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Technical and Economic Modeling of the 2.5kW Grid-Tie Residential Photovoltaic System

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Abstract- The rising cost of electricity and environmental concerns have driven research in the photovoltaic panels. In this paper, we used Matlab Simulink to model the photovoltaic module. The PV module is connected to the DC-DC boost converter, MPPT, full-wave inverter and transformer stage using the SimPowerSystems of Matlab. The economic model of the PV system is done using the Systems Advisor Model (SAM) in South African context. The inputs used are obtained from the draft document of National Energy Regulator of South Africa (NERSA) Renewable feed-in tariff (REFIT) of 2011. The result obtained shows that PV electricity is viable within the NERSA REFIT program however for a residential PV operator the cost of PV electricity is still higher than the utility electricity tariff.

Keywords- Photovoltaic, systems advisory model (SAM), levelised cost of electricity (LCOE), Maximum power point tracker (MPPT), DC-DC converters, full-wave inverter.

1. Introduction

Photovoltaic cells are classified as the direct solar power devices because they convert light directly to electricity. They are semiconductors that generate photocurrent by a process known as the photovoltaic effect. This is a process whereby electrons are transferred from the valence band to the conduction within the material resulting in the build-up of voltage across the electrodes. This process was first observed by Alexandre-Edmond Becquerel in 1839 [1]. In most photovoltaic applications, the radiation is sunlight hence they are called solar cells. In the case of a p-n junction solar cell, illuminating the material creates an electric current as the excited electrons and holes are swept in different direction by a built-in electric field of the depletion region. There are currently many research groups and universities with research focused on the development of the solar photovoltaic cells, and that their works are divided into making solar cells cheaper, more efficient compared to other energy sources, developing new technologies and architectural designs, and developing new materials with enhanced light absorption and charge carrier capabilities.

Solar power is renewable and pollution free which means no greenhouse gases are emitted once they are set up. The sun keeps coming back every day (in many places). The solar energy landing on the earth in one day is enough to power the planet for a year. The main disadvantages of the solar power devices are high installed cost per unit watt and the intermittent nature of the output power. Consequently, the solar panels are often used in conjunction with power electronics and batteries which further add to the total installed cost. Subsidies and grants are available in many countries to alleviate the issue of high cost of the panels [2]. The solar cells are classified as the Silicon, thin film, organic and the Concentrated Photovoltaics (CPV). The concentrated photovoltaic solar cells have shown the best performance than the rest.

2. Theory Development

A solar cell is basically a p-n junction fabricated in a thin wafer of semiconductor. The electromagnetic radiation of solar energy can be directly converted to electricity through photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor creates some electron-hole pairs proportional to the incident irradiation. The equivalent circuit diagram of a photovoltaic cell is shown in Fig.1

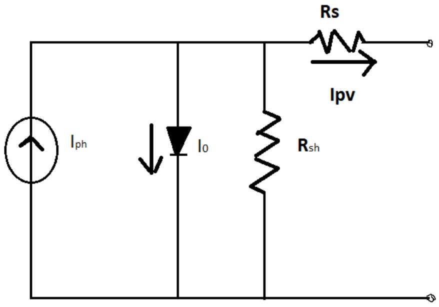


Fig. 1. Photovoltaic equivalent circuit

2.1. Nomencleture

V_{PV} is output voltage of a PV module (V) Ipv is output current of a PV module (A)

T_r	is the reference temperature = 298 K
T	is the module operating temperature in Kelvin
I_{Ph}	is the light generated current in a PV module (A)
I_o	is the PV module saturation current (A)
A	= B is an ideality factor = 1.6
K	is Boltzman constant = 1.3805 × 10-23 J/K
q	is Electron charge = 1.6 × 10-19 C
D	is the diffusivity of the majority carrier for silicon as a function of doping
Rs	is the series resistance of a PV module
I_{SCr}	is the PV module short-circuit current at 25°C and 1000W/m2 = 2.55A
K_i	is the short-circuit current temperature co-efficient at
I_{SCr}	= 0.0017A / °C
λ	is the PV module illumination (W/m2) = 1000W/m2
Ego	is the band gap for silicon = 1.1 eV
N_S	is the number of cells connected in series
N_P	is the number of cells connected in parallel
N_D	is the doping
n_i	is the intrinsic carrier concentration for silicon
P`	is another temperature dependent constant typical value 3.9 x 1016
I_{rs}	is the cells reverse saturation current at a reference temperature and a solar radiation
Q_n	is the electricity generated in year n (kWh)
n	is the analysis period in years
R_n	is the project revenue from electricity sales in year n
D_{real}	is the discount rate;
$D_{nominal}$	is the nominal discount rate

Table 1. Electrical characteristics data of Solkar 36W PV module

Rated Power	37.08W
Voltage at maximum Power (V_{mp})	16.56V
Current at Maximum power (I_{mp})	2.25A
Open circuit voltage (V_{OC})	21.24V
Short circuit Current (i_{SCr})	2.55A
Total number of cells in series (N_S)	36
Total number of cells in parallel (N_P)	1

For an ideal PV cell, there is no series loss and no leakage to the ground hence $R_S = 0$ and $R_{SH} = \infty$. The voltage-current characteristic equation of a solar cell is given by equation (1)

$$I_{PV} = I_{ph} - I_{SCr}\{exp(q(V + IR_s)/kRTA) - 1\} - \frac{V + IR_s}{R_{SH}} \quad (1)$$

The photocurrent depends on the solar insolation and cell`s working temperature which is described in equation (2)

$$I_{ph} = [I_{SCr} + K_i(T - 298)] * \lambda/1000 \quad (2)$$

For Intrinsic Carrier concentration in Semiconductors increase in temperature reduces the band gap of the semiconductor thereby affecting most of the semiconductor material parameters and vice versa. The saturation I_0 from one side of the p-n junction is given by equation (3)

$$I_0 = qA\frac{Dn_i^2}{LN_D} \quad (3)$$

The equation for the intrinsic carrier concentration is by equation (4)

$$n_i^2 = PT^3 \exp(-\frac{qE_{G0}}{BkT}) \quad (4)$$

Substituting n_i in equation (3) we obtain

$$I_0 = qA\frac{D}{LN_D}PT^3 \exp(-\frac{E_{G0}}{kT}) = P'T^3 \exp\left(-\frac{qE_{G0}}{BkT}\right) \quad (5)$$

We define the saturation current at a reference temperature as shown in equation (6)

$$I_{rs} = P'T_r{}^3 \exp(-\frac{qE_{G0}}{BkI_{ref}}) \quad (6)$$

Solving equations (5) and (6) we obtain equation (7)

$$I_0 = I_{rs}[\frac{T}{T_r}]^3 \exp[\frac{q*E_{g0}}{Bk}\{\frac{1}{T_r} - \frac{1}{T}\}] \quad (7)$$

In general, the solar cell efficiency is insensitive to the variation in R_{SH} and the shunt-leakage resistance can be assumed to approach infinity without leakage current to the ground. A small change in R_s will affect the output of the panel`s power [3]. Hence equation (1) could be modified as shown in equation (8)

$$I_{PV} = I_{ph} - I_0\left[exp\left\{\frac{q*(V_{PV} + I_{PV}R_s)}{AkT}\right\} - 1\right] \quad (8)$$

If $R_s = 0$ then equation (8) is rewritten as in equation (9)

$$I_{PV} = I_{ph} - I_0\left[exp\left\{\frac{q*(V_{PV})}{AkT}\right\} - 1\right] \quad (9)$$

The levelized cost of electricity (LCOE) which is given by equation (10)

$$Real\ LCOE = \frac{\sum_{N-1}^{N}\frac{R_n}{(1 + d_{nominal})^n}}{\sum_{N=1}^{N}\frac{Q_n}{(1 + d_{real})^n}}$$

3. Modeling a Photovoltaic Module with Matlab

Matlab is a high-level language and interactive environment for numerical computation, visualization, and programming. Matlab could be used to analyze data, develop algorithms, and create models and applications. At the matlab command prompt, command "ver" could be used to display the list Matlab tool boxes. Simulink, SimPowerSystems and Simscape which are opened at the command prompt 'Simulink' are used to build the photovoltaic model. SimPowerSystems is a sub-toolbox under Simulink used to build the physical model of the solar panel. The Simulink model of a photovoltaic module is shown in Fig 2.

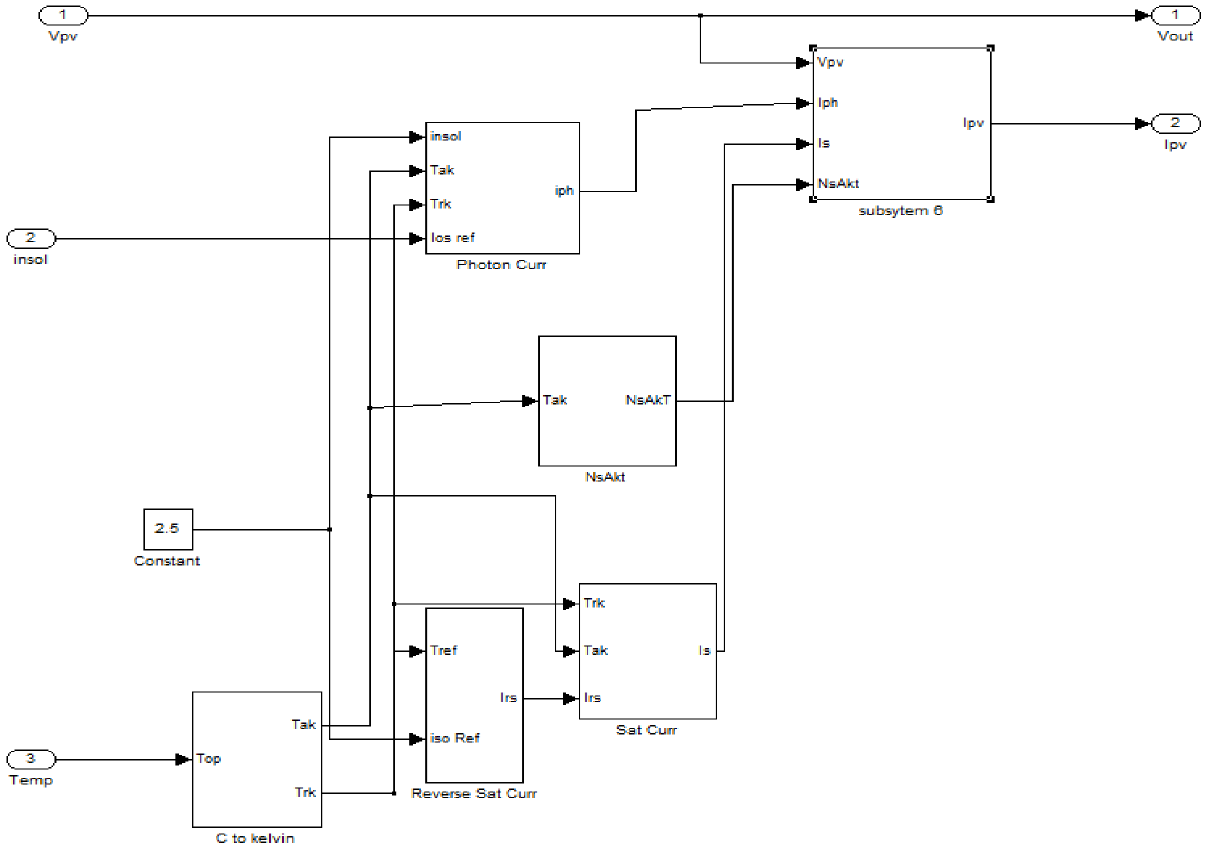


Fig. 2. PV module

The 9 modules per string are arranged in 2 parallel strings and are connected to the solar cell circuit through the controlled current source (CCS) IL found in SimPowerSystems Matlab toolbox as shown in Fig. 3.

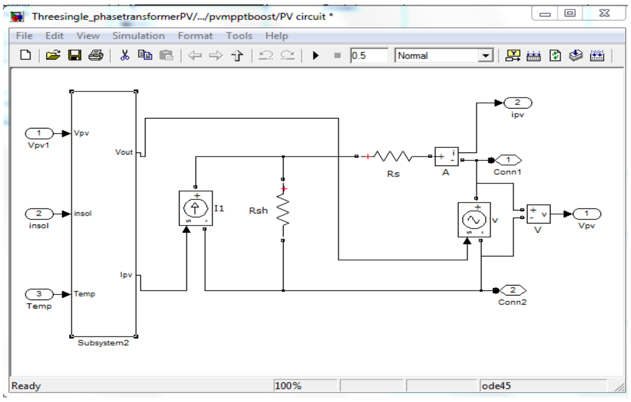
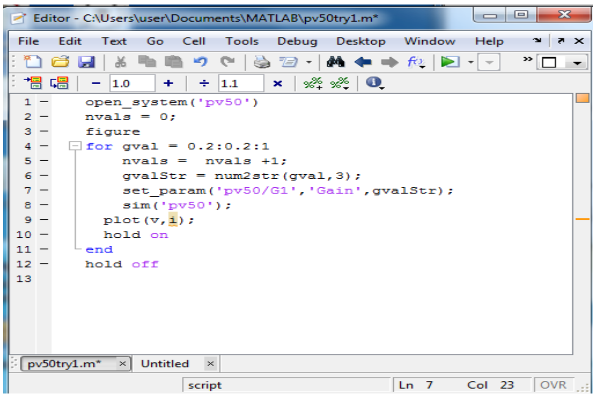


Fig. 3. SimPowerSystem physical circuit model

The diagram in Fig. 4 is a code written in Matlab file editor to iterate different levels of solar radiations and temperatures [4]. It starts from solar radiation of 200W/m2 and increases the solar radiation levels to 1000W/m2.with steps of 200Wm2 at each level.



```
open_system('pv50')
nvals = 0;
figure
for gval = 0.2:0.2:1
    nvals =  nvals +1;
    gvalStr = num2str(gval,3);
    set_param('pv50/G1','Gain',gvalStr);
    sim('pv50');
  plot(v,i);
  hold on
end
hold off
```

Fig. 4. Matlab code to iterate different radiation levels

The PV output voltage levels and PV output currents are exported from Simulink to the Matlab main pane using the to workspace block of the Simulink. The values are then plotted using the plot command in Matlab. The graph of iPV and VPV against different radiation levels is shown in the Fig. 5.

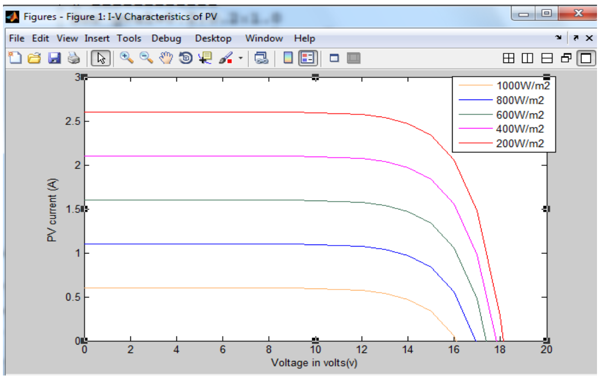
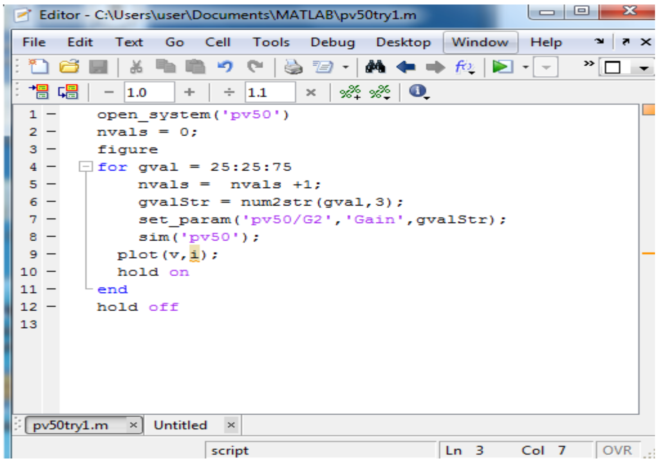


Fig. 5. IPV/VPV for insolation 200-1000W/m2

The code that iterates PV output for the temperatures ranging from 250 to 750 (Fig.6)



```
   open_system('pv50')
   nvals = 0;
   figure
   for gval = 25:25:75
        nvals =  nvals +1;
        gvalStr = num2str(gval,3);
        set_param('pv50/G2','Gain',gvalStr);
        sim('pv50');
     plot(v,i);
     hold on
   end
   hold off
```

Fig. 6. Matlab programme to iterate the temperature effect on the PV

The result is exported from Simulink to Matlab main window and plotted with the plot command in showed Fig. 7.

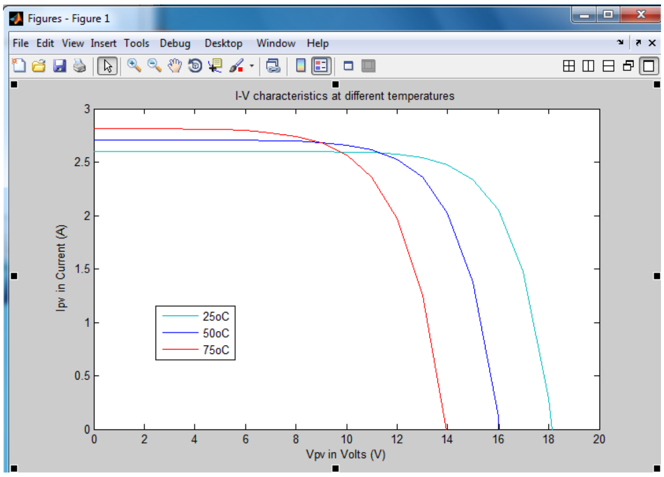


Fig. 7. Temperature effects on the Current voltage characteristics of the photovoltaic cell

3.1. DC-DC Converters

Power electronics provides a link or buffer that connects the solar panel to the load or the electrical power grid. It is the application of solid-state electronics for the control and conversion of electric power. It also refers to a subject of research in electrical engineering which deals with design, control, computation and integration of nonlinear, time varying energy processing electronic systems with fast dynamics. The power electronics could be found anywhere we need to change voltage, current or frequency of electric power. DC-DC, AC-DC, DC-AC converters are different classes of power electronics devices.

Types of DC-DC converters are boost, buck and cuk converters. The boost converters are used to raise the voltage levels of our appliance while the buck is used when high voltages are expected to be reduced. A cuk converter has an output voltage that is either greater or less than the input voltage.

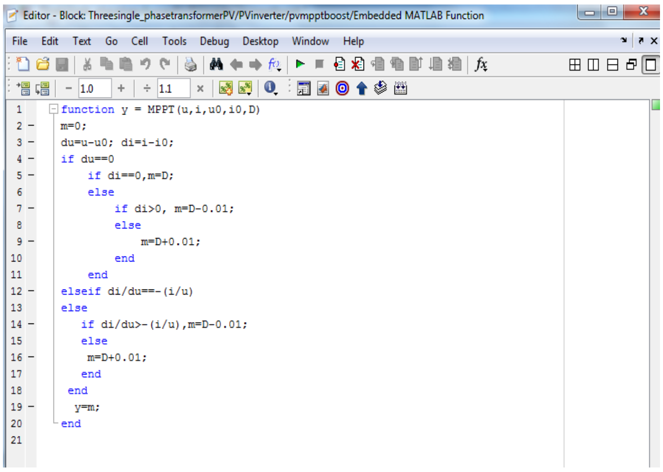
3.2. Maximum Power Point Tracking

Maximum power point tracking (MPPT) is a technique that grid-tie inverters, solar battery chargers and similar devices use to get maximum possible power from one or more solar panels. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency known as the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.

Perturb and Observe: This is the most common method of MPPT due to its ease of implementation. The controller adjusts the voltage by a small amount and measures the power, if the power increases, further adjustments in that direction are tried until power no longer increases. This is often called hill climbing method because it depends on the rise of the curve of power against voltage below the maximum power point and often results in oscillation of the power output.

Incremental Conductance: Here, the controller measures incremental changes in array current and voltage (dI/dV) to compute the sign of the change in the power with respect to the voltage (dP/dV). This method requires more computation in the controller but can track changing conditions more rapidly than P & O.

It can also produce oscillations in the power output. When the incremental conductance is zero, the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated. The IC method is used to transfer the maximum power from the PV panel to the energy storing capacitor as shown below. The code for the realization of the IC MPPT is also shown in Fig. 8.



```
function y = MPPT(u,i,u0,i0,D)
m=0;
du=u-u0; di=i-i0;
if du==0
    if di==0,m=D;
    else
        if di>0, m=D-0.01;
        else
            m=D+0.01;
        end
    end
elseif di/du==-(i/u)
else
   if di/du>-(i/u),m=D-0.01;
   else
    m=D+0.01;
   end
 end
  y=m;
end
```

Fig. 8. Matlab code for incremental conductance MPPT

The output of the PV module is a functuating output. In order to extract maximum power from the panel an MPPT is used with the DC-DC converter as is shown in Fig. 9. The MPPT algorithm is them inserted into the Matlab embedded block to form the MPPT block. The outputs (ie the current and voltage terminals) of the PV module are fed into the Matlab embedded block while the output of the MPPT is routed to the IGBT of the DC-DC boost converter.

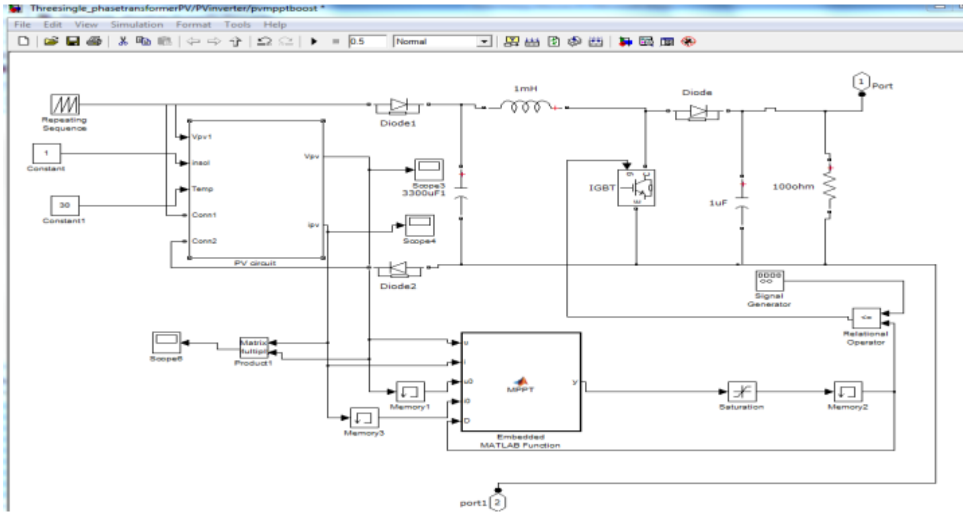


Fig. 9. PV module connected to the MPPT and the DC-DC boost converter

3.3. Inverters

In recent years, the industry has begun to demand higher power requirement which now reaches the megawatt level. Controlled ac drives in the megawatt range are usually connected to medium-voltage network. Today, it is hard to connect a single power semiconductor switch directly to medium voltage grids (such as 2.3, 3.3, 4.16, or 6.9KV). For these reasons, a new family of inverters has emerged as the solution for working with higher voltage levels. These are called the multi-level inverters.

Types of inverters are single phase inverters and three phase inverters, three step inverters are the simplest types however, in situations where sensitive appliances like the computers are used these inverters are not desirable because of their tendencies to produce other disadvantages of the three level inverters are low efficiencies. These problems have been addressed by the multi-level inverters such as the seven level inverters and the true sine wave inverters but these inverters have the disadvantage of high circuit complexity and high cost. A novel type of inverter is currently been developed which is the current source inverter (CSI). All the previously discussed inverters are the voltage source inverters (VSI). The CSI have much less complicated circuitry, cheaper and are not sensitive to voltage fluctuations [5]. The circuit diagram of a three level full-wave with the energy storing capacitor is shown in fig.10.

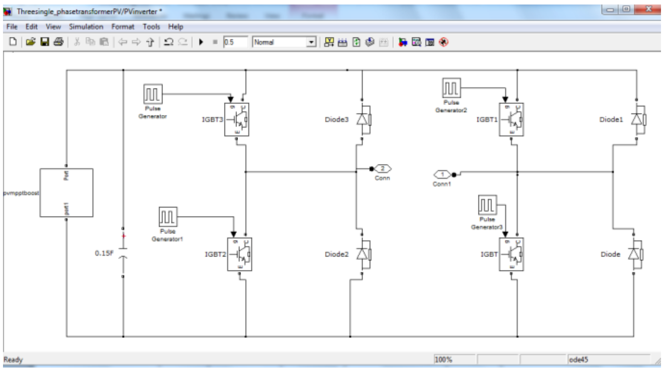


Fig. 10. Full-wave three-level PV inverter

3.4. Transformer

The output of the inverters is about 6V so we use a step up transformer to step up the voltage to 220V which is the distribution voltage. Filters are used to remove some of the harmonics as shown the Fig. 11. The PV module, MPPT, DC-DC converter and the inverters are wrapped up in a subsystem and labelled the PV module. This output is sent to the load and the grid

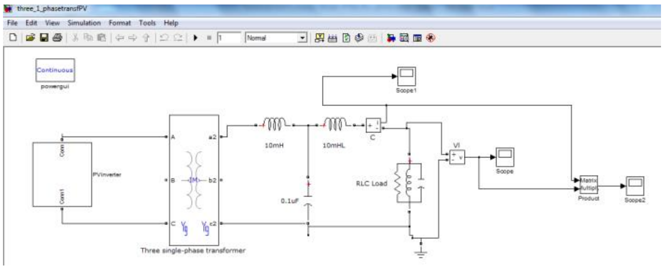


Fig.11. PV module and the transformer

4. Result

This signal in figure 12, 13 and 14 are the power, voltage and current of the PV panel sent to the grid and to power the load. Fig. 12 represents the AC power at the output of the PV system. The peak power is 2.5kW.

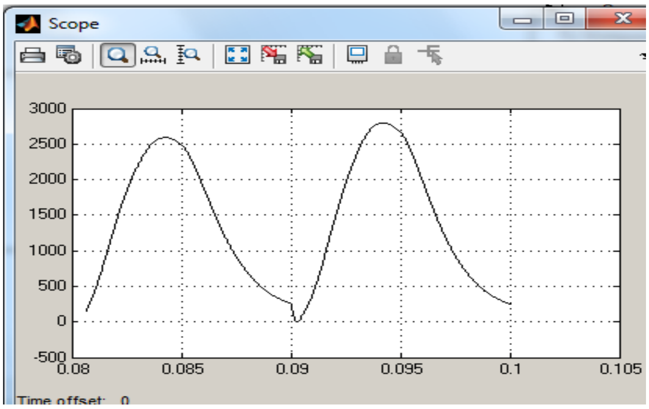


Fig. 12. Power output of the panel

Fig. 13 represents the PV system`s output voltage with the peak voltage of about 200V which corresponds with the South Africa domestic single phase a.c. supply voltage.

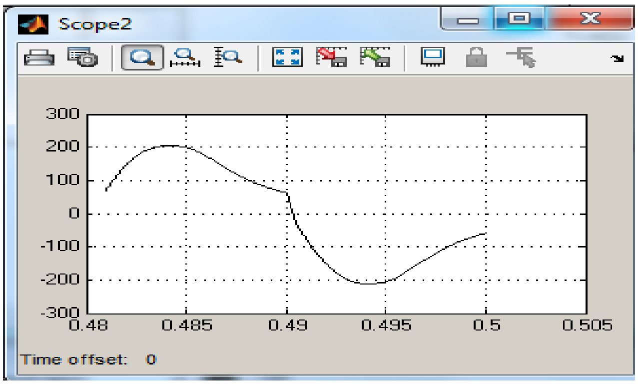


Fig. 13. PV Output Voltages

Shown in fig. 14 is the PV system`s output current which is an alternating current. The harmonic distortions observed on the signals are caused by the three level inverters used in this work. Modeling of superior inverters is not covered in this work.

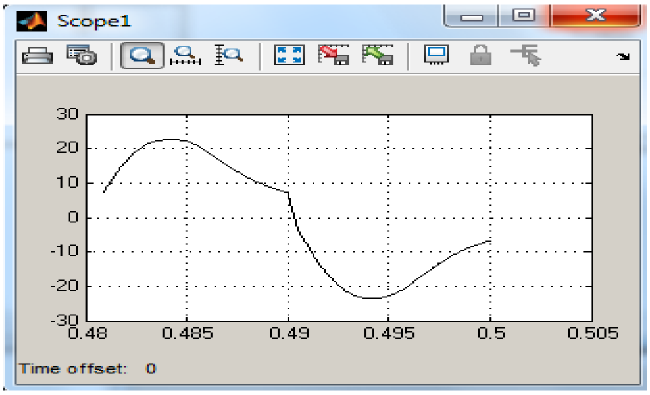


Fig. 14. PV Output Current

5. Economic Model with Sam

The software used for the economic and technical modelling of the photovoltaic panel is the Systems Advisory Model (SAM). SAM, originally called the ‘Solar Advisory Model’ was developed by the National Renewable Energy Laboratory in collaboration with Sandia National Laboratories in 2005 [6].

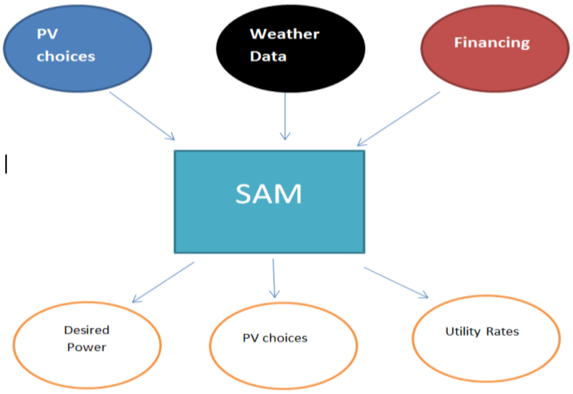


Fig. 15. SAM layout

SAM accept inputs like the climate, geographical location, size of the panel, interest rate, inflation, term of the loan and type of technology, runs the simulation and optimization to give outputs such as hourly, weekly, monthly and annual output power for the life of the plant; efficiency, the cash flow and levelized cost of electricity shown in figure 15.

5.1. Nersa Refit

The input parameters used in these simulations are based on the draft document of Review of Renewable Energy Feed-in-Tariff (REFIT) of the National Energy Regulator of South Africa (NERSA) consultation paper March 2011[7]. The exchange of R9.00 to $1 is used.

In 2007, the terms of the Act, the energy regulator commissioned a study on the Renewable Energy Feed-in-tariffs (REFITs) to support renewable energies in South Africa. The Feed-in tariffs (FITs) would be based on levelized cost of electricity (LCOE). The term of the Power Purchase Agreement (PPA) is to be twenty years and is to be reviewed every year for 5 years of implementation and every 3 years thereafter and the resulting tariffs will apply to only new projects.

In March 2009, the first REFIT tariffs were announced for wind, small hydro, landfill-to-gas and CSP (parabolic trough with 6hr storage. In October 2009, the second REFIT tariffs were announced for CSP (parabolic trough without storage), PV, solid biomass, biogas and CSP (Tower with 6hrs storage). In March 2011, the REFIT tariffs were revised, proposing to reduce tariffs between 7.3 to 41.5%. In August 2011, the 'REBID' was announced with 5 bidding windows: November 2011, March/August 2012, and March/August 2013. The initial total renewable energy allocation (RE) was increased from 1250MW to 3725MW [7]. The US-based costs from SAM are used and the results are converted to the South African Rand for the simplicity of the model. Inflation is assumed to be constant because inflation forecasting is not covered in this paper. The power purchase agreement (PPA) which in South African context is the Renewable Energy Feed-in Tariff (REFIT). NERSA approved term is 20 years. The South Africa annual tax rate is fixed at 28% [8].

5.2. Inputs

For Cape Town climate the weather direct normal radiation DNI is shown in the figure below. Time zone GMT 2, latitude -33.980, longitude 18.60, Elevation 42m, Direct normal 1923kW/m2, Dry-bulb temp 16.5oC, Wind speed 5.1m/s, Global horizontal 1900.7kW/m2. The consumer price index (CPI) or inflation of South Africa is about 5% [8]. Interest Rate (Prime) 8.5%; Exchange Rate R/$ is 9.0; Size of the panel is 2.5kW. Tilt angle 200

Table 2. The summary of inputs

Climate	Cape Town Climate
Inflation Rate	5%
Discount Rate	8%
Loan Rate	6%
Analysis period	20%
Debt Fraction	70%
Name plate capacity	2.5kW

5.3. Results

The cost of electricity generated by the photovoltaic systems includes the cost of generating electricity at the point of connection to the load or grid and it includes capital, discount rate as well as the costs of continuous operation, fuel and maintenance. The levelized cost of electricity (LCOE) is given by the in equation (10) of section 2

Table 3. Summary of the Outputs

Total Installed Cost	R97,200
Total installed cost per capacity	R56.7/Wdc
Annual Energy Output	3,275kWh
Capacity factor	14.9
Payback Period	19.77years
LCOE	R2.15

Monthly electrical energy output of the panel is shown in Fig. 15. The electrical energy output of the photovoltaic panel is best (about 400kWh) in summer period than in the winter because during this period, sunlight is it peak and shines longer hours of the day. Cloud cover is also minimal.

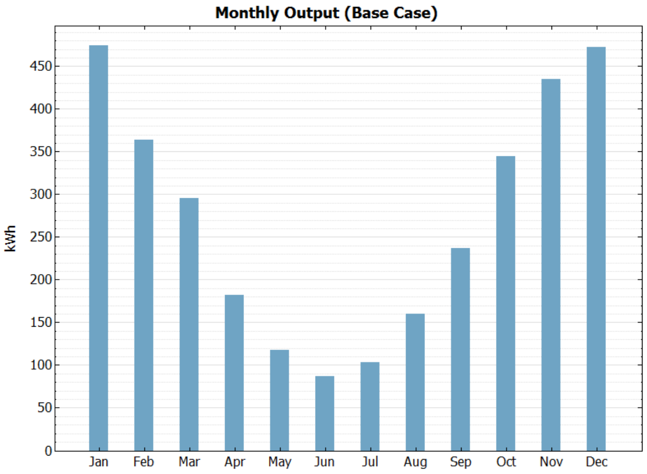


Fig. 15. Shows the monthly electrical energy output of the PV plant

NERSA document advises debt fraction of 70% however our simulations has shown that the lower LCOE of up to R2 is achieved at up to 100% debt fraction.

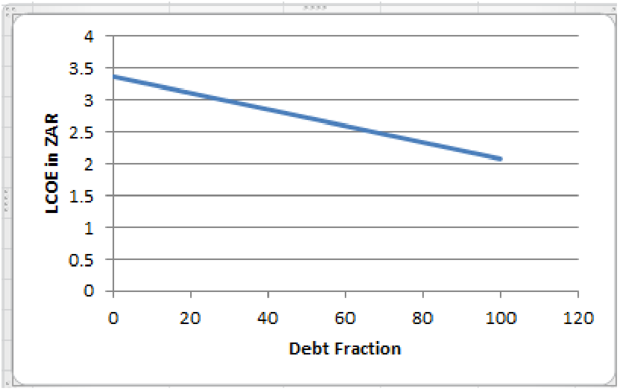


Fig.16. The Effect of Debt Fraction on the LCOE

6. Discussion

The cost of the PV panel from out result is about R2.15 which shows a substantial mark-up from the NERSA REFIT price of R3.94 (i.e. 83%) [7]. This shows that for an independent power producer whose main purpose is to produce and sell electricity, PV system is economically viable however, for a residential consumer PV system is still expensive compared to the utility electricity which costs R1.60 per unit (Block 4 tariff). Block 4 consumers refers to consumers that consume an average of 600kWh and above of electricity monthly [9]. Government and utility incentives are therefore required to motivate consumers to invest in the residential photovoltaic systems. On the interim research efforts which target development of materials and novel manufacturing methods that will bring down the cost photovoltaic modules as well as power electronics should be encouraged.

7. Conclusion

This article brings to light the steps taken to model the photovoltaic module from equivalent circuit and the equations of a solar cell. The photovoltaic module which is modeled with Simulink is then coupled with the power electronic circuits built with SimPowerSystems. The economic model shows the cost/performance of the photovoltaic systems within the NERSA Refit tariff of South Africa. The LCOE is found to be R2.15 which is still higher than the utility electricity.

Acknowledgements

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