creating an experimental setup with real solar panels, inverter and an arc creator. The results shown focus on the response of the system voltage and current to various arcs over a short period of time. Spectrum analysis results and IV curves are shown.

H. Haeberlin, L.B., Daniel Gfeller and Ph. Schaerf, *BIPV: Aesthetics alone are not sufficient – Long-term Energy Yield and Safety are Equally Important*, in *26th European Photovoltaic Solar Energy Conference*. 2011: Hamburg, Germany.

The final paragraph in this paper has a short discussion on the bonding material and how it has degraded over the years and how this could lead to arcing and other damage.

Johnson, J., et al. *Creating dynamic equivalent PV circuit models with impedance spectroscopy for arc fault modeling*. in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.

There is the potential for PV components to filter or attenuate arcing signature that could render an arc detector ineffective. In this paper measurements of the impedance of various PV modules were taken and a MATLAB/Simulink models were developed. It was found that there was no appreciable attenuation or filtering through the PV module models.

Jay Johnson, C.O., Michael Montoya, Armando Fresquez, Sigifredo Gonzalez and Ash Patel.*Crosstalk Nuisance Trip Testing of Photovoltaic DC Arc-Fault Detectors*.in*38th IEEE Photovoltaic Specialists Conference*. 2012. Austin, Texas.

A system may have more than one arc detection device so that when there is an arc the whole system of modules is not shutdown. Cross talk could be described as when a signal is such as an arc is produced in a wire and the wire transmits that signal and a nearby wire receives it and both arc fault detectors see a fault in both wires and deactivates both not just the one with a fault. TI devices are susceptible to this situation but generally the device with the real arc will trip first.

Ammerman, R.F., et al., *DC-Arc Models and Incident-Energy Calculations.* Industry Applications, IEEE Transactions on, 2010. **46**(5): p. 1810-1819.

This journal article gives data on minimum arc voltages, current and gap distances. It also provides estimates and formulas for calculating the energy in an arc.

Dini, D.A., P.W. Brazis, and Y. Kai-Hsiang.*Development of Arc-Fault Circuit-Interrupter requirements for Photovoltaic systems*.in*Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.

This paper explains a number of DC PV arc faults. It also shows a setup for generating arcs and frequency spectra of arc waveforms. It also sets a limit for the total energy into the arc of 750 Joules this may give an indication of the heat that may be dissipated into and test device.

Jay Johnson, M.M., Scott McCalmont, Gil Katzir, Felipe Fuks, Justis Earle, Armando Fresquez, Sigifredo Gonzalez and Jennifer Granata. *Differentiating Series and Parallel Photovoltaic Arc-Faults*.in*38th IEEE Photovoltaic Specialists Conference*. 2012. Austin, Texas.

The authors discuss the differences between series and parallel arc faults. The difference in their characteristics, how to detect the difference and how to properly de-energise the system in the different cases.

Luebke, C., et al. *Field test results of DC arc fault detection on residential and utility scale PV arrays*. in*Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.

This work shows a field experimental setup to test an arc detection device. It details equipment used, methodology and results. The DC AFCI trip on arcing events, masking effects did not influence the operation of the detector and the device did not nuisance trip.

Seagle, J., *Heading off accidental fires in solar arrays.*Machine Design, 2011.**83**(16): p. 50-54.

This article provides a good general overview of; the need behind arc detection devices, the state of US domestic and international standards and comments on the importance of staying up to date with guidelines and regulation.

Johnson, J., et al. *Photovoltaic DC Arc Fault Detector testing at Sandia National Laboratories*. in*Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.

This report is of an Eaton detector prototype tested in various PV system configurations. Details of baseline measurement and arcing measurements are given along with spectra results and current and voltage time series data.

Heinrich Haeberlin, L.B.a.P.S., *PV and Fire Brigade Safety: No Panic, but Realistic Assessment of Danger and Possible Countermeasures*, in *26th European Photovoltaic Solar Energy Conference*. 2011: Hamburg, Germany.

This article; analyses the real dangers,has a look into the safety of fire fighting personnel, provides information on technical solutions and steps to take to reduce the risk posed by PV systems on fire.

Smith, J., *PV system installation and maintenance.* Consulting - Specifying Engineer, 2011: p. n/a.

This article gives situations of improper installations that could lead to problems and guidelines for maintenance of PV systems that can reduce the probability of any problems.

Schimpf, F. and L.E. Norum.*Recognition of electric arcing in the DC-wiring of photovoltaic systems*.in*Telecommunications Energy Conference, 2009. INTELEC 2009.31st International*. 2009.

This work has a focus on per module arc detection and disconnect devices. The experiment was conducted using a variable DC power supply not a PV module. It discusses various methods that are used to detect arc. A new digital detection method is proposed that can be used on low power low cost microcontroller.

Rogers, J.H., et al. *RF arc detection using harmonic signals*. in*Fusion Engineering, 1995. SOFE '95. 'Seeking a New Energy Era'., 16th IEEE/NPSS Symposium*. 1995.

A method considered in this work is RF detection of arcs. This is a possible method for detection and is electronically simple to implement but can be prone to false readings depending on the frequency band chosen.

Edward D Spooner, N.W. *Safety Issues, Arcing and Fusing in PV Arrays*. in*ISES-AP - 3rd International Solar Energy Society Conference – Asia Pacific Region (ISES-AP-08)*. 2008. Sydney, Australia.

This work promotes an emphasis on producing high quality installations to reduce bad joints, arcing and short circuits. It does discuss more passive protection for more general electrical faults, options such as fuses.

Hastings, J.K., et al. *A study of ignition time for materials exposed to DC arcing in PV systems*. in*Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.

This considers the fact that once and arc happens how long does the surrounding material have before it ignites and burns through possibly leading to an open flame.

Real, M.G., et al. *Sunplicity: from complex system design to standard product level*. in*Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on*. 1994.

This article is mainly focused on developments in standardising various parts of a PV system to make it more cost effective. It also refers to micro inverters on modules to create AC modules and how they may be cost effective against a DC PV system. The paper also discusses a successful RF arc detector.

AS 5033:2012 Installation and safety requirements for photovoltaic (PV) arrays. 2012, Standards Australia: Australia.

This standard dictates the safety requirements, details the selection and installation of electrical equipment, requirements for signage and maintenance recommendations.

AS 4777-2005 : Grid connection of energy systems via inverters. 2012, Standards Australia: Australia.

This is a three part standard covering; installation requirements, inverter requirements and grid protection requirements of grid connected energy systems via inverters which includes PV systems.

Handelsman, L. *SolarEdge - Arc*. in *Photon 1st Solar on Fire Workshop*. 2009. Aachen, Germany.

This video demonstrates an experimental setup for creating a DC arc and has close up shots of the device and how it operates. Also shown is the current through the arc and system voltage.

Barikmo.*Sunset - Module Arc Presentation*.in*Photon 1st Solar on Fire Workshop*. 2009. Aachen, Germany.

This video demonstrates a situation in a module where there is a fault that creates an arc and the arc continues to burn for more than 5 minutes until the experiment is ended. It also shows arc voltage and current.

FlorentBoico, et al., *Application Note 2154 SolarMagic RD-195 DC Arc Detection Evaluation Board*, T.I. Incorporated, Editor. 2012, Texas Instruments Incorporated: Dallas, Texas.

This instruction leaflet covers the; features, setup procedure, commands and theory of operation of the TI arc detection device.

Deutsche Gesellschaftfür, S., *Planning and installing photovoltaic systems: a guide for installers, architects and engineers*. 2008, Sterling, VA: Earthscan.

This book has a few pages on breakdowns, typical faults and maintenance of PV systems with statistics, pictures and charts.