

On-line Global Maximum Power Point (GMPP) Identification of Solar PV Plants

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Abstract— This paper introduces an algorithm to identify the global maximum power point (GMPP) of a solar Photovoltaic (PV) plant while operating under the partial shade condition (PSC) or fault condition (FC). Conventionally a complete current vs. voltage (or I-V) curve of the faulty PV array is swept to identify the GMPP. However, this paper proposes that a part or ‘region of interest’ of the I-V curve would be sufficient to identify the GMPP, and there is no need to sweep complete I-V curve. For verification purposes, real-time experimental tests were conducted.

Keywords—solar Photovoltaic plant, maximum power point, GMPP, partial shade, online.

I. INTRODUCTION

Solar Photovoltaic (PV) plants installed in an urban locality often operate under partial shade condition (PSC) or fault condition (FC) [1]-[8] due to the shade of neighboring PV modules, or buildings, or other structures. In PSC, some of the PV modules receive less solar irradiance compared to the others. Consider a PV plant schematic shown in Fig. 1(a). A total of 16 modules have been connected in 4-by-4 Total-cross-tied (TCT) architecture (Note that, conventional PV systems employ series-parallel (SP) array architecture [1]-[8]). Under normal irradiance conditions, the scheme results in the single-peak I-V curve shown in the blue colored dotted line of Fig. 1(b) and the MPPT converter attached to the PV array starts tracking the maximum power point (MPP) and produces maximum power.

Under PSC or FC, the PV array may exhibit multi-peak current vs. voltage (I-V) curve characteristics similar to one as shown in the red colored dotted line of Fig. 1(b) [3]. The highest power peak is called global maximum power point (GMPP), and each of the remaining peaks is called local maximum power point (LMPP). Under these conditions, the MPPT converter may slip to track an LMPP as shown in Fig. 1(b). This has led to several novel research techniques to improve the power output by identifying and tracking the GMPP [2]-[8].

The techniques reported in [2]-[6] are mainly dependent and based on the I-V curve. However, as per the beta algorithm [2], and the modified beta algorithm [3], the PV array will be perturbed at 60-70% of the per module open-circuit voltage V_{mdloc} to sweep the I-V curve and, then the

algorithms will be applied. It is based on a premise that each perturbed sample will have a single peak. However, this approach may not yield results particularly in the case of the PV array with each module having more than one by-pass diode because each PV module may exhibit multiple peaks when different sections within a PV module start experiencing different quantities of shade. The GMPP algorithms reported in [7] [8] are not dependent on I-V curves and utilize either camera images [7] or thermal images of the PV array [8] to detect the PSC and identify GMPP. The I-V curve based GMPPT techniques reported in the literature commonly suffer from some of the following drawbacks:

1. They often sweep the PV array I-V curve regularly [2] [3] to detect PSC and to identify GMPP. The loss of PV energy for sweeping the array regularly can be mitigated by first identifying PSC and performing I-V curve sweeping only when needed [4].
2. Global search based algorithms generally need full I-V curve data. However, sweeping full I-V curve requires increased time and operational loss. Further, fast-changing irradiance conditions may worsen the situation by producing inconsistent I-V curves. To reduce the time in global sweeping and searching, it is possible to perturb the array at a fixed voltage-window [2] [3].
3. Windows-based search techniques choose a fraction of module voltage (V_{mdloc}) as the width of the window. However, this approach may fail in case of the PV modules having more than one by-pass diode for the reasons explained previously.
4. More importantly, some conventional converters (buck, boost) cannot sweep full I-V curve [9] as needed by the global search algorithms. Hence, the special design of a number of SEPIC converters may be needed to sweep full I-V curve [9]. This may increase the cost of investment.

Overcoming some of the above drawbacks, this paper proposes an approach to identify and track the GMPP. The main contributions of this paper are summarized as below:

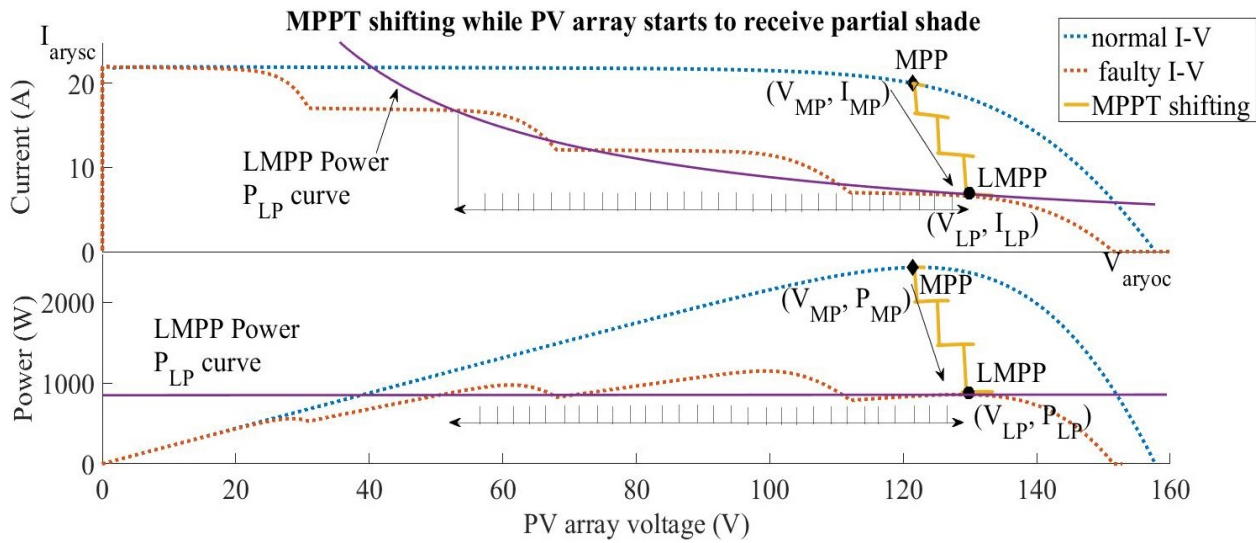
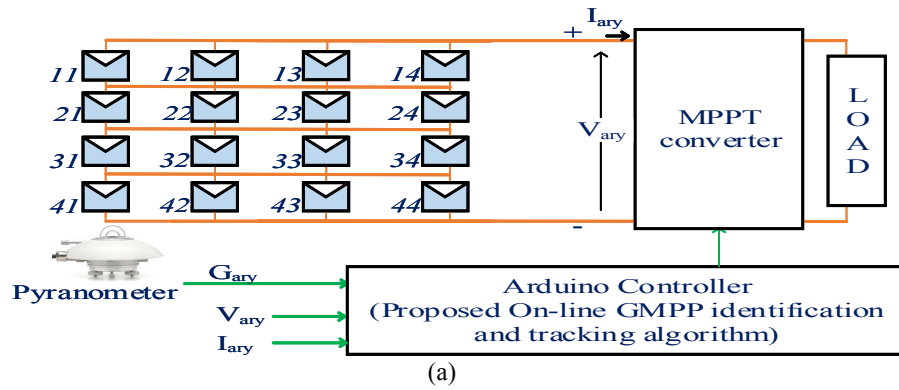


Fig. 1: (a) Total-cross-tied (TCT) PV plant schematic, and (b) normal and faulty I-V curves. According to the proposed approach, GMPP lies in the region above P_{LP} (LMPP) power. Hence, the part above LMPP is sufficient and only will be swept.

1. According to the proposed approach, full I-V curve data and sweeping are not needed. Conventional techniques often need sampled or full I-V curve over the whole range of voltage shown in red color dotted line of Fig. 1(b) to reach GMPP. However, the proposed technique needs a smaller portion of the I-V curve spanned over a limited voltage range (shown using double-ended arrows in Fig. 1(b)).
2. Not requiring full I-V data and sweeping may save processing time and operational loss. Also, this approach may be applicable to fast-changing irradiance conditions.
3. For sweeping a region of I-V curve or 'region of interest', conventional converters (buck, boost) can be used for this purpose. Proposed approach reuses the MPPT converter to sweep the I-V curve of the faulty PV array and therefore only software changes are needed to existing MPPT hardware.
4. This paper assumes TCT type array architecture, which is an emerging research field in PV array reconfiguration [10]-[12]. But, there has been a limited analysis of GMPP identification of TCT array until this paper. However, the proposed technique can also be adopted into SP architecture.

The remainder part of the paper is presented in the following order: stair-case analogy behind the I-V curves is presented in Section-II, the process of identifying the GMPP region of interest and illustration of the proposed algorithm is presented in Section-III, experimental tests and results in discussion in Section-IV and conclusions are in Section-V.

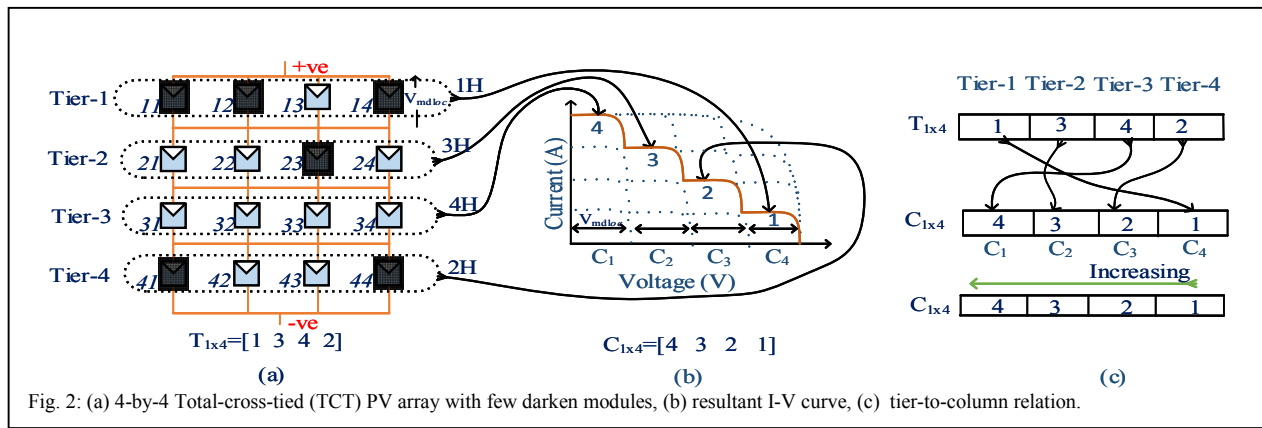


Fig. 2: (a) 4-by-4 Total-cross-tied (TCT) PV array with few darkened modules, (b) resultant I-V curve, (c) tier-to-column relation.

II. ASCENDING STAIR CASE ANALOGY OF I-V CURVES

Irrespective of the size of PV array, the number of modules shaded or faulty, or type of PV array architecture (TCT or SP) employed, a faulty I-V curve resembles the shape of ‘ascending staircase’. The proposed GMPP identification approach is based on this staircase shape of I-V curves. Consider an example 4-by-4 size total cross tied (TCT) type PV array as shown in Fig. 2(a). All 16 modules are identical in nature and each one is connected with one by-pass diode. Note that, the number of by-pass diodes connected per module does not affect the performance of proposed approach.

For understanding purposes, assume few modules belonging to different tiers (rows) were dark shaded or receive 0 W/m^2 solar irradiance. Based on the number of healthy modules present in each tier, construct a row matrix $T_{1 \times 4} = [\text{Tier-1 Tier-2 Tier-3 Tier-4}]$ with each element representing the number of healthy modules in each tier. In Fig. 2(a), $T_{1 \times 4} = [1 \ 3 \ 4 \ 2]$.

The resultant I-V curve of the example faulty PV array is shown in Fig. 2(b). Note that, each block below the I-V curve represents a healthy module of the faulty PV array. For understanding purposes, the x-axis is divided into four columns each labeled as $C_1, C_2, C_3,$ and C_4 . Construct a row matrix $C_{1 \times 4} = [C_1 \ C_2 \ C_3 \ C_4]$ with each element representing the number of blocks present in the respective column. Example, the first column has four blocks $C_1=4$. In above case, $C_{1 \times 4} = [4 \ 3 \ 2 \ 1]$. Further, each column has one-peak.

The inherent nature of the I-V curves is such that a tier with the highest number of healthy modules contributes to the first column and the least number of healthy modules to the last column of the I-V curve. For understanding purpose, tiers in Fig. 2(a) and corresponding columns in Fig. 2(b) are connected using free arrows. A simplified version of it is presented in Fig. 2(c). Above illustrated ‘ascending staircase’ phenomenon applies to SP array architecture as presented in [13] with string voltage along x-axis and number of strings along the y-axis.

III. GMPP REGION IDENTIFICATION AND ILLUSTRATION OF PROPOSED ALGORITHM

A. Constant- power curves

Assume a faulty I-V curve of an m-by-n size TCT array consisting of multiple peaks, as shown in the orange colored solid line of Fig. 3(a). In which, some of the columns have more than two peaks. Further, each point on the I-V curve represents different amounts of power supplied by the PV array. Assume, under PSC or FC, the MPPT converter slips to a point labeled A (V_A, I_A). The power at this point is $P_A = V_A * I_A$. A constant power curve, termed ‘ P_{LP} ’ can now be drawn as $P_{LP} = P_A = V_A * I_A$ on the same plot. This curve will contain the power point P_A . In Fig. 3(a), the P_{LP} curve also intersects the I-V curve at another point labeled B.

B. Region of interest for GMPP

The region of interest is the part of the I-V curve in which the GMPP may lie. During any shade condition, the complete shape, or extreme points of I-V curve (open-circuit voltage V_{aryoc} , short-circuit current I_{arysc}) are unknown. Yet, logically, the GMPP will have greater power than P_{LP} . In case of Fig. 3(a), the region of interest or part of the I-V curve where greater than P_{LP} power lies is shown using up-arrows in Fig. 4. Interestingly, the region is spanned over the length of few columns. Hence, sweeping the voltage range spanned by these columns would be sufficient to know the GMPP. In simple words, the actual voltage range of I-V curve to be swept is between the points ‘A-B’. However, the voltage at point B cannot be known, and it varies as the shape of I-V curve changes. Instead, it is proposed to sweep the region spanned between ‘A-C’, where C is a point on the normal I-V curve. The (V_{low}, V_{LP}) are voltage limits of ‘region of interest’ and the V_{low} is voltage at point C or lowest voltage of the ‘region of interest’ that can be calculated as

$$V_{low} = P_{LP} / I_{arysc_theo} \quad (1)$$

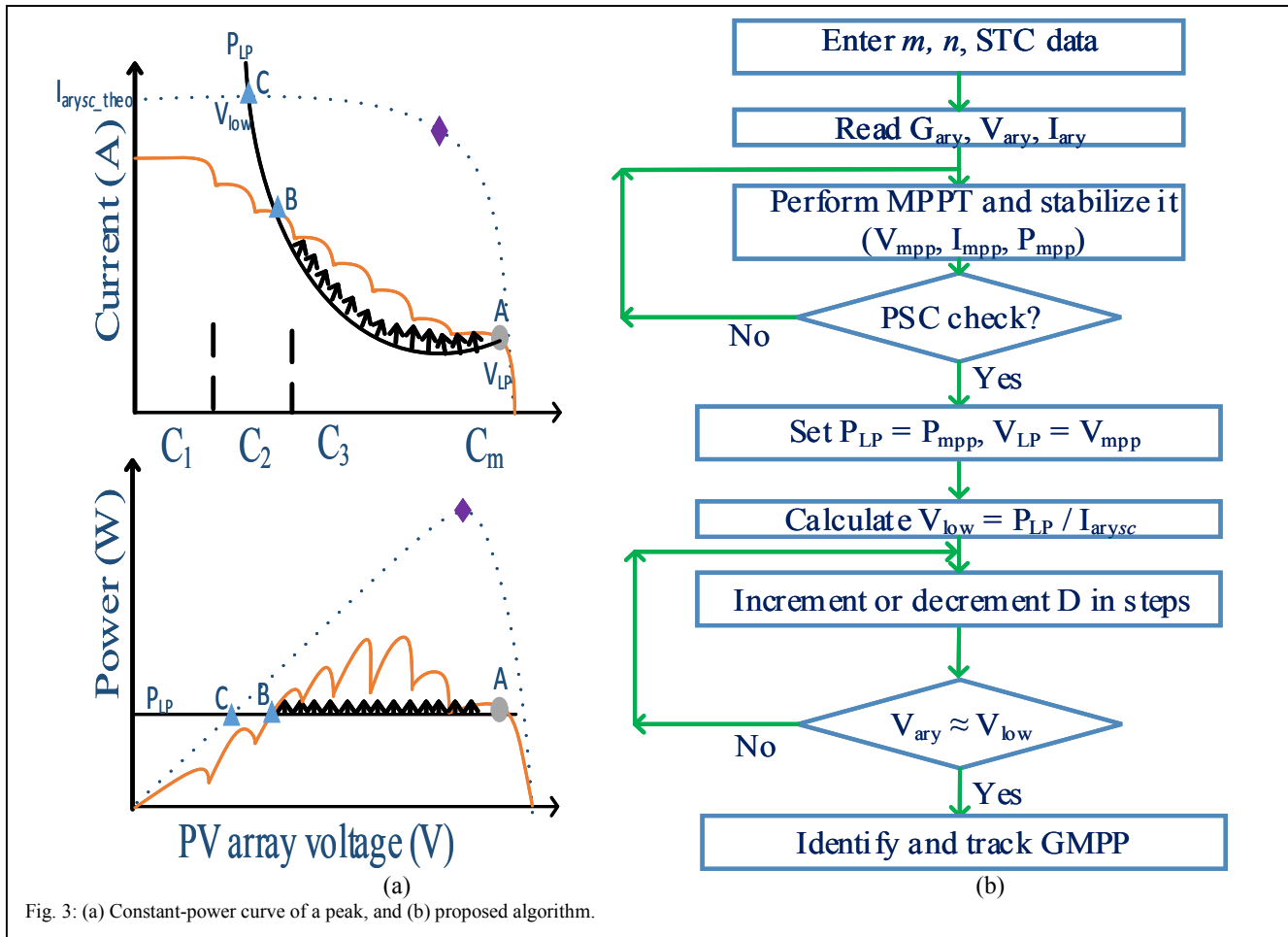


Fig. 3: (a) Constant-power curve of a peak, and (b) proposed algorithm.

where I_{arysc_theo} is theoretical short-circuit current of the PV array. It can be calculated from standard test conditions (STC) data and measured solar irradiance G_{ary} as

$$I_{arysc_theo} = I_{STCsc} \times G_{ary} [1 + \beta (T - 25)] / 1000 \quad (2)$$

where I_{STCsc} is STC short-circuit current of the PV array, β is temperature coefficient of current, T is the actual operating temperature of the PV array. In absence of temperature

measurement, T may be set to 25°C.

C. Illustration of proposed algorithm

Flowchart of the proposed algorithm is shown in Fig. 3(b). Its working is illustrated for the fault condition discussed in Fig. 2(a). Initially, the MPPT converter is allowed to track and stabilize the MPP. Let the MPP be V_{MP}, I_{MP} , and P_{MP} . Then, PSC detection check is performed,

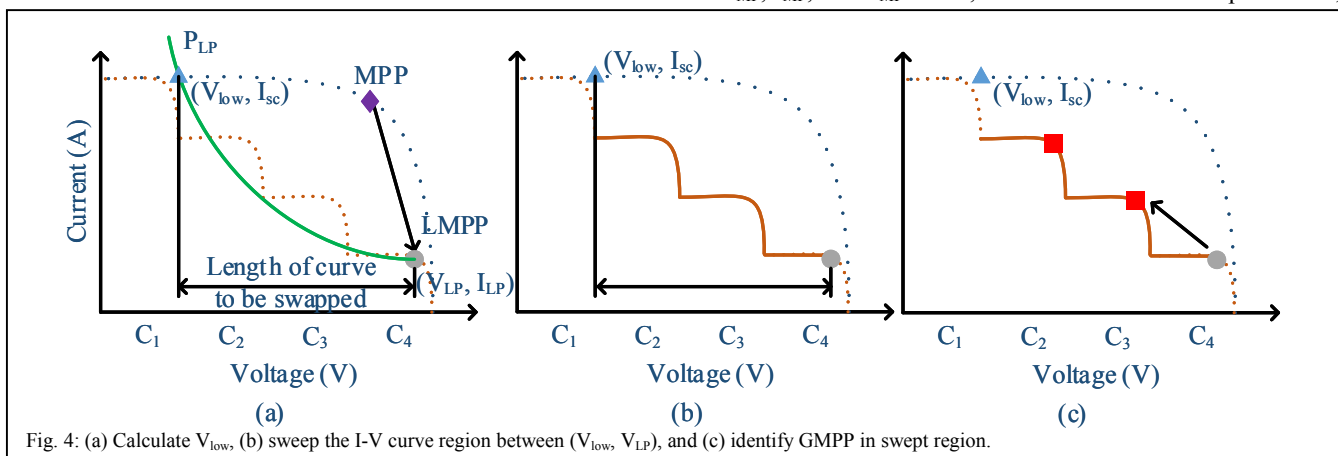


Fig. 4: (a) Calculate V_{low} , (b) sweep the I-V curve region between (V_{low}, V_{LP}) , and (c) identify GMPP in swept region.

such as in [4] [6]. If it is found to be shaded, the MPPT converter may be tracking an LMPP as shown in Fig. 4(a). Set $V_{LP}=V_{MP}$, $P_{LP}=P_{MP}$. Note that, as shown in Fig. 3(a), the MPPT converter is presently operating the array at V_{LP} . From (1), calculate the ‘region of interest’ voltages (V_{low} , V_{LP}). Now, sweep the region (V_{low} , V_{LP}) of I-V curve by altering the duty cycle (D) in steps. The D is increased if it were a buck-converter, or decreased if it were a boost-converter. The MPPT converter reduces the operating voltage V_{ary} and stops perturbations of D when $V_{ary} \approx V_{low}$. In case of the example, the obtained I-V curve region is shown in Fig. 4(b). Then a search of the swept data is performed and the point with maximum power is located. Designate this point as GMPP and start tracking it [9].

D. Advantages in sweeping a part of I-V curve

This approach reduces the conventional processing time taken by the GMPP methods that depend on full range voltage data and sweeping [2]-[8]. Adding to this, it is not needed to sweep extreme points (V_{aryoc} , I_{arysc}) in the region left side of V_{low} and right side of V_{LP} . The conventional converters might not be able to sweep extreme points. Moreover, the higher the P_{LP} power the smaller the sweeping range (V_{low} , V_{LP}).

IV. EXPERIMENTAL TESTS AND RESULTS DISCUSSION

A. Test setup description

The test schematic is shown in Fig. 1(a) and the photograph of the setup is shown in 4(a). A total of eight PV modules were connected in 4-by-2 TCT architecture. Standard test condition (STC) ratings of each PV module: $V_{mpp} \approx 9V$, $I_{mpp} \approx 0.34A$, $P_{mpp} \approx 3W$ and a by-pass diode were connected to it. A buck-converter was employed for MPPT purposes. For measurement of normal solar irradiance G_{ary} , a low-cost sensor was used [14]. A voltage divider was used to sense

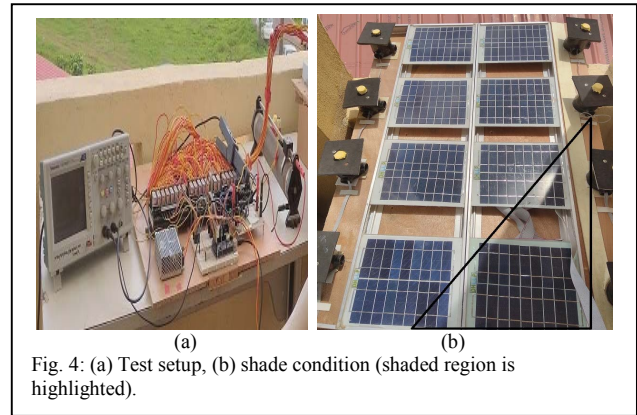


Fig. 4: (a) Test setup, (b) shade condition (shaded region is highlighted).
the array voltage V_{ary} , and ACS712 IC to sense the array current I_{ary} . A fixed resistive load ($R=10\Omega$) was connected across output terminals of the converter. For control purposes, Arduino ATMEGA 2560 micro-controller was used. A desktop computer was connected to the controller to store the data. For recording purposes, a digital storage oscilloscope, voltage and current (scaling factor: 100mv/A) measuring probes were used.

B. Results discussion

The shade condition under which the test was conducted is shown in Fig. 4(b). The recorded response of the test is shown in Fig. 5. The $0 < t < T_1$ is the response of MPPT converter operating under PSC with very low power. It may be operating at a LMPP and the voltage $V_{LP}=37.6V$, current $I_{LP}=0.06A$. From (1), the controller had calculated $V_{low}=18.5V$. The voltage limits of ‘region of interest’ are (18.5V, 37.6V). Now, the controller starts increasing the duty cycle (D) to sweep the ‘region of interest’. The $T_1 < t < T_2$ is when the ‘region of interest’ swept by the converter, and the notches indicate the by-passing of modules belonging to different tiers. Immediately, the

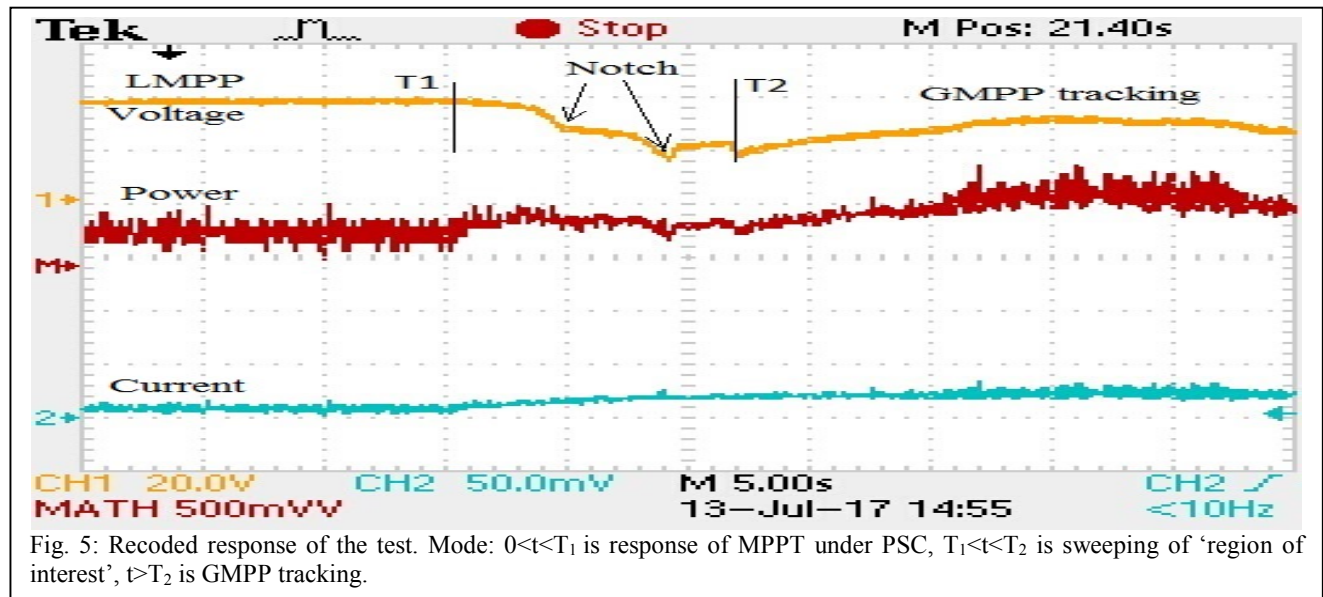


Fig. 5: Recorded response of the test. Mode: $0 < t < T_1$ is response of MPPT under PSC, $T_1 < t < T_2$ is sweeping of ‘region of interest’, $t > T_2$ is GMPP tracking.

controller starts performing the scan to identify the GMPP (V_{GP} , I_{GP}) and sets the converter duty cycle [9] to operate the PV at correct GMPP. The $t > T_2$ is the response of the converter to track correct GMPP. The voltage was $V_{GP}=28.8V$, $I_{GP}=0.28A$. The percentage improvement in array output power after tracking GMPP was 258%. In this test, a total of 200 samples of I-V curve (18.5V, 37.6V) were collected. Further, a 30 ms delay between two samples was maintained to stabilize the parameters and allow the Arduino controller to record the data. It had resulted in a total processing time of about 9s prior to tracking GMPP. Using high-frequency digital processors, the processing time can be further reduced.

V. CONCLUSIONS AND FUTURE WORK

This paper proposes a new global maximum power point (GMPP) identification technique to improve the performance of partially shaded or faulty PV array. For verification, real-time experimental tests were conducted and the results have upheld the proposed technique of GMPP identification by yielding greater output power. For GMPP identification purposes, the proposed algorithm had swept a limited region of current vs. voltage (or I-V) curve called 'region of interest'. It had resulted in less processing time by not sweeping full I-V curve. Moreover, the MPPT converter was re-used to perform the sweeping test. In this paper, TCT array architecture was considered and the proposed method may be applied to SP architecture without any changes. In case of fast-changing irradiance conditions, I-V curve sweeping produces erroneous data. The remedy may be to perform the sweeping test in less time. Hence, further reduction of processing time would be a future research work.

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