A Modified Maximum Power Point Tracking Technique For Grid-Connected Cascaded H-bridge Photovoltaic Inverter Under Partial-Shading Conditions

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Abstract - *To extract maximum power from PV arrays at all time, it is crucial to employ maximum power point tracking (MPPT) controls. However, conventional MPPT controllers fail to track maximum power point during partial shaded conditions. A novel maximum power point tracking technique for grid-connected Cascaded H-Bridge (CHB) inverters is developed in this paper. Under proposed technique, dc-link voltage of each cell can be controlled independently, enabling the maximum power point tracking of each PV array in different insolation conditions. Based on the mathematical analysis, an analytic constraint is imposed on the H-bride cells' modulation index to guarantee the stable operation of the PV system. The proposed method, moves the operating point of shaded and unshaded PV arrays such that the total harmonic distortion (THD) of the injected current into the grid, remains below 5% and prevents instability issues. To evaluate the effectiveness of the proposed method, multiple case studies in the MATLAB/SIMULINK environment are carried. To verify the simulation results, experimental results are also presented*

Key Words: MPPT, cascaded H-bridge, grid connected inverter, multilevel inverter, photovoltaic system

1.INTRODUCTION

Due to the increasing demand of energy consumption and the shortage of fossil fuels and need for non-polluting energy infrastructure, many research and investments have been made on clean energy conversions and energy sources mainly including electrified transportation and renewable energy sources [1,22]. Among these, the solar energy is freely available and photovoltaic (PV) system can minimize total costs and energy losses of the system if they are optimally placed [2]. The electric energy then can be injected into the grid by the PV inverters. The conventional inverters process the electric power in two stages [22], where the first stage is a DC/DC converter which steps up the DC voltage and the second stage is the conventional inverter which is known as Voltage Sourced Converter (VSC) and its control strategy is discussed in [3]. The control strategy in this structure is simple, but it suffers from low efficiency.

Recently multilevel converters have become popular in renewable energy applications due to their higher reliability, efficiency, and near sinusoidal output voltage, and especially have been utilized in PV system [4, 25]. The current with low total harmonic distortion (THD) can be injected to grid through these inverters. Due to transferring power in just one stage, its efficiency is higher than the two stage topologies and they can inject current into the grid with low total harmonic distortion (THD) which makes connecting PV cells to grid without large filter possible. Among different proposed topologies for grid connected system, cascaded H-bridge (CHB) inverters have attracted lots of interest due to its modularity, simple structure and providing individual dc-link for each PV [5]. Controlling the CHB inverters under symmetrical condition when each H- bridge transfer same power is simple. However, solar arrays may have different characteristics and aging of the solar array or partial shading could change the maximum available power of each arrays. Therefore, some control methods should be designed to let maximum power point tracking (MPPT) continue under these asymmetrical conditions. Considering this fact that in this system, n + 1 variables (n DC voltage and 1 injected current into the grid) are controlled through n control decisions (n switching function of the inverters), the controller suffers from intrinsic instability which limited the stable operation range of the CHBs [6, 7].

Recent studies lead to different control methods for grid connected CHB-based PV systems includes current controlling and MPPT [5, 6, 8–12]. In [11] a fuzzy logic based controller is proposed that could control the CHBs without any internal controller. Despite the simplicity, this controller could not eliminate the currents harmonics and does not evaluate the stability issues under unbalance condition. In [12], classic control strategies are used for CHBs. In [18], the PI controller which is followed by SVM is applied at the inverter stage. These controlling methods under symmetrical condition are effective but under unbalance condition, as mentioned, are intrinsically unstable. In [19], a robust MPC controller is employed to provide a robust and optimal control in noisy condition. In [6] input power factor of converter is used as a degree of freedom to make the system stable. Although good performance under symmetrical and asymmetrical condition but the proposed method is based on complex mathematics equation and the implementation of this method is very complex and difficult.

Adding battery as a controlling reserve is also discussed as a solution in literature [13]. High price of battery is its major drawback that make the final price of using solar energy economically high. Although, load coordination approaches and demand respond (DR) strategies are suggested as an alternative to grid size batteries which bring flexibility to the system operator [14–17], tuning them with single stage CHB inverters are challenging and complicated. Also, there are some efforts to update the reliability of the power injection into the grid under uncertain renewable resources [27]. In [26] a novel topology with over 50% reduction in number of components for modular multilevel inverter is proposed, however, stability margin and possibility of operating under unbalance condition are not be evaluated on these methods.

In this paper, based on mathematical and circuit analysis, a new method for controlling the CHB-based PV systems is proposed. In this method, the modulation index of each CHB is used as controlling parameter to ensure the system stability all the time. Performance of the proposed method has been verified by the simulation and experimental results.

2. TOPOLOGY DESCRIPTION

Structure of a single phase seven-levels grid connected PV systems through a filter inductor is shown in figure 1. This structure includes three cascaded H-bridge. Each cell (H- bridge) contains four power switches, four anti-parallel diodes and one dc bus capacitor which connected to PV arrays. Some different switching methods for CHBs are proposed in [24]. Among these methods, in this paper we implement Phase Shifted PWM (PSPWM) as it is easy to implement and distribute transferred power equally between power switches. However, the proposed method is valid for any other switching scheme.

Behavior of a CHB inverter can be modeled based on the relationship between its current, DC voltages and modulating waveforms. Based on Fig 1 and considering steady state operation, modulation wave form for each cell is defined in (1)

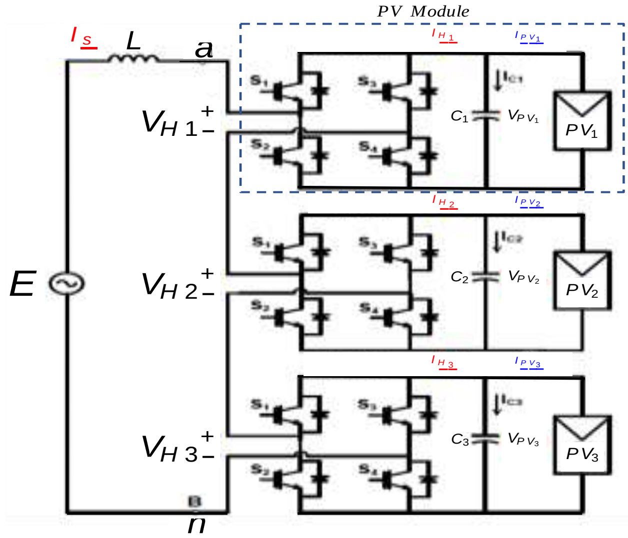


Figure1: Grid connected 7-level CHB PV converter

$$S_j = \frac{V_{Hj}^1}{V_{PV_j}} \tag{1}$$

where V_{PVj} and V_{Hj}^1 represent DC side voltage of cell number j and the fundamental harmonic of voltage of the AC side. Under assumption of linear operation of the inverter, Sj is sinusoidal and limited to [−1, 1]. In this paper, we define the criteria of the instability as follow

$$|S_j| \leq 1 \tag{2}$$

By considering circuit analysis, (1) gives dynamic of the

injected current and voltage of the dc bus capacitor as follow

$$\frac{dI_s}{dt} = \frac{1}{L}(E - RI_s - \sum_{j=1}^{3} S_j V_{PV_j}) \tag{3}$$

$$\frac{dV_{dc}^j}{dt} = \frac{1}{C_j}(I_{PV_j} - S_j I_s) \tag{4}$$

where I_s, E, C, R and L represent the injected current into the grid, voltage of the grid, DC bus capacitor of the j^{th} cell, resistance and inductance of the path. however, it should be mentioned that if non-linear operation of the inverter is tolerable, the modulation index can increase to (4/pi) and yet has the stable operation region of inverter. By calculating the mean of (4) we can show

$$I_{PV_j} = \frac{1}{2}|S_j||I_s|cos\delta \tag{5}$$

where δ is phase angle difference of injected current and fundamental harmonics of the j^{th} cell voltage and $|I_s|$ is magnitude of the injected current. By assuming δ ≈ 0, (5) can be shown as

$$I_{PV_j} = \frac{1}{2}|S_j||I_s| \tag{6}$$

By considering (2) and (6), we can show

$$|S_j| = \frac{2I_{PV_j}}{|I_s|} \leq 1 \quad \forall\ j \in \{1,2,3\} \tag{7}$$

Under assumption of negligible switching and ohmic losses, injected power to the grid should be equated the derived power from the PV arrays

$$P = \sum_{j=1}^{3} I_{PV_j} V_{PV_j} = \frac{1}{2}|E||I_s| \tag{8}$$

By combining (7) and (8), stability condition is reached as a function of the grid voltage and PV array voltage and current output

$$|S_j| = \frac{I_{PV_j}E}{I_{PV_1}V_{PV_1} + I_{PV_2}V_{PV_2} + I_{PV_3}V_{PV_3}} \leq 1 \quad \forall\ j \in \{1,2,3\} \tag{9}$$

Based on (9), reduction in extracted power from one PV (e.g. in case of partial shading) leads to increasing of the modulation index of the other converters. On the other words, significant reduction in extracted power of on PV can push modulation index of other VPPs to exceed 1 which makes the system unstable.

The proposed controller consists of three parts including voltage controller, current controller and modulation index controller. Overview of the voltage controller is shown in fig 2.

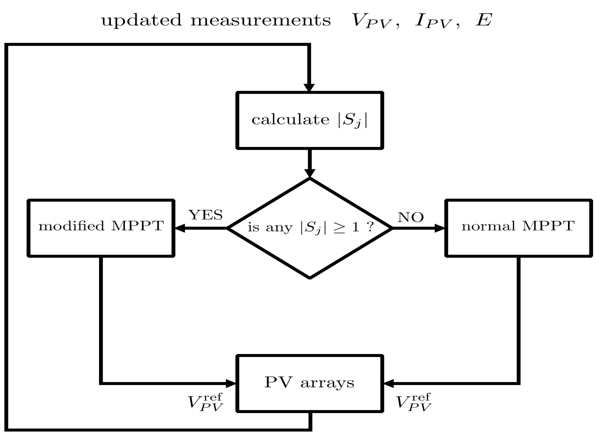


Figure2: Overview of the voltage controller

Based on measurement of the grid and PV arrays, modulation index of the CHBs are calculated as shown in (9) and if all the modulation indexes are within their limits, normal MPPT continues providing voltage set points of the PVs. However, if any modulation index exceeds the stability limits, the voltage set points of the VPPS will be decided by the modified MPPT.

To calculate the injected current set-points, the grid voltage phase angle, θ, is extracted by phase locked loop (PLL) and sin(θ) is multiplied by the output of the PI controller which is tracking the total voltage set-points of the PVs computed by the voltage controller. The difference of the inverter current, I_s and its desired set-point, is called current error. In this paper proportional resonant controller (PR Controller) [23], is used to control the inverter current fundamental harmonic distortion and elimination of 3rd and 5th harmonics. The PR controller defines the AC voltage reference for the CHB AC side, as shown in fig 3. Active power transferring component of each cell is determined based on the their three utilization coefficients M_1, M_3 and M_3. While M_1 and M_2 are produced based on the dc voltage error of the corresponding cell as shown in fig 4. The third utilization factor is chosen to be constant (i.e. $M_3 = 1$).

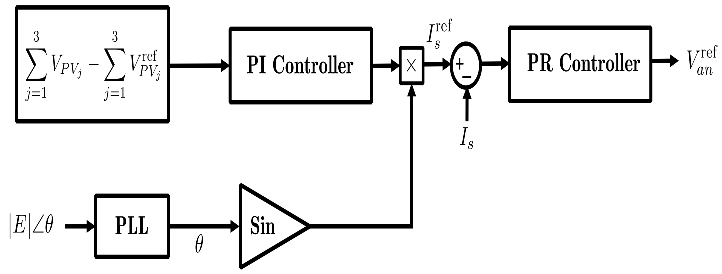


Figure3: Overview of the current controller

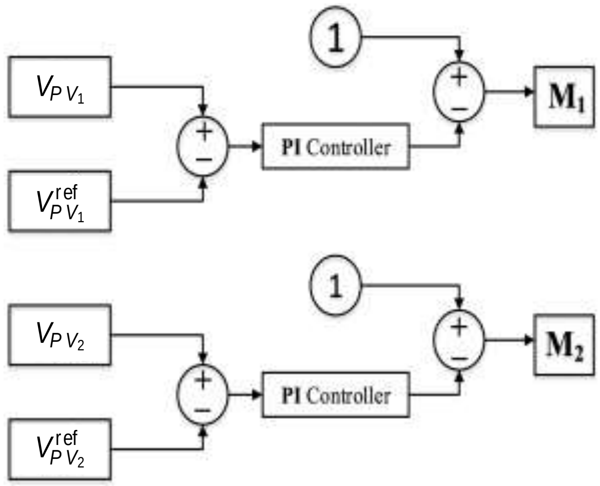


Figure4: Utilization coefficients controller

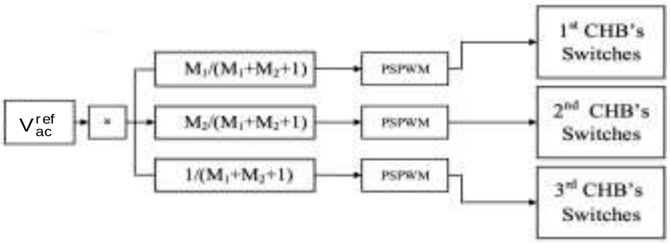


Figure5: Modulation waveform controller

Before Since current controller decides the total DC voltage and voltage of cell 1 and 2 are controlled by utilization coefficients, voltage of cell 3 can also be calculated (see fig 5). Therefor is no need of PI controller for regulating the third cell's dc voltage. Also, modulation index and utilization coefficients of the cells are related to each other as follow

$$|S_1| = \frac{M_1}{M_1 + M_2 + 1} \tag{10}$$

$$|S_2| = \frac{M_2}{M_1 + M_2 + 1} \tag{11}$$

$$|S_3| = \frac{1}{M_1 + M_2 + 1} \tag{12}$$

Under asymmetrical condition, in case of exceeding of any modulation index from 1, to bring back the system to stable region, the voltage controller shall increase voltage reference of cell by constant step until the modulation index magnitude comes back below 1. By this method, the system remains stable and there is no need to isolate the converters from the grid.

2. Simulation results

The effectiveness of proposed control method for single stage grid-connected CHB converters have been evaluated in MATLAB/SIMULINK. Parameters of the under evaluation system are shown in Table-1 and parameters of the solar panel are shown in Table-2 Simulation of PV module is done based on [20] and the MPPT method is Perturb and Observe which is done based on [21].

Table -1: Parameters of the under-evaluation system

Parameter	Symbol	Value
Grid Voltage	E_{max}	120 V
Grid frequency	f	50 Hz
DC link capacitor	C_{dc}	1 mF
Inductor filter	L	1mH
Switching frequency	f_{sw}	1 kHz
Number of series module (per array)	N_s	3
Number of parallel module (per array)	N_p	1
Maximum injected power to the grid	P_{tot}	360 W

Table -2: Parameters of the solar panel

Parameter	Symbol	Value
Open circuit voltage	V_{OC}	20.58 V
Short circuit current	I_{SC}	2.98 A
Maximum power	P_{max}	40 W
MPP voltage	V_{mpp}	16.3 V
MPP current	I_{mpp}	2.45 A
Photonic current	I_{pho}	2.98 A
Diode saturation current	I_{SO}	0.23 nA
Diode idealization index	η	1.136
Series resistance	R_s	0.503 Ω
Parallel resistance	R_p	726 Ω

To evaluate the effectiveness of proposed method under asymmetrical condition, the temperature of all PV modules set at T = 25°C and while solar irradiance of the first and second cells are set at G = 1000W/m^2, solar irradiance of the third cell is set at the G = 450W W/m^2. Initially normal MPPT has been used and at t = 0.8 sec, the control method is changed from normal MPPT to the modified MPPT. The injected current to the grid under normal and modified MPPT are shown in fig 6 and fig 7 respectively. Based on IEEE-519 injected current THD shall be less than 5% while under normal MPPT injected current THD is 38% and the PV array should be isolated from the network immediately. However, by utilizing modified MPPT, injected current THD decreases to 2.9% which satisfies the standard.

To better understand the proposed method, AC-side voltage of the 7-levels CHB inverters, under normal and modified MPPT are illustrated in fig 8 and fig 9. By

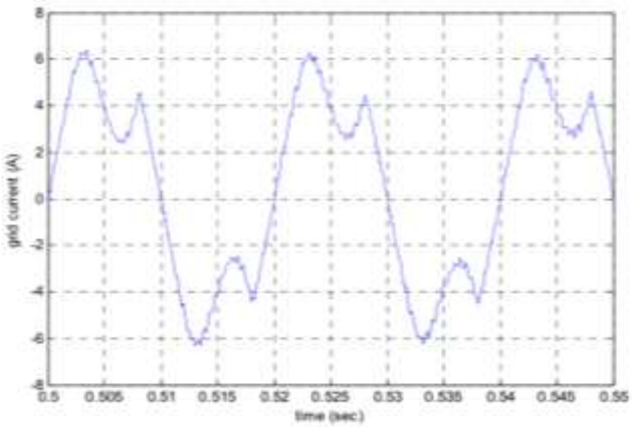


Figure6: Injected current to the grid under normal MPPT during asymmetrical condition

comparing the AC- side voltage of the 7-levels CHB inverter, it can be seen that during asymmetrical condition, normal MPPT fails to provide seven levels of voltage on AC-side voltage which leads to poor quality injected current (i.e high THD).

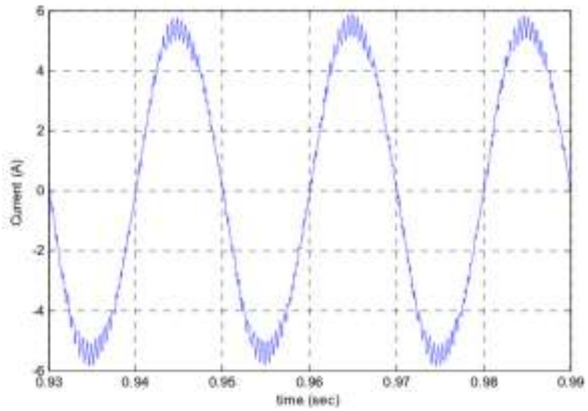


Figure7: Injected current to the grid under modified MPPT during asymmetrical condition

However, modified MPPT overcomes this issue and current with low THD can be injected to the grid such that there is no need to large, expensive filter and subsequently, with lower cost, system perform more efficiently.

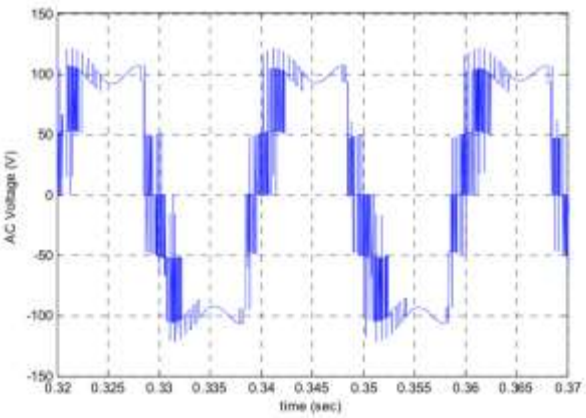


Figure8: AC-side voltage of 7-levels CHB inverter under normal MPPT during asymmetrical condition

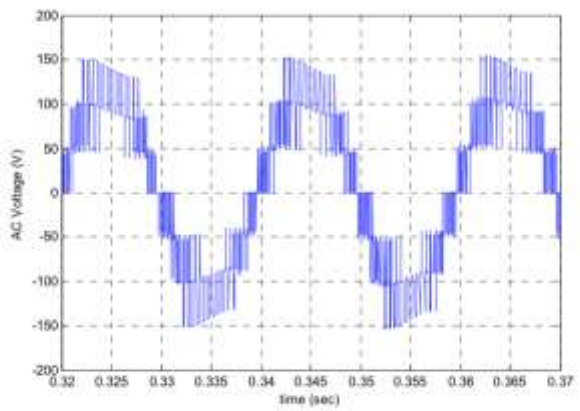


Figure9: AC-side voltage of 7-levels CHB inverter under modified MPPT during asymmetrical condition

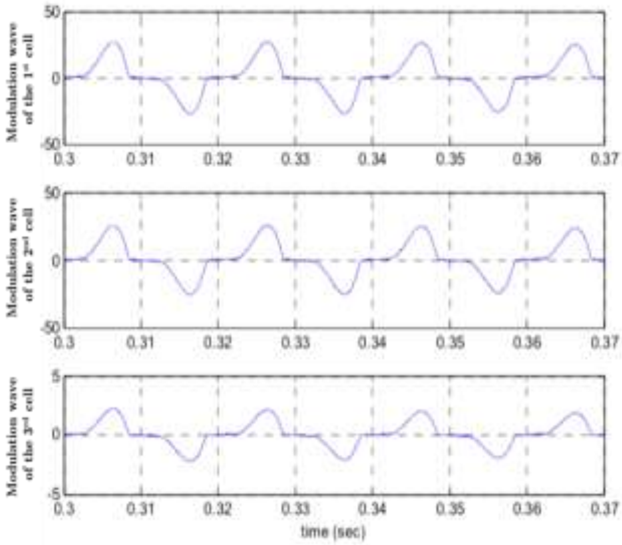


Figure10: Modulation wave of the three cells under normal MPPT during asymmetrical condition

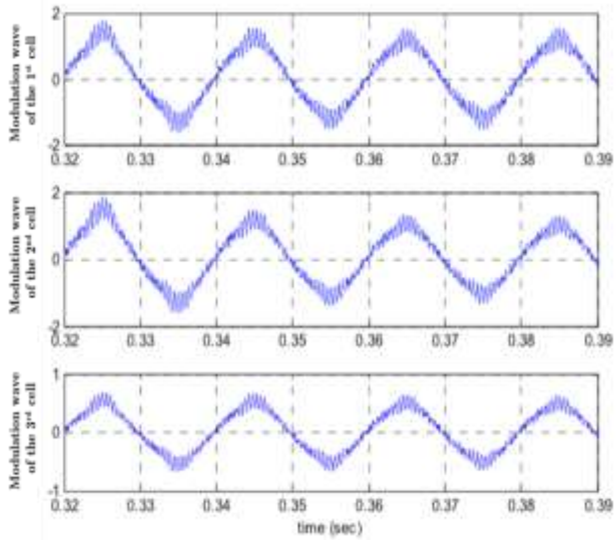


Figure11: Modulation wave of the three cells under modified MPPT during asymmetrical condition

As shown in fig 10, under asymmetrical condition, modulation index of the cells exceed 1 by 50 times which leads to poor quality of injected current and isolation of the PV system. However, as shown in fig 11, by manipulating operating points of cells, modulation indexes are limited to 1 after a few cycles (see the last cycle of the modulation index) which allows providing 7 levels of voltage at the AC-side of the inverter. Also, it is evident that as modulation indexes come back within the desired limit (i.e $|S| \leq 1$), quality of multi-level voltage at AC-side of the inverters increases and injected current to the grid gets closer to sinusoidal shape and its THD decreases.

3. Experimental results

To verify the validity of the proposed method, a seven-level CHB has been constructed and used with DSP and autotransformer as shown in fig 12. Parameters of the under-experiment system is shown in table-3. In the first experiment, the system works under symmetrical condition and the PV system is connected to grid through an auto transformer. As it is shown in fig 13, the injected current is sinusoidal and in same phase of the grid voltage. Total power transferred to the grid is 235W, equals to 87.1W for each array and 26W for each module. Voltage and current of each module at maximum power point are shown in table 4. The injected current THD is 3% and the system efficiency is 95% while under traditional methods, despite using LC filters, the injected current THD is 12% and the system efficiency is 92%[13].

Figure12: Experimental set up to validate the simulation results

Table -3: Parameters of the under-experiment system

Parameter	Symbol	Value
Grid Voltage	E_{rms}	80 V
Inductor filter	L	4mH
DC link capacitor	C_{dc}	1 mF
Open circuit voltage	V_{OC}	18 V
Short circuit current	I_{SC}	2.2 A
Maximum power	P_{max}	26.5 W
MPP voltage	V_{mpp}	13.9 V
MPP current	I_{mpp}	1.9 A
Maximum injected power to the grid	P_{tot}	360 W

After setting up the system and implementing the modified MPPT and validating maximum power point tracking during symmetrical condition, performance of the proposed method is evaluated during asymmetrical condition (i.e. partial shading).

Table -4: Voltage and current of cells and the grid

Parameter	Symbol	Value
1^{st} cell MPP voltage	V^1_{mpp}	39.4 V
1^{st} cell MPP current	I^1_{mpp}	1.82 A
2^{nd} cell MPP voltage	V^1_{mpp}	38.1 V
2^{nd} cell MPP current	I^1_{mpp}	1.75 A
3^{rd} cell MPP voltage	V^1_{mpp}	38.8 V
3^{rd} cell MPP current	I^1_{mpp}	1.71 A
Grid voltage	E_{rms}	75.8 V
Grid current	I_{rms}	2.56

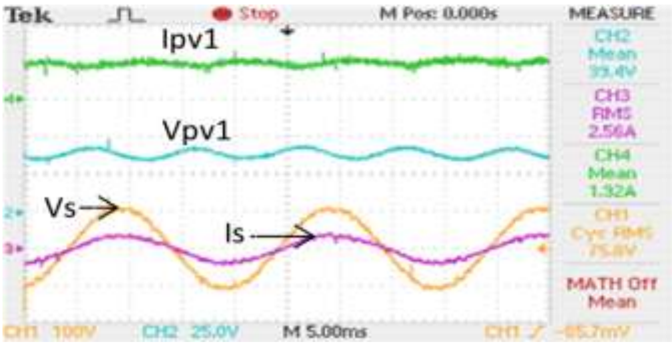


Figure13: Injected current into the grid, voltage of the grid, voltage and current of one PV cell during symmetrical condition

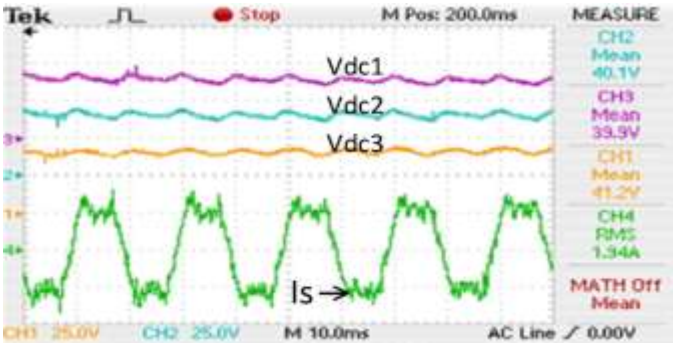


Figure14: Injected current into the grid and voltage of the arrays under normal MPPT during asymmetrical condition

To do so, partial shading condition is emulated by covering the third PV cells by blue shield panels as shown in fig 12 (left) which leads to decrease in the output power of the shaded module. Voltage of arrays and injected current into the grid under normal and modified MPPT are shown in fig 14 and fig 15. Also Injected current into the grid and its corresponding THD during the asymmetrical condition under normal and modified MPPT are shown in fig 16 and fig 17. THD of injected current into grid under normal MPPT is 78% and the PV cells shall be disconnected from the grid immediately. However, By increasing voltage of arrays which are not shaded, the injected current THD is bounded to 4.8% (to satisfy standards THD of the injected current should be less than 5%) which makes continuing power transferring into the grid possible.

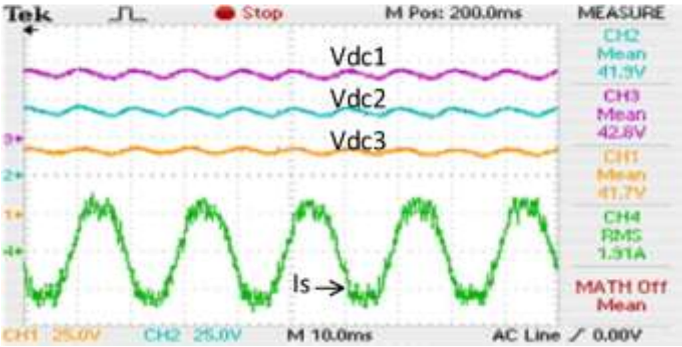
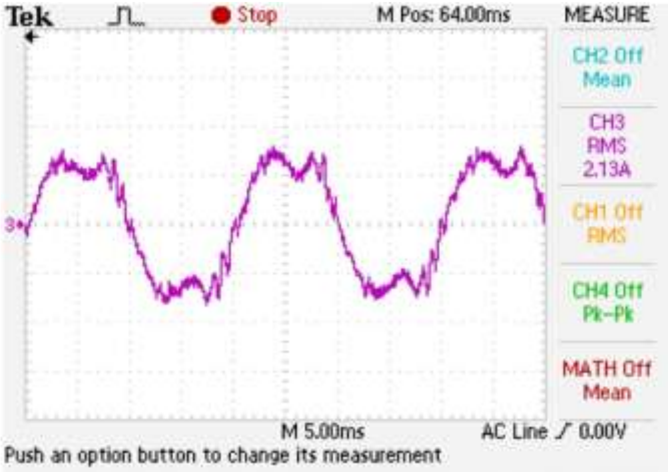
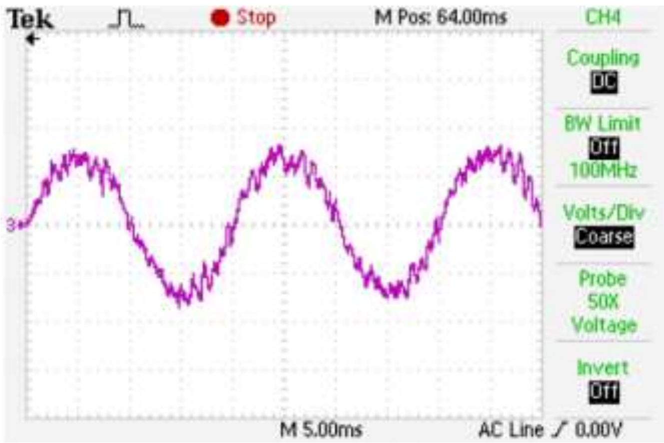


Figure15: Injected current into the grid and voltage of the arrays under modified MPPT during asymmetrical condition



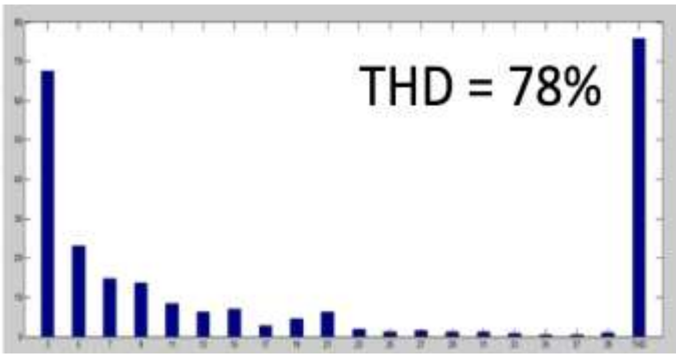
(a)



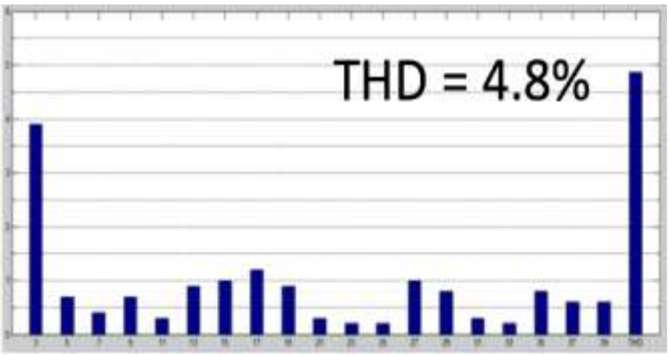
(b)

Figure16: Injected current into the grid during asymmetrical condition: (a) normal MPPT, (b) Modified MPPT

It can be concluded that the normal method in contrast to the modified version, could not make 7-level voltage at the AC-side of the inverter which causes injected current contains higher THD compare to modified method. Figure 18 illustrate Grid voltage, injected current to grid and one of arrays voltage under asymmetrical condition and using modified MPPT. The injected current is sinusoidal with 4.8% THD which qualified all standards.



(a)



(b)

Figure17: THD of the injected current into the grid during asymmetrical condition: (a) normal MPPT, (b) Modified MPPT

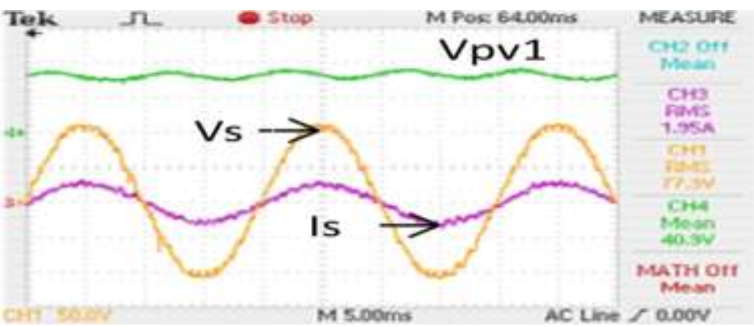


Figure18: Injected current into the grid and voltage of the arrays under modified MPPT during asymmetrical condition

4. Conclusion and future works

In this paper, a new control method of CHB based Grid-connected PV system is proposed. This method works based on changing the operation point under asymmetrical condition which causes instability. The stability boundaries defined by circuit and mathematical analysis. Effectiveness of proposed method evaluate by simulation. Also an experimental model of 7 level CHB-based inverter designed and implemented to verify the simulation results. Implementation results verified the proposed method effectiveness under asymmetrical condition such as partial shading and make the system to transfers power to grid continually under all conditions.

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