



Design and Economic Analysis of a Grid-Connected Photovoltaic System in Saudi Arabia using PVsyst Software

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DOI: <https://doi.org/10.30880/ijie.2022.03.01.005>

Received 10 July 2021; Accepted 04 October 2021; Available online 30 June 2022

Abstract: This paper presents the design and analysis of a grid-connected photovoltaic system (GCPV) in Al Juaima'h, Dammam, Kingdom of Saudi Arabia. The main objective of this study is to design the suitable GCPV system and investigate the potential of electricity costs and CO₂ emission reduction by using PVsyst software. The sizing of the proposed GCPV system has been conducted using mathematical calculation and PVsyst software. It shows that both calculation and simulation software obtained the same result of 1920 PV panels and 8 inverters required for the same location. Therefore, further analysis of the proposed 960 kWp GCPV system has been simulated in PVsyst software. From the simulation, it found that the system performances of PV array generation is 1649.9 MWh/year, energy injects into the grid is 1616.9 MWh/year, performance ratio is 82.3%, payback period is 6.9 years and CO₂ reduction is 29878.2 t. Therefore, the proposed GCPV system can provide significant electricity cost saving and CO₂ reduction to the consumer.

Keywords: CO₂ emission, Grid-Connected Photovoltaic, PVsyst, PV Sizing, Renewable energy, Solar Energy

1. Introduction

The Kingdom of Saudi Arabia has become one of the largest countries in the market for photovoltaic energy projects in the Gulf Cooperation Council countries and is expected to be the leader in the field of solar energy [1]. Solar energy is a cheap and durable source of electrical energy Helping society overcome its dependence on traditional fuels [2]. Moreover, it is non-polluting, clean, and consistent. Fortunately, as energy prices rise internationally, the cost of solar energy is declining. The cost of PV decreased by 50% between 2010 and 2014 [3]. The earth's energy consumption can be generated entirely annually by one hour of sunshine [4].

The photovoltaic system one of the main sources of the energy production world. The photovoltaic system reduces the cost of electricity consumption and thus reduces the cost to the consumer. The system will also be able to cover the site's energy needs completely. The photovoltaic system will help reduce environmental pollution significantly, as it will reduce carbon dioxide emissions from waste energy sources such as petrochemical products. Based on all these advantages, the PV system can be considered a great solution to the above-mentioned energy problems.

The Kingdom of Saudi Arabia is one of the largest energy consumers in the Middle East [1]. The Kingdom of Saudi Arabia plans to increase its production of electric energy to 120 gigawatts by 2032, and the reason for this is the increased demand for energy in the country [1]. According to the BP statistic regarding energy in the world in 2014, the Kingdom of Saudi Arabia produced 1 billion kilowatt-hours of electricity throughout 2013 [5]. As the consumption of Saudi Arabia increased in the past decade at a rate of 7.5-10% annually, and the intention to increase from 2007 to 2020 [2]. The reason for this increase is due to the recent increase in population and industrial development [1]. According to the latest statistics, the Kingdom of Saudi Arabia has the largest expansion plan in the Middle East to produce energy from

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renewable sources to build a certain future for the Kingdom of Saudi Arabia [1]. Nine Saudi Arabia in Khalil Amin to add 41 gigawatts of solar energy and gigawatts of other renewable sources to expand the electricity supply [1].

This paper design a GCPV system for Al Juaima'h, Dammam, Saudi Arabia (26 ° 43'12.2 "N 49 ° 53'42.0" E) using both mathematical calculation and PVsyst software. The main purpose of this study is to determine the suitable of GCPV size including the number of PV panels, inverters, losses and system performances for the selected location. The proposed GCPV system is expected to reduce electricity costs and CO₂ emissions. The GCPV system design is based on location data, historical electricity bills, selected solar panels and inverters as discussed in the next subtopic.

2. Methodology

The method discussed for designing the GCPV system is divided into three sections. The three sections consist of GCPV system mathematical calculation, PVsyst software and AutoCAD. Fig. 1 shows the main methodology flowchart of the project.

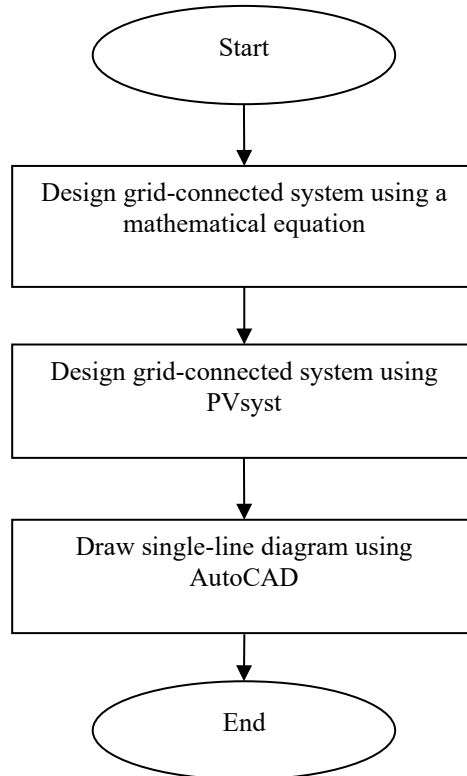


Fig. 1 - Main methodology flowchart of the project

2.1 Design GCPV System Using a Mathematical Equation

The mathematical design for the GCPV system shows the model-row spacing, GCPV components and protection device. The solar panel technology used for the design is monocrystalline. The monocrystalline model name is BLUESUN with model number BSM500PM5-72SB [6]. The inverter technology was used for the design of a three-phase grid-connected PV system with multiple MPPT inverters. The selected inverter model is HUAWEI with model number SUN2000-100KTL-M1 [7].

2.1.1 Model-row Spacing

The shading must be taken into consideration to reduce solar panels losses. The row spacing can be done using the sun altitude and tilt angle. Fig. 2 shows the shading model row spacing. The tilt angle can do using Equation (1). Referring to Fig. 2 The tilt angle can calculation using Equation. The PV model height (X) from the ground can be done using Equation (2) [8].

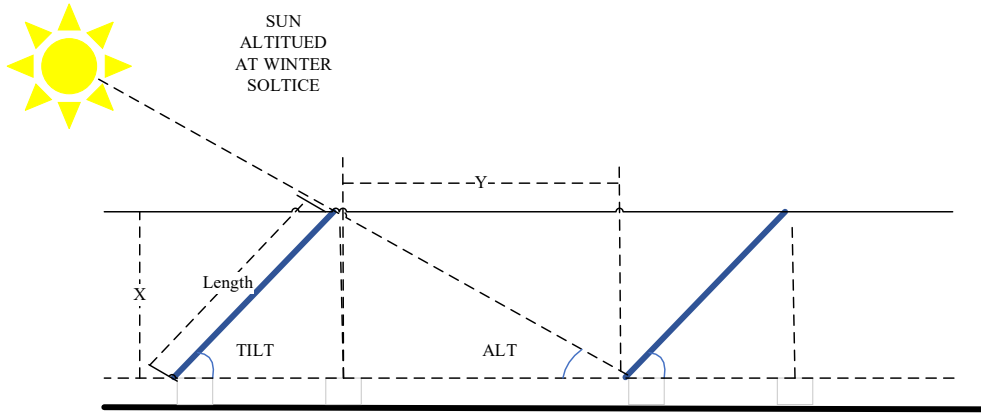


Fig. 2 - The shading model row spacing

$$Tilt^\circ = (ALT \times 0.93) - 21 \quad (1)$$

$$X = Length \times \sin(Tilt^\circ) \quad (2)$$

where $Tilt^\circ$ is the tilt angle in degree, 0.93 is the constant number for altitude more than 25 degrees, 21 is the constant number for altitude more than 25 degrees, X is the tilt height in m and $Length$ is the module length, in m.

The model row spacing (Y) can be done by referring to Fig. 2 from the ground using Equation (3).

$$Y = X \times \tan(ALT) \quad (3)$$

where Y is the model row spacing in m.

2.1.2 The GCPV Components

The daily consumption can be calculated using Equation (4). The method used in this calculation depends on the method described in reference [9] with some modifications. The total energy accumulated in the day.

$$Eday = \frac{Eyearly}{Days} \quad (4)$$

where $Eday$ is the energy used daily in kWh and $Eyearly$ is the energy used yearly in kWh.

The daily sun peak hours are calculating using Equation (5). Also need to get the global solar irradiation using the result of PVsyst the duration of solar irradiance can get Sun peak hours.

$$SPH = \frac{PSH_{period}}{365} \quad (5)$$

where SPH is the daily Sun peak hours and PSH_{period} is the duration of solar irradiance annually in kWh/m².

The photovoltaic system power output shows in Equation (6). The data that needs to calculate the photovoltaic system power output is the energy daily, sun peak hours, and duration of solar irradiance. The array output shows in Equation (7).

$$P_{pvac} = \frac{Eday}{SPH} \quad (6)$$

$$P_{pvdc} = P_{pvac} \times 1.25 \quad (7)$$

where P_{pvac} is the power output for inverter in kWh and P_{pvdc} is the power output for array in kWh.

The number of solar panels required for the GCPV system can be calculated using Equation (8).

$$N_{module} = \frac{P_{PVdc}}{P_{mp_stc}} \quad (8)$$

where N_{module} is the number of solar panels, P_{pvdc} is the expected power output of the solar system and P_{mp_stc} is the module standard test condition.

$$(N_{module} \times P_{mp_stc} \times 0.9) \leq P_{nominal_inv_expected} \leq (N_{module} \times P_{mp_stc} \times 1) \quad (9)$$

where $P_{nominal_inv_expected}$ is the power nominal inverter expected.

Any inverter can be selected based on the power nominal inverter expected. To estimation of PV array power based on selected inverter using Equation (10).

$$\left(\frac{P_{nominal_inv_expected}}{1.00}\right) \leq P_{array_stc} \leq \left(\frac{P_{nominal_inv_expected}}{0.90}\right) \quad (10)$$

where P_{array_stc} is the estimation of PV array power based on the selected inverter.

The estimated number of PV modules can be calculated using Equation (11).

$$\left(\frac{P_{array_stc}}{P_{mp_stc}}\right) \leq N_{module} \leq \left(\frac{P_{array_stc}}{P_{mp_stc}}\right) \quad (11)$$

where N_{module} is the optimum number of PV modules.

After done, the Optimum array configuration needs to calculate the minimum and maximum number of PV per string using the Equations below. Then determine the optimum array configuration.

Minimum number of PV per string:

$$V_{min_mp} = V_{mp_stc} \times \left[1 + \frac{\gamma_{Pmp}}{100} \times (T_{cell_max} - T_{stc})\right] \quad (12)$$

$$V_{min_mp_eff} = 0.95 \times V_{min_mp} \quad (13)$$

$$V_{min_win_inv_allow} = 1.1 \times V_{min_win_inv} \quad (14)$$

$$N_{min_per_string} = \frac{V_{min_win_inv_allow}}{V_{min_mp_eff}} \quad (15)$$

Maximum number of PV in series per string:

$$V_{max_oc} = V_{oc_stc} \times \left[1 + \frac{\gamma_{voc}}{100} \times (T_{cell_min} - T_{stc})\right] \quad (16)$$

$$V_{max_inv_allow} = 0.95 \times V_{max_input_inv} \quad (17)$$

$$N_{s_max} = \frac{V_{max_inv_allow}}{V_{max_oc}} \quad (18)$$

$$N_{p_max} = \frac{I_{max_dc_inv}}{f_{safety} \times I_{sc_stc}} \quad (19)$$

where V_{min_mp} is the minimum operating voltage, V_{mp_stc} is Is the operating voltage during STC from solar panel datasheet, γ_{Pmp} is the temperature coefficient for power maximum from solar panel datasheet in % / °C, T_{cell_max} is the maximum temperature solar panel datasheet, °C, T_{stc} is the STC temperature, $V_{min_mp_eff}$ is the minimum operating voltage with cable losses, $V_{min_win_inv}$ is the minimum voltage from inverter datasheet, $V_{min_win_inv_allow}$ is the minimum allowed voltage for inverter, $N_{min_per_string}$ is the minimum number of PV modules in series per string, N_{p_max} is the maximum number of PV modules in series per string, V_{max_oc} is the maximum open circuit voltage, V_{oc_stc} is the open circuit voltage during STC from solar panel datasheet, V, γ_{voc} is the temperature coefficient for open circuit voltage from solar panel datasheet, % / °C, T_{cell_min} is the minimum temperature solar panel datasheet, °C, $V_{max_inv_allow}$ is the maximum allowed voltage for inverter, N_{p_max} is the maximum number of PV string per inverter, $I_{max_dc_inv}$ is the maximum DC current for inverter from inverter datasheet, f_{safety} is the safety factor $1.25 P_{nom}$ and I_{sc_stc} is the short circuit current from solar panel datasheet.

Total energy generated for 1 year can be calculated using the following Equations.

$$E_{sys} = P_{array_stc} \times PSH_{period} \times f_{temp_avg} \times f_{mm} \times \eta_{pv} \times \eta_{inv} \quad (20)$$

$$f_{temp_avg} = 1 + \left[\frac{\gamma_{Pmp}}{100} \times (T_{cell_avg} - T_{stc})\right] \quad (21)$$

where E_{sys} is the estimation energy generate after 1 year, f_{temp_avg} is the temperature factor, f_{mm} is the positive power tolerance, η_{pv} is the efficiency for solar panels from solar panel datasheet, η_{inv} is the efficiency for inverter from inverter datasheet, T_{cell_avg} is the average temperature from solar panel datasheet, °C.

To calculate the specific yield can be using the following Equation (22).

$$Y_f = \frac{E_{sys}}{P_{array_stc}} \quad (22)$$

where, Y_f is the specific yield in Wh/W.

The performance ratio can be calculated using the following Equation (23).

$$PR = \frac{E_{sys}}{P_{array_stc} \times PSH_{period}} \quad (23)$$

where PR is the performance ratio.

2.1.3 Economics and Environment

To ensure the system's efficiency, the project cost and its impact on the environment are calculated. Then compare the project cost with the electricity bill. To calculate the project cost, need to use the total energy generated. Calculate the cost per kilowatt-hour for an off-grid PV system based on the annual cost divided by the number of kilowatt-hours generated in one year. Calculate annual cost based on device price and lifetime. The cost per kilowatt-hour for a grid-connected PV system is calculated based on the number of costs involved in the year divided by the number of kilowatt-hours generated in one year based on price and equipment life [10]. The generation cost for each component annually can be done using Equation (24). The number of components, the cost per unit component, the lifetime component, and the calculation of the generation cost of each component annually. The cost of the PV system can be done using Equation (25). The total cost for a PV system per year considers the component lifetime. The tariff for PV system can be done by the cost of generating power annually into the total energy produced by the photovoltaic per kilowatt-hour by using Equation (26).

$$Q_i = n \times \frac{Cu_i}{L_i} \quad (24)$$

$$C_{Tper-year} = \sum_{i=1}^n Q_i \times \frac{Cu_i}{L_i} \quad (25)$$

$$Tariff = C_{Tper-year} / E_{sys} \quad (26)$$

where Q_i is the generation cost of each component annually, n is the number of components, Cu_i is the cost per unit component, L_i is the lifetime component, $C_{Tper-year}$ is the cost of a solar energy system annually, $Tariff$ is the price of the tariff is calculated.

2.1.4 Protection System

The grid-connected PV system has protection components that save from any damage. The DC surge protective device such as DC cables and DC switches. The AC surge protective device such as AC cables, AC switch, residual current device, and meter.

2.1.4.1 DC Protective Device

The wiring is an essential part of the electricity design for safety and PV system performance. Very necessary conductors and insulation are the perfect sizes. If the selected cable for the design is below the advised, the cables will get damaged and cause a fire on the other hand if the cable size is below the advised size the system efficiency will drop. There are two major cable types for DC parts on solar system array cable and string cable. The array cables calculation can be done using Equation (27). The string cables calculation can be done using Equation (28) [11].

$$A_{array_cable} = \frac{2 \times L \times (N_p \times I_{mp_stc} \times \rho)}{\frac{\%V_{drop}}{100} \times V_{min_mp} \times N_s} \quad (27)$$

$$A_{string_cable} = \frac{2 \times L \times I_{mp_stc} \times \rho}{\frac{\%V_{drop}}{100} \times V_{min_mp} \times N_s} \quad (28)$$

where A_{array_cable} is the DC cable from string to an inverter in mm^2 , L is the length for the cable in m, ρ is the cable resistivity in $\Omega mm^2 m^{-1}$ %, V_{drop} is the voltage drop in the system and A_{string_cable} is the DC cable for between the series modules in mm^2 .

The DC fuse current can be selected using Equation (29). The voltage and current for DC SPD and DC breaker can be selected using Equation (30) and Equation (31).

$$1.5 \times I_{sc_{stc}} \leq I_{trip} \leq 2 \times I_{sc_{stc}} \quad (29)$$

$$V_{dc_{rating}} > 1.2 \times V_{oc_{stc}} \times N_s \quad (30)$$

$$I_{dc_{rating}} > 1.3 \times I_{sc_{stc}} \times N_p \quad (31)$$

where I_{trip} is the current rate for fuses, $V_{dc_{rating}}$ is the voltage rate for SPD and breaker and $I_{dc_{rating}}$ is the current rate for SPD and breaker.

2.1.4.2 AC Protective Device

The AC wiring is an essential part of the electricity design for safety and PV system performance. Very necessary conductors and insulation are the perfect sizes. If the selected cable for the design is below the calculated value, the cables will get damaged, cause a fire and the system efficiency will drop. To select the AC cable, there is some factor essential. For example, the cable grouping factor assumes all cables carrying rated current. It can ignore calculating the cable grouping factor if expected to carry less than 30% of the ground rated current. The table shows the cable grouping factor.

For the AC cable, there are two types of cable that need to select. First cable from each inverter to the busbar. Second cable all inverter combined in one cable from busbar to load and electricity utility. Equation (33) shows the AC cable calculation[11][12].

$$I_{tmix_{inv}} = I_n \times 1.25 \quad (32)$$

where $I_{tmix_{inv}}$ is the current rating in the air at 40°C, A and I_n is the maximum current.

The AC circuit breaker, therefore, circuit protection, is set by the installer from any overload. Also, during the maintenance time can shut down the system. The faulty circuit can easily quickly be restored. Equation (33) shows the calculation for the AC circuit breaker.

$$I_z = I_n \times 1.25 \quad (33)$$

where I_z is the current rating.

2.2 PVsyst Simulation

PVsyst is a PV design and simulation program. It is designed to be used by electrical engineers and researchers. It provides an easy-to-use approach to project development. PVsyst has a large database of meteorological data for several locations around the world. It also provides manual entry of measured data for sites not included in the program. It presents the results in the form of a complete report that includes specific graphs and tables. The data can be exported for use in other programs. To get the results, we must provide some inputs to the program, such as the type of system on/off-grid, current location, output power, type of solar panels, size of the inverter, and capacity of the batteries. Simulation variables in PVsyst are:

- Meteorological data
- Radiation incident at the collector level
- Incident energy factors
- The behavior of the PV array
- Losses of the inverter
- System operating conditions
- Energy use
- Efficiency
- Normal performance index

2.2.1 Select Design Type

It is essential to choose the design type for the PV system. The PVsyst software allowed us to choose the design PV system. This project designs a grid-connected system. Fig. 3 shows the home page for the software.



Fig. 3 - The home page for PVsyst

2.2.2 Main Parameters

The main parameter is essential to shows the correct result for the system. In the beginning, we need to choose the location for the design and import the climate data. After this should enter orientation and system based on design calculation. Fig. 4 shows the main parameters are orientation and system.

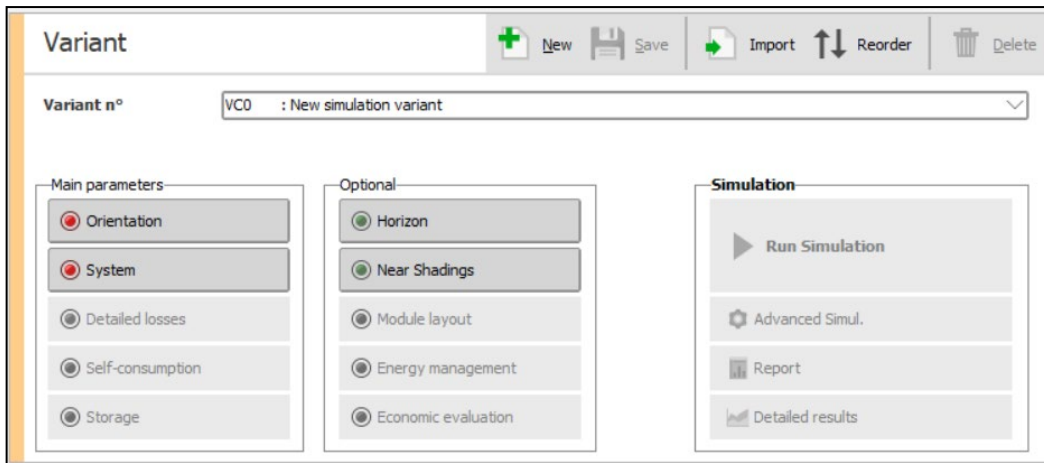


Fig. 4 - The main parameters are orientation and system

2.2.3 Orientation Parameter

The orientation is to select the tilt and azimuth value that transposition factor (FT) using tilt angle. The loss should be near zero percentage by using the yearly irradiation. The tilt angle and azimuth should be entered based on the design calculation. Fig. 5 shows the orientation parameters.

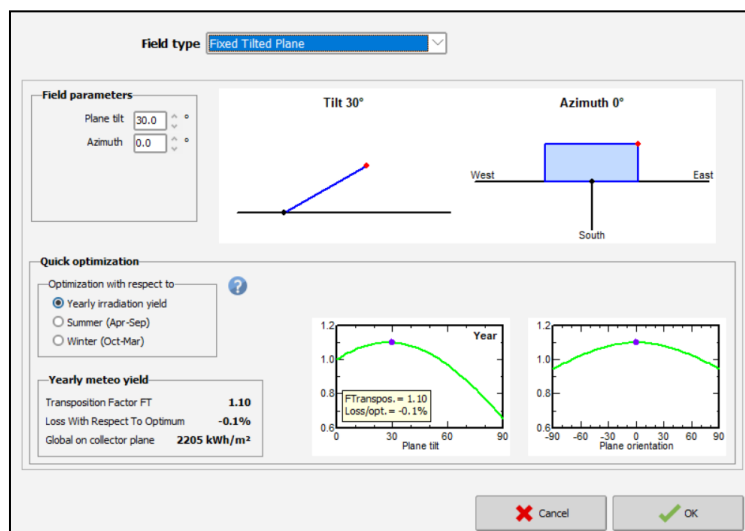


Fig. 5 - The orientation parameters

2.2.4 System Parameters

The PVsyst software needs three main inputs: the power plan, select the solar panel type, and select inverter type. The power plan is the DC power for the array. The DC power should be more than AC power 25%. The solar panel is an essential component of the design. The solar panel select based on power plan, economics and efficiency. The inverter is an essential component of the design. The inverter converting the energy from DC input to AC output. Therefore, the inverter must be specified with the design. The project design is used an MPPT inverter which increases the efficiency of the system. The PVsyst shows the number of series and strings. Fig. 6 shows the system parameter.



Fig. 6 - The system setting of the GCPV system

2.2.5 Running Simulation

The simulation starts to run after interring all input data. The simulation shows the output parameter for the system, such as energy generated for the array, energy injected into the grid, performance ratio, specific yield, losses diagram, economics analysis and save CO₂. Fig. 7 shows the simulation window.

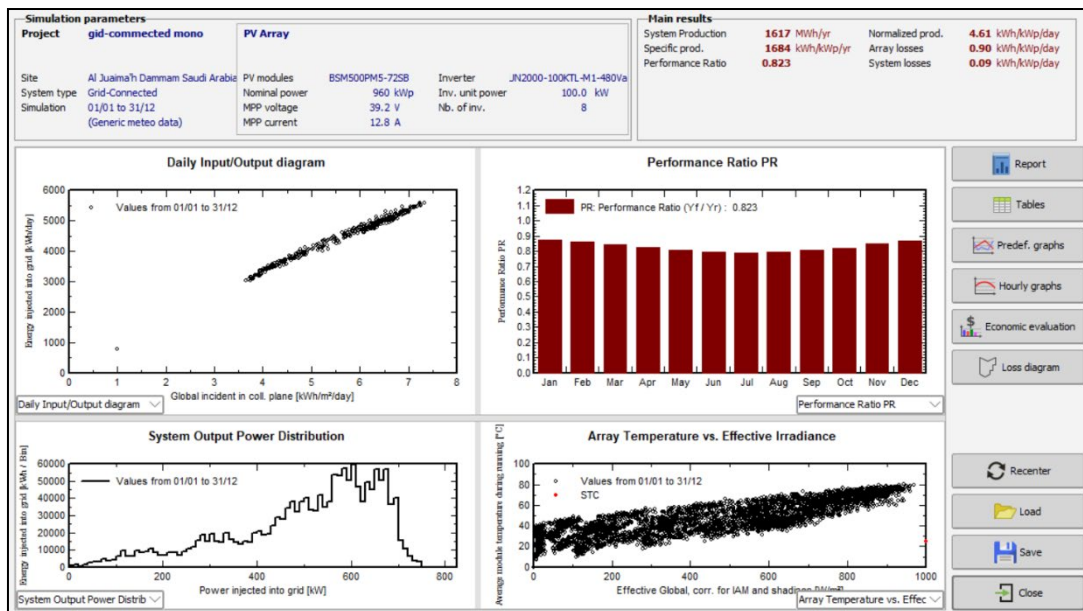


Fig. 7 - The simulation window

2.2.6 Economics Evaluation

After the system runs can add the financial cost for the project. The insulation cost such as the solar panel's cost, inverter, stander, cables, insulation cost, maintenance, tariff, lifetime and other components. Fig. 8 shows the interface of economics evaluation and required input data for the PVsyst software.

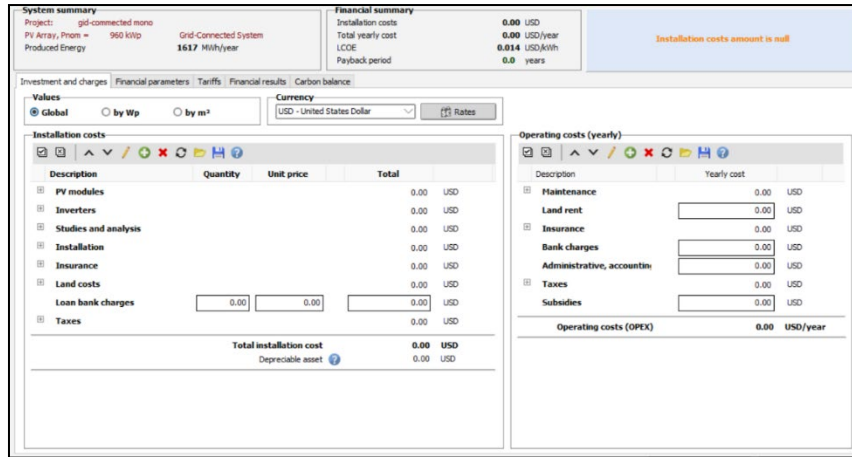


Fig. 8 - The economics evaluation in PVsyst software

2.3 Draw Single-Line Diagram Using AutoCAD

A single-line diagram is to shows the number of strings and the series model for the design. AutoCAD was used to draw a single-line diagram to show this equipment by returning to design output. Hence that to design the single-line diagram, one also needs to know the number of strings, series models, amount of inverter and protection device. There are many single-line diagrams for PV systems depending on the voltage and inverter. The schematic diagram of a three-phase grid-connected PV system with multiple MPPT inverters.

3 Results and Discussion

This section is organized based on the result and analysis from the conducted methodologies from subtopics 2.1, 2.2 and 2.3 respectively.

3.1 Design of GCPV System using Mathematical Calculation

The calculation of the GCPV system is based on electricity consumption which is 1537500 kW/year for the proposed location. The monocrystalline PV panel with 500 W (BSM500PM5-72SB) [6] from BLUESUN is chosen for this project. While the inverter 100 kW from HUAWEI (SUN2000-100KTL-M1) [7] is used to convert from DC to AC power. The model-row spacing is the distance between each row to decrease shading losses during the sun window (9:00 am to 3:00 pm) and has been calculated and presented in Table 1.

Table 1 - The output calculation model-row shading calculation

The output calculation for model-row shading	
Tilt°	3°
X	0.059 m
Y	0.029 m

The proposed GCPV design is on the total annual energy consumption of 1537.5 MWh and Global irradiation of 2007.3 kWh/m² and an average temperature of 26.8°C. Table 2 shows the input parameters for the selected PV panel and inverter. Table 3 shows the output calculation of the GCPV design.

Table 2 - The input data for PV panel and inverter

Solar panel [6]		Inverter [7]	
P_{mp_stc}	500 W	$P_{nominal_inv}$	100 kW
V_{mp_stc}	39 V	$V_{min_win_inv}$	200 V
V_{oc_stc}	46.8 V	$V_{max_input_inv}$	1000 V
γ_{Pmp}	-0.34	$I_{max_dc_inv}$	260 A
T_{cell_max}	80°C		
γ_{voc}	-0.27		
T_{cell_min}	0°C		
I_{sc_stc}	13.4 A		

Table 3 - The output calculation for the proposed GCPV system

DC and AC Power Requirement from PV Panel	
<i>SPH</i>	5.5 hr
P_{pvac}	766000 W
P_{pvdc}	957500 W
<i>Min no. of module required, N_{module}</i>	1915 Panels
Module_Inverter Matching	
$N_{min_per_string}$	7.30 \approx 8 Panels
$N_{S_max_string}$	19.01 \approx 19 Panels
N_{P_max}	15.52 \approx 15 String
<i>Selected Nseries per string</i>	16 Panel
<i>Selected Nparallel per inverter</i>	15 String
<i>Total Panel per Inverter</i>	16x15 = 240 Panels (120 kW)
<i>No. of Inverter</i>	1915/240 = 7.98 \approx 8 units
<i>No. of panels required</i>	16x15x8 = 1920 panels
Performance Calculation	
E_{sys}	1581.069 MWh
Y_f	1646.946 MWh/MW
PR	0.820
$C_{Tper-year}$	22303.76 \$
<i>Tarif</i>	0.014 \$/kWh

Based on the optioned result, the grid-connected power planned 0.6825 MWh. The selected number of the series module per string is 16 panels and the number of strings per inverter is 15 strings. Therefore, the number of the required inverter for the proposed system is 8 units, and the selected number of the solar panel is 1920 units. The expected energy generated is 1581.069 MWh per year. The specific yield is 1649.946 MWh/MW. The performance ratio of 82% is indicated the high performance because greater than the normal PR of 80 %. The tariff for the proposed GCPV design is 0.014 \$/kWh which is less than 0.05 \$/kWh from the existing tariff.

The DC string cable calculate is 7.3373 mm². So, from the standard, the DC cable size is 10 mm² by using appendix F. The DC fuse calculate is between 20.1 A and 26.8A. So, from the standard, the DC fuse is 25 A by using appendix G. The DC SPD size for voltage is 898.56 V and current 17.42 A. So, from standard, the DC SPD is 1000 V. Table 4 shows the DC protection devices calculation.

Table 4 - The DC protection devices calculation

The calculation for the DC protection devices	
A_{String_cable}	7.3373 \approx 10mm ²
I_{trip}	> 20.1 A
I_{trip}	< 26.8 A
$V_{dcrating}$	> 898.56 V
$I_{dcrating}$	> 17.42 A

From the calculation, the first cable is 162.5 A and the second one is 1300 A. The first cable size is 50 mm² and the second cable size is 1000 mm². For this design circuit breaker from the inverter to the busbar is MCCB 200 A. The busbar size for the inverter is 6.3 x 25 mm. The circuit breaker for all inverters is ACB 1400 A. The busbar size for load and electricity utility is 2 x 6.3 x 80. Table 5 shows the calculation for AC protection devices. The maximum current for inverter I_n is 130 A.

Table 5 - The AC protection devices parameter

The calculation for the AC protection devices	
I_{tmix_inv}	162.5 A
I_z	1300 A

3.2 PVsyst Simulation of the Proposed GCPV System

The solar panel manufacturer is Bluesun with the module number (BSM500PM5-72B). The solar panel's power output is 500 W. From the simulation in Fig. 2, it shows that the number of PV modules is 1920 with an STC (Stander Test Condition) input power of 960 kW. The number of the series model per string 16 and the number of the string is 120. At operating condition 50°C, the output power will decrease to 878 kW, the voltage MPP 570 V and the current 1540 A. The available area for 1920 modules is 4500 m². The inverter manufacturer is HUAWEI with the model number of SUN2000-100KTL-M1 and rated power of 100 kW. The number of inverter modules is 8 units. The operating voltage is between 200 V until 1000 V. The Power normal ratio from DC to AC is 1.20 as shown in Fig. 9.

PV module		Inverter	
Manufacturer	Generic	Manufacturer	Generic
Model	BSM500PM5-72SB	Model	SUN2000-100KTL-M1-480Vac
(Custom parameters definition)		(Original PVsyst database)	
Unit Nom. Power	500 Wp	Unit Nom. Power	100 kWac
Number of PV modules	1920 units	Number of inverters	8 unit
Nominal (STC)	960 kWp	Total power	800 kWac
Modules	120 Strings x 16 In series	Operating voltage	200-1000 V
At operating cond. (50°C)		Max. power (=>40°C)	110 kWac
Pmpp	878 kWp	Pnom ratio (DC:AC)	1.20
U mpp	570 V		
I mpp	1540 A		
Total PV power		Total inverter power	
Nominal (STC)	960 kWp	Total power	800 kWac
Total	1920 modules	Nb. of inverters	8 units
Module area	4500 m ²	Pnom ratio	1.20

Fig. 9 - The PV module and inverter sizing obtained by PVsyst software

Fig. 10 presents the array losses obtained by PVsyst software. It shows that the module mismatch losses are 2% at MPP. The Dc wiring losses 1.5% at STC. The module mismatch losses are 0.1%. The module quality losses are 1.3%. The reflections on the glass cover 0.05.

Thermal Loss factor	DC wiring losses	Module Quality Loss
Module temperature according to irradiance	Global array res.	Loss Fraction
Uc (const)	6.1 mΩ	-1.3 %
Uv (wind)	Loss Fraction	
	1.5 % at STC	
Module mismatch losses	Strings Mismatch loss	IAM loss factor
Loss Fraction	Loss Fraction	ASHRAE Param: IAM = 1 - bo(1/cosi - 1)
2.0 % at MPP	0.1 %	bo Param.
		0.05

Fig. 10 - The array losses

The annual global horizontal irradiance on the plane is 2007.3 kWh/m². The annual temperature 26.81°C. The annual DC energy generated from the PV array is 1649.9 MWh and the annual AC energy injected into the grid is 1616.9 MWh. The performance ratio is 82.3 % high-performance because it up to 80 %.

Based on the optioned result, during the summer season, the global horizontal irradiance is higher than the winter season because the sun is far from earth. The temperature is higher during the summer season more than in the winter season. The performance ratio is higher during the winter season more than the summer season because high temperature increases the losses on the system. Table 6 shows the balances and main results.

Table 6 - The main results obtained by PVsyst simulation

Month	GlobHor kWh/m ²	T-Amb °C	EArray MWh	E-Grid MWh	PR
January	124.9	14.46	112.6	110.4	0.873
February	126.1	16.68	110.3	108.1	0.864
March	158.8	21.39	134.2	131.6	0.846
April	182.3	26.46	149.3	146.2	0.827
May	206.2	32.74	163.0	159.7	0.805
June	207.9	35.36	161.6	158.4	0.795
July	207.5	37.16	160.7	157.5	0.791
August	195.1	36.60	152.6	149.5	0.793
September	186.3	22.57	150.0	147.0	0.807
October	165.7	28.92	137.6	134.9	0.820
November	129.8	21.98	113.3	111.0	0.848
December	116.7	16.75	104.7	102.6	0.866
Year	2007.3	26.81	1649.9	1616.9	0.823

Table 7 shows that results of the PV array and inverter sizing obtained by the calculation and PVsyst software. It found that the calculation and simulation results are almost same.

Table 7 - Comparison of the main results obtained by calculation and PVsyst

Parameter	Calculation	PVsyst
No. of PV Panel	1920 Panels	1920 Panels
No. of Inverter	8 Units	8 Units
Yearly PR	0.820	0.823

The monthly average per year of collection loss, system loss and the produced energy yield close to 0.9 kWh/kW/day, 0.09 kWh/kW/day and 4.61 kWh/kW/day respectively for fixed-tilt panels. Fig. 11 shows the normalized productions (per installed kW).

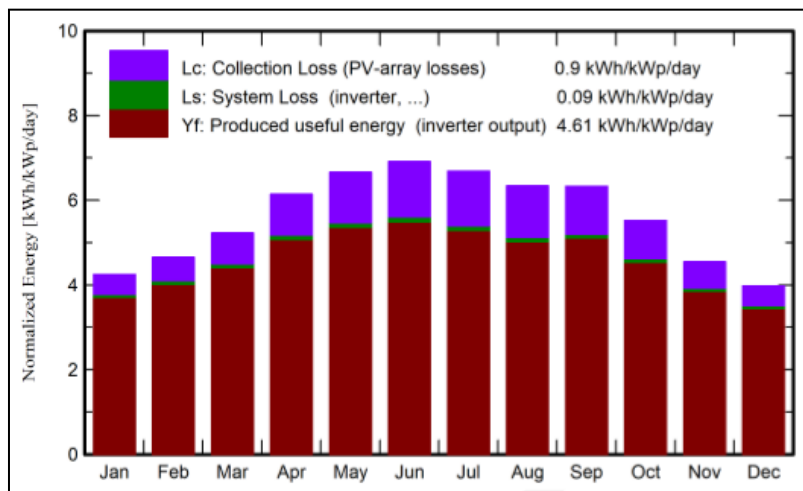


Fig. 10 - The normalized productions (per installed kW)

The global horizontal irradiation is 2007.3 kWh/m². But the incident irradiation on the PV array collectors is 1967 kWh/m². This because there is loss due to irradiance level 0.59%. The IAM factor on global is 2.75% due to the irradiation reflected on the solar panel glass. The Shadings losses also are 1.19%. The electricity is 1650 MWh after conversion at the STC efficiency of the panels is 21.34%. The temperature loss on the PV panel is 10.40%. The mismatch loss, modules and strings are 2.1%. The ohmic wiring loss is 1.06%. The inverter loss during the operation process is 1.33%. The

maximum MPP of the PV array is 1889 MWh. The energy injected into the grid after losses are 1617 MWh/year. Fig. 11 shows the loss diagram.

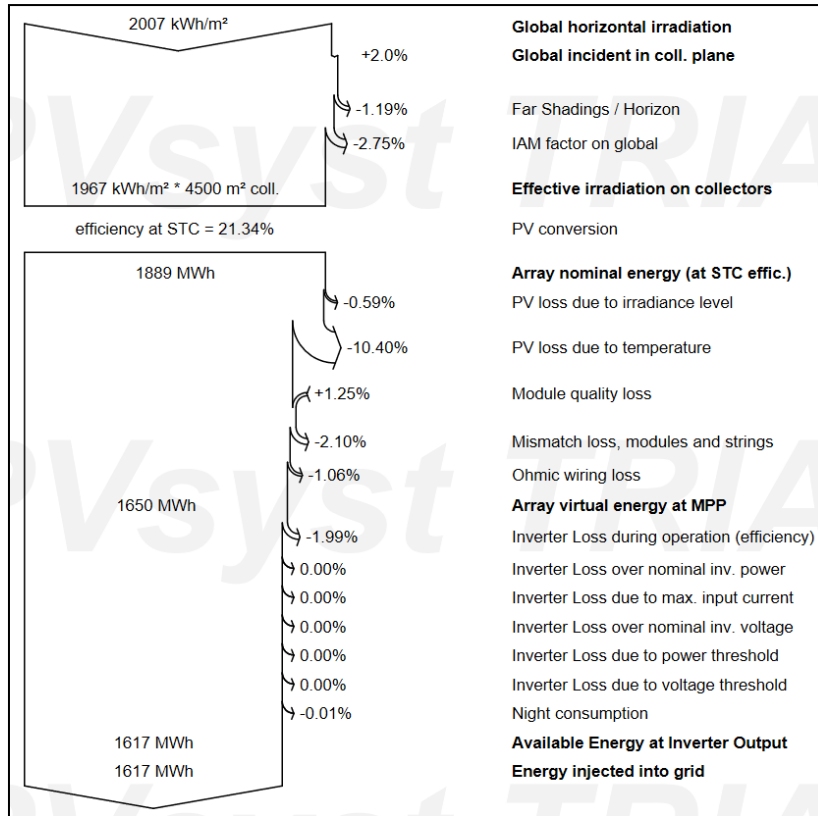


Fig. 11 - The loss diagram

The project lifetime of 25 years starting from 2022. The financing cost for the project 557424 USD. The tariff cost for the project is 0.05 USD/kWh. The payback period for the project is 6.9 years. The NPV (Net Present Value) for the project is 1459581.03 USD. The ROI (Return on Investment) for the project is 261.8%. Fig. 12 shows the financial analysis for the project.

Financing	
Own funds	557'424.00 USD
Electricity sale	
Feed-in tariff	0.05 USD/kWh
Duration of tariff warranty	25 years
Annual connection tax	0.00 USD/kWh
Annual tariff variation	0.0 %/year
Feed-in tariff decrease after warranty	50.00 %
Return on investment	
Payback period	6.9 years
Net present value (NPV)	1'459'581.03 USD
Return on investment (ROI)	261.8 %

Fig. 12 - The financial analysis for the project

The result shows that the CO₂ emission balance will save a total is 29878.2 tCO₂. The replaced emissions total is 36040.2 tCO₂. The Produced emissions total is 1392.62 tCO₂. The Lifetime is 30 years. The annual degradation for the system is 1%. Fig. 13 shows the CO₂ emission balance.

Total:	29878.2 tCO ₂
Generated emissions	
Total:	1392.62 tCO ₂
Source:	Detailed calculation from table below:
Replaced Emissions	
Total:	36040.2 tCO ₂
System production:	1616.88 MWh/yr
Grid Lifecycle Emissions:	743 gCO ₂ /kWh
Source:	IEA List
Country:	Saudi Arabia
Lifetime:	30 years
Annual degradation:	1.0 %

Fig. 13 - The CO₂ emission balance

3.3 Single-Line Diagram of the Proposed GCPV System

The single-line diagram for the DC part using the design calculation. The solar panel modules for case 1 are 1920 units. The inverter units are 8. The number of series modules 16 and string 120. The DC string cable size is 100 mm². The DC fuse size 25 A. The DC SPD voltage rate 1000 V. Fig. 14 shows the single-line diagram for the DC part.

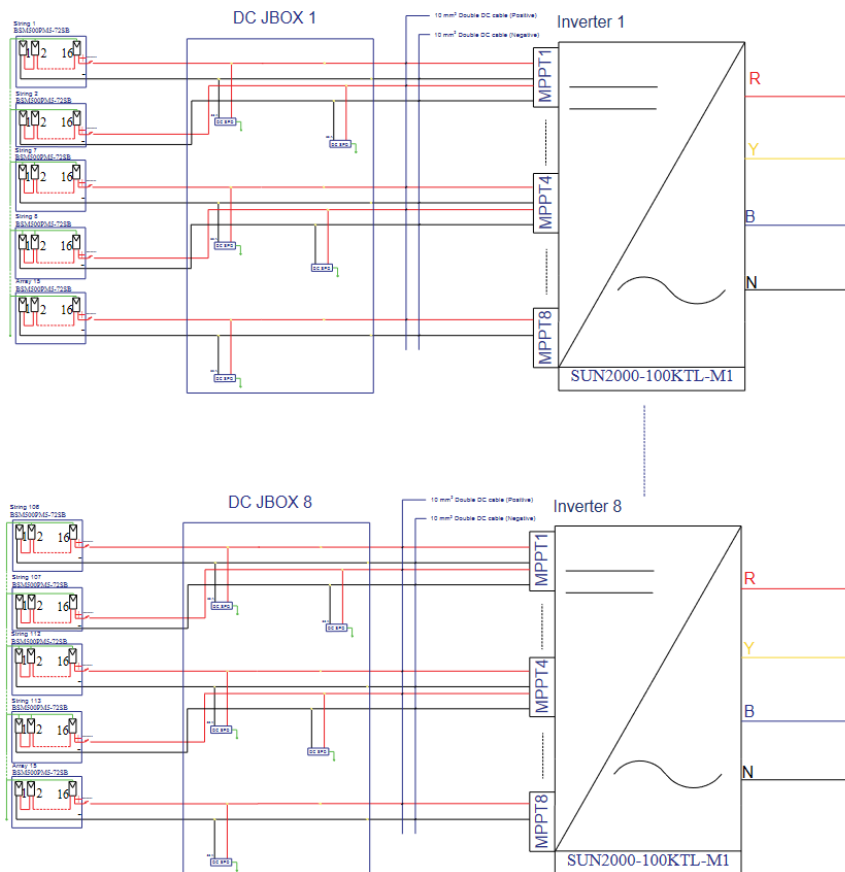


Fig. 14 - The single-line diagram for the DC part

The single-line diagram for the AC part using the design calculation. The inverter units are 8. The first AC cable size is 50 mm². The second AC cable size is 1000 mm². The MCCB size is 200 A. The ACB size is 1400 A. The first busbar size is 6.3 x 25 mm. The second busbar size is 2 x 6.3 x 80 mm. Fig. 15 shows the single-line diagram for the AC part.

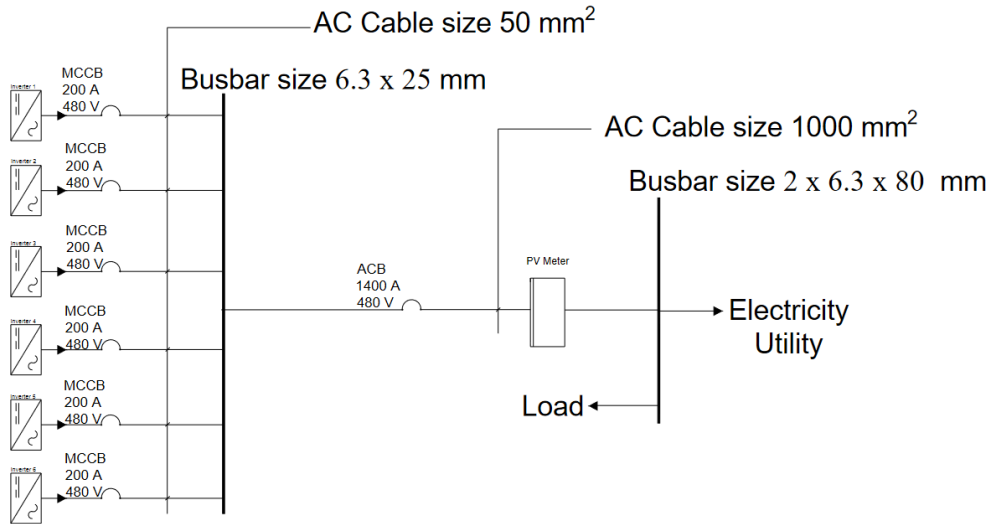


Fig. 15 - The single-line diagram for the AC part

4 Conclusion

The paper presents the proposed design of the GCPV system in Saudi Arabia by using mathematical equations and PVsyst software. The proposed 960 kW_{peak} of GCPV system is based on the 500 W monocrystalline PV panel from Bluesun (BSM500PM5-72B) and 100 kW HUAWEI inverter (SUN2000-100KTL-M1). It is found that the results obtained by mathematical calculation and PVsyst software can produce the same results with 1920 panels and 8 inverters. It shows that the PV array generation is 1649.9 MWh/year, energy injects into the grid is 1616.9 MWh/year, performance ratio is 82.3%, the payback period is 6.9 years and CO₂ reduction is 29878.2 t. Therefore, the proposed GCPV system is optimum in terms of economics environmentally friendly for the selected location of this study.

Acknowledgement

This research was supported by Ministry of Higher Education Malaysia through Fundamental Research Grant Scheme (FRGS/1/2018/TK04/UTHM/02/17). The authors would also like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

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