The impact of large-scale solar generation on utility revenue

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Abstract — ***The upsurge of renewable energy penetration has hit the South African mainstream. The photovoltaic (PV) products are becoming cheaper, and they gain people's trust for onsite local power generation since it does not bear any transmission and distribution cost. The market acceleration of the product becomes a drawback to the utility industry working tirelessly to regulate and maintain their existing centralized network. In this paper, we looked at the different component of a PV system and narrowed down to the low costs inverters which took the market by storm. We did a case study on a property that has a utility installation and PV generation. We populated the data from the PV system and the history to analyze the offset percentage and the possible revenue loss by the municipality. The outcome for this case study is discussed in conclusion to evaluate the utility losses on massive PV penetration in residential sectors.***

Keywords—**Smart-meter (SM), Smart-grid (SG), Conventional grid (CG), Master-slave Metering Hierarchy (MSMH), Internet Protocol (IP), Real-time (RL)**

I. Introduction

The electricity supply-demand problems have caused a strain on the centralized power entity. Developing countries like South Africa are finding it challenging to meet the desired outcome for both satisfying the customer needs and covering the operational costs [1]. South Africa has one of the highest energy intensities in the world compared with only a few countries having higher intensities. South Africa's primary energy consumption per unit of GDP is among the highest in the world [2]. According to [2], South African's history of low electricity prices substantiated to lower energy efficiency compared to the international standards and other countries. In recent years ESKOM is playing a catch-up game to cover the capital and operational costs. Due to these reasons, electricity prices skyrocket each year and encourage users to think of low-scale alternative methods to meet their electricity demand needs at reduced costs.

This paper aims to examine whether the utility is ready for the massive rollout of embedded energy generation to the residential, commercial, and industrial customers connected to the grid's utility. Most energy users are hesitant to go off the grid; instead, they invest in hybrid system energy generation, using one source as a base and the other as a backup, in sharing the grid with embedded energy generation from users by researching the standard means to mitigate electricity consumption and significantly reduce electricity costs.

The concept of embedded power generation simply means that you generate electricity onsite for local consumption and possibly export excess. Since this concept is local, the scale is just a fraction of the electricity in the entire network. Renewable energy and embedded generation are used interchangeably, but not the same. Renewable energy is derived from natural undepleted resources such as sunlight, wind, rain, tides, waves, and geothermal heat. Embedded generation can be of renewables or non-renewable generation type. For example, a diesel generator is not part of the renewable family, but it is also used for embedded generation. In this paper, the term embedded generation relates to the renewables such as wind energy, biogas energy, hydro pump energy, or photovoltaic (PV) energy, also known as solar energy. The discussion in this paper will only be narrowed to solar PV energy generation.

The energy source discovered by a human directly from the land was biomass energy [3]. This energy was formed from natural resources such as firewood and dried dung from cows to create fire or heat. Technology evolved when fuels such as oil, coal, and gas were extracted and mined from nature to be used for controlled combustion. Over the years, these technologies sustained and accelerated the development of countries and improve humankind's livelihood. The main challenge with these fossil fuels, they become very harmful to nature due to their global carbon footprint. The further evolution of energy technologies gave birth to renewable energy, also known as green energy. PV technology is the leading renewable energy that has hit the mainstream.

1.1. Solar energy

Solar energy is old technology. The work and power of sun irradiation were discovered before electricity [4]. The technology was recorded in the 7th century BC where a magnifying glass or mirrors captured the solar energy to start a fire. In 1839 PV was discovered and evolved as many researchers continued to work on them. The initial solar panels were as good as 1% efficiency, and they cost as $300 per watt, but conventional electricity costs between $2 - $3 per watt, which makes a difference of 10000%. Due to this reason, solar electricity never gained popularity because it was not economically feasible.
Over the years, the capital costs of solar energy reduced concerning its counterpart conventional generation energy, according to table in Fig.1 below by [5]. The projected capital costs include the land and building costs. The lower running costs for PV generation encourage investors and users to consider them as mass generation and local generation for consumption use.

Technology	Capital Cost ($/kW)	Operating Cost ($/kWh)
Coal-fired combustion turbine	$500 — $1,000	0.02 — 0.04
Natural gas combustion turbine	$400 — $800	0.04 — 0.10
Coal gasification combined-cycle (IGCC)	$1,000 — $1,500	0.04 — 0.08
Natural gas combined-cycle	$600 — $1,200	0.04 — 0.10
Wind turbine (includes offshore wind)	$1,200 — $5,000	Less than 0.01
Nuclear	$1,200 — $5,000	0.02 — 0.05
Photovoltaic Solar	$4,500 and up	Less than 0.01
Hydroelectric	$1,200 — $5,000	Less than 0.01

Figure 1. Power generation costs

The efficiency of the solar panels was another drawback for the system to gain popularity. Efficiency is defined as the ratio between the output power and the input power, as in equation 1.

$\mu = \frac{Pout}{Pin}$ (1)

P_{in} represents the power that enters the module in terms of irradiation when the PV module absorbs the photons, and Pout is the output power represented in an IV curve.

The improvement of efficiency means that you can harvest more energy with a smaller number of panels. Researchers are working tirelessly to improve efficiency, and this is encouraging people to move towards PV generation.

Remarkable progress has been made in improving the conversion efficiencies of a variety of PV devices. Gallium arsenide and its ternary alloys have been used to create ultrahigh-efficiency (>30%) solar cells. On a silicon-based solar cell based on single-crystal and multi-crystal technology, record-level efficiencies have been achieved [6].

2. Literature review

In the literature, we looked at few case studies of renewable energies connected to the grid. The case study in [7] was conducted in Ghana to assess the power quality regulated by the international standards and national grid code. The study was conducted on a 20MW existing PV plant to record power quality data for three days. The findings were not complying with the standards, yet the plant is operating. In the study, the Total Harmonic Distortion (THD) was recorded to be as high as 65%. The few proposed recommendations in the survey were power factor mitigation, harmonic reduction, and plant efficiency.

In the study [8], an impact of the line impedance and loading on voltage profile was simulated. In the results, there is an apparent change in the load impedance and causes a rise in voltage at the far end of the radial distribution line. The study reveals that the voltage is inevitable if control techniques are not in place.

The Utility industry has invested in power-line infrastructures and distribution networks according to estimated demand. The energy consumption must match the estimated demand for positive return-on-investment (ROI). The influx of embedded energy has an impact on power consumption since the energy that is generated onsite offsets the total consumption, as shown in (2).

$$E_{net} = E_{demand} - E_{eg} \qquad (2)$$

Where:

E_{net} is the total energy supplied by the utility.

E_{demand}, is the total energy used by the consumer.

E_{eg}, is the onsite embedded generation.

The three factors stated in the literature review could dampen energy distributors to encourage their consumers on embedded power generation. But if the embedded generation is controlled and managed, it could also help energy distributors to optimize their distribution network. Mitigation strategies are needed to benefit both the consumers and the utility industry.

2.1. Photovoltaic system

In this paper, we have narrowed the embedded generation to PV generation. The PV phenomenon is divided but not limited to three primary sections: generation, power-conversion, and energy storage system (ESS). Generation is the solar panel that converts the sun into DC power for usage and storage. Power inverters are used to convert electricity from DC to AC, and they are configured to interface with the utility to perform algorithms such as in (2) and others. ESS is the chemical battery storage that stores DC and discharges it in a time of need.

2.1.1. Power inverters

Power inverter is the heart of the PV embedded generation. There is much to cover on inverters, but this paper narrows the discussion to the inverters concerning the utility grid. There are three primary types of inverters: Grid-tie, off-grid and hybrid inverters. Off-grid inverters are mainly isolated from the grid; they do not have any AC input but only the output. Grid-tie and hybrid are both connected to the grid as a reference or bi-directional system. A grid-tie works in correlation to the main to access the maximum energy supplied from the panels and add to the power given by the utility to provide the given load. In the grid-tie system, the ESS is generally excluded unless in certain conditions. If an electrical installation existed before the embedded generation, there would be a significant utility supply reduction after the solar is installed and commissioned. During shaded or rainy days, the solar panels usually do not generate at capacity, and this will result in less power provided embedded generation and more energy needed from the utility.

Hybrid inverters work like grid-tie, and the difference is that they can feedback to the utility grid, meaning that the grid will procure power from the consumers. In the procurement process, the utility is virtually increasing its installed plant capacity. By virtual plant capacity, it means that the net-power capacity of the utility is increase at the time of embedded energy availability.

The power inverter circuit is shown in Figure 2, [9] that shows the fundamental schematic and function. The difference between the inverters mentioned in 3.1.1 is the algorithm. The outcome remains the same, DC input and AC output for both single-phase and three-phase systems. In South Africa, Eskom is the central power entity. A part of Eskom handles its distribution, but most of its energy is distributed by local municipalities. In municipalities as distributors, they manage their utility businesses and tariffs guided by NERSA. Some municipalities allow the bi-directional flow of energy between utility and embedded generations and forbid the bidirectional flow. This condition forces the inverter industry to design their product to suit all needs. They resolve to develop their inverters to be digitally flexible in accepting any changes required by the utilities. The inverter study shows that there is one universal type and different algorithms that create the variety of inverters in the solar market.

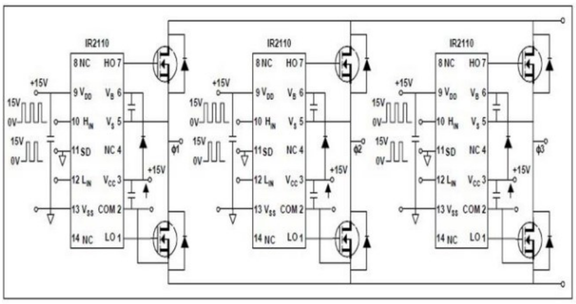

Figure 2.Inverter power circuit

The inverter study shows that the PV system embedded generation has a direct influence on utility revenue. The diffusion of the PV solar systems is inevitable. Scientific methods are required to eliminate losses of revenue to the utility and embracing the power of renewable energy.

3. Inverter algorithms

The basic principle of inverters is the same as seen in Figure 2. The difference in inverters is that the market sells their products based on their different functions and working principles that are derived from the algorithms in the microprocessors.
The inverter is the intelligence of the solar generation system. The conversion principle is the same, but the categories are the same. There are two fundamental categories of the inverter design that are: transformer isolation and transformerless inverter. The transformer isolation inverter has the Low Frequency (LF) and High Frequency (HF) inverter.
Inverters come in different types, makes, and models. The inverter types are derived from their architect and their roles in the network; these inverters include but not limited to

- Grid-tie inverters
- Off-grid inverters
- Hybrid inverters

These three are known in the industry, but many new inverters are produced of these three types. For example, the inverter in Figure 3 is the expert inverter, called the hybrid inverter. When zooming in the architecture, you see a combination of the off-grid and the hybrid inverter since it can not synchronize with the grid as the hybrid type does. The bypass switch gets the inverter to an off-grid type.

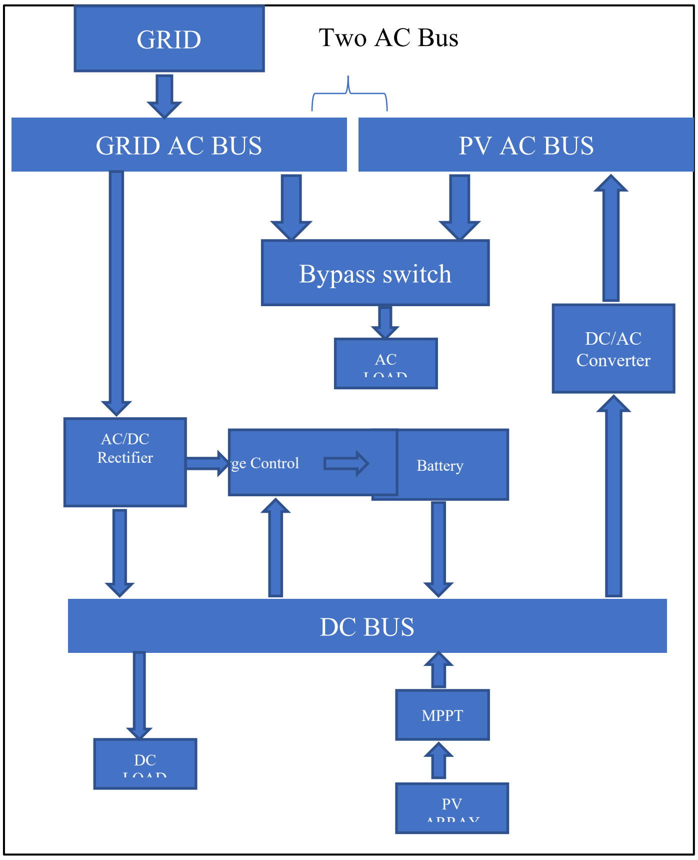

Figure 3. Expert Inverter architecture

The primary architect of the expert inverter is shown in Figure 3. The expert is one typical affordable inverter that is common to the South African residential market. This inverter gained popularity due to its simplicity and affordability. It encompasses all the essential elements in solar generation, such as MPPT solar charge, a rectifier AC charge control, and the DC/AC inverter. Most of these inverters use similar algorithms. When the PV array generates enough electricity, it is used to charge the storage batteries and supply the given load. But when the load required is greater than the generated load, the AC load goes on the bypass mode of the inverter to get power directly from the grid, and the PV array will only charge the batteries. This inverter has different operation modes, prioritizing the PV array or utility as the primary power source and the other as the backup source. Each mode can either benefit the utility for revenue collection or satisfy the customer to cut revenue costs. The nature of this kind, replace UPS systems for power backup and minimum power generation.

4. Residential Impact

Residential consumers are opting for the off-grid inverter because of its affordability. This inverter is not tied to the grid, it only uses the utility power for the sinewave reference, and it generates its 50Hz frequency. The reference frequency is not necessary in-phase with the power grid, but their phase shift difference will be locked for as long as the machine is running. These inverters do not necessarily synchronize to the utility; it is one reason they are the cheapest in the market. Most of the inverter companies improve their product's switching time to be between 10ms and 20ms. Figure 4 shows the operation of the off-grid inverter, and the bypass switch toggles the load between the utility grid and the inverter. The inverter is the PV system that includes the PV array and the ESS.
The nature of these inverter makes them difficult to regulate because the South African national standards SANS only regulates their installation. They fall in between a backup system and a small-scale energy generator (SSEG). NERSA regulates the SSEG, which mainly uses the grid-tie inverter. The grid-tie inverters differ in nature because they are coupled with the network permanently. Off-grid generation is not embedded generation because it does not synchronize with the grid.

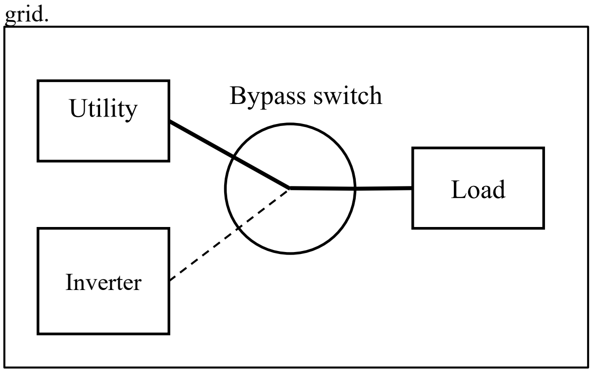

Figure 4. Off-grid inverter block diagram

The operation mode and algorithms of the 0ff-grid become the deciding factors to the utility energy business. For example, if the consumer uses 7200 kWh per annum, the average usage per month is 600 kWh and an average of 19.35 kWh per day. The usage in hours is divided into peak and off-peak hours. The utility put an effort to provide the connection to match the demand. The utility will collect revenue of 7200kWh per annum from that customer. If the customer installs a renewable PV that generates 50% of the total consumption, the system will offset the initial usage of 20 kWh to 10 kWh. The utility will lose 50% of revenue. These revenue losses go to the capital costs, which must be paid overtime. During the later hours of the day and in the evening when the sun is not shining anymore, the utility must carry the burden alone to supply every customer in the block.

5. Case Study

A study was conducted on a residential premise at 241 Manser street in Meyerspark. This case study was done to examine the impact of renewable penetration into residential premises. Figure 5 below shows the diagram of the installation to be used for the analysis. The maximum power output from the PV array is 3.65 kW before losses, and it produces the array voltage of 143 V_{dc} and maximum current of 25.2A. The total battery capacity is rated as 3.5 kWh at 48V_{dc}.

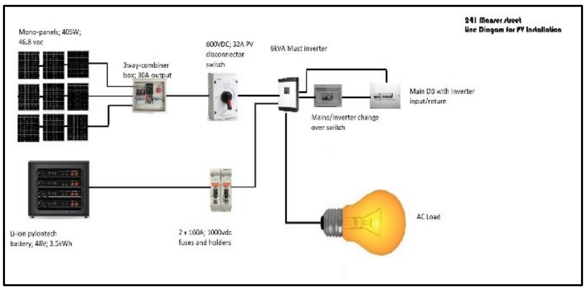

Figure 5. 241 Manser street Solar installation

6. Results and discussions

We have examined the history of the energy consumption at 241 Manser street over the past years, and the results are shown in the chart in Figure 6. The graph shows the actual municipal consumption. The system was commissioned in February; hence the energy has dropped significantly in March and April in 2021 since the mark is below 200 kWh and below the average.

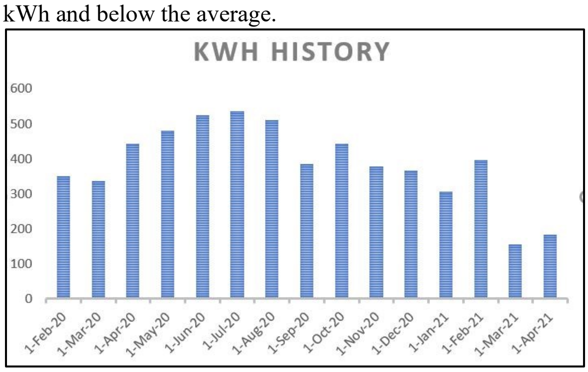

Figure 6. Municipal consumption history

A. Inverter results

Fig.7 displays the daily generation curve extracted from the monitoring software. From this 24hr plot, it can be seen that the PV starts generating as early as before 07 am, wintertime until 17h00 in the evening. The power generated in the early hours is enough to charge the batteries but not enough to run the load in the house as soon as the sun peaks up, the radiation increases, and then the inverter switch to solar mode. In solar mode, the DC power converted is the sum of the PV current and battery current. The inverter output current is given by (3).

$$I_{inv\_out} = \begin{Bmatrix} i_{pv} + i_{batt} \, , if \; i_{load} < (i_{pv} + i_{batt}) \\ i_{grid} \, , \; if \; i_{load} \geq (i_{pv} + i_{batt}) \end{Bmatrix} \quad (3)$$

Where:

i_{pv}: current generated by solar PV
Iinv_out: Inverter output current
i_{load}: current demanded by the running load
i_{grid}: current supplied by the utility grid
i_{batt}: current provided by the battery

From (3), it is clear that after sunset, the battery alone cannot sustain the peak power needed, and the inverter will revert to the grid.

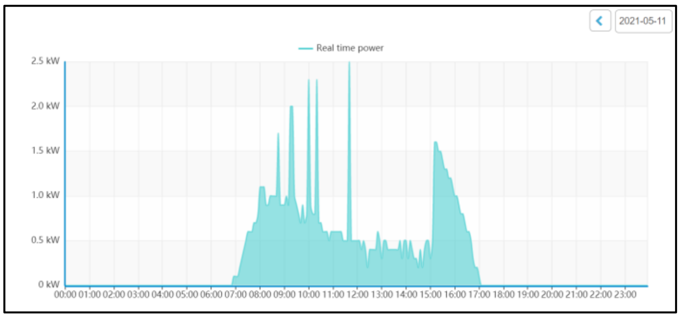

Figure 7. PV power daily generation curve

Fig.8 shows the inverter status in real-time. This plot was extracted from the monitoring software in real-time. The horizontal axis of this plot is the 24hr time from 00h00 to 23h59. The green plot is the power supplied from the grid, the blue plot is the power that charges the battery, and the red plot is the load as it can be seen on the plot that during the daytime, the grid power is zero, meaning that the load is running from the PV. In the instances where the grid power rises, the load current is greater than the PV current. From the left of the horizontal plane, the grid power drives the load; hence the power is greater than zero. The plot shows the algorithms of the inverter

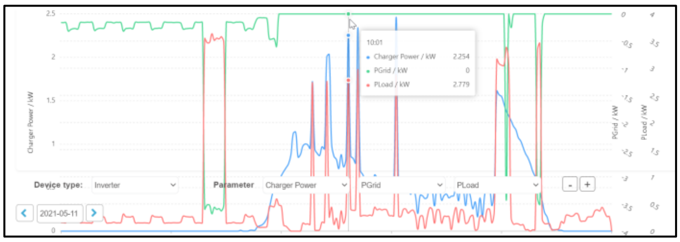

Figure 8. Real-time power-flow chart

In the subsequent figures, we will zoom in on the PV generation history over the past three months since it was installed to examine the generation pattern. We will look at the daily, monthly, and annual generation curves to establish the pattern.
The monthly energy charts we populated from the shine monitor are the accurate-time monitor for the system. The software system was commission in February, and the monitoring hardware was installed in March; hence there is no data for the month of February. Figure 9, 10, and 11 are the 3months plots as the chart in Figure 9 only goes to the 10^{th} of May, and that is the day that the information was extracted.

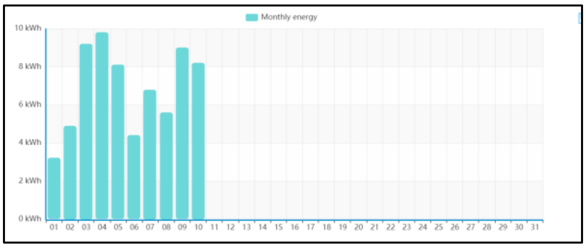

Figure 9. May monthly energy

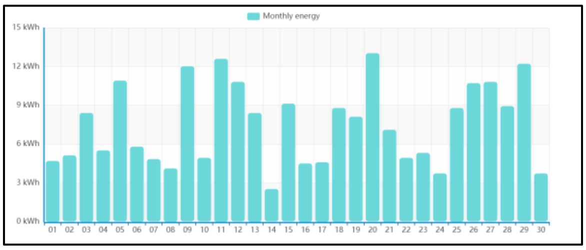

Figure 10. April Monthly energy

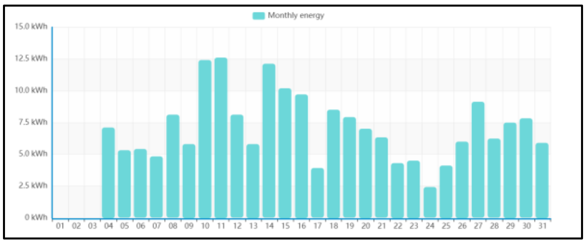

Figure 11. March monthly energy

B. *Discussion*

The PV capacity is 3.6 kW, and the grid installed capacity is 13.8 kW, which means the plant installed at 241 Manser street is 26% of the installed capacity. The adequate capacity by power utilities is 30% of the grid capacity. However, the results, shows that in March, the energy generated was 177.4 kWh, and in April, the total generation was 224.7 kWh. The energy projected in these Figures 9, 10, and 11 offsets the energy projected in Figure 6. The average consumption in Figure 6 is 420 kWh per month, and the average of March and April is 200 kWh per month. The system in the study is not operating at its optimal level yet, and the PV average is estimated to rise when the system is fully running at its optimal level.

7. Conclusions

The system is a simply off-grid system operating as a backup and onsite generation. The inverter algorithms are not advance compared to the grid-tie inverters. With these inverters, if the DC is less than the running load, the inverter will switch to the utility grid. That will help the grid to collect maximum revenue when the PV is not generating enough. The grid-tie inverters prioritize solar generation and take the fraction difference from the main, and that will cause a further financial strain to the utility. This case study shows the onsite generation offsets above 50% of the projected income by the utility, and over time, the utility will run at losses. As the solar system is getting cheaper, the penetration will rise exponentially proportional to revenue losses to the utility.

8. Recommendations

The utility industry must champion renewable energy to be able to stay in business. This technology is flooding the space, and utility must use as to their advantage. The renewables technology is battle of algorithms that requires studying the different systems to counter the losses. The utility needs to find ways to work with onsite generators and find ways to gain access to the algorithm so that the distribution and onsite generation are controlled in real-time. Utilities can also use the battery storage from each generation point as their central storage to mitigate the upsurge during peak hours without straining its system and investing in the network upgrade. ICT technology for communication and control is a way to go for utilities. When the utility finally embraces ICT technology and renewables, they can be able to create energy ecosystem to keep the energy business revived.

II. Acknowledgements

The authors would like to thank the University of Johannesburg's University Research Committee (URC) grant for the year 2019, which was awarded to Dr. K. Ogudo, for their financial support, as well as the Department of Electrical and Electronics Engineering Technology for their lab and research tool support throughout this research project.

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