REPORT ON OPERATION OF PV POWER GENERATORS

CONTENTS:

- Effects of ideality factor, parasitic resistances, temperature, and irradiance on the operation of PV modules
- Operation of series-connected PV modules under partial shading conditions and the effect of bypass diodes
- Operation of basic MPPT algorithm (perturb and observe) under varying operating conditions
- Thermal behavior of PV modules

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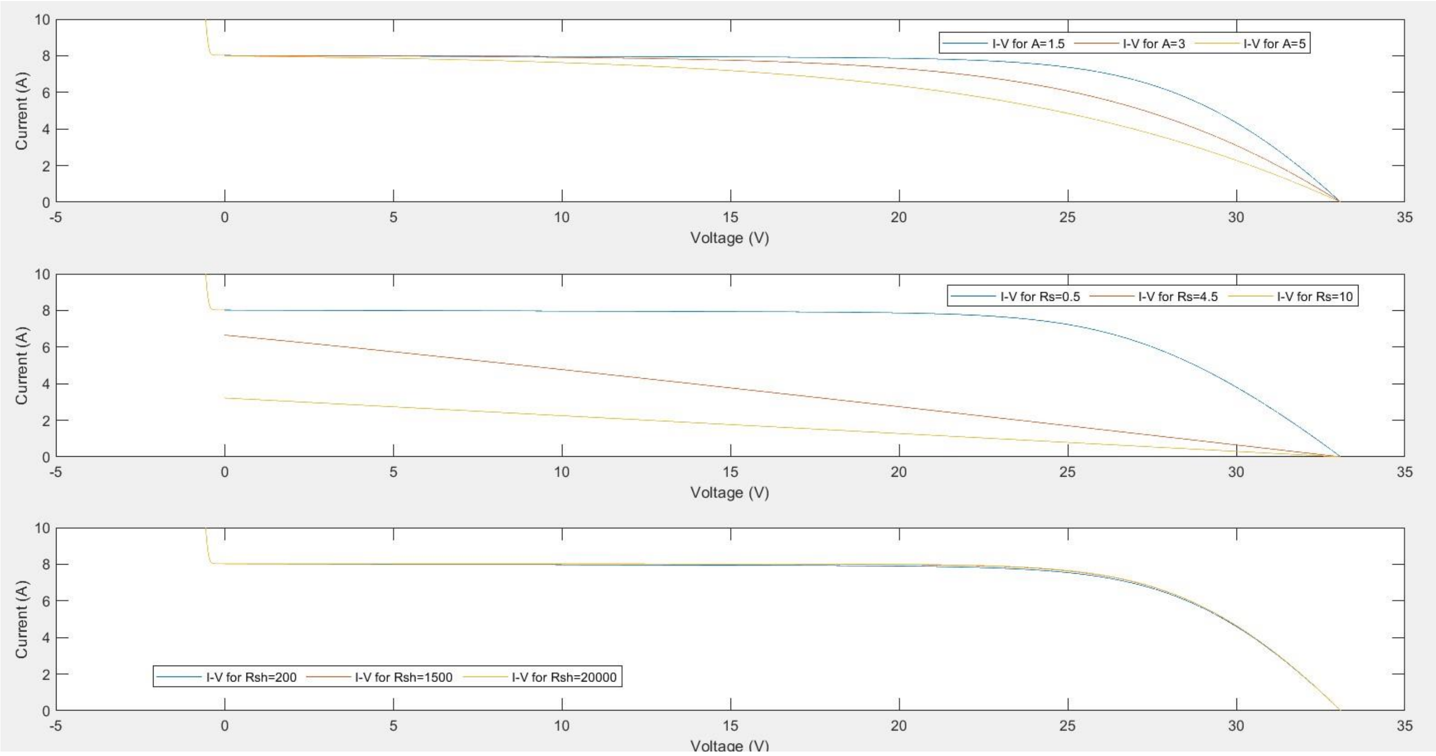
Effects of ideality factor, parasitic resistances, temperature, and irradiance on the operation of PV modules:

1. **Operation of PV modules**

1.1

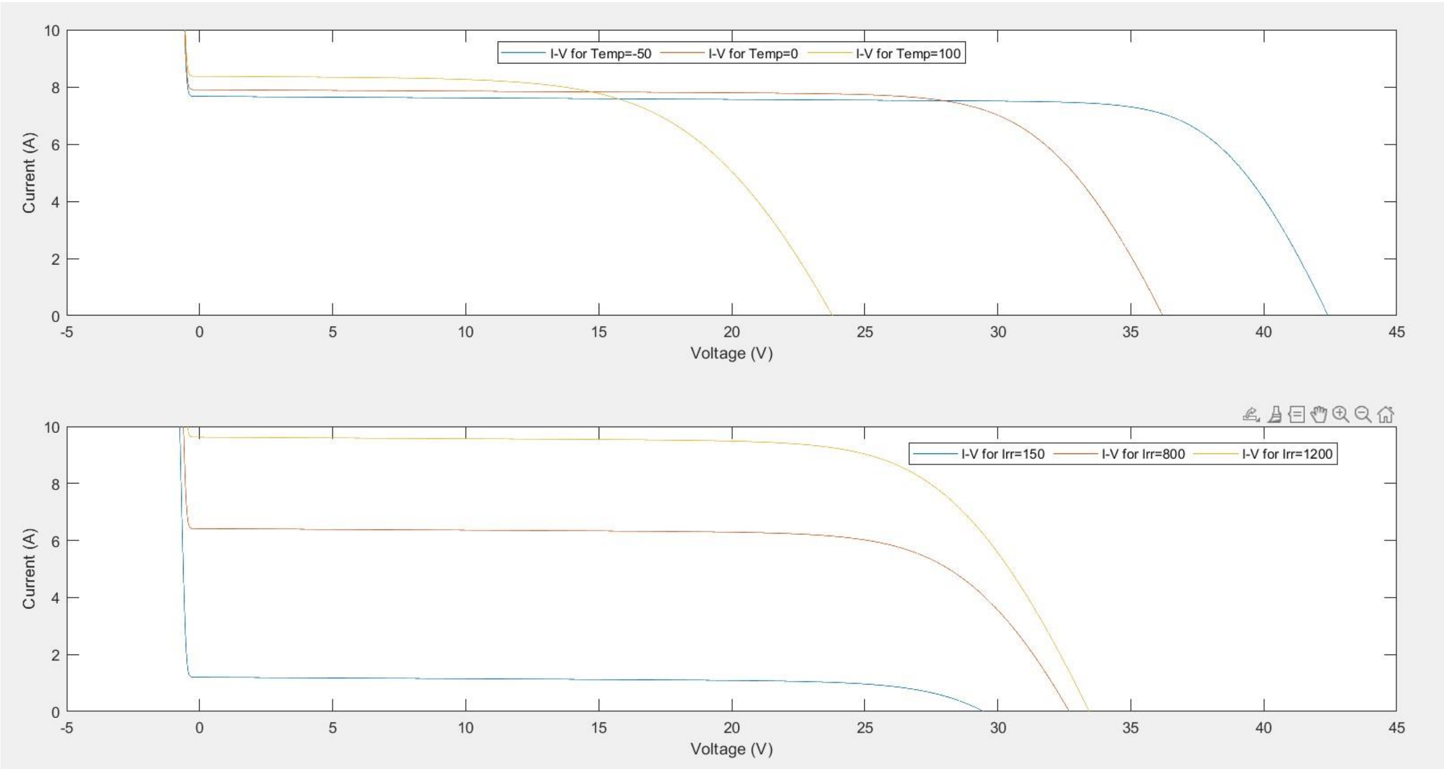


The ideality factor (n) is a measure of how closely a diode follows the ideal diode equation. It is dependent on the junction quality, temperature, and a few other variables. Decrement in ideality factor raises the output rms voltage, implying a larger MPP, however in practice, ideality factors below 1 are impossible to achieve. It affects the fill factor of the solar cells and so, if n increases, the fill factor decreases. We know, conversion efficiency PCE=Isc. Voc FF/Pi where Pi=incident solar power. Hence, if the fill factor (FF) decreases, PCE will also decrease which is not desirable. So, the ideality factor should be kept as low as possible. Typically it is in the range of 1.3-3.3.

The increase in series resistance is identified as the prominent reason for module performance degradation. Series resistances are used to reduce the fill factor (FF). Higher series resistance reduces the short circuit current of the PV module and decreases the maximum achievable power. Typical area-normalized series resistance values for laboratory solar cells range from 0.5cm^2 to 1.3cm^2 for commercial solar cells.

Shunt resistance is infinite in ideal conditions. When connecting multiple solar cell modules in series, the cells may not produce the same amount of current and due to the shading conditions, some of the current flows to the shunt resistance and so, the current flow through the load resistance decreases. Shunt current is the leakage current in the solar cell junction leading to a short circuit of the solar cell. So, it is recommended to have as large value as possible.

1.2



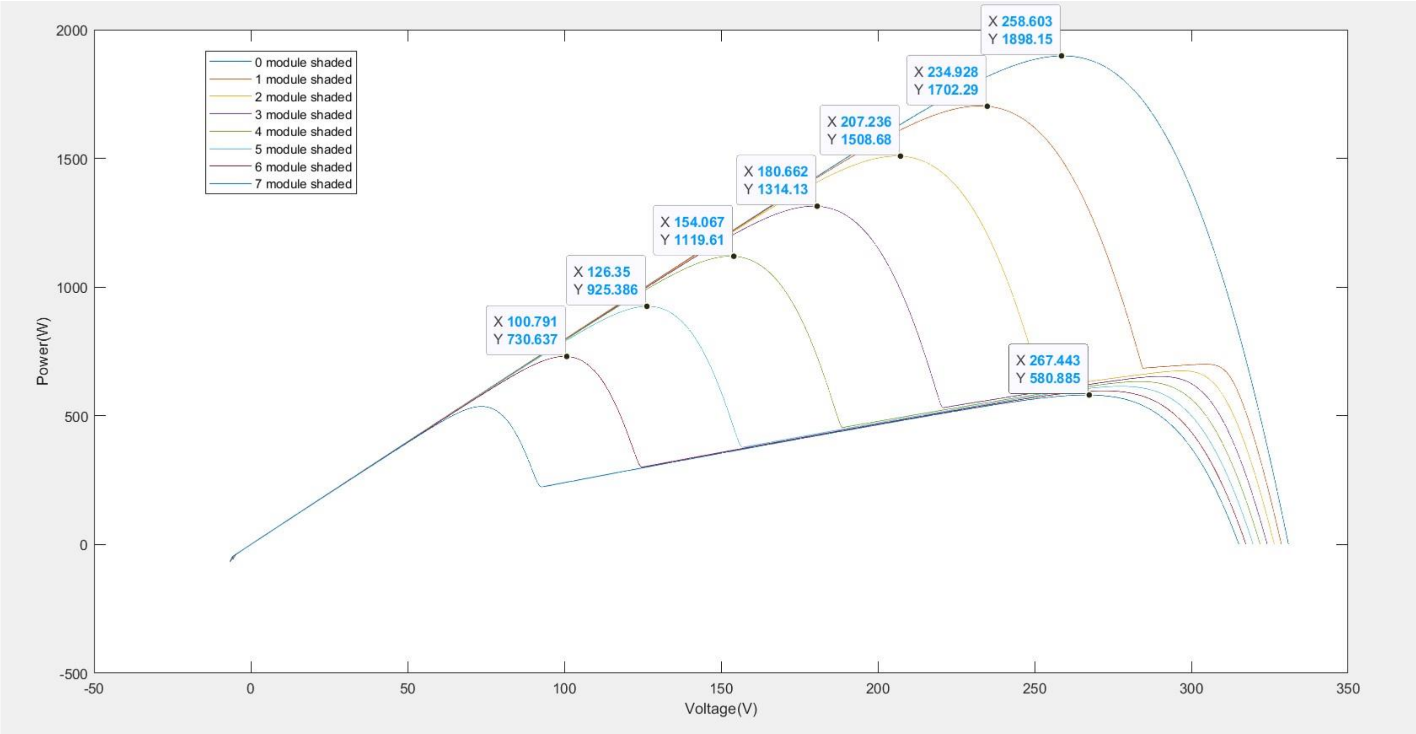
With the increase in temperature of the module, open circuit voltage drops. Heat can severely weaken the solar panel's power production as it increases recombination of current carriers. It is necessary to keep the module temperature within some limits to efficiently getting power as an output. At higher temperatures, the short circuit current of a solar cell can increase a bit due to lower band gap energy, but low band gap energy is directly proportional to open circuit voltage of a cell which can clearly decrease it with rise in temperature and hence, MPP getting reduced.

With an increment in irradiance, the open-circuit voltage only increases slightly. Short circuit current is directly proportional to irradiance and so, it increases dramatically. As current carriers increase, the diffusion current also increases. This, in turn, increase the possibility of getting maximum power output. With a decrement in irradiance, the current decreases but the voltage can be quite high under low irradiance as it does not decrease much.

Operation of series-connected PV modules under partial shading conditions and the effect of bypass diodes:

2. **Operation of series-connected PV modules under partial shading**

2.1



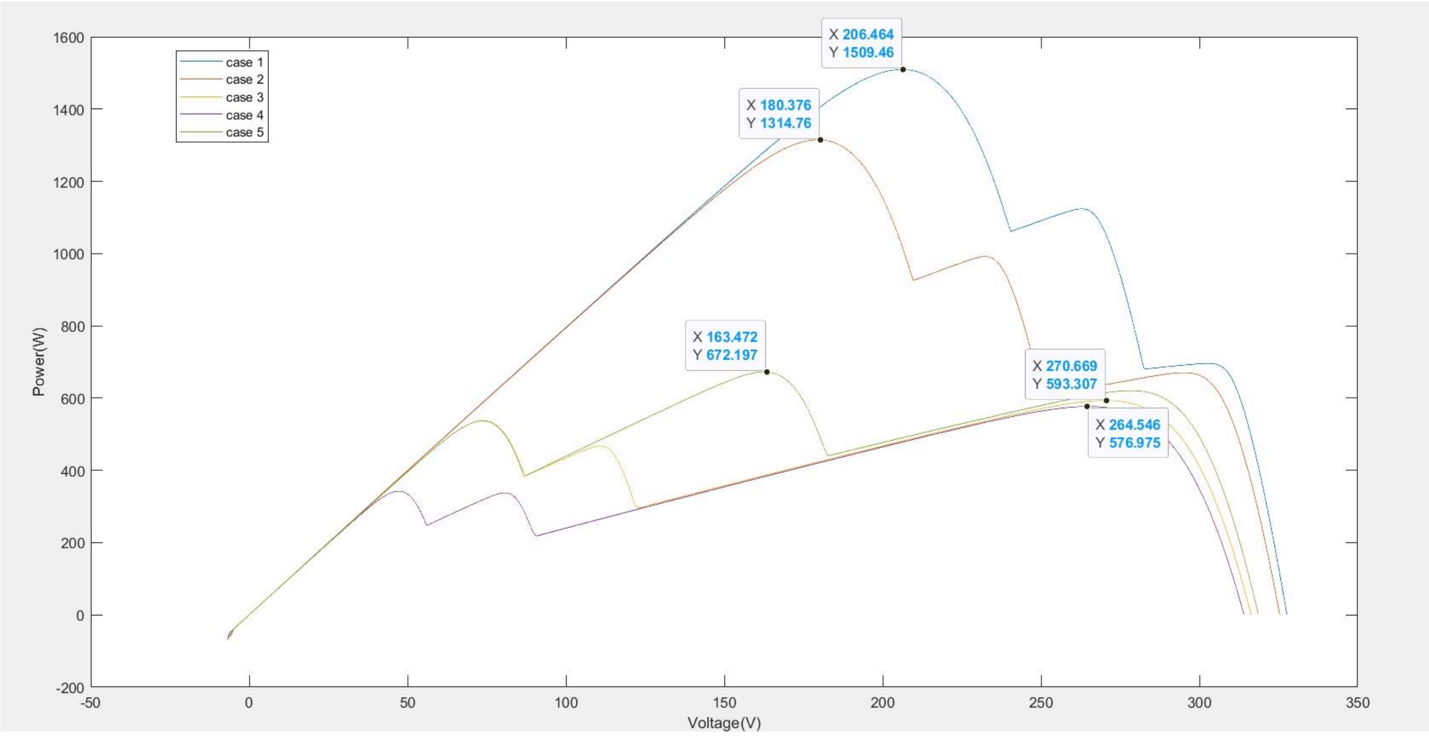
It is observed that with an increment in the number of shaded modules, the power output reduces distinctively which means irradiance is directly related and proportional to the current and voltage of the PV module, hence, power as an output. Also, multiple MPPs can be noted from the graph above with an increase of shaded modules. This is due to various irradiance levels which resulted in global and local MPP formation. However, with constant irradiance level, there is only one global MPP formation observed.

In the figure, we have plotted 8 power-voltage curves out of which we can see 8 global MPPs out of 15 MPPs in total, one for each case. The values for voltage are given below:

CASES	GLOBAL MPP Voltage
1.	258.6V
2.	234.9V
3.	207.2V
4.	180.6V
5.	154.0V
6.	126.3V
7.	100.7V
8.	267.4V

Different irradiance level creates different voltage and current level that in turn activates the bypass diodes of the PV array. Partial shading creates multiple maximum power points due to the presence of bypass diodes. Because bypass diodes are present, unshaded modules in all series assemblies will be able to conduct their maximum current at given insolation and temperature. However, if the bypass diodes are not present, the shaded modules will limit the current output of the series assembly's unshaded modules. This could result in the PV modules being destroyed by heat, as well as a reduction in the PV array's available output power.

2.2



From the graph above, it can be observed that there are 5 global MPPs out of 15 MPPs in total for each case of Power-Voltage curves. The differentiation of the global and local MPPs is done using different sophisticated MPPT algorithms. Under non-uniform conditions, conventional MPPT algorithms like Perturb and Observe and Incremental Conduction methods get trapped at local MPPs thus failing in locating maximum power point. The 5 cases are listed below:

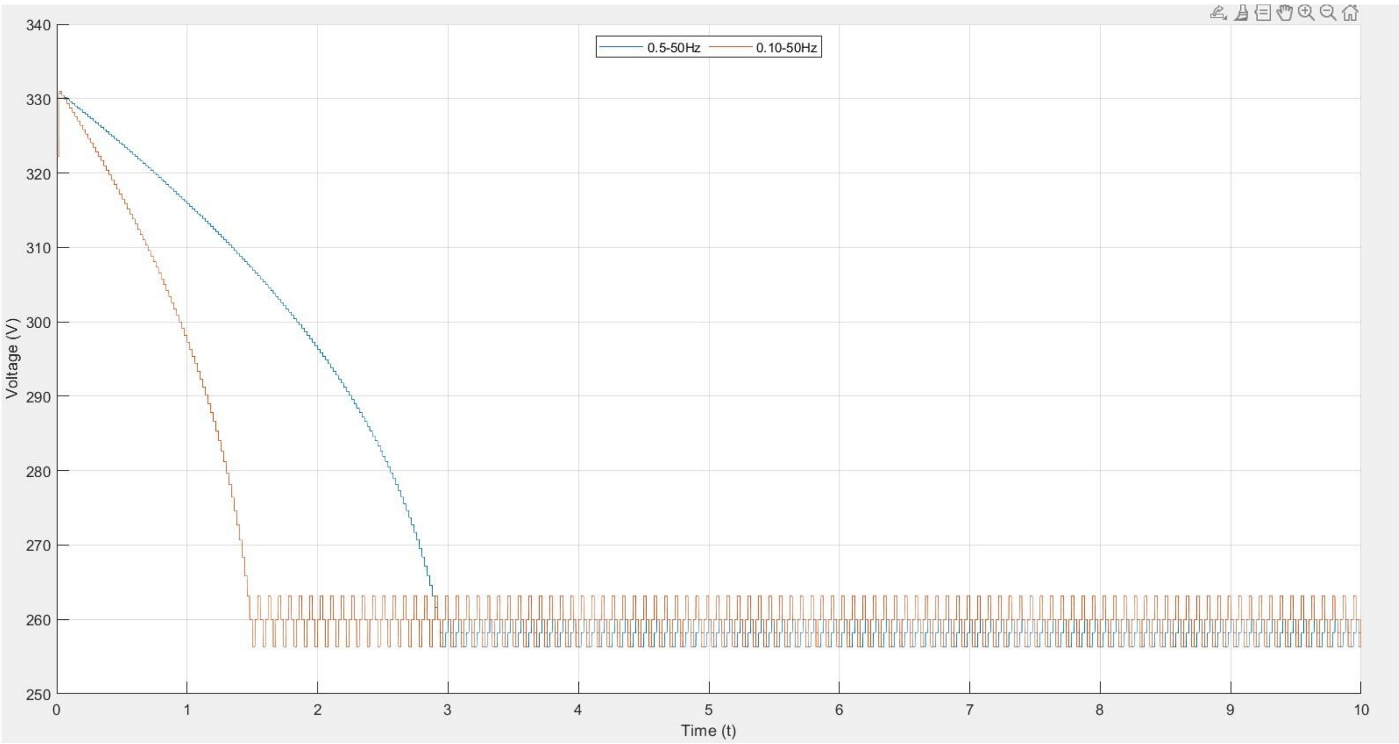
CASES	GLOBAL MPP Voltage
1.	206.46V
2.	180.37V
3.	270.66V
4.	264.54V
5.	163.47V

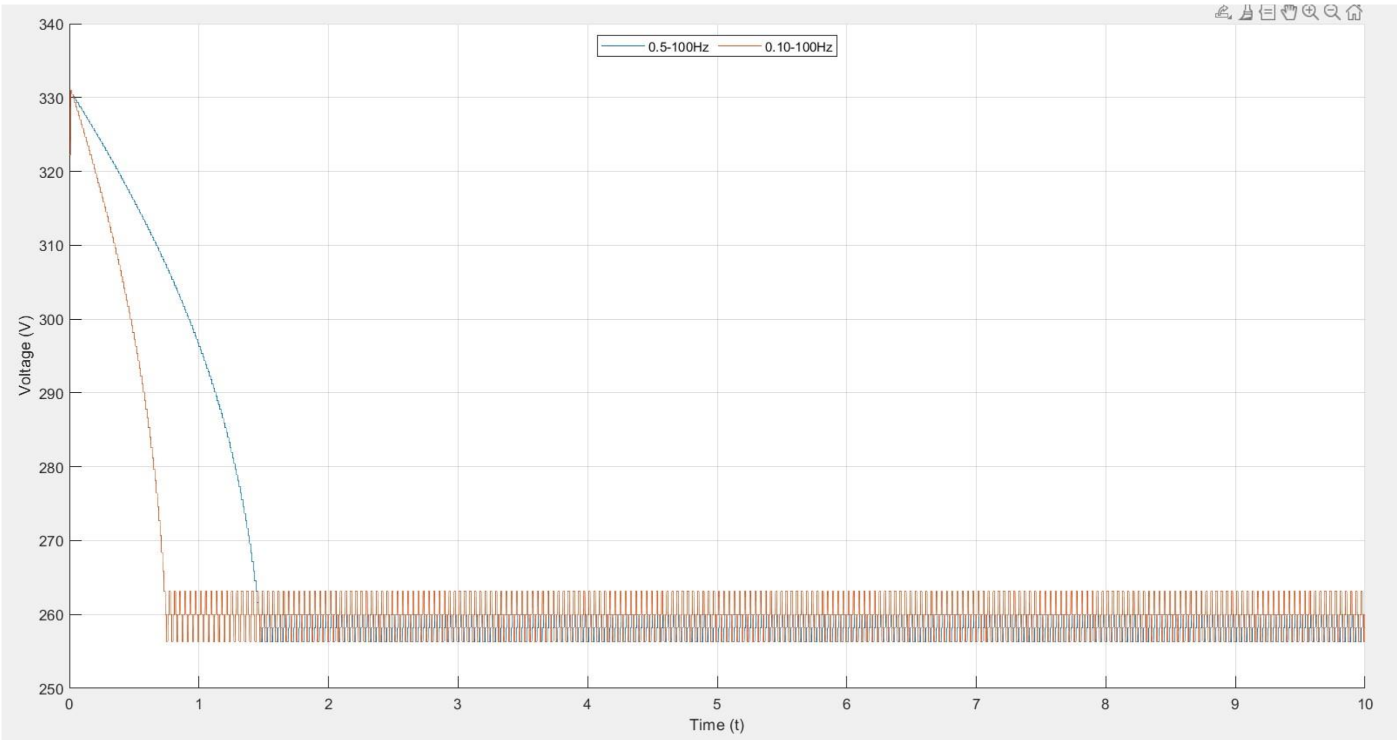
If there are more than 3 irradiance values, then the number of MPPs may also increase.

Operation of basic MPPT algorithm (perturb and observe) under varying operating conditions:

3. **Operation of Perturb and Observe (PO) MPPT algorithm**

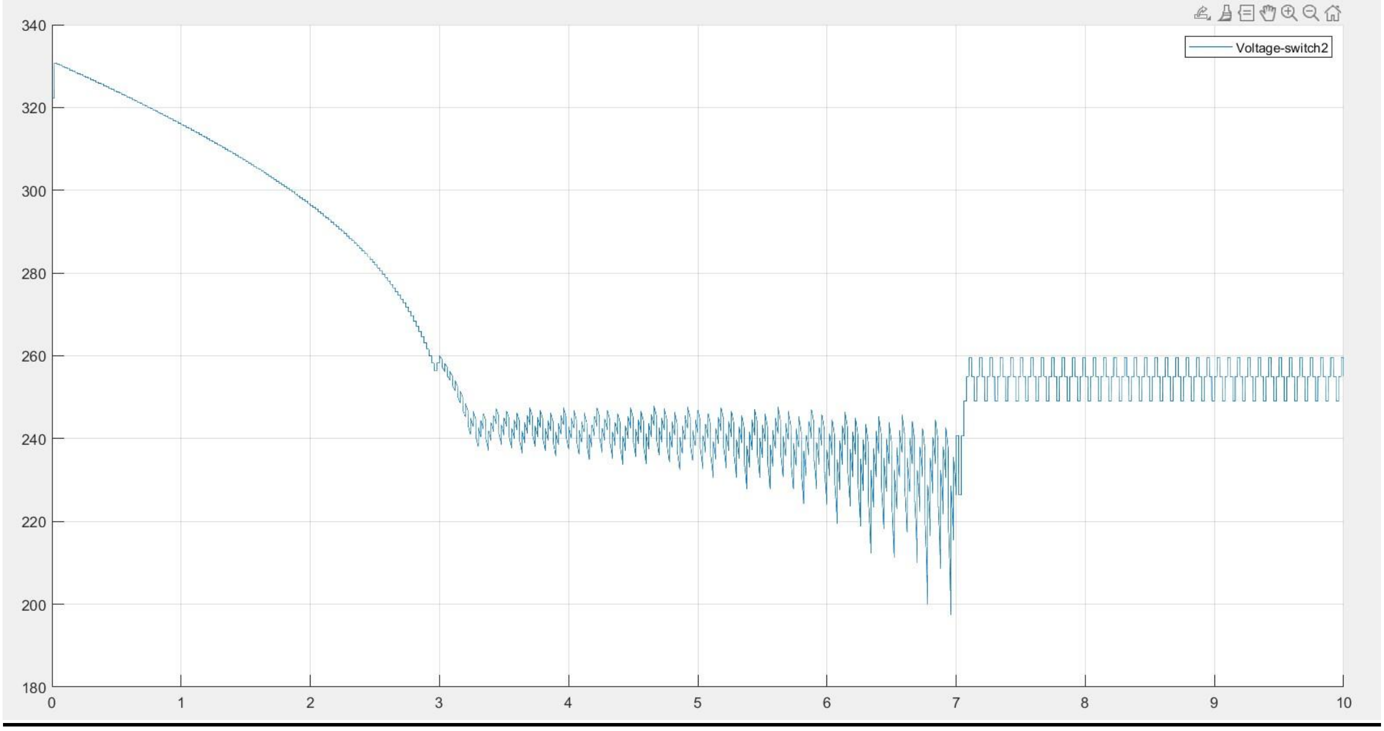
3.1





A lower step size and perturbation frequency results in lower steady-state oscillation and slower transient response. If a very low step size is used, the noise superimposed on the PV array output current/voltage may cause a comparable change in the measured power to that resulting from the perturbation made by the MPPT algorithm. As a result, the P&O algorithm's stability may deteriorate, lowering energy use efficiency. By adopting a larger perturbation rate, the slow transient response can be compensated.

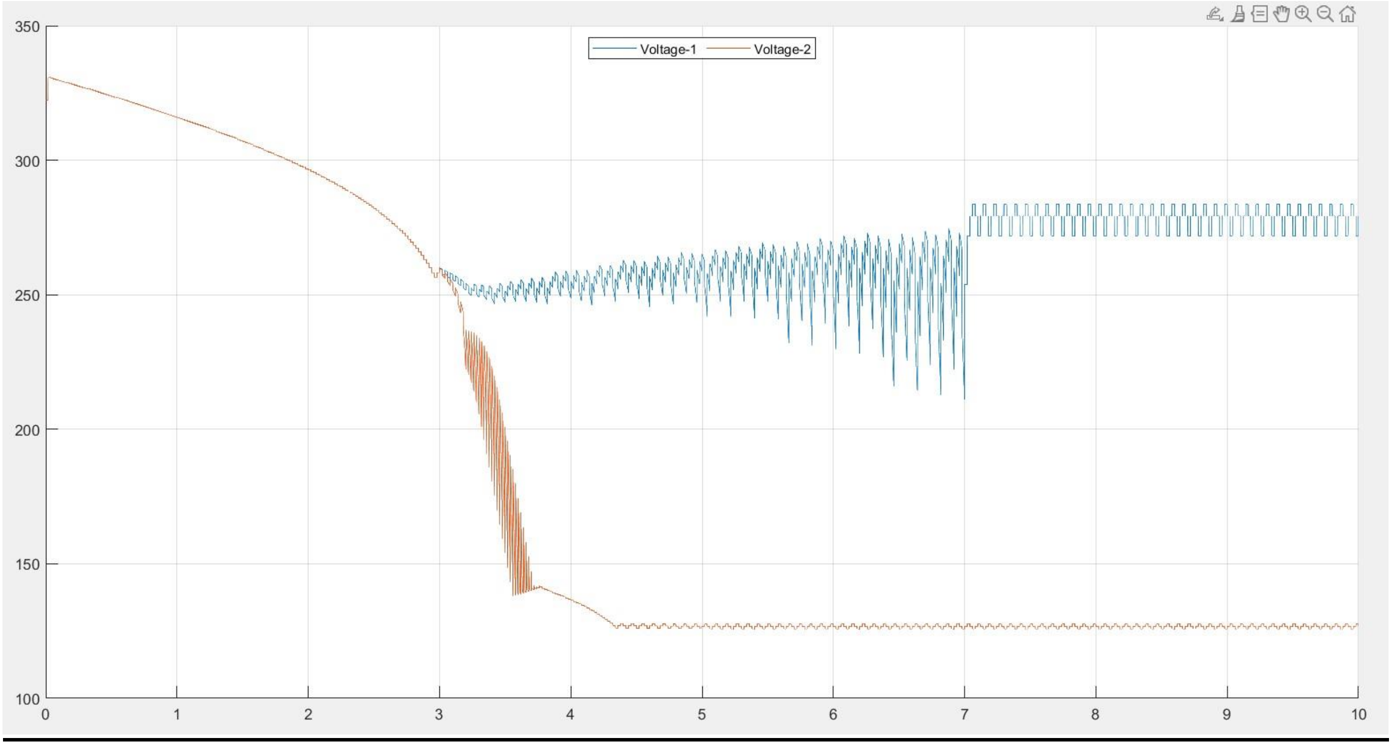
3.2



X-axis = time(s), Y-axis = voltage(V)

Both the source and output voltage and current keep track of the change in irradiance. Here, the P&O algorithm compares the current at hand to the one calculated before and decides whether to shift upward or downward, depending on the perturbed step size permitted. During the irradiance ramp adjustment, we can see the current tracking. Currents eventually converge at the MPP and oscillate at a steady rate. The voltage here follows the current disturbance and eventually settles with the current. This continual oscillation guarantees that any changes in irradiance are detected and recorded.

3.3



X-axis = time(s), Y-axis = voltage (V)

From the above figure, it has been noted that the voltage level of global MPP (126.61V) that we recorded in section 2 is almost reached for 2s ramp signal by the quick ramp change whereas, 4s ramp signal MPP is achieved at voltage level 279.23V. Therefore, we can say that a faster change in irradiance settles the global MPP at a lower voltage level, while a slower shift settles it at a higher voltage level.

3.4

Advantages of Perturb and Observe method are:

1. Easy to implement
2. Accurate, upright, and good performance under uniform radiation
3. Online and does not depend on PV array

Disadvantages include:

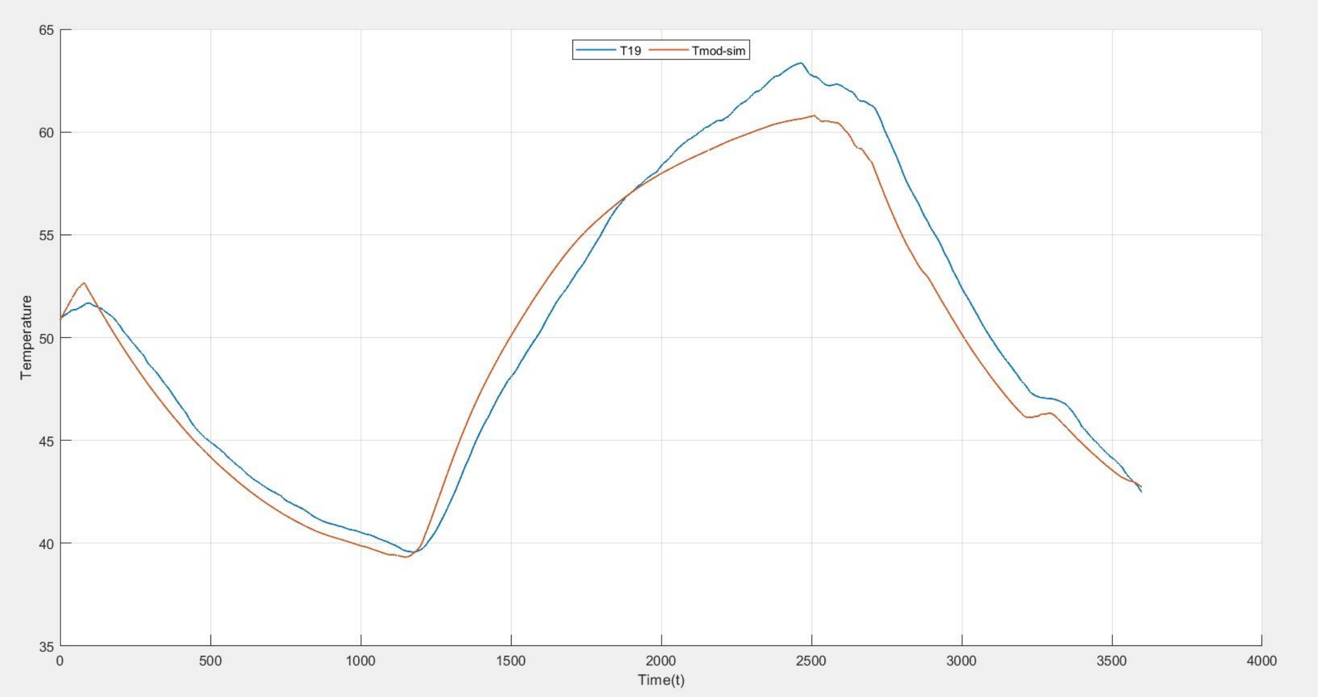
1. Oscillations around steady-state occur during fast-varying environmental conditions/ non-uniform radiation.
2. The difficulty of the step size control

In real PV systems, I think mostly controlling the operating voltage of the PV system is commonly used. Based on the P-V graphs, when a voltage rise causes a power increase, the PV module's operating point is on the left side of the MPP. As a result, to get to MPP, further perturbation is required to the right. If an increase in voltage causes a power reduction, the PV module's operating point is to the right of the MPP, requiring more perturbation to the left to achieve MPP. It is easy to implement, and this is the reason, this method is more common.

Thermal behaviour of PV modules:

4. Thermal behaviour of PV modules

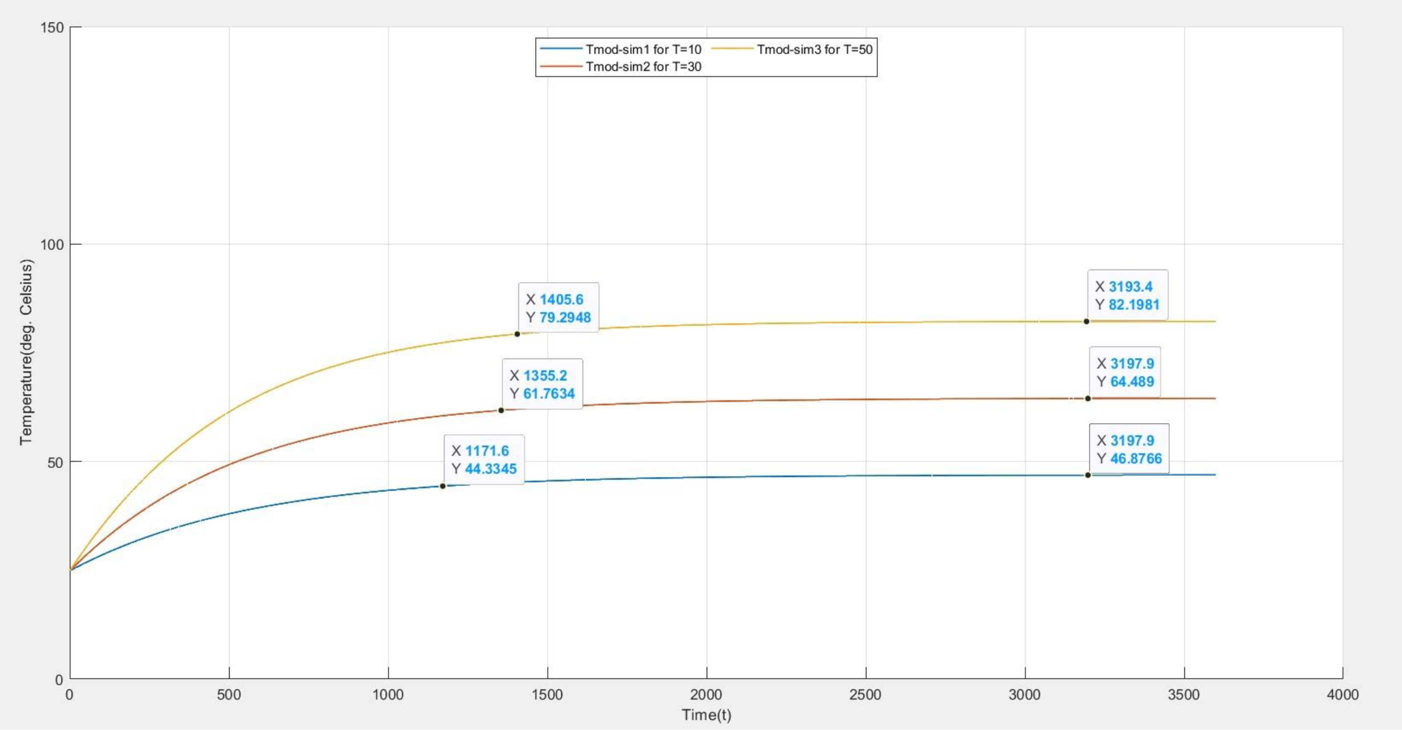
4.1



It is noted that the simulated results show a substantial decrement in the temperature of the module as compared to the measured results. Since wind speed is closely related to the efficiency of the PV module the distinct difference is due to the wind speed which reduces the temperature of the junction thus increasing the overall efficiency of the PV cells. It is recommended to keep the temperature of a PV module within a limit. Another reason could be the sensors used as no appliance can give 100 percent accurate results which is why we can spot the error between the practical and the simulated results.

4.2

4.2.1



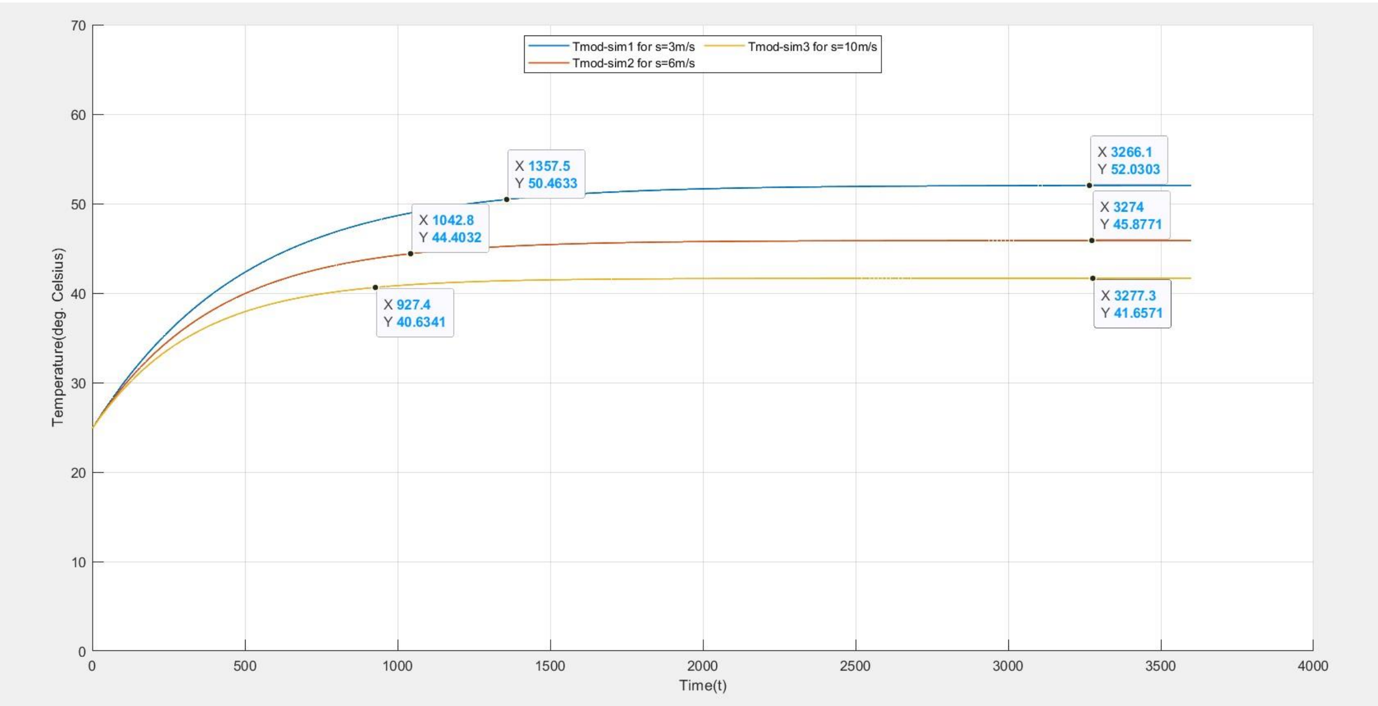
From the above graph, with an increase in temperature, settling times are slower. With the increment in ambient temperature, module temperature also increases and vice versa.

For temperature =10 deg. C, settling times = 1171sec

For temperature =30 deg. C, settling times = 1355sec

For temperature =50 deg. C, settling times = 1405sec

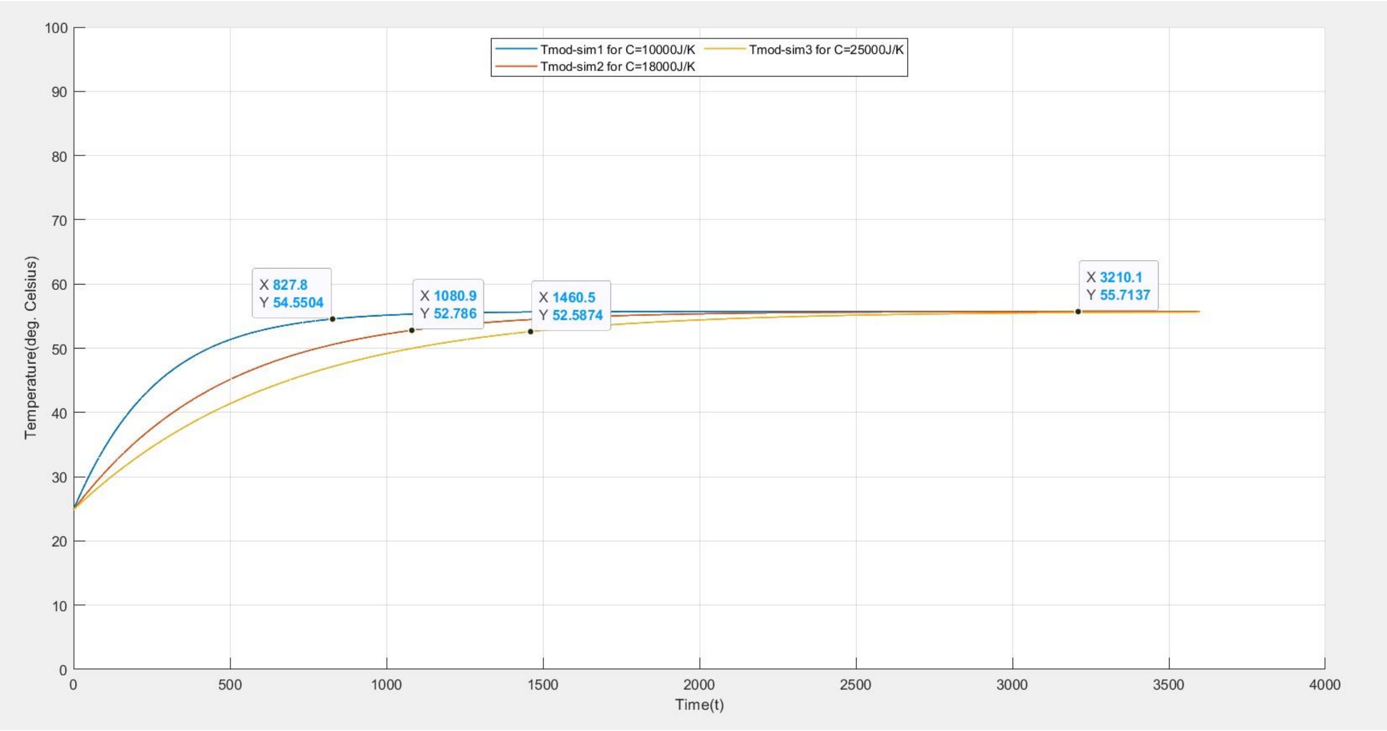
4.2.2



From the above graph, it is noted that with an increase in wind speed, the temperature of the module decreases. The settling times of the graph suggest that with the increase in wind speed, the temperature of the module settles faster as compared to the low wind speed curves.

For wind speed = 3m/sec, settling times = 1357sec
For wind speed = 6m/sec, settling times = 1042sec
For wind speed = 10m/sec, settling times = 927sec

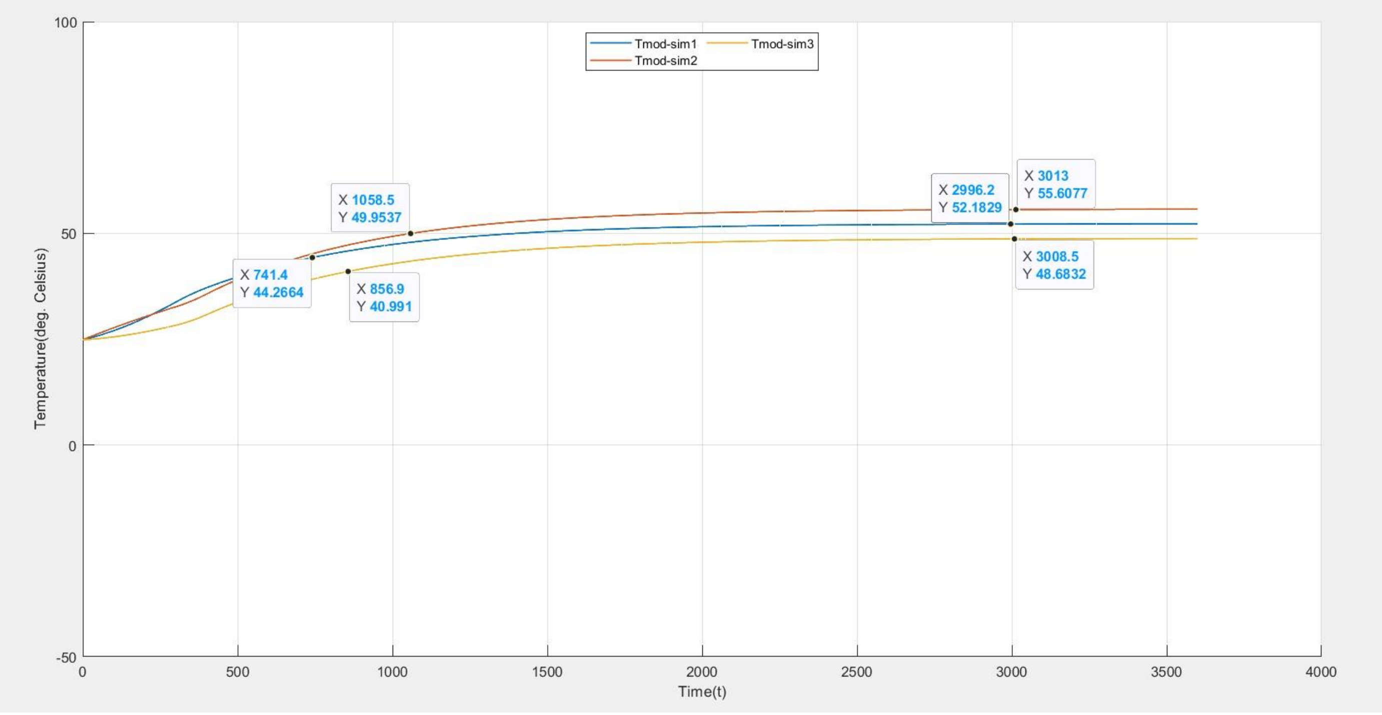
4.2.3

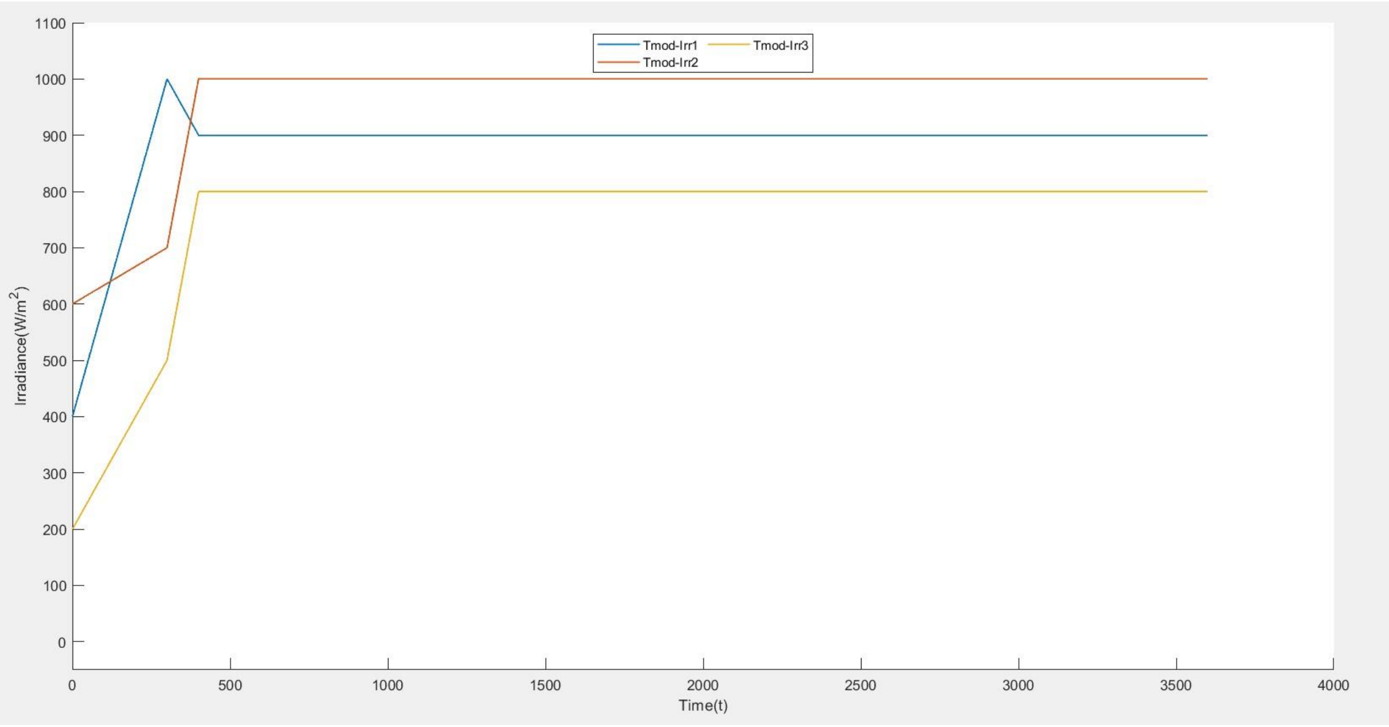


Heat capacitances affect the gradient of module temperature. From the above graph, it can be noted that with a decrement in Heat capacitance value, the settling times are faster as compared to increased Heat capacitance values.

For Heat Capacitance = 10000J/K, settling times = 828sec
For Heat Capacitance = 18000J/K, settling times = 1081sec
For Heat Capacitance = 25000J/K, settling times = 1461sec

4.2.4





From graphs 1 and 2, it can be observed that with increased irradiance changes, the settling times are slower. Fewer changes in irradiance mean settling times are faster.

Irradiance case 1 → Settling Times 741 sec
Irradiance case 2 → Settling Times 1058 sec
Irradiance case 3 → Settling Times 856 sec
Standard Test Conditions (STC) specify an irradiance of 1000 W/m2 and a cell temperature of 25°C. STC is based on laboratory conditions and is the first guide towards the planning and sizing of PV modules. However, these conditions are rarely encountered in the real world. The performance of a

PV panel under indoor STC measurements and actual operating conditions when installed on a rooftop or support can be vastly different, and the user may be disappointed.

STC requirements are not diligently met by the manufacturers' internal quality control team, with frequent deviations in lamp spectrum, cell temperature, environment temperature, irradiation etc. Therefore, the customers of solar modules frequently engage the services of third-party solar PV module quality inspectors to check whether the manufacturer's stated performance promises are accurate.