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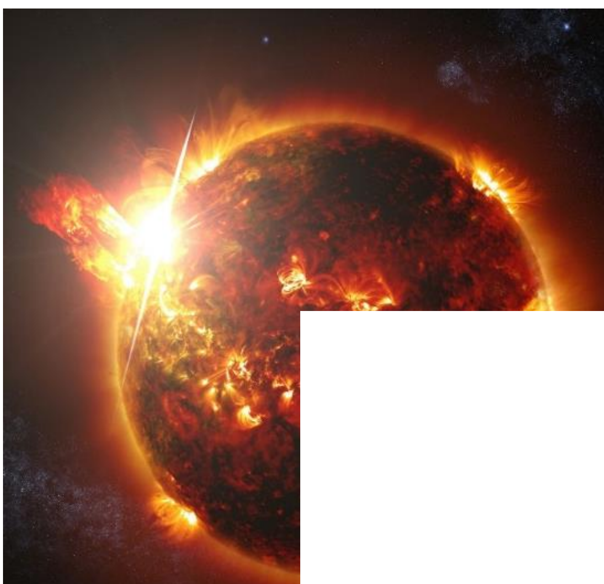


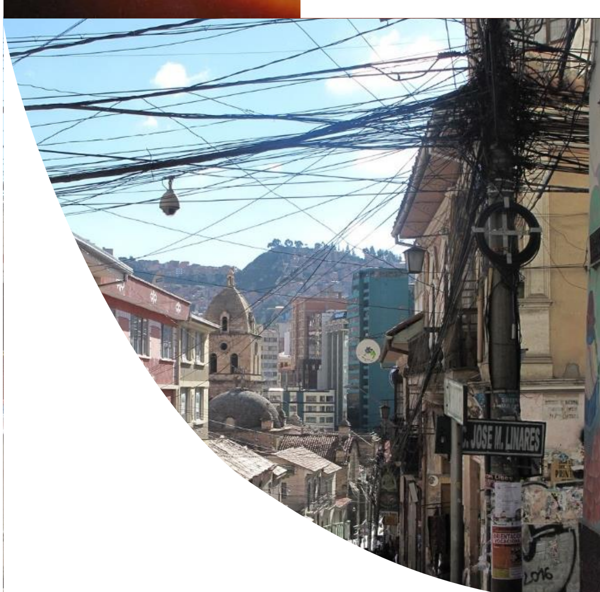

High reliability microgrid based infrastructure for high altitudes and the hidden threat of cosmic rays

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In this article we hear about the research of PhD student Matthew Littlefair to try to resolve a problem experienced by microgrids in high altitude locations such as rural communities in Bolivia. He explains how understanding electronic device performance under the influence of cosmic rays is crucial for developing more effective microgrids to enable these communities to have reliable access to energy.

Matthew Littlefair is a PhD student in Engineering supervised by Dr Alton Horsfall. Both Matthew and Alton are DEI Fellows.
Find out more at www.durham.ac.uk/dei/aboutus/dei.fellows/

Many rural areas worldwide are not directly connected to the national electricity grid, mostly due to the cost of extending the high voltage transmission infrastructure across often treacherous terrain. One solution to this challenge is the increasing development of renewable energy sources, including photovoltaics and wind that are connected to local consumers through microgrids. Microgrids are independent small-scale electricity networks that are operated at lower voltages than the national grid infrastructure, but they still require these voltages stepping up for distribution.

> *"Independent renewable energy systems, based on technologies such as microgrids, are the only feasible method of providing electricity to these communities."*

Bolivia – a case study

Bolivia, with 11 million inhabitants, is considered to be one of the poorest countries in the world. Urban areas, including the modern cities of La Paz and Santa Cruz have a relatively good supply of modern energy services (Figure 1), whereas most of Bolivia's rural areas still experience a lack of basic services, including reliable and affordable electricity. The country has a lot of inaccessible, mountainous terrain, much 10,000ft (3000m) above sea level which is mainly inhabited by rural communities. Over 200,000 rural

Figure 1: The SIN - the Bolivian equivalent of the national grid, which does not reach across to the West where many communities inhabit.

homes are without electricity despite recent grid extensions and therefore, independent renewable energy systems, based on technologies such as microgrids, are the only feasible method of providing electricity to these communities. In 2005 Bolivia had the lowest rate of electricity access in Latin America, with only about 30 percent of the rural population connected.

Villamar Mallcu a region in the SW of Bolivia has dry, desert-like conditions with little vegetation. Many of the roads and pathways are dirt tracks, indicating a lack of funding for infrastructure. The majority of houses in the region are made from stones that have been built up with limited cement,

Figure 2: The Deutsche Gelleschaft fuer Internationale Zusammenarbeit GmbH – creative commons license Reproduced in L. Franklyn, 'Bolivia embarks on microgrid strategy as part of universal energy access goal [4]', https://microgridnews.com/bolivia-embarks-on-microgrid-strategy/

suggesting a low-income area where natural, local resources have been used. Bolivia is embracing the move to renewable energy with three major windfarms totalling 93MW, a 180-hectare photovoltaic installation being completed in the past two years and an ambitious vision to generate over 50% of the electricity from renewable sources by 2025, whilst it is currently at under 30% from hydroelectric schemes.

Part of the comprehensive electricity plan for Bolivia is based on the necessary increase in capacity to support the increasing population. This is being supported by the rapid development of distributed renewable energy, including the construction of microgrids.

Microgrids are key to improving energy access in remote areas of the country, and in helping Bolivia to meet its goal of 97 percent national energy access in 2020, with 100 percent access in urban areas and 90 percent in rural areas.

> *"Wide bandgap semiconductors has enabled the realisation of higher operating frequencies and higher efficiencies than conventional silicon based devices."*

Whilst extensions to the existing grid infrastructure have made it possible to increase energy access to rural communities in the past, this is reaching a practical limit because of the inaccessible, mountainous terrain. Hence, a new paradigm using microgrids is required to provide electricity to these rural communities that are located beyond the national grid infrastructure. The application of renewable energy, in terms of powering individual home and small communities, including infrastructure, is a key enabler of the Bolivian energy strategy, but this requires cutting edge electrical engineering in order to make it a reality.

An engineering solution

The conventional method to connect renewable energy sources to a microgrid is through the use of line frequency transformers, which increase the voltage to reduce losses. These transformers are large, heavy and do not offer the possibility to control the energy flow in a network that is governed by the intermittent nature of the supply and demand. Recent research work has demonstrated the possibility of using power electronics to produce a Solid State Transformer (SST).

As outlined in Figure 3 and 4, these circuits comprise a physically small, high frequency transformer that provides the voltage boost surrounded by power electronic converters. The AC to DC converter that is connected to the renewable energy source and the DC to AC converter connected to the grid are conventional power electronic converters that can be obtained commercially. The operation of the overall SST circuits can be controlled by the behaviour of these two circuits to offer a greater level of control of the electrical energy, including the ability to isolate the source or demand from the grid in the event of failure.

Solid State Transformers were originally developed for use in applications where space is at a premium, such as rail traction. The key to the operation is the high

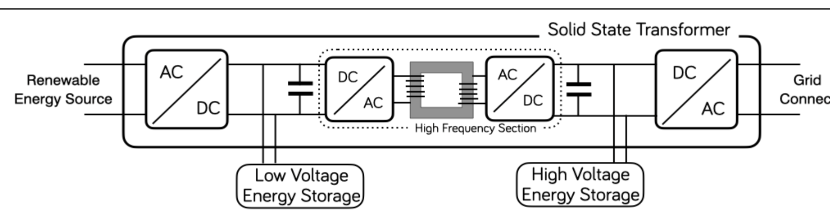

Figure 3 The Solid State Transformer

frequency power electronics that is directly adjacent to the high frequency transformer that can be seen at the centre of the figure. Because the physical dimensions of a transformer are linked to the reciprocality of the operating frequency, a shift from the 50 Hz line frequency to 50 kHz, reduces the volume of the magnetic components a billion times, making transformers the size of shoeboxes possible. These high frequency electronic systems are now becoming a reality, driven by the move to wide bandgap semiconductors, such as silicon carbide and gallium nitride.

For grid applications. the inherent flexibility and ability to integrate energy storage technology at either of the DC links, is more relevant than the reduction in weight and volume. The high frequency section of the SST contains an inverter (DC to AC power converter) as well as a high speed rectifier (AC to DC power converter). Each of these converters comprises a number of individual power transistors, as shown below. The move to wide bandgap semiconductors has enabled the realisation of higher operating frequencies and higher efficiencies than conventional silicon based devices, based predominantly on the enhanced critical electric field in these materials.

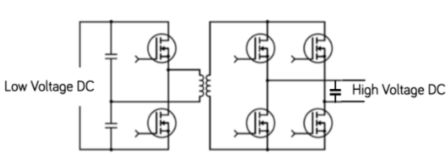

Figure 4 The high frequency component of the SST, featuring 6 transistors which are pivotal to its operation.

This means that modern semiconductor devices operate at significantly higher electric fields than those based on silicon and this raises questions about the reliability when used for critical infrastructure.

Limitations

It has been known for over 50 years that ionizing radiation has the potential to influence the performance and operation of electronics. Single Event Effects (SEEs) are a form of radiation effect on devices which occur when an ionizing particle strikes a sensitive region on an electronic device, altering its typical operation under standard conditions by injecting additional charge which the device cannot support. This behavior was first postulated by Wallmark and Marcus in 1965 [5], suggesting that as the size of the electronic components was reduced, the amount of injected charge required

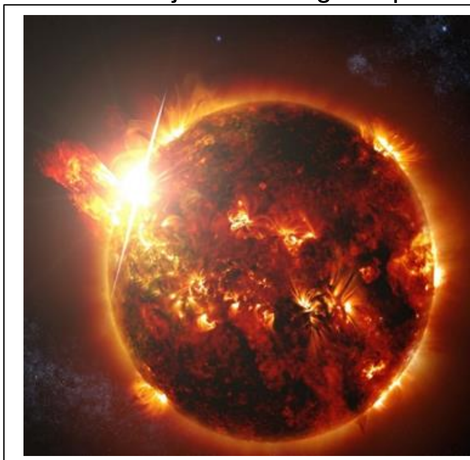

Figure 5 Coronal Mass Ejections and solar flares are some of the main sources of cosmic ray generation [8]

from external sources to result in a SEE was also reduced. The first SEE was reported by Binder in 1975 [6] when anomalies were discovered with satellite data, these were termed non-destructive SEEs as the device can be reset and return to original operating conditions. The first destructive SEE was reported in 1992 by Adams [7], when satellite components failed and could not be reset.

SEEs do not only affect experimental electronics above the atmosphere – they also affect the electronics used closer to home. At flight altitudes of 35,000ft the computers onboard transatlantic flights must be reset 3 times during a flight because of the SEEs. SEEs also pose an issue at terrestrial levels, in 2010 over 9 million Toyota vehicles were recalled due to SEEs causing malfunctions to the accelerator, causing it to stay on after release resulting in several fatalities. Both incidents arose from the interaction of cosmic rays with the semiconductor used to manufacture the electronics.

Cosmic radiation constantly showers the earth with particles of extremely high energy. They are generated by various astrophysical processes in our galaxy, examples include stellar explosions where billions of particles are thrown at speeds up to millions of miles per hour towards the earth, known as coronal mass ejections and solar flares (Figure 5).

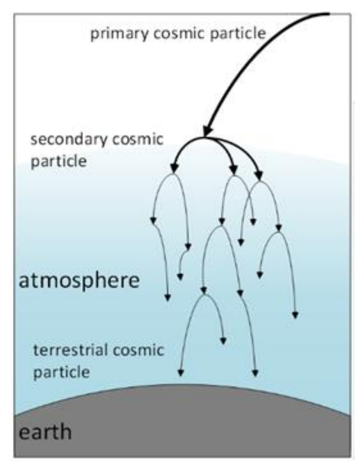

Figure 6 Cosmic Rays on earth [9].

These particles do not penetrate the atmosphere but collide with air molecules, generating showers of secondary particles (Figure 6). Neutrons generated by the cosmic rays are the biggest threat to electronic systems in SSTs due to their abundance as they do not undergo the same ionization losses as protons.

At altitudes of 10,000ft, which is typical for ground level in Bolivia, there is typically a neutron flux of 0.04 neutrons $cm^{-2}s^{-1}$, resulting in over 1 million neutrons striking a transistor of the size 1 cm2 every year. Each of these neutrons have the potential to induce instantaneous and catastrophic failure of the device, known as Single Event Burnout (SEB). When a neutron impacts the transistor a significant amount of energy is deposited internally. This energy generates a large current which is then amplified by the voltage operating conditions of the device. This enhanced current leads to severe localized heating, resulting in internal temperatures that exceed the maximum safe operating temperatures of the device. The outcome of this is that regions of the device melt and explosion can occur within a few billionths of a second.

> *"Each of these neutrons have the potential to induce instantaneous and catastrophic failure of the device"*

The rural West regions of Bolivia are some of the highest inhabited areas on earth, with an altitude that is typically 10,000ft above sea level. The rural location of these areas makes them ideally placed for the development of micrograds, however the neutron flux at this altitude is two orders of magnitude higher than in Durham and this has the potential to cause catastrophic failure in the solid state transformers that are a critical part of the electrical system. These failures have the potential to deposit huge amounts of energy in the microgrid, resulting in the catastrophic failure of the entire system and any devices that are connected to it.

Research question

To have SSTs which are resilient to high altitudes the physics behind the mechanism responsible for the failure is required to be fully understood. To understand the physical origin of this failure, the criteria that leads to the failure mechanism needs to be determined. Over the years the testing for single event effects has been performed with a range of experimental methods, the main focus of which is on the use of accelerated testing. This is a technique that increases one of the parameters significantly above that experienced in normal operation, for example the temperature of the device, then statistical techniques are used to extrapolate the expected lifetime. In the case of single event testing, concentrated beams of high energy particles are used that give the equivalent of 40 to 50 years' worth of neutrons in the space of a few hours.

To support the testing, computer simulations are used to identify the sensitivity of the different parts of the transistor to impact from the cosmic ray passing through the semiconductor. The parameters of the transistor can be changed easily to examine the possibility of variations in the structure and how they affect the characteristics during operation and, more importantly, during the occurrence of single event failure.

Experimentally, the charge deposited in electronics by high energy particles can be replicated using highly focused pulses of light. High precision lasers can be manipulated to deliver these pulses in a billionth of a second and this enables charge to be deposited in a defined region, mimicking the cosmic ray interaction with the device. At low light intensity, the light passes through the semiconductor with minimal loss, however if the intensity is increased by focusing the laser pulse to a small spot size and using a pulse duration of 100fs, the semiconductor absorbs two photons at the same physical location and this allows measurements to be taken at carefully selected locations in the device. The charge injection in the device can be matched to that of a cosmic ray by altering the intensity of the laser pulse at different locations in the semiconductor.

However, this technique does not allow us to determine the effect of different cosmic ray energies on the single event failure. The only method to achieve this is to characterize the devices at high altitudes – not something that is simple in Durham, or the UK in general.

The Jungfraujoch research laboratory in the swiss alps, located at 12,000 feet above sea level offers state of the art testing facilities at similar altitudes to some of those inhabited in Bolivia. This testing environment gives researchers access to an accurate high altitude neutron energy spectrum that cannot be reproduced in the lab. Over several months, tests will be performed on the electronic devices that can be used to realise state of the art solid state transformers to identify their failure rates. This will enable us to identify the optimized designs for the transistors and circuits that will enable highly reliable microgrids to support the access to electricity in high altitude, underdeveloped, parts of the word including Bolivia and the Himalayan region.

Matthew Littlefair and Alton Horsfall, December 2020

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Electrical Energy Engineering Research:

Dr Alton Horsfall and the Electrical Energy Engineering group at Durham are undertaking associated research looking at:

- **Using power electronics to protect renewable energy systems**, particularly those that include solid state transformers (this will ensure protection of the distribution grid more rapidly than current technology), and
- **Use of power electronics to ease the integration of different renewable energy sources**, such as wave and offshore wind (particularly the infrastructure) where the electricity generated is very different in terms of the time variation and peak / average power ratio.

Smart Electrical Energy Conversion, Transmission & Distribution

The main research themes in this area are;

- Renewable Energy Devices and their Reliability & Asset Management
- Energy Networks - Smart Grids, Power System Optimisation and Integration
- Electrical Machines and Systems for Transportation, Power Generation and Industrial Processes

Find out more at **www.durham.ac.uk/engineering/research/future-energy/**

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