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Up and Down Conversion of Photons with modified Perturb and Observe MPPT technique for Efficient Solar Energy Generation

Atul Manmohan[a,*], Akhil Prasad[a], Ravi Dharavath[b], S. Prabhakar Karthikeyan[b], I.Jacob Raglend[b]

[a]*Transportation Infrastructure, Larsen and Toubro, Faridabad, India*
[b]*Department of Electrical and Electronics Engineering, VIT University,Vellore,India*

Abstract

Despite many decades of research on the photovoltaic cells, still it is a great struggle to get efficiencies more than 25%. Transmission of low energy photons & thermalization of high energy photons are the two losses which form the backbone of the Shockley – Queisser limit. In this paper, a way to diminish both these losses along with modified Perturb and Observe MPPT method, which will boost the overall efficiency up to 35% is demonstrated. At first Singlet Exciton Fission is utilized as a down converting process for photons with energy greater than silicon bandgap of 1.12 eV in which a single high energy photon fissions into two photons of half the energy. Then, Triplet-Triplet Annihilation (TTA) is utilized as an up converting process for photons with energy less than 1.12 eV & wavelength more than 1100 nm in which two low-energy photons get converted into a single high-energy photon of twice the energy and finally Modified Perturb & Observe MPPT method with ZVS technique is used to reduce the DC to DC converter losses.

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Keywords: External Quantum Efficiency; Singlet Exciton Fission; Triplet-Triplet Annihilation; MPPT; Perturb &Observe; ZVS

1. Introduction

* Corresponding author. Tel.: +91-9600440510.
E-mail address: mannuu@lntecc.com

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It is estimated that by 2030 the world energy consumption will encroach up to 30 TW [5]. Finding 15 TW of energy generation is itself a daunting task and even finding 15 TW of clean, renewable energy doubly so. Abundance amount of light energy falls on earth surface around 89,000 TW. Even 0.3% of that energy is sufficient to fulfill our future load demand of 30 TW & provide pollution free energy generation. Despite so many advantages still solar energy represents only 0.5% of our total energy generation [7]. In today's market almost 93% of solar cells are constructed from silicon as per NREL. The world's best silicon solar cells have efficiency of less than 25% [9]. Silicon has a bandgap of 1.12 eV, corresponding to light of 1100 nm wavelength. Light at this energy is efficiently absorbed and converted into electricity. Light greater than silicon bandgap is also absorbed but the generated carriers rapidly thermally relax to the band edge of the device and the excess energy is wasted as heat. Therefore a single high energy blue photon & low energy infrared generate the same output energy. Energy captured by silicon solar cell is indicated in purple. The loss from high energy photons is termed as thermalization, shown in Fig. 1 (a). Losses in visible spectrum are high due to thermalization; almost half of the incident energy is wasted. A second loss is also shown in Fig. 1 (a): photons with energy less than the silicon bandgap will pass through solar cell unabsorbed. Therefore, no energy is generated from photons of wavelength greater than 1100 nm. These two losses form the backbone of Shockley-Queisser limit, which limits silicon solar cells efficiency up to 33% [6].

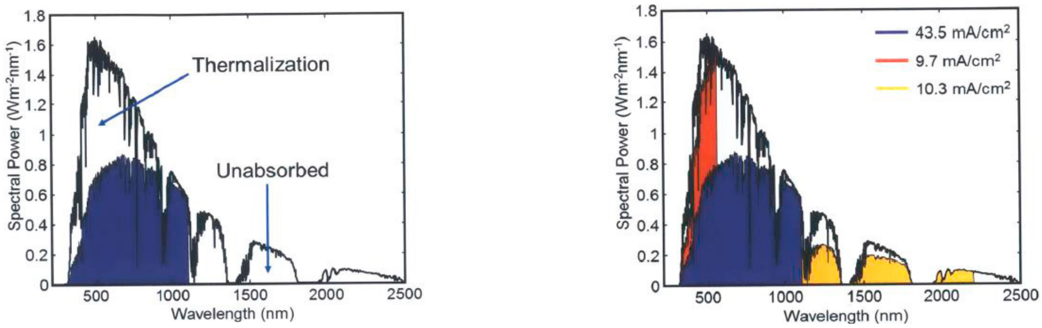

Fig. 1 (a) Spectral power density of the sun (black line) and the amount of the power collectable by silicon solar cells (purple).

Fig. 1 (b) Gains from down conversion (red) and up conversion (yellow).

Nomenclature

HOMO	Highest Occupied Molecular Orbital
LUMO	Lowest Unoccupied Molecular Orbital
DBR	Distributed Bragg Reflectors
EQE	External Quantum Efficiency
IQE	Internal Quantum Efficiency
TTA	Triplet-Triplet Annihilation
NREL	National Renewable Energy Laboratory
ZVS	Zero Voltage Switching

2. Photovoltaic Device Operation

To generate photocurrent, an organic photovoltaic absorbs light energy into the excited state, which diffuses with the interface where the electron jumps to the acceptor. This generates a bound charge transfer state in which it get separated into free charge and then it can be collected at the contacts [11].

3. Down Conversion

Down conversion is the process by which one high energy photon splits into two low energy photons of half the initial energy shown in Fig. 2. A high energy photon is absorbed by the down converter, which then emits two photons of half the energy. It is operating for all wavelengths twice or greater the energy of the bandgap or 550 nm and bluer for silicon. The potential of spectral gains are highlighted in red in Fig. 1(b). A perfect down converter can generate an extra 9.7 mA/cm^2 of photocurrent, increasing the power conversion limit by approximately 40% [2].

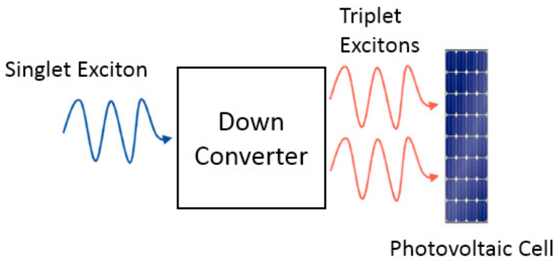

Fig. 2 Basic Scheme for down conversion.

3.1 Singlet Exciton Fission

It is the spin-allowed, energy conserved process of splitting one singlet exciton into two child triplet excitons which reduce the losses due to thermalization and boost the solar cell efficiency. Singlet fission can have efficiencies more than 100%, it can be proved through a simple electron counting experiment and a simple optical cavity used to increase the absorption in the active layer, allowing for even higher efficiencies. This section will focus on external quantum efficiency (EQE) which is a measure of how well a photovoltaic device converts incident light into electricity [2]. The expression is shown in Equation 1.

$$EQE = \frac{Collected\ Electrons}{Incident\ Photons} \tag{1}$$

An important parameter wrapped up in the EQE is the absorption by the device. Internal quantum efficiency (IQE) is simply the EQE normalized by the absorption as shown in Equation 2.

$$EQE = \frac{Collected\ Electrons}{Absorbed\ Photons} = \frac{EQE}{Absorption} = \frac{EQE}{1 - Re\ flection} \tag{2}$$

3.1.1 Device Structure

Pentacene (Pc) has been shown to be both a fast fission material and a strong photovoltaic performer when utilized in a junction with Buckminsterfullerene (C_{60}), shown in Fig. 3 [10, 13]. A Bathocuproine (BCP) blocking layer is used in conjunction with silver (Ag) to form the cathode, with the standard Indium tin oxide (ITO) as the anode. The pentacene layer is kept thin to reduce exciton diffusion losses. The EQE of the pentacene peak at 670 nm is only 24% [2, 16] because there is a significant quenching of the excitons at the ITO anode. A thin layer of Poly, 3-hexylthiophene (P3HT) is added because it has a shallower HOMO, allowing for charge extraction, yet larger singlet and triplet energies, blocking the migration of excitons to the ITO. With insertion of the P3HT there is an increase in EQE up to 82% [2]. To further improve the efficiency of singlet fission devices, absorption must be increased, but thickening the pentacene layer will increase the exciton diffusion losses. So, light management is a feasible method to improve the absorption within thin pentacene layers. Enhanced absorption has been observed for structures including micro-lens arrays, non-planar substrates and Distributed Bragg Reflectors (DBR) [12]. Almost all of these approaches require growing the organic solar cell on structured substrates. In contrast, for improving absorption in thin film organic solar cells by exploiting the slow light modes that appear at the band edge of a DBR. Using this approach there will be 50% enhancement in absorption and EQE of singlet exciton fission based solar cells [2]. The placement of the DBR between the ITO anode and the glass substrate will enhance the absorption without increasing the device fabrication complexity. The absorption is increased due to the presence of long lived slow light modes that

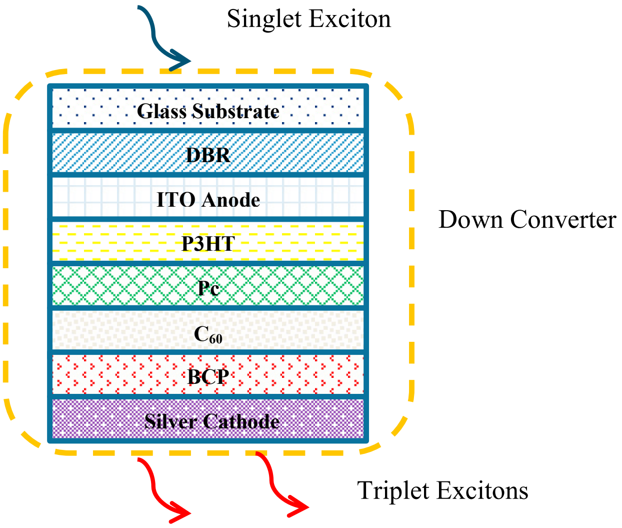

Fig. 3 Architecture of Down Converter

exist at the band edge and the associated increase in photon density of states. The photons dwell time increases in high frequency band edge mode (effective interaction length) between the absorbing organic layers and light by a factor of 2.7. After inclusion of DBR there is an increase in absorbance observed in the solar cell by a factor of 2.5 [2]. The DBR is designed to have the high frequency band edge overlap with the spectral position of the singlet exciton absorption of pentacene. The band edge can be spectrally tuned by tilting the device relative to the incident light. When the DBR Band edge mode is tuned to the peak wavelength of pentacene's extinction coefficient have an EQE peak of 126% [14, 2]. An identical control solar cell is fabricated but without the DBR has achieved an EQE peak of only 83 %.

4. Up Conversion

Up Conversion is the process by which two low energy photons are fused to become one high energy photon, shown in Fig. 4. Two low energy photons are absorbed by Up Converter, which then emits a single photon at twice the energy. It is operational for all wavelengths half or greater the energy of the bandgap, or 2200 nm and bluer for silicon. The potential spectral gains are highlighted in yellow, shown in Fig. 1 (b). A perfect Up Converter can generate an extra 10.3 mA/cm^2 of photocurrent, increasing the power conversion limit by approximately 40% [2].

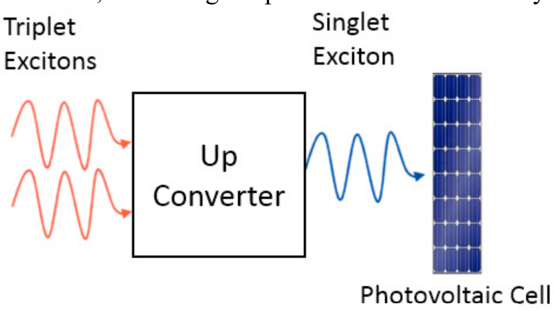

Fig. 4 Basic scheme for Up conversion.

4.1 Triplet-Triplet Annihilation

Optical up conversion is a process which generates a high energy photon by combining two low-energy photons. This reduces transmission of low energy and boosts the solar cell efficiency. There are two general approaches to optical up conversion. For high intensity, coherent light, it is possible to directly generate higher harmonics by exploiting the nonlinearity susceptibility of many materials. It can be highly efficient when properly phase matched but it is poorly suited to the conversion of broadband, incoherent sunlight. To up convert relatively low intensity incoherent light, it is generally necessary that the input energy be initially stored in the form of a molecular excited state or a long-lived atomic. Following this it is possible to reach a higher energy state through subsequent absorption or energy transfer. So, Triplet-Triplet Annihilation (TTA) is a promising approach to up convert relatively low intensity light. It utilizes a sensitizer and an annihilator for up conversion of photons energy level.

4.1.1 Device Structure

A thin layer of Lead sulfide Nano crystals (Pbs NCs) is first rolled on glass as the sensitizer. Rubrene is utilized as the annihilator, shown in Fig. 5 [15, 3, 2]. By adding 0.5% by volume of Dibenzotetraphenylperiflanthene (DBP) enhances the fluorescence intensity by a factor of 30 from the device. Doping Rubrene with DBP is to increase the emissivity in the solid state. The sensitizer absorbs the incident light and then transfers the energy as spin-triplet excitons to the annihilator via Dexter transfer. When two triplets come across in the annihilator, then they form a single higher-energy spin- singlet exciton via TTA, which can then FRET (Fluorescence Resonance Energy Transfer) to the DBP emitter molecule, which emits light with high efficiency. Up conversion is accomplished from pump wavelengths greater than λ = 1 μm to emission at λ = 610 nm [3]. Upon excitation at λ = 808 nm, a pair of excitons existing in the sensitizer are converted into one higher energy state in the emitter at a yield of 1.2±0.2%. Up conversion efficiency peaks at an absorbed intensity equivalent of slightly lower than one sun. This solid-state architecture for up conversion may prove useful for enhancing the capabilities of solar cells and photodetectors. For up conversion, this solid state architecture may present a viable solution for boosting the capabilities of photodetectors and solar cells.

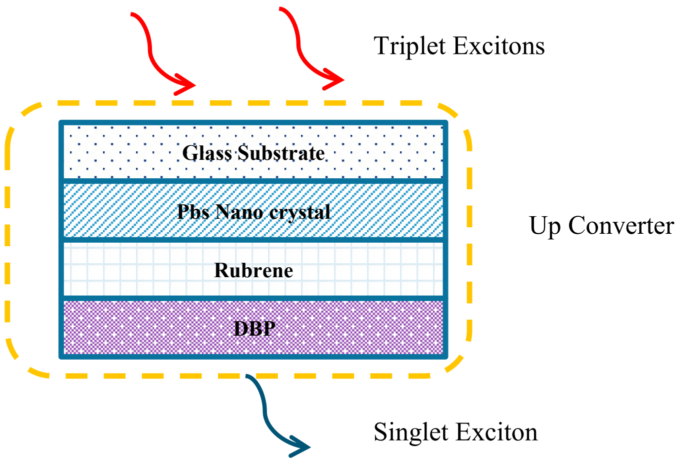

Fig. 5 Architecture of Up Converter

5. Modified Perturb & Observe Method

The conventional Perturb & Observe Maximum Power Point Tracking algorithm works under the assumption that the photovoltaic power variation is the outcome of PV voltage variation. Whereas environmental conditions like such as irradiance and temperature also affect the photovoltaic power. During a period characterized by abrupt variations in solar irradiance, the conventional P&O method fails to attain the maximum power point (MPP), Due to taking only simple observation of the photovoltaic power and voltage reference leads to send a wrong control signal to the device. So the conventional P&O method fails to track the maximum power point. This problem is addressed employing a modified P&O algorithm for efficient tracking of MPPT. This method is characterized by distinguishing the power variation caused by the MPPT control from that caused by the irradiance. This is achievable if a PV power measurement structure is added in between the control period. In the flowchart, shown in Fig. 6, $dP_{0.5}$ is the power difference between the starting point ($dPk-1$) and the middle-point ($dPk-0.5$), which includes the combined power

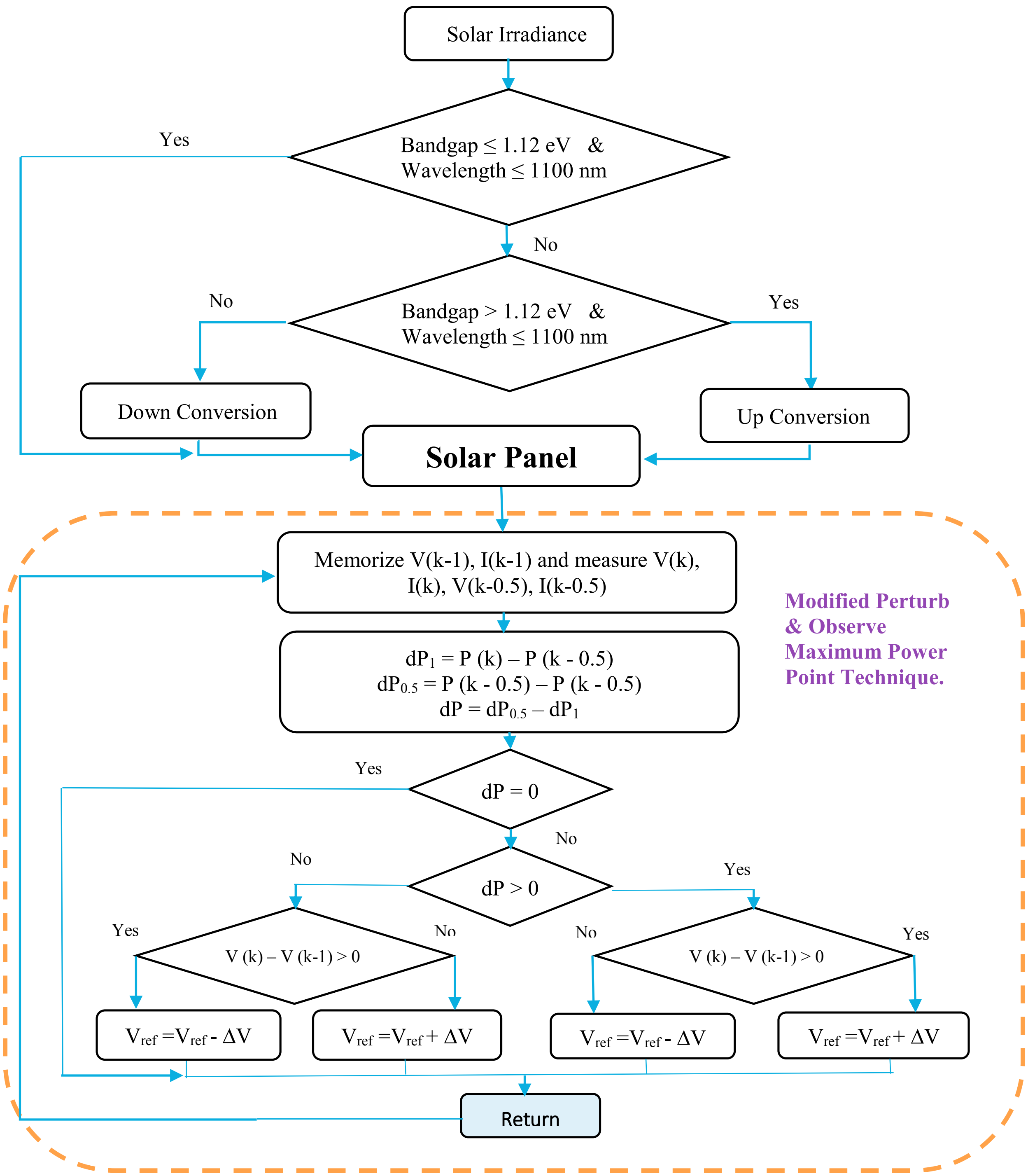

Fig. 6 Flowchart of Photovoltaic cell operation.

of MPPT control as well as solar radiation; $dP1$ contains power variation caused solely by irradiance change and dP contains power variation caused by the MPPT control alone[1, 4, 8]. The working process is mentioned below in the flowchart, shown in Fig. 6. The photons will undergo up conversion or down conversion based on the solar intensity and their corresponding wavelength in order to keep the maximum photons in the suitable bandgap of silicon solar cell. So, maximum solar energy can be absorbed and converted into electricity and then MPPT solar charge controller is used with modified Perturb & Observe MPPT algorithm in order to maximize the amount of current going into the battery from PV module. Every time MPPT feds the DC input from the solar panels, then convert it into high frequency AC, transformer action will step up the voltage level and then convert it again into DC voltage and current which matches the panels to the batteries.

5.1 Full-bridge DC/DC boost converter operation

A full-bridge DC to DC converter is employed as a boost or step - up converter, shown in Fig. 7 (a). The operating voltage of the photovoltaic panel is V_{PV}. The purpose of decoupling capacitor C_{PV} is to contain the impact of high frequency current ripple produced by the boost converter in the photovoltaic panel. The mosfets employed convert DC into alternating waveform which is fed to the transformer primary for stepping up the voltage level. The charging/discharging time of mosfets result in losses. Zero Voltage Switching (ZVS) technique is employed to minimize these losses. So, a time period is kept in which the voltage at the primary side of the transformer remains zero due to ZVS technique, so the switching time of the mosfets are different to minimize the losses, occurs due to applying voltage & current at the same time [4, 8]. After voltage level is stepped up in secondary side of the transformer to V_2, rectification of the voltage is done by using CMOS rectifier instead of normal rectifier in order to reduce further losses. Lastly inductor L and the capacitor C_{link} are used to reduce the current and voltage ripple then in order to filter the ripple in current & voltage being fed to the battery.

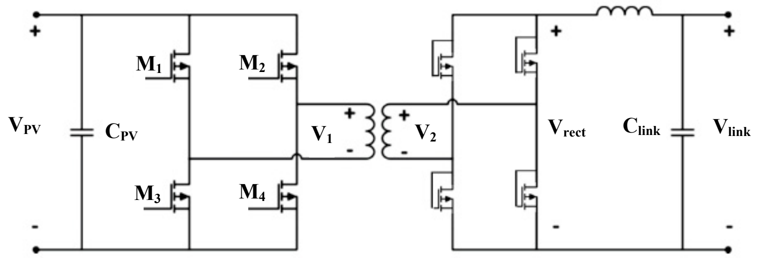

Fig. 7 (a) DC - DC Full Bridge Power Converter Circuit.

The modified P&O MPPT method will correct the MPPT control signal during rapid change in solar insolation. Both methods works properly during steady state but when the PV module is subjected to rapid excursions in irradiance,

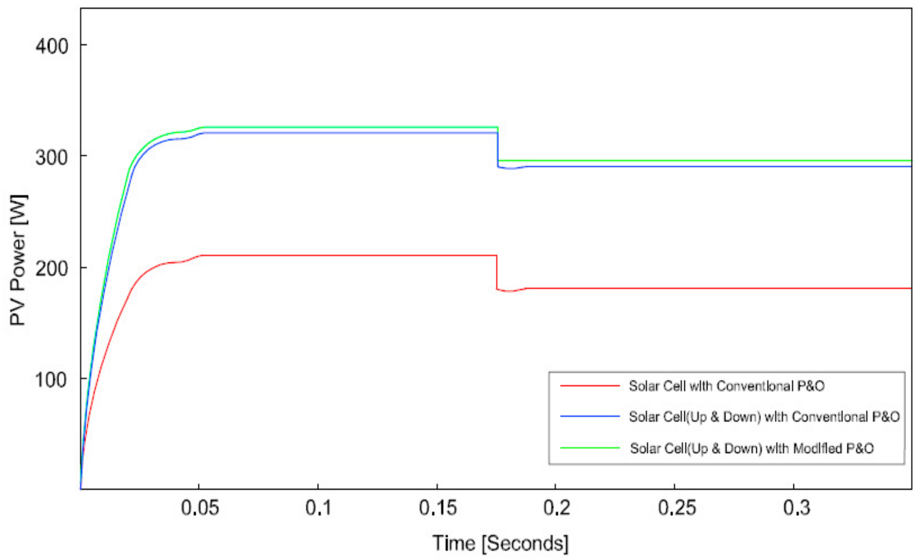

Fig. 7 (b) Comparison between Conventional & Modified P&O MPPT then the recovery time of the modified P&O MPPT algorithm is lower than the Conventional P&O MPPT algorithm. The efficiency of the panel can be calculated using Equation 3.

$$\eta = \frac{\int_0^T p(t)dt}{A_C \int_0^T G(t)dt} \qquad (3)$$

Where p (t) is the power output of the panel, A_C is the area of the panel and G (t) is the solar irradiance.
The modified P&O MPPT will enhance the panel efficiency by 5.06% in contrast to classical P&O MPPT method, as shown in Fig. 7 (b) [4, 17].

6. Conclusions

Sl. no.	Solar cell Technology	Efficiency (%)
1	Solar cell with Conventional P&O MPPT Technique	21.37
2	Solar cell with Up & Down Conversion + Conventional P&O MPPT Technique	33.9
3	Solar cell with Up & Down Conversion + Modified P &O MPPT Technique	35.66

A scheme to improve the efficiency of the Solar cells has been described, which will boost the efficiency of solar cells by more than 50 % of conventional P&O MPPT Technique (i.e. net efficiency = solar cell efficiency x MPPT efficiency). The ideal Up & Down Conversion can boost the solar cells efficiency up to 48 %. So there is a huge scope to further boost the efficiency of Solar cell.

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