Modelling and Output Power Evaluation of Series-Parallel Photovoltaic Modules

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ABSTRACT
The performance of PV modules array is affected by several factors the most important one is the array configurations. This paper focuses on study of various array configurations like series, parallel and series/parallel combination theoretically by Matlab programming and experimentally at the outdoor exposure of Baghdad city under constant 1000W/m2 incident solar irradiance. Fifteen different connection type ten PV modules is chosen to examine the voltage, current and power production. In order to get maximum power of the array, it was found that the ten modules should be connected in parallel. While the lowest array configuration was when six parallel strings, two strings have four modules each and the others each one has one single module. In general, square or rectangle array produce much more power, above 30% greater than uneven connected arrays.

Keywords
Photovoltaic system, solar module. Modeling, series, parallel.

1. INTRODUCTION
All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes. Global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply leading to a rapid growth in greenhouse gas (GHG) emissions. Greenhouse gas concentrations lead to an Increase in global average temperature. The using of these fuels is much more than they are being created. Eventually, they will run out. In the meantime, the nation's energy needs are expected to grow by 33 percent during the next 20 years.

Renewable energy can help to fill the gap of energy needs in the world. Renewable energy (RE) sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use.

Solar energy simply is the energy produced directly by the sun and emitted in the form of electromagnetic radiation. The photovoltaic (PV) power generation plays an important role due to the fact that it is a green source. The only emissions associated with the PV power generation are those from manufacturing of solar PV components. After their installation PV cells generate DC electricity during the day, which can be immediately consumed or stored in batteries for future consumption [1].

The energy generated by a single module is not enough to use for commercial purpose. Therefore, Photovoltaic array is made by connecting many modules in series / parallel manner to provide the power requirement.

This paper illustrates the effect of different types of connection of PV panels array consist of ten PV panels at constant solar irradiance and at constant operating temperature.

2. SOLAR CELL PHYSICS
Solar cell is a device which converts photons in Solar rays to direct-current (DC) and voltage. A typical silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction).

When the sunlight falls on the semiconductor surface, an electron springs up and is attracted towards the N-type semiconductor material. This will cause more negatives in the n-type and more positives in the P-type semiconductors, generating a higher flow of electricity. This is known as Photovoltaic effect **[2]. Fig. 1** shows the working mechanism of a silicon solar cell Current-Voltage (I-V) characteristics curve represents all possible current and voltage operating points for PV cell. As shown in **Fig.2**, when voltage increases, the current start at its maximum value then decreases gradually to reach the zero. The I-V curve can be obtained by the electrical load.

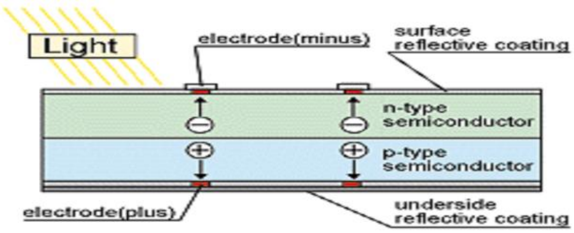

Fig 1: Silicon Solar Cell with mechanism of working [7]

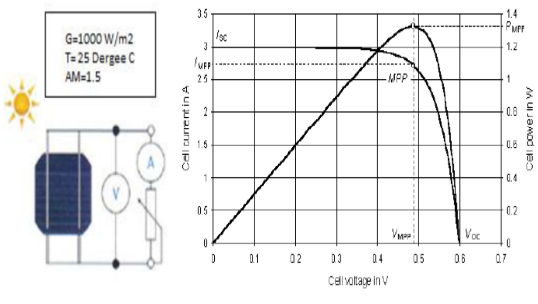

Fig 2: Current–voltage and power–voltage characteristics of solar cell

It is important to define some terminologies those frequently mention in any solar PV cell, module mathematical modelling.

2.1 Short Circuit Current (ISC)

Short circuit current is the maximum possible current in the circuit, at zero voltage. The short circuit current is directly proportional to the available sunlight **[3].**

2.2 Open Circuit Voltage (VOC)

Open circuit voltage is the maximum voltage, at zero current, which occurs when a huge load in connected to the circuit or in case of no load [3].

2.3 Maximum Power Point (MPP)

Which is the point on the I-V characteristic at which the solar cell works at maximum power. Where Vmpp and Impp are voltage and current the values that gives the maximum operating power. MPP is the rate of the unit by Wp (watt peak) [3].

2.4 Fill Factor (FF)

The fill factor is an indicator of the quality of the PV cell. FF is defined as the ratio between the maximum generated power at MPP and the maximum theoretical power (Isc multiply by Voc) **[3].**

$$FF = \frac{P\ max,practical}{P\ max,theoretical} = \frac{Vm \times Im}{Voc \times Isc} \quad (1)$$

Where I_{max} and V_{max} are the current and voltage for maximum power.

2.5 Efficiency of Solar Cell

The conversion efficiency of PV cell is defined as the ratio between the produced electrical power and the amount of incident solar energy per second. The equation of solar cell power conversion efficiency is:

$$\eta = \frac{P\ max}{P\ in} = \frac{Voc \times Isc \times FF}{It \times Ac} \quad (2)$$

3. MATHEMATICAL MODELLING

The building block of PV arrays is the solar cell; it has an equivalent module for solar cell with four parameters associated with mathematical modeling of the current-voltage I-V curve as shown in **Fig.3**[4].

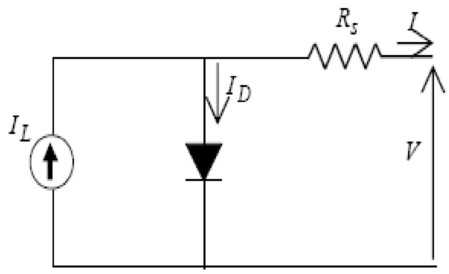

Fig 3: Four parameters equivalent model for solar cell

In this model the effect of the shunt resistance is neglected because its value is particularly important, especially for Si-crystalline modules.

The model has four unknown parameters: IL (the photocurrent), Io (the saturation current), A (ideality factor) and Rs (the series resistance). These parameters are not available in the manufacturing data. These parameters must be calculated from the system of equations I-V at various operating reference points given by the manufacturer or from experimental data [5]**.**

IL (the photocurrent): the current generated directly by incident of solar radiation on the PV cell. This current varies linearly with sun irradiation and depends on temperature [6]**.**

Io (the saturation current): It is a part of the reverse current in a diode caused by diffusion of minority carriers from the neutral regions to the depletion region [7].

A (ideality factor): It is the measure of how much a practical diode deviates from ideal diode equation [7]. The average value assumed during the determination of unknown parameters in the photovoltaic system usually equals to 1.3.

From this modeling presented one can describe the cell current-voltage curve.

$$I = I_L - I_o \left[EXP\left(q\frac{(V+IRs)}{Ns\ AKT}\right) - 1\right] \quad (3)$$

I: current at any point.

V: voltage at any point.

q: is the electron charge (1.60217646 × 10¯19 C).

Ns: Number of modules in series.

K: is the Boltzmann constant (1.3806503 × 10¯23 J/K).

T: module temperature.

Observed from the above equation there are four unknown parameters in this model are: IL (the photocurrent), Io (the saturation current), A (ideality factor) and Rs (the series resistance). These parameters can be obtained from measurements of the I-V characteristic at reference values of irradiance and temperature (E ref =1000 W/m², T ref =25°C), which is available by the manufacturer or from the direct measurement on the module [8]**.**

These measurements are necessary to simplify the data necessary for the characterization of the various unknown model parameters (Vco open circuit voltage, Isc short circuit current, Vm and Im are voltage and current at the maximum power point respectively) [9]**.**

From the I-V curve can observed three remarkable couples of points (0, Isc), (Voc, 0) and (Vm, Im), can be employed in order to determinate the unknown parameters, as:

$$I_{sc} = I_L - I_o \left[\exp\left(q\frac{Isc\ Rs}{NsAKT}\right) - 1\right] \quad (4)$$

$$0 = I_L - I_o \left[\exp\left(q\frac{Voc}{NsAKT}\right) - 1\right] \quad (5)$$

$$I_m = I_L - I_o \left[\exp\left(q\frac{Vm + Im\ Rs}{NsAKT}\right) - 1\right] \quad (6)$$

By observing the equations (4, 5 and 6) it is clear that there is a problem of four equations and three unknowns. To solve this problem, we will consider a simplified method which is based on a purely mathematical resolution with some simplifications.

This method considers the following approximation and simplifications of equations (4), (5) and (6) obtained,

$$I_{sc}=I_L \qquad (7)$$

$$0 = I_L - I_o\left[\exp\left(q\frac{V_{oc}}{NsAKT}\right)\right] \qquad (8)$$

$$I_m = I_L - Io\left[\exp\left(q\frac{Vm+ImRs}{NsAKT}\right)\right] \qquad (9)$$

From Eq.(7) and Eq.(8) one can deduce the saturation current

$$I_o = I_{sc}\exp\left(-\frac{q}{NsAKT}Voc\right) \qquad (10)$$

And from that Eq.(3) becomes,

$$I = I_{sc}\left[1 - \exp\left(q\frac{V-Voc+IRs}{NsAKT}\right)\right] \qquad (11)$$

The equation at the point of maximum power at is turn becomes

$$I_m=I_{sc}\left[1-\exp\left(q\frac{Vm-Voc+Im\ Rs}{NsAKT}\right)\right] \qquad (12)$$

From this equation, we can deduce the value of series resistance

$$R_s=\frac{\frac{NsAKT}{q}\ln\left(1-\frac{Im}{Isc}\right)+Voc-Vm}{Im} \qquad (13)$$

The last parameter to be determined is the ideality factor A, by exploiting the fact that the derivative of the maximum power is zero:

$$\frac{dP}{dV} = 0 = \frac{\partial I}{\partial V}V + I\ \frac{\partial V}{\partial V} \qquad (14)$$

And using Eq. (1) one can find:

$$A = \frac{q(2Vm-Voc)}{NsKT\left[\frac{Isc}{Isc-Im}+\ln\left(1-\frac{Im}{Isc}\right)\right]} \qquad (15)$$

4. EXPERIMENTAL SETUP

Experimental measurements were done on a PV array of 10 solar modules. The PV array fixed on a metal structure in a correct position to receive the desired radiation flax. the basic unit to build the solar array is a monocrystal solar module with a power of 50 Watts and consists of 72 solar cell connected in series. **Table. 1** shows the solar module specification.

Table 1. General specifications of solar module (available from the manufacturer datasheet)

Area [m²]	0.46
V_{oc} **[V]**	21.8
I_{sc} **[A]**	3.25
V_m **[V]**	17.2
I_m **[A]**	2.9
P_m **[W]**	50
Ns	72

4.1 Measuring Devices

Prova 200 solar module analyzer as shown in **Fig 4**. A device to measure power output, efficiency, Vmax, I max and Fill factor for PV modules array.

Solar power meter "Data Logging Solar Power Meter TES-1333R" as shown in **Fig 4**, an instrument that simply measuring the intensity of solar radiation in W/m².

PV module Temperature Sensor a Resistance thermometers TPM-900 Probe, and also called resistance temperature detectors (RTDs) as shown in **Fig 4**. It is a sensor used to measure the temperature of the module. **Table. 2** illustrates the apparatus range, resolution and accuracy.

Fig 4: Measuring devices, top: solar module analyzer, middle: Solar Power meter, bottum: temperature sensor

Fig 5: Experimental setup

Table2. Measurement apparatus range, resolution and accuracy

	Measuring range	Resolution	Accuracy
Solar module analyzer PROVA 200A			
DC voltage measurements	0-360 V	0.001-0.01 V	±1% ±(1% of Voc±0.09 V)
DC current measurements	0-36 A	0.1-1 A	±1% ±(1% of Isc±0.9 mA)
Solar power meter TES1333R			
Solar Radiation measurements	0-2000 W/m^2	0.1 W/m^2	±10 W/m^2 or ±5%. higher temperature induced error of ±0.38 W/m2/°C from 25°C
Digital thermometer TPM-900			
Temperature measurement	-30~110 °C	0.1 °C	±1 °C

4.2 Experimental steps

1. Arrangement the PV panels on a metal structure in correct position so could receive the desired radiation flux.
2. Cleaning process has to be done for the PV panels array.
3. Solar meters placed normal to the surface of the PV panels to measure the radiation flux, at 1000) w\m2 radiation flux value.
4. Measure the temperature of PV panels by temperature sensor (i.e. steady state temperature).
5. Connecting the PV panels to form an array with the desired configurations. Firstly, connected the 10 PV panels in series, secondly connected the 10 PV panels in parallel and thirdly connected the 10 PV panels in series – parallel with various Probabilities as shown in **Figs. (6- 20)**.

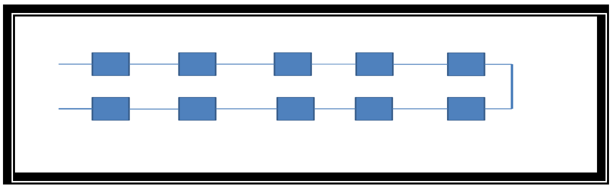

Fig 6: 10 PV modules connected in series

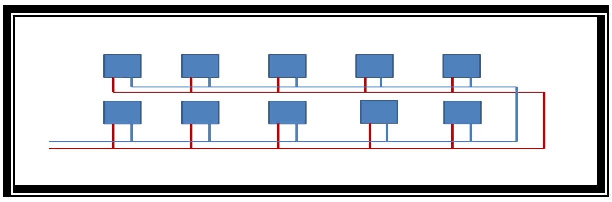

Fig 7: 10 PV modules connected in parallel

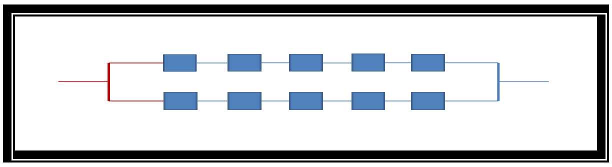

Fig 8: 5pv modules in series connection in parallel with 5pv modules in series connection

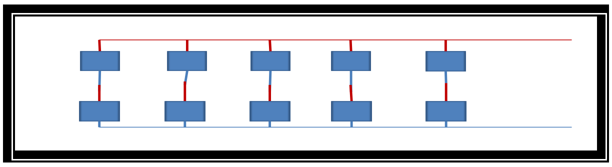

Fig 9: 5 branches of 2series pv modules

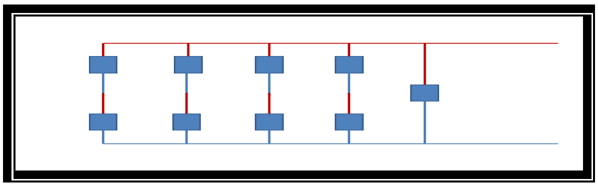

Fig 10: (4branches of 2series PV modules) parallel with 1 series

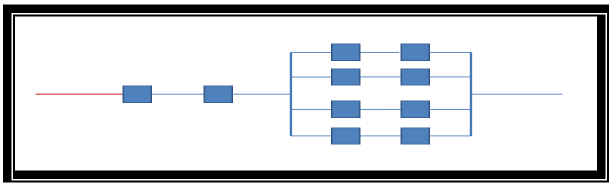

Fig 11: 2pv modules in series connection in series with (4branches of 2series pv modules)

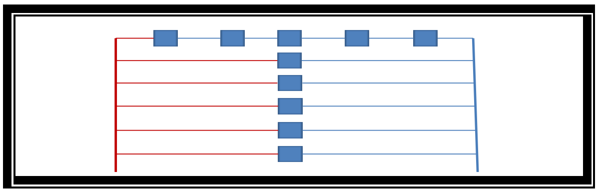

Fig 12: 5pv modules in series connection in parallel with 5pv modules in parallel connection

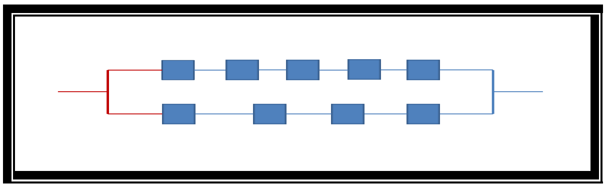

Fig 13: 5pv modules in series connection in parallel with 4pv modules in series connection

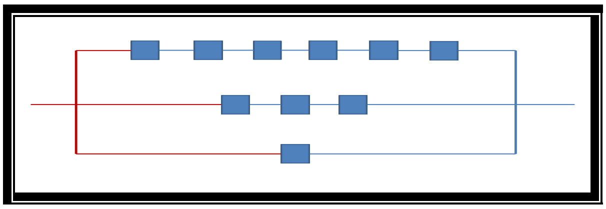

Fig 14: 6 series in parallel with 3series in parallel with 1series pv modules

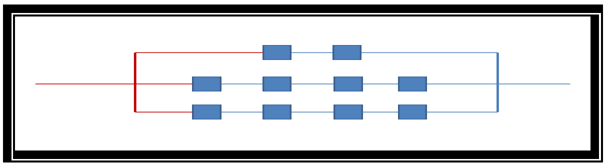

Fig 15: 2 series in parallel with 4series in parallel with 4 series pv modules

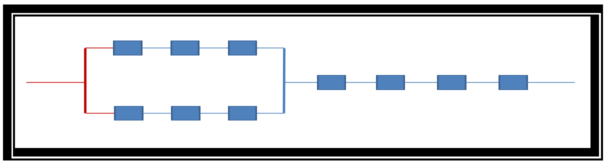

Fig 16: (Two branches of three series) series with four series pv modules

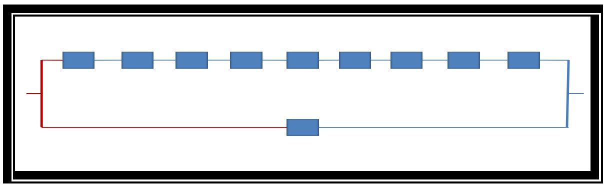

Fig 17: Nine series in parallel with one series

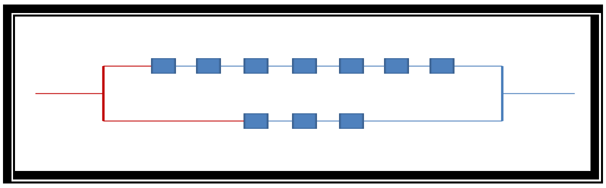

Fig 18: Seven series in parallel with three series pv modules

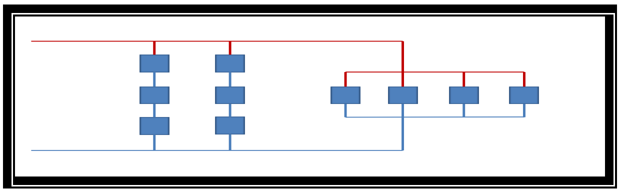

Fig 19: (Two branches of three series) in parallel with (four branches of one series

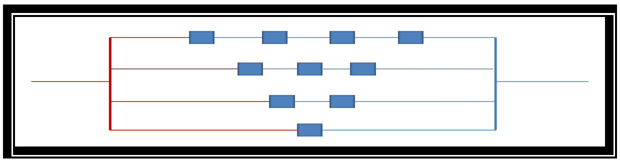

Fig 20: Four series in parallel with three series in parallel with two series in parallel with one series

6- Connect prova with the PV panels array. Incorporation the value of the solar array area, as well as radiation value to the device. Power and other electrical parameters will automatically calculate and then transfer the information to a computer be saved as a spreadsheet of excel program.

5. RESULTS AND DISCUSSION

5.1 Connection Types Results

Results have been found from laboratory measurements by the PROVA200 solar module analyzer and the theoretical results by the Matlab model for different configurations.

5.1.1 Series Connection

Fig. 21 shows the experimental and modeled I-V and P-V characteristic curves of a string of ten modules connected in series, the results show that the total output current is the same as for one module which is equal to 3.163A. While the output voltage of one module is added to the next one and the total output current ends up with ten times the voltage of one module which is equal to 210V. The maximum power output of this string is ten times the power of one module and has a value of 501.3W.

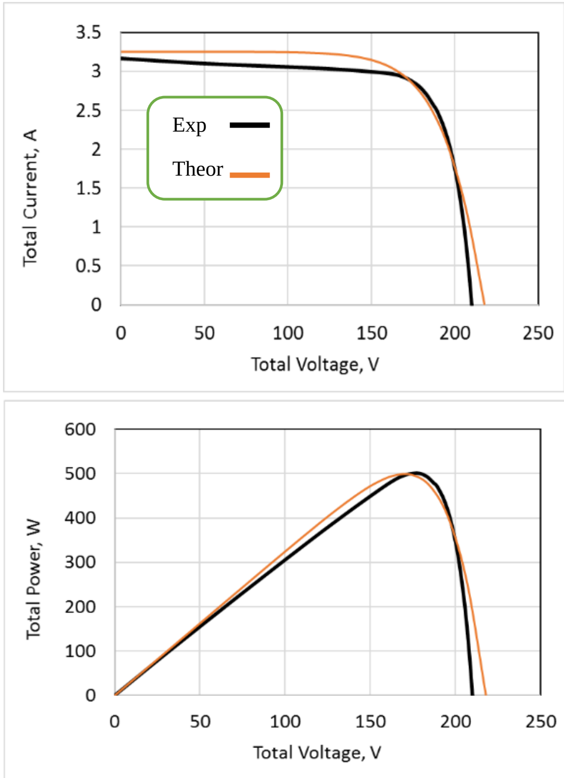

Fig 21: Experimental and theoretical, Current-Voltage and power-voltage curves of the series connection at 1000W/m2 solar radiation.

5.1.2 Parallel connection

Fig. 22 shows the experimental and modeled I-V and P-V characteristic curves for an array consists of ten modules connected in parallel. Note that for this case the output voltage is the same as for one module, while the current is nearly ten times the current of one module. Where the values of Isca and Voca are 33.025A, 21.093V.

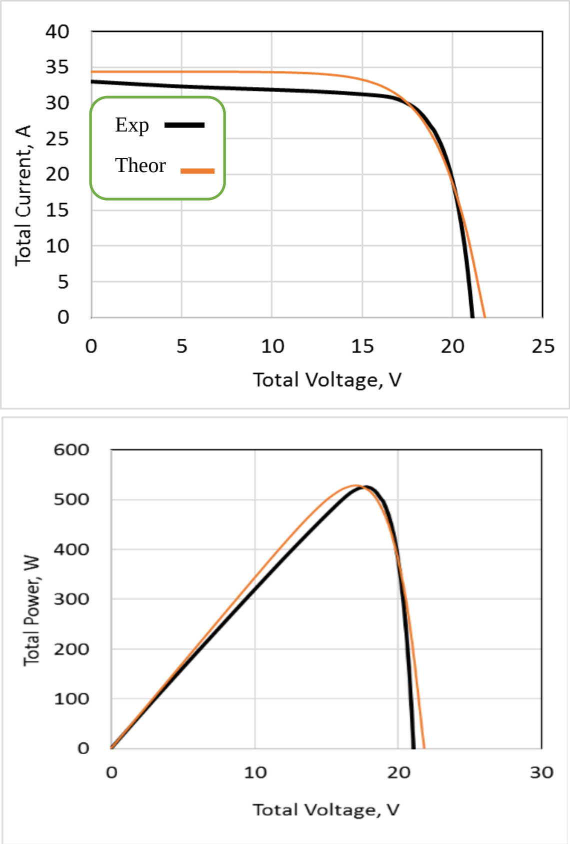

Fig 22: Current-Voltage and power-voltage curves of the parallel connection

The maximum power output in this case is higher than the series connection with about 30Watts which is the current summation case, and the effect of solar radiation is greatly affect the output current (linear relationship) while in series connection which is voltage summation case the increase in solar radiation does not has a noticeable effect (logarithmic relationship, nearly constant at high radiation levels).

5.1.3 Series- parallel connection

In this type of connection there are multiple Probabilities. The experimental and theoretical results of these types are well illustrated by the IV and PV curve presented in the followings.

C-3 (connection three) which is a perfect array of two strings. In this case note that the output current is duplicated and the output voltage is the sum of five modules. Where in **Fig. 23** the value of Isca and Voca are 6.407A, 106.056V. The maximum power output in this case is less than that of parallel connection which is equal to 512.2W.

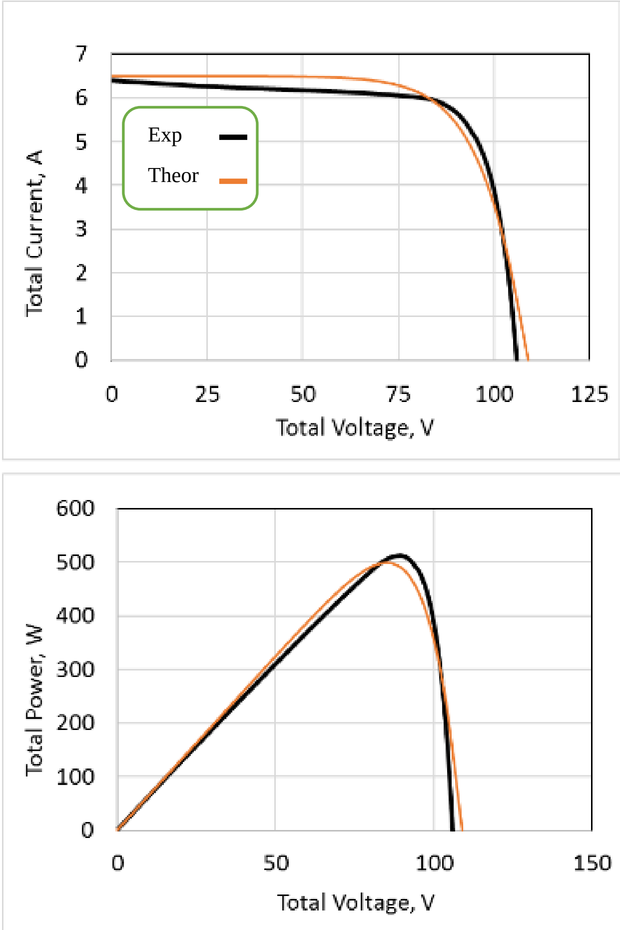

Fig 23: Current-Voltage and power-voltage curves of the connection C-3.

C-4 which is a perfect array of 5 strings with two modules. In this case note that the output current is the sum of the current of five modules while the output voltage duplicated. Where in **Fig. 24** the value of Isca and Voca are 15.903A, 42.168V. The maximum power output in this case is similar to approximately the power resulting from series connection and less than in a little amount the power resulting from C-3. It has a value of 505.6W.

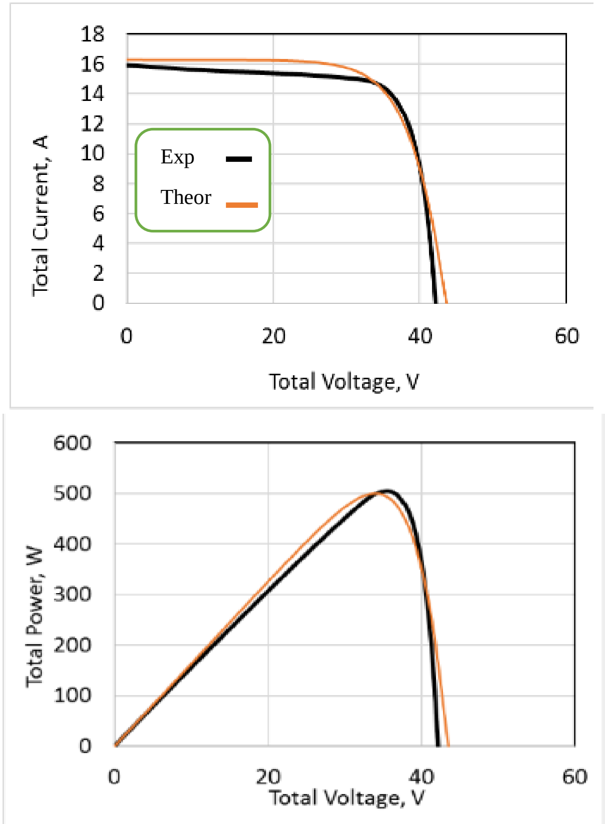

Fig 24: Current-Voltage and power-voltage curves of the connection C-4

C-5, a case was assumed if one of the modules in C-4 is shorted (removed and replaced with a connecting wire). The array produces Isca approximately equals the Isca of C-4. The output current also has the same trend as in C-4 then starts to drop at a voltage value near the voltage of the one module string which is the half the voltage of the other strings.

This case revealed that in **Fig 25**, the array output current is restricted by the string with the lowest current while the array voltage is the same for each string. The value of Isca and Voca are 16.139A, 39.594V. The maximum output power in this case is reduced significantly to about 385.4W.

C-6 which is a combination of a perfect array of four strings (two modules per string) connected on series with a string of two modules. In this case note that the IV curve is divided for two zones of voltage, the output current in the first zone is four times the module current and as the voltage increases by adding the voltage of the second zone (which is the voltage of the string on series) the current drops nearly to the current of one single module as in **Fig. 26** the maximum values of Isca and Voca are 12.422A, 84.675V. The maximum power output in this case is higher than C-5 and equal to 396.5W.

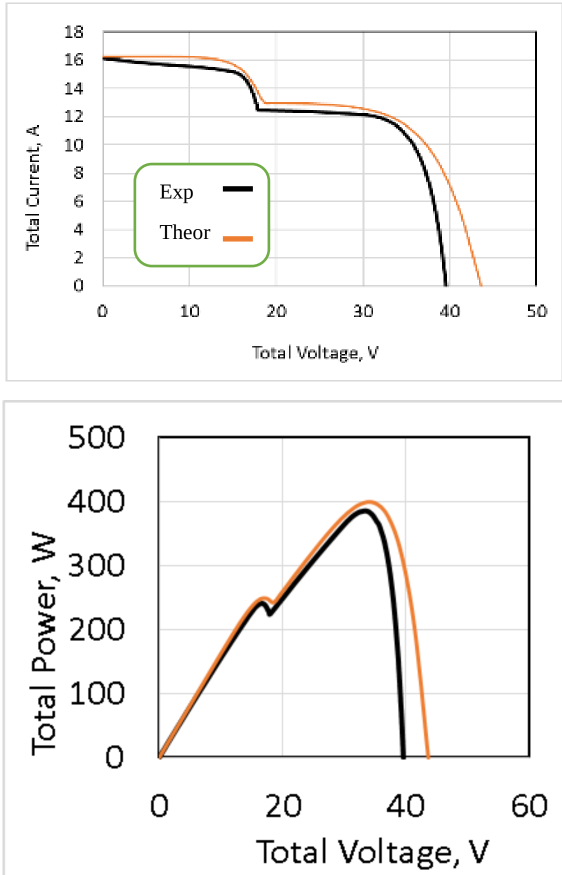

Fig. 25: Current-Voltage and power-voltage curves of the connection C-5

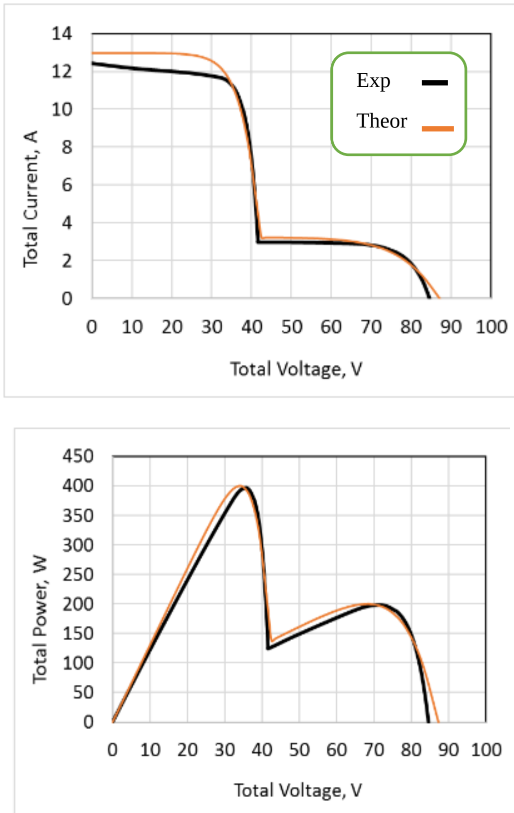

Fig. 26: Current-Voltage and power-voltage curves of the connection C-6

C-7 which is a random array of six strings, where only one string consists of five modules and the remaining strings has one module each. In this case note that the output current is sum of six individual modules and then drops sharply at a value of voltage which is the maximum output. Then, the array produces a current equals the current of one module until it drops at a voltage value which is the sum of the voltage of five modules. The maximum value of Isca and Voca are 19.136A, 106.547V. The maximum power output in this case is less than that of C-6 and has a value equal to 307.4W as shown in **Fig. 27** .

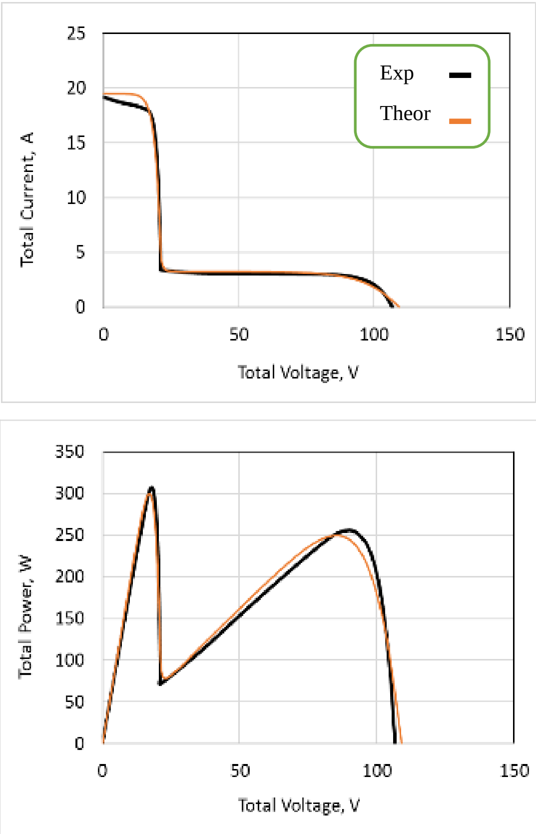

Fig. 27: Current-Voltage and power-voltage curves of the connection C-7

C-8 which is the resulting connection of C-3 if one module in any string is shorted (removed). In this case note that the array voltage is the same as for the string of highest voltage while the current drops with amount equals to the current of one module as the voltage increases. The maximum values of Isca and Voca are 6.298A, 102.128V. The maximum power output in this case is approximately similar to C-5 and has a value equal to 387.9W as shown in **Fig. 28**.

C-9 which is a random array of three strings with six, three and one module respectively (see **Fig. 29**). In this case note that The IV curve is divided for three steps. At short circuit condition (V=0), the current is about three times the current of one module. Then the current begin to drop slowly until reaches a value equal to the current of one module. While the output voltage is the sum of voltage of six individual modules. The maximum value of Isca and Voca are 9.482A, 126.597V. The maximum power output in this case is approximately similar to CT-7 and has a value equal to 301.7W.

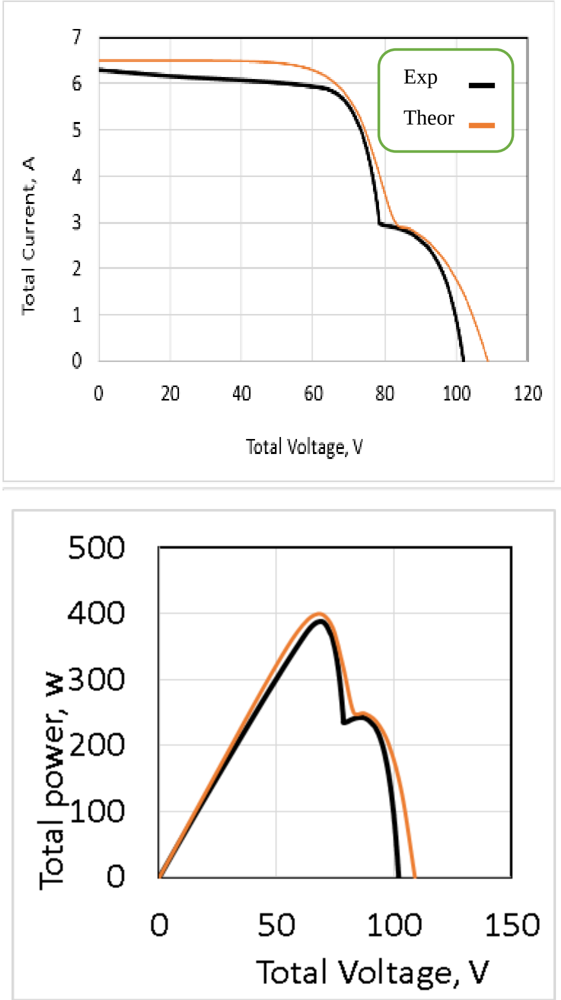

Fig. 28: Current-Voltage and power-voltage curves of the connection C-8

C-10 which can be considered a perfect array of three strings (four modules per string) but one of the strings misses two modules (replaced with a simple connecting wire) as shown in **Fig. 30**. In this case note that the current at low voltage region is three times the current of one module. After voltage of two modules the current steps down to a current value of two modules and stay constant until it vanishes at the open circuit voltage of four modules. The maximum values of Isca and Voca are 9.335A, 81.702V. The maximum power output in this case is approximately similar to C-5 and has a value of 383.3W in spite of the difference in connection.

C-11which is a perfect array of two parallel string (three modules per string) connected on series with a string of four modules. In this case note that the output current is the sum of two strings for voltage range of three modules, then the current drops for the remaining four series modules. The maximum Isca and Voca are 6.287A, 147.291V. As shown from **Fig. 31** the maximum power output in this case has a value of 349W

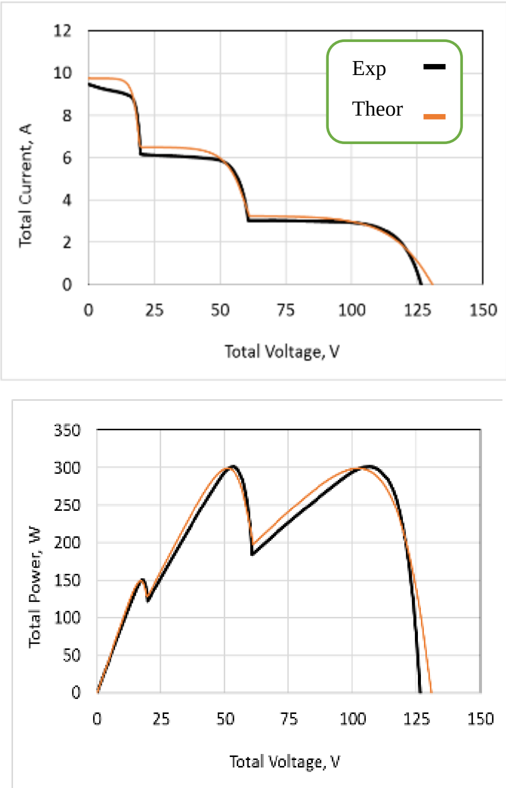

Fig. 29: Current-Voltage and power-voltage curves of the connection C-9

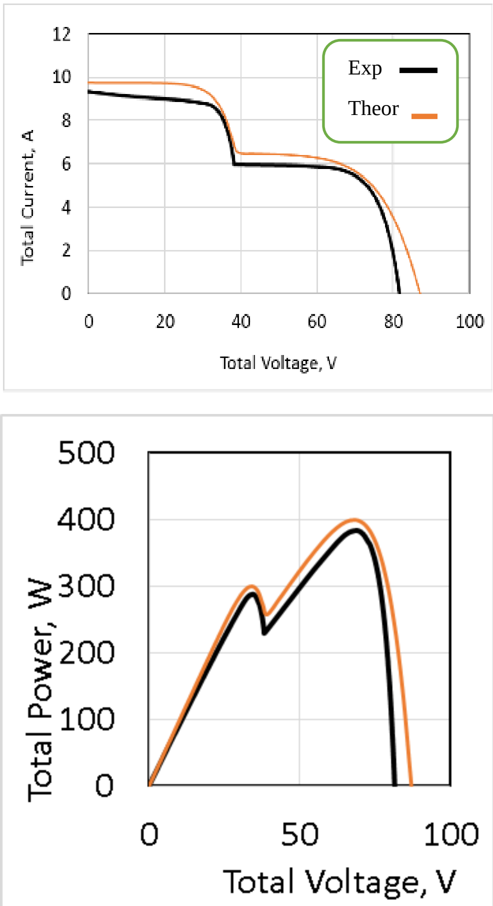

Fig. 30: Current-Voltage and power-voltage curves of the connection C-10

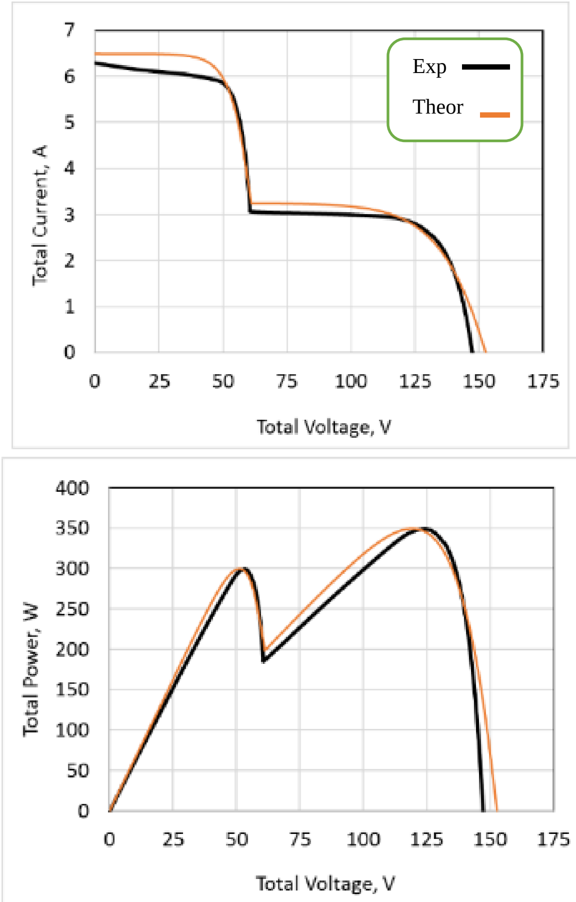

Fig. 31: Current-Voltage and power-voltage curves of the connection C-11

C-12 which is a random array of two strings connected on parallel, one of them has nine modules and the other has only one module as shown in **Fig. 32**. In this case note that the current is duplicated for the voltage range of one module, after that voltage value the current drops hardly at a specific voltage where the current keeps its value until the maximum voltage where the current falls to the voltage of the sum of nine modules. the maximum values of Isca and Voca are 6.332A, 179.114V. The maximum power output in this case is higher than the other specific type of connection and has a value of 427.5W.

C-13 which is a random array of seven modules string connected with three modules string on parallel.in this case note that the current is duplicated for the current range of two modules, after that the current begin to drop gradually until reaches for the current range of one module. The maximum values of Isca and Voca are 6.351A, 149.3V as shown in **Fig. 33**. While the output voltage is the sum of voltage of seven individual modules. The maximum power output in this case is 357.4W.

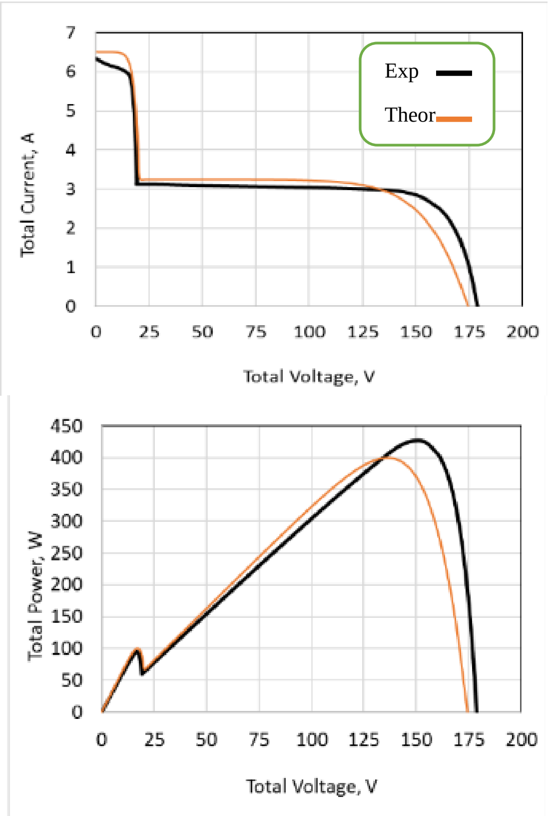

Fig. 32: Current-Voltage and power-voltage curves of the connection C-12

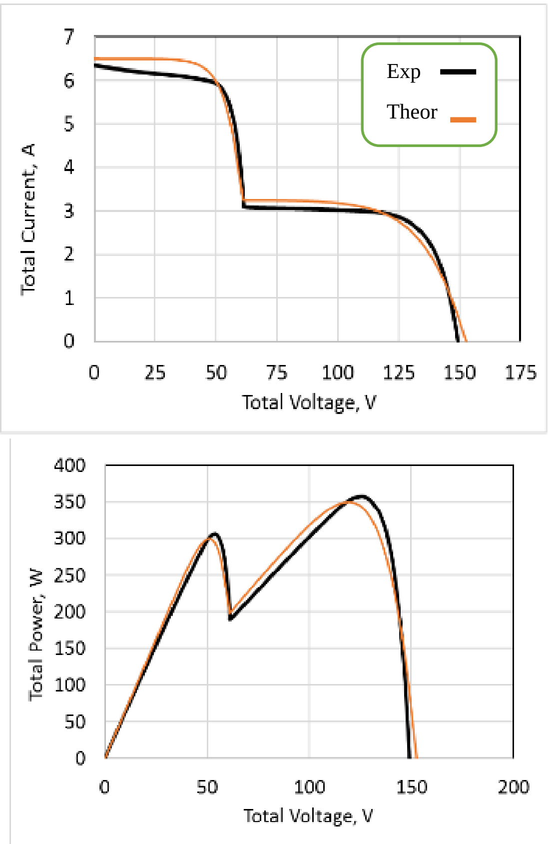

Fig. 33: Current-Voltage and power-voltage curves of the connection C-13

C-14 which is a random array of six strings, two of them with three modules and the remaining ones each has only one module. In this case note that the current is duplicated for the current range of six modules, after that the current begin to decrease gradually until reaches to the current range of two modules. While the output voltage is the sum of voltage of three individual modules. The maximum values of Isca and Voca are 18.476A, 63.364V as shown in **Fig. 34**. The maximum power output in this case is the less power among the other types of connection and has a value of 294.2W.

C-15, four strings connected on parallel with four, three, two and one module. In this case note that the IV curve is divided for four steps. At short circuit condition (V=0), the current is about four times the current of one module. Then begin to drop slowly in three steps until reaches to the current of one module. While the output voltage is the sum of four modules. the maximum values of Isca and Voca are 12.74A, 84.726V as shown in **Fig. 35**. The maximum power output in this case is 305.2W.

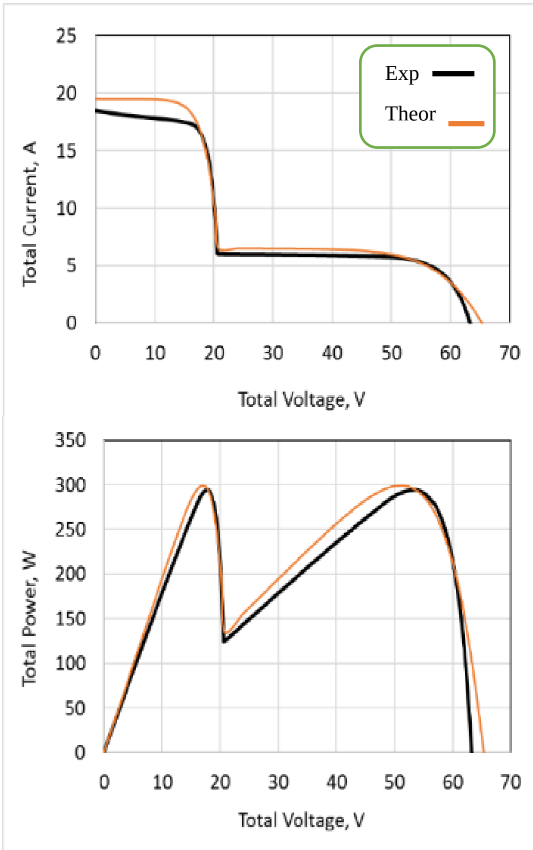

Fig. 34: Current-Voltage and power-voltage curves of the connection C-14

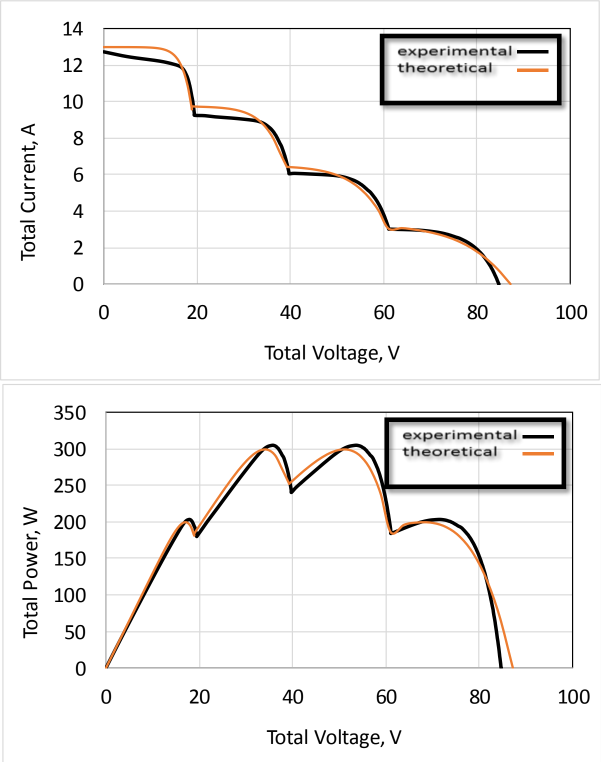

Fig. 35: Current-Voltage and power-voltage curves of the connection C-15

5.2 Mathematical Model Validation

The deviation between the experimental results and the mathematical model is represented by the absolute error and the percentage of the absolute error to the experimental value is the relative error.

$$Absolute\ Error = |experimental - theoretical| \quad (16)$$

$$Relative\ Error = \frac{Absolute\ Error}{experimental} \times 100$$

(17)

Table .3 presents the absolute and relative error for the maximum power output. Due to the solar radiation fluctuations and measurement devices error, there are a deviation between experimental and theoretical results. Overall, the relative error percentages range in acceptable values from 0.1% to 6.76%.

Table 3. Experimental and theoretical power of fifteen types of connections for PV array at solar radiation flux 1000W/m2 with absolute and relative error for each case

	Pmax exp., [W]	Pmax model, [W]	Abs. Err., [W]	Rel. Err., [%]
1	501.3	497.37	4.00	0.80
2	525.16	526.64	1.48	0.28
3	512.2	497.38	14.86	2.90
4	505.6	497.38	8.19	1.62
5	385.4	397.91	12.51	3.25
6	396.5	397.91	1.42	0.36
7	307.4	298.43	9.00	2.93
8	387.9	397.91	9.99	2.58
9	301.7	298.93	2.74	0.91
10	383.3	398.57	15.23	3.97
11	349.0	348.75	0.34	0.10
12	427.5	398.57	28.92	6.76
13	357.4	348.75	8.68	2.43
14	294.2	298.93	4.73	1.61
15	305.2	298.93	6.23	2.04

6. CONCLUSION

From the results presented, the following point can be concluded:

- The maximum voltage could be achieved from connected PV Modules in series while the current will be minimum compare with the other types of connection and the values of voltage and current for series connection are 210.204V and 3.163A .
- The results show that the most important advantage of having parallel connection of PV modules array is that all of the modules share the same voltage that could be easily measured and controlled which is equal to

21.093V while the output current has the maximum value which is 33.025A.

- In the case of series – parallel configuration the results were volatile from case to case depending on the type of connection.
- The results show that there is an agreement between the theoretical and experimental work with little difference between them.

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