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VOLTAGE REGULATION OF DISTRIBUTION FEEDERS DURING HIGH-PHOTO VOLTAIC PENETRATION DUE TO ROOF-TOP SOLAR

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ABSTRACT

In recent times, much attention has been given to developing renewable energy sources and utilising them to their maximum capacity. In Sri Lanka, solar power has topped the list. One of the adverse effects of increased Photo-voltaic penetration on the low-voltage distribution system is a decrease in reliability which is the root cause of overvoltages. This research has examined the impacts of overvoltage in roof-top PV on the distribution network and evaluates possible mitigation actions in terms of voltage and power quality. A simulation is done, and a real-time implementation of a buck converter is designed for roof-top solar PV users to limit the power output to a value at the threshold of commencement of overvoltage without tripping due to high photo-voltaic penetration. The results show that the developed controller can drive the output voltage of the buck converter to the desired voltage reference and reduce a pre-defined power output regardless of solar PV input voltage variations.

KEYWORDS: *Rooftop solar PV, Overvoltage, High photovoltaic penetration, System stability*

1. INTRODUCTION

Due to the depletion of fossil fuel resources and the adverse effects caused by the burning of fossil fuels, more attention has been given to maximising renewable energy sources. As Sri Lanka has an abundance of sunlight during the dry season, solar power has topped the list in renewable energy generation.

Solar panels have increased in popularity as a viable energy source as the cost of production has decreased dramatically in recent decades. Solar power also has numerous advantages, including the emission of fewer greenhouse gases contributing to less environmental pollution (Eltawil and Zhao, 2010). As Sri Lanka is situated near the equator and receives a good amount of sunlight during the day, focusing on improving issues regarding grid integrations could majorly help the energy security and economy of the country. Some of the issues associated with the grid integration of solar are overvoltage issues, voltage fluctuations, and reverse power flow, especially in low voltage feeders, without proper regulations (Ehara, 2009). The overvoltage issue becomes prominent with the increase of PV installations on a distribution feeder. Due to high PV penetration, the voltages rise of the inverters may become more than the nominal accepted limit. It has been observed that some inverters' voltage exceeds 255V, even though the specified upper limit is 244 V (6% over the nominal 230 V) as per regulations (Karunadasa et al., 1970). An overvoltage on a distribution feeder causes loss of coordination, increased fault current, unnecessary tripping, and incorrect operation of equipment. Hence, this issue should be mitigated to increase solar power generation capacity.

Most of the modern inverters can provide grid support and voltage regulation. Inverter-based renewable energy systems, such as solar photovoltaic (PV) and wind power, can inject power into the grid, and these inverters are equipped with advanced grid support features that ensure stable and reliable grid operation. This includes features such as reactive power control, voltage ride-through capability, and anti-islanding protection (Wang and Chen, 2015). Nowadays inverters address the voltage control by using advanced voltage control algorithms to maintain a stable AC output voltage.

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Inverters continuously measure the AC output voltage and adjust the output voltage using pulse-width modulation (PWM) techniques (Morais et al., 2014). This ensures that the output voltage remains within a specified range, even if the input voltage or load changes.

Inverters can also curtail the output of the PV system to prevent overvoltage on the low voltage feeders. This is particularly important during periods of high PV penetration when the grid voltage may already be elevated due to other sources of generation. But these active power control methods implemented at the inverter stage of the PV system, results in many disadvantages such as implementation complexities and excessive oversizing of the converter which can add up to system's complexity, increase the risk of failure, inefficiencies, and cost. Advanced control methods, such as MPPT require more complex hardware and software implementation, which can increase the cost and complexity of the system. Some control methods may require oversizing of the inverter or converter to handle high transient power demands. Oversizing the converter can result in inefficiencies during low power output periods (Sanseverino et al., 2016). These conditions are not ideal for rooftop solar PV modules.

There are various methods found in literature to mitigate the overvoltage issue on low voltage feeders such as Battery Energy Storage Systems (BESS), On Load Tap Changer (OLTC), automatic voltage regulators (AVR), droop based active power control (APC), multi objective optimal (MOO) power flow control etc. (Verma et al., 2022). Though there are many types of research and studies on this overvoltage issue due to high Photo-Voltaic penetration, most of the suggested solutions in those publications do not apply to Sri Lanka because of various network structures, network component types, climatic conditions, solar temperature and irradiation levels, load profiles and load density in feeders, feeder lengths, different varieties and sizes of conductors, and Voltage Regulations in various Utilities (Comester et al., 2020).

1.1. DC-DC Converters

With the thrust of the world energy market towards distributed generation via solar PV and wind resources, which produce direct current (DC) output, the importance of DC-DC conversion to increase or decrease the output voltage, is an extreme necessity. Electronic DC-DC converters use switching to achieve this (Cobben et al., 2020). By momentarily storing the input energy and then releasing it to the output at a different voltage, switched-mode dc-dc converters convert one dc voltage level to another, which may be higher (Figure 1).

Buck Converter

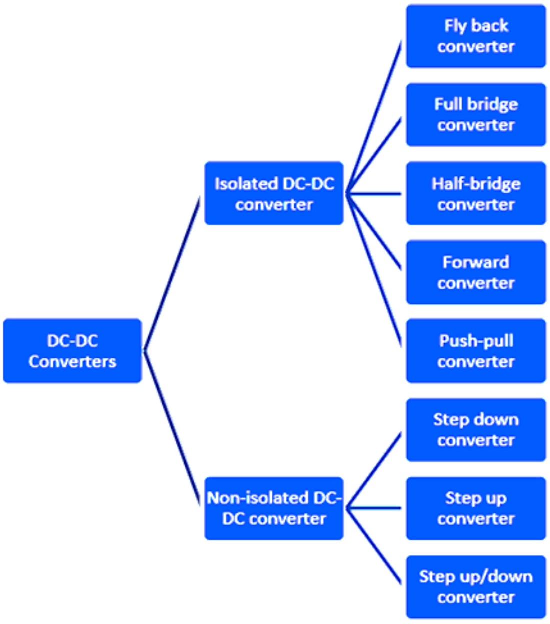


Figure 1: Types of DC-DC converters

The buck converter is a non-isolated DC-DC converter used to lower the output voltage and has two modes of operation considering the current through the inductor (IL). They are continuous mode and discontinuous mode. In the discontinuous mode, the IL is interrupted for a period, while in the continuous mode, there is no period when the inductor current is zero. The continuous mode is usually used in the DC-DC conversion (García-Villalobos et al., 2017).

2. METHODOLOGY

This research focuses on the voltage rise issue of solar PV systems. For the voltage rise issue, a buck converter design has been implemented to be placed in between the solar PV panel and the inverter in the solar power generation system. The basic idea is to reduce the overvoltage conditions by curtailing the power injected into the grid, thus reducing the voltage increase in low voltage (LV) feeders. Since buck converters step down the voltage, this changes the V-I curve of solar panels. This changed V-I curve is then inputted to the Maximum Power Point Tracking Inverter (MPPT). As now the MPPT sees this shifted V-I curve, it generates and injects less power into the grid than before. When the injected power to the LV feeders is decreased, the amount of voltage rise when there is high PV penetration is also reduced. When there is too much solar injection into a particular LV feeder, the feeder voltage will rise. But this only happens when there is high PV penetration which occurs for a short period of time. Utility providers cannot control this because this is a local situation. When there is an overvoltage of a particular feeder, all the rooftop solar panels connected to that feeder will contribute to it. The prototype is designed to operate as the voltage rises due to solar injection. When it reaches the upper threshold of 244V (+6% of 230V), it takes power delivered by the solar panel and limits it to that value so that the solar panel voltage does not increase anymore. However, this does not prevent other solar panels connected to that feeder from increasing the voltage by injecting more power into the said feeder. If all the feeder's rooftop solar panels have this device connected in between the solar panel and the inverter, the voltage of that feeder will automatically be controlled. The following steps are followed to develop this concept into a prototype.

2.1. Identifying and analyzing already existing mitigation actions for voltage rise

By referring to already performed research, both online and offline, already existing mitigation actions were identified. However, most of these mitigation actions are not applicable in Sri Lanka because of differences in the network, climatic conditions, solar irradiation levels and feeder profiles.

Collection of Data

The data necessary for the study was collected from a power distribution company and a solar PV panel installation company. This includes the output power of solar panels, output AC voltage injected into the grid, and voltage and current of solar PV. The data was taken from three household rooftop solar from the Colombo district. These data were then analyzed to find out how the solar power curve behaves during different times of the day and how AC voltage injected into the grid changes along with it. Out of the three inverters the output voltage and output power of inverter 1 is plotted in Figure 2.

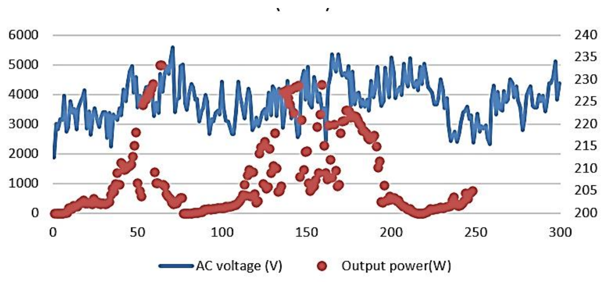


Figure 2: Output voltage vs output power of a selected inverter (5kW)

Figure 2 shows that the solar PV curve hits its maximum value when the AC voltage output also hits its maximum value. Thus, it can be clearly stated that by injecting less power to the grid the voltage regulation of LV feeders due to high rooftop solar can be achieved.

2.2. Perform a simulation of the desired prototype using MATLAB

Using the MATLAB Simulink software, the desired prototype was simulated. The designed prototype includes a buck converter with a voltage controller. The circuit also includes a solar panel (a DC voltage source is used instead of a solar panel, considering the cost and change in irradiance levels), a buck converter, and an inverter. Figure 3 demonstrates the modelled MATLAB Simulink.

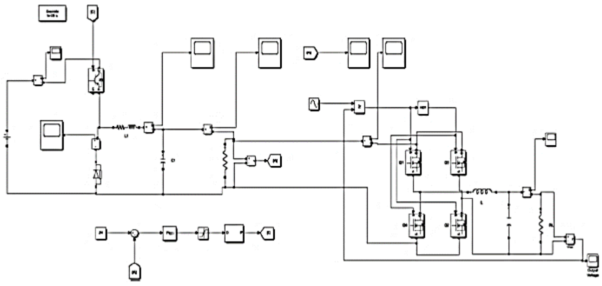


Figure 3: Model of the designed prototype

Buck Converter

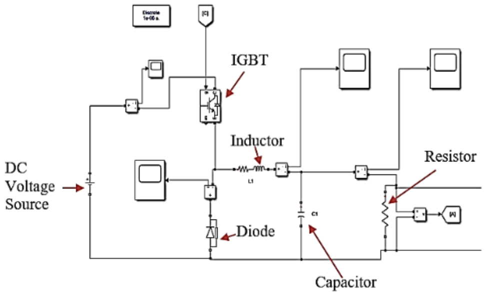


Figure 4: Model of the designed buck converter

Figure 4 shows the designed buck converter for a 48V DC source and the values for the power diode, inductor, capacitor were chosen accordingly.

Voltage Control

The designed voltage controller is shown in Figure 5.

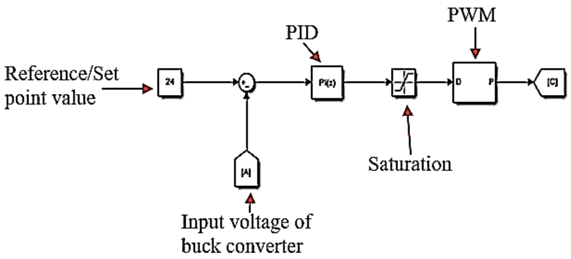
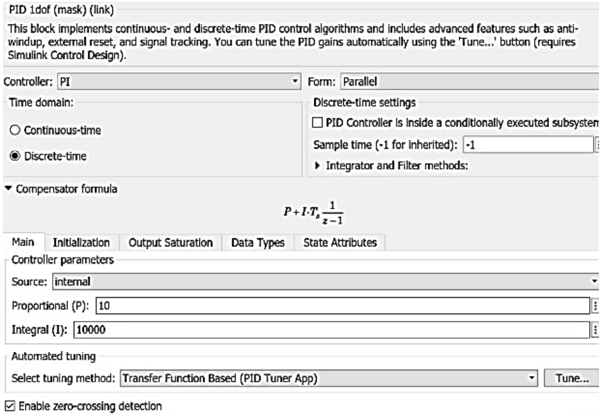


Figure 5: Model of the designed voltage controller

This operates on the basics of PID control. The voltage controller compares the input DC value of the buck converter with the provided reference/set value (24V) and feedbacks the error signal so that no matter what voltage is given to the buck converter (must not exceed the maximum voltage), it outputs a pre-defined value. For this to occur smoothly, the PID should be tuned. This was done from the trial-and-error method. The saturation function is simple, but it is a powerful function used to obtain a smooth function with a continuous derivative. PI control is used to generate the required PWM switching signal from the microcontroller for switching the IGBT of the buck converter. The tuned PI values using the trial-and-error method are shown in Figure 6.



PID 1dof (mask) (link)

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PI

Form: Parallel

Time domain:

○ Continuous-time

● Discrete-time

Discrete-time settings

☐ PID Controller is inside a conditionally executed subsystem

Sample time (-1 for inherited): -1

Integrator and Filter methods:

Compensator formula

$$P + I \cdot T_s \frac{1}{z-1}$$

Controller parameters

Source: internal

Proportional (P): 10

Integral (I): 10000

Automated tuning

Select tuning method: Transfer Function Based (PID Tuner App)

☑ Enable zero-crossing detection

Figure 6: Tuned PI values

Inverter

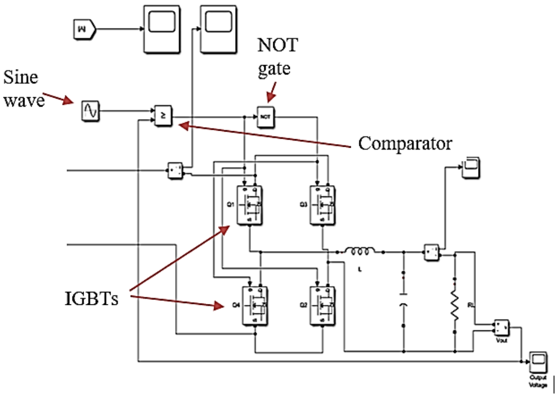


Figure 7: Model of the designed inverter

An inverter was implemented which is used to convert DC voltage output from solar to an AC output to be fed into the grid as shown in Figure 7.

Design of the Buck Converter

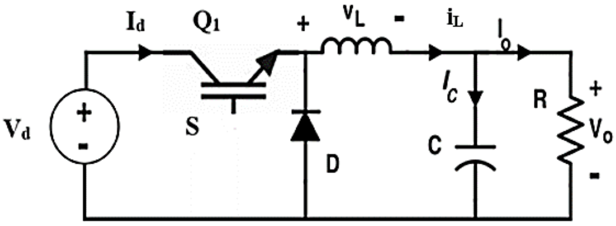


Figure 8: A simplified buck converter

By using the given set of equations below, the ratings and values of the buck converter were calculated.

$$\frac{V_0}{V_d} = D \qquad \text{Equation 01}$$

$$\Delta V_0 = \frac{(1-D)V_0}{8 f_s^2 LC} \qquad \text{Equation 02}$$

$$I_0 \geq \frac{(1-D)V_0}{2 f_s L} \qquad \text{Equation 03}$$

$$\left(I_{pk}\right)_{Q_1, D_1,} = I_0 + \frac{(1-D)V_0}{2 f_s L} \qquad \text{Equation 04}$$

$$\left(V_{pk}\right)_{Q_1, D_1,} = V_d \qquad \text{Equation 05}$$

$$\left(I_d\right)_{mean} = D I_o \qquad \text{Equation 06}$$

where,

V_o - Output voltage of buck converter

V_d - Input voltage of buck converter

D - Duty factor

ΔV_o - Super imposed ripple voltage

S_1- Switching signal of IGBT as a PWM (between 0 to 1)

f_s - Switching frequency

L - Inductor value

C - Capacitor value

I_o - Output current of the buck converter

$(I_{pk})_{Q1, D1}$ - Peak current value of the transistor and diode

$(V_{pk})_{Q1, D1}$ - Peak voltage value of the transistor and diode

V_d - Output current of the buck converter

$(I_d)_{mean}$ - Mean value of input current of buck converter

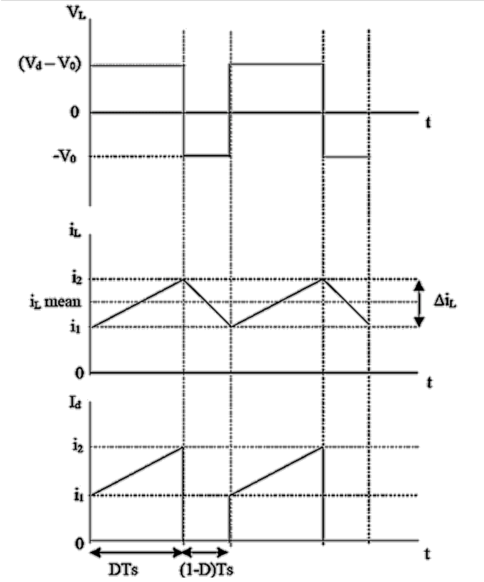


Figure 9: Inductor voltage, inductor current and input current variations with time of buck converter.

2.3. Switching of the buck converter

For the switching of the buck converter, a power semiconductor switching device is used. First, the required computer code was uploaded to the microcontroller, and it was checked if the generated PWM signal modifies its duty cycle based on the input voltage value using an oscilloscope as shown in Figure 10.

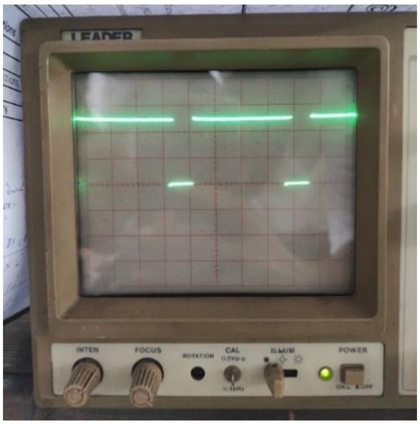


Figure 10: PWM signal generated with 20V input voltage

2.4. Develop a voltage controller

To control the voltage in the buck converter, a voltage controller is used because of the need to maintain a constant output voltage and reduce the output voltage side's current. The voltage sensor output is then connected to an Arduino UNO board (microcontroller) analogue pin. Then the output signal is taken from the Arduino, which is a PWM signal. This PWM signal is adjusted to the computer-coded value's modulation index (m). The PID should be tuned to reduce the error signal. An optocoupler is then used to isolate various output voltage levels. (48V is the input of the DC source, 5V is used to power up the microcontroller, and 15V-18V DC supply is used to provide power supply to the gate drive) Then the gate drive is used to provide the necessary switching to the IGBT. The gate drive adjusts the voltage values as required by the IGBT. Finally, the output of the buck converter is sent via a DC-AC converter to be fed into the electrical network.

2.5. Build the complete prototype

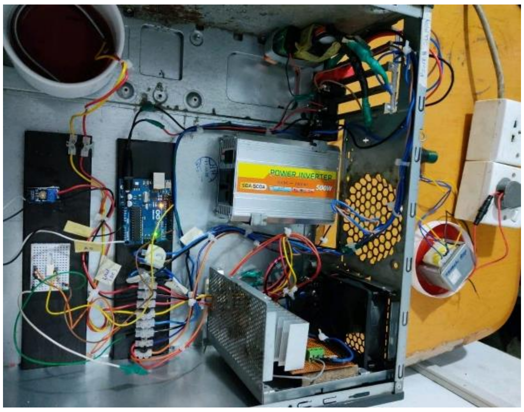


Figure 11: The complete designed prototype

By combining all the parts, the complete prototype was developed. Further testing and debugging of errors should be performed to improve the accuracy and efficiency of the prototype.

Figure 11 demonstrates the completely assembled prototype. Block diagram which demonstrates the complete working of the developed prototype is shown in Figure 12.

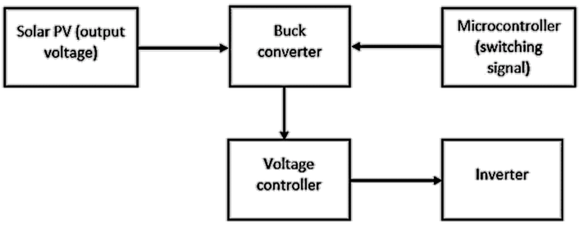


Figure 12: Block diagram of the power electronic converter

3. RESULTS

The waveforms obtained from the MATLAB simulation and the prototype connected to an oscilloscope are compared to check if they are identical in waveform shape. Figures 13,14, and 15 show that the 48V DC input voltage is now reduced to 19V DC voltage. The inductor current waveform is in the standard waveform shape (Figure 9). The output waveform of the inductor is in the shape of an AC sinusoidal waveform.

3.1. MATLAB simulation results

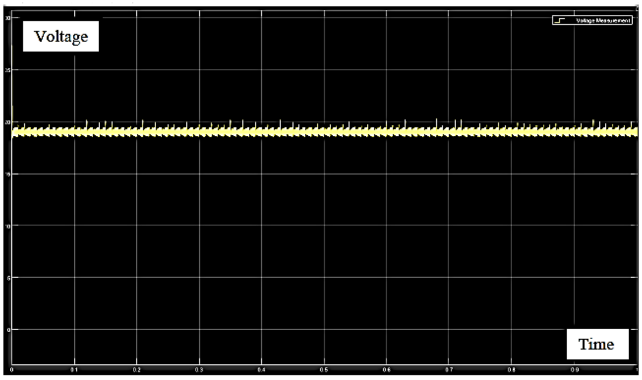


Figure 13: Output voltage waveform of the buck converter graph

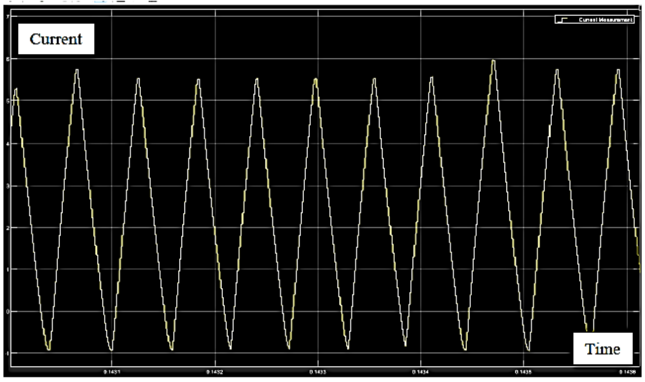


Figure 14: Inductor current waveform of the buck converter

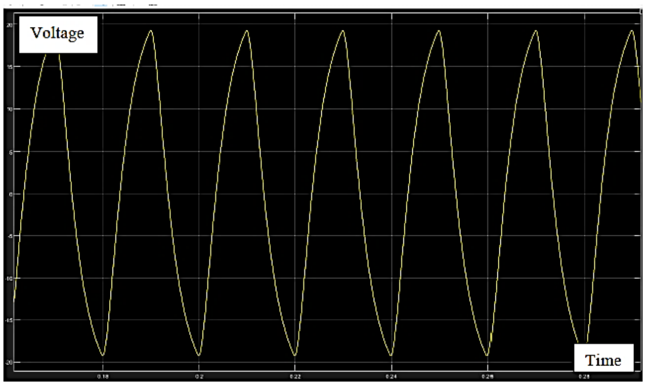


Figure 15: Output voltage waveform of inverter

Prototype Design Results

By testing the protype of the buck converter using a multimeter it was observed that the input voltage of 48V has been stepped down to 19V, while the input power of 65W has been reduced 50W.The output wave form of the inverter takes the shape AC sinusoidal waveform which is the expected outcome.

3.2. Solar PV curve

An online calculator called Oscilla solar IV is used to obtain the solar PV curve. Figure 19 shows the solar PV curve before (shown in red color) and after (shown in blue color) using the designed prototype. From this, it is clearly visible that the power generated and injected into the LV feeder is indeed now reduced. The voltage rise issue is also controlled as the power injected into the grid is reduced. These calculations are performed considering 25 Celsius solar cell temperature and 100 W/m2 irradiance level.

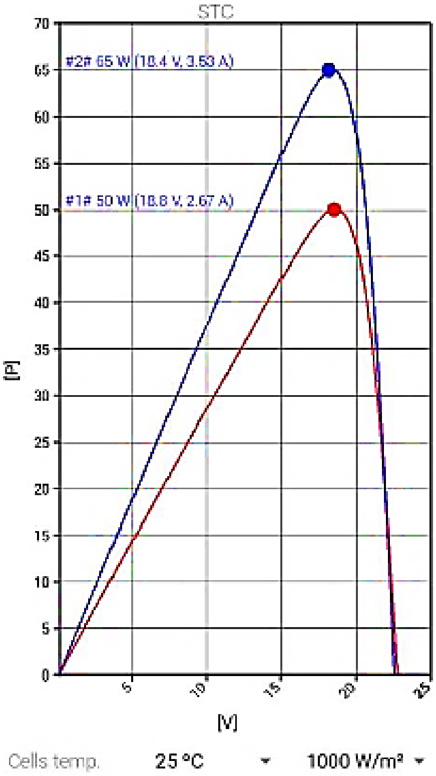


Figure 16: Solar PV curve

THD/Waveform Distortion

As this proposed power electronic device consists of a buck converter it can improve the overall efficiency of the system as it reduces the voltage level before it is converted to AC. This reduces the switching losses in the inverter and can result in lower power losses overall. Also, addition of a buck converter can improve the power quality of the output by reducing harmonic distortion. As buck converter can operate as a low-pass filter, it can reduce high-frequency noise in the output waveform thus reducing THD and waveform distortion of the output signal by providing a stable DC voltage input to the inverter (Al-Absi et al., 2017). Hence the THD of the proposed converter will be within 5% as defined by CEB regulations.

4. CONCLUSION

This research has examined the impacts of overvoltage in rooftop PV on the distribution network and evaluated possible mitigation actions regarding the voltage and power quality. Based on a MATLAB simulation, a prototype was designed to limit the power injected into the grid during periods of anticipated voltage. This is done by voltage control using a buck converter only when high PV penetration leads to overvoltage. The waveforms of the simulation and the prototype were then compared and confirmed that they were in a similar shape compared to the calculated values. Also, an input of 65 W is reduced to 50 W by reducing the input DC voltage from 48V to 19V. Hence this prototype operates with an efficiency of 76.9 %. It was then confirmed that the power injected into the grid can indeed be controlled by voltage control.

4.1. Future work

The following work is suggested to enhance the present work.

- Developing a boost converter: Develop the prototype by adding a boost converter to step-up the voltage when there is low PV penetration so that more solar power can be injected into the grid. This must be done carefully so as not to overvoltage the LV feeder.
- Addition of a dynamic braking resistor; currently, the loads are immersed in engine oil to dissipate the heat more efficiently.
- Addition of a BESS (Battery Energy Storage System): In this prototype, the extra power generated is dissipated. This power can be used to charge a DC battery which can be utilized at night.
- Development of a communication link: In here the prototype is being operated manually. By developing a communication link between the utility provider and the prototype, the utility provider can monitor the system using smart meters, and when there is an overvoltage of a LV feeder, the utility provider can send a message to the prototype to reduce the power injection to the grid.
- Control the solar power injection to the grid to any desired level: Currently, the prototype can only reduce the power to one level, that is, 65 W to 50W. This can be developed into being controlled by the utility providers to any value that they desire. (Example: If the utility provider wants to reduce the power from 65W to 60W or 55W)

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