PERFORMANCE ANALYSIS OF PHOTOVOLTAIC FED GRID TIED MODULAR MULTILEVEL CONVERTER

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The proposed paper edifies the investigation of a novel converter topology with regular and partial request control strategies. Since there is an extension in worldwide vitality day by day, the utilization of renewable energy resource has become more significant. Among all the accessible renewable resources, photovoltaic (PV) source is widely utilized because of its bounteous accessibility all through the globe. The photovoltaic system has non-linear electrical characteristics and the peak power tracking technique is employed to improve the power conversion efficiency. This paper demonstrates the performance analysis and comparative study of various controllers for proposed system and a novel MPPT technique which traces the peak power efficiently with low oscillation under partially shaded conditions.

Keywords: Modular multilevel converter; Maximum power point tracking; Proportional integral controller; Fuzzy controller; Fractional order controller

1. Introduction

Due to increase in the population, the necessity of world power consumption is steadily rising. Hence, it is necessary to extend the power generation capability to fulfill the growing demand [1]. The renewable energy becomes more predominant in the generation of electric power over other available sources. Varied renewable sources like solar energy, wind energy, geothermic etc. are used for power generation [2]. Solar PV systems could be a good selection for power generation, as a result of its handiness and cleanliness [3].

The PV system has non-linear characteristics and hence the peak power can oscillate due to deviation in the load and source. Hence, peak power tracing strategy is employed to operate the system at maximum power point to obtain maximum efficiency. There are different MPPT techniques to achieve the maximum peak power from the PV system such as constant voltage (CV), perturb and observe (P&O), and incremental conductance (IC), etc. [4]. The drawback of above mentioned MPPT techniques is increased power loss, low energy

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conversion efficiency, output power fluctuation under varying insolation condition, etc. To report these issues and to assure system stability, the extremum seeking tracking algorithm is proposed by [5] under changing environmental conditions alone.

Due to partial shading condition, the hotspot issue arises due to non-linearity in the isolation conditions. To overcome this issue, bypass diodes across a PV panel/group of cells have been used and this causes multiple peaks in characteristics. The tracing of global peak power in presence of multiple peaks is a challenging factor. Many algorithms and methods have been reported in the literature to address this issue [3].

The synchronization is the main factor to be considered in the grid tied system. The synchronization must satisfy specific standards such as IEEE standards [6].

Among the converter topologies, modular multilevel converter (MMC) is considered in recent years [7]. Among the various topologies of MMC, the cascaded H-bridge is considered and output levels are based on the sub modules present in each arm. Each leg consists of two arms with an inductor connected at the end. The number of levels (NL) is determined as given NL = (2×NSM) +1, where NSM is the number of sub module in each arm. The MMC is considered for the dc-ac conversion due to its advantages and mainly it is used for grid integrated system.

In this paper, grid PV system is utilized using a boost converter as MPPT device and MMC as an interfacing converter between source and grid. The extremum seeking MPPT algorithm is implemented to obtain the peak power from PV source. The other issue addressed in this paper is that, the voltage balancing of MMC with different controllers like conventional proportional-integral (PI) controller, fuzzy-tuned PI controller, fractional order PI controller (FOPI), fractional order fuzzy-based PI controller. The performance of the controllers is compared and concluded that fractional order fuzzy-tuned PI controller provides better optimum control characteristics. Moreover, the proper synchronization between source and the grid is achieved in compliance with IEEE 519 standard.

2. Proposed System

The schematic of proposed system with the different controllers is illustrated in Fig.1. The electrical input is fed from the PV array to dc-dc converter. The MPPT method is implemented to track the maximum power from the PV source under varying insolation. The modified P&O technique is considered in this work, in which, the different controllers are used to track the maximum power efficieny. The output from the dc-dc converter is given to the

MMC which is connected to the grid. The output voltage of MMC is controlled by the various controllers such as PI controller, fuzzy-tuned PI controller and fractional order controller. The synchronization is carried out by using a phase locked loop (PLL) with different controllers. The output from the controller is used to generate the pulses for the MMC. The brief explanation of the proposed system is explained in the following sections

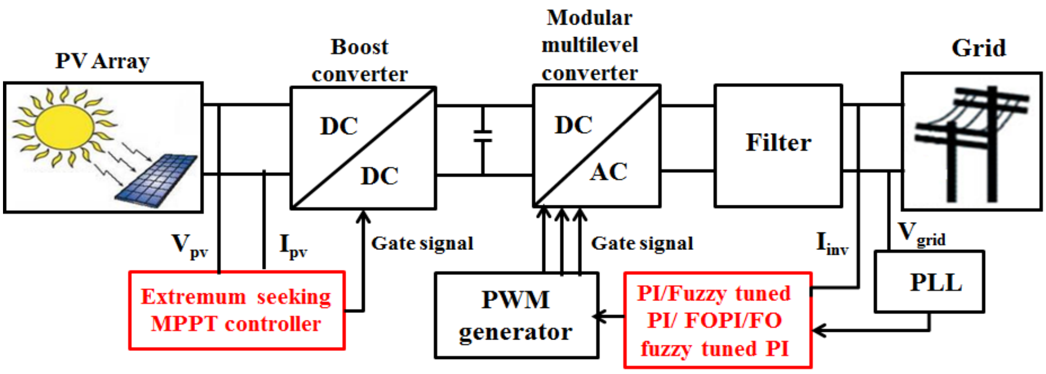

Fig. 1. Block diagram of PV fed grid connected MMC with different control techniques

3. Modeling of PV Array and maximum power point tracking algorithm

A single diode model is considered in the PV array modelling. Standard equations available in the literature [8] are used to develop the PV array model. The important parameters of PV array are peak power 37 W, maximum voltage 16.56 V, maximum current 2.25A, open circuit voltage 21.24V and short circuit current 2.55A. The array size is chosen as 14× 1 to meet the grid specification of 230 V, 50 Hz grid.

To trace the maximum power from the PV array, it is significant to have an effective and appropriate MPPT algorithm for a PV system. A variation of MPPT technique is developed by researchers to obtain the maximum power. The extremum seeking algorithm is most predominant in the generation of electric power from the PV array. The extremum seeking control (ESC) system consists of an integrator, differentiator, logic circuit and an amplifier as shown in Fig. 2.

This extremum seeking algorithm was proved to trace the maximum peak under changing environmental conditions, where the single peak is present. In this paper, the parameters of integrator and differentiator of the algorithm are properly tuned with variable sine input to make the extremum seeking algorithm suitable to track global peak which will be depicted in Fig. 3.

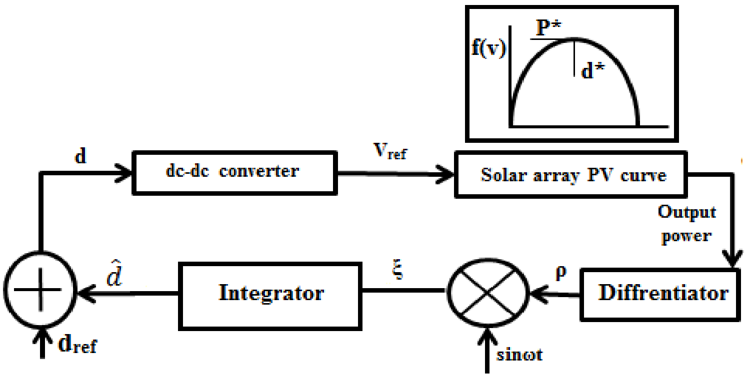

Fig. 2. Representation of ESC method under uniform insolation

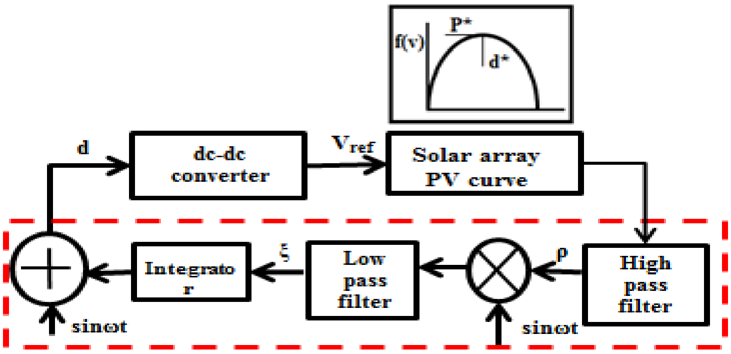

Fig. 3. Representation of ESC method under partial shading

The equations describing the system behavior [8] is given through (1) to (3):

$$\frac{dV}{dt} = A \tag{1}$$

Where, 'A' is positive constant.

$$\frac{dP}{dt} = b \tag{2}$$

Change in the sign of 'A' if b < 0 and the same sign of A if b >0. The behavior of extremum seeking control for uniform insolation explained in Fig. (4(c) left). The operating point is determined based on the increasing or decreasing the value of A as shown in Table 1.

Table 1

Operating Principle of MMC

Region	Point	dV/dt	dP/dt	Positive constant	Operating point
Left	P	> 0	> 0	A	Towards the operating point
	R	< 0	> 0	A	Away from operating point
Right	Q	> 0	< 0	-A	Away from operating point
	S	< 0	< 0	-A	Towards the operating point

$$\frac{dV}{dt} = Asign\left(\frac{dP}{dt}\right) \quad (3)$$

The method determines the sign of dP/dt and the resulting dynamics is given by dP/dV. The positive definite function V(t) is defined by (4) and the conditions derived vide (5) to (7). The equations used are based on [8].

$$V(t) = \frac{1}{2}\left(\frac{dP}{dV}\right)^2 \quad (4)$$

$$V'(t) = \frac{dP}{dV}\frac{d^2P}{dV^2}\frac{dV}{dP} = \frac{dP}{dV}\frac{d^2P}{dV^2}\left(Asign\left(\frac{dP}{dV}\right)\right) \quad (5)$$

The concavity of y(x) infers

$$\frac{d^2P}{dV^2} < 0 \quad (6)$$

$$\frac{dP}{dV} sign\left(\frac{dP}{dV}\right) > 0 \quad (7)$$

The behaviour of modified extremum seeking control under partial shading condition explained in Fig. 4 (right) which consists of three peaks.

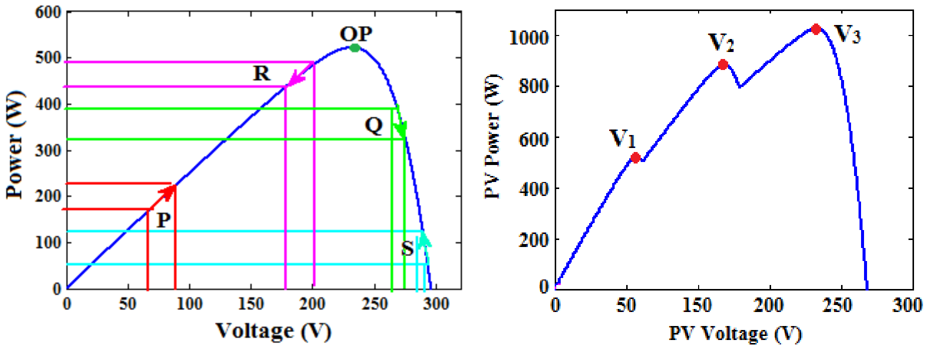

Fig. 4. Graphical analysis of ESC (left) and modified ESC (right)

This method is used to determine the power gradient to trace global peak. Initially, this method identifies the voltage at each peak power and splits them into segments. ESC is performed to track the local peaks. The global peak is identified based on the power and the power gradient in each segment. If the resultant peak point is greater than the previous point, then the previous determined point is eliminated. The process is carried out until peak power is identified. Thus, modified ESC under partial shaded condition is effectively tracked the global peak.

4. Modular Multilevel Converter

Modular multilevel converter is considered due to its attractive features [9]-[17]. The schematic of MMC is depicted in Fig. 5.

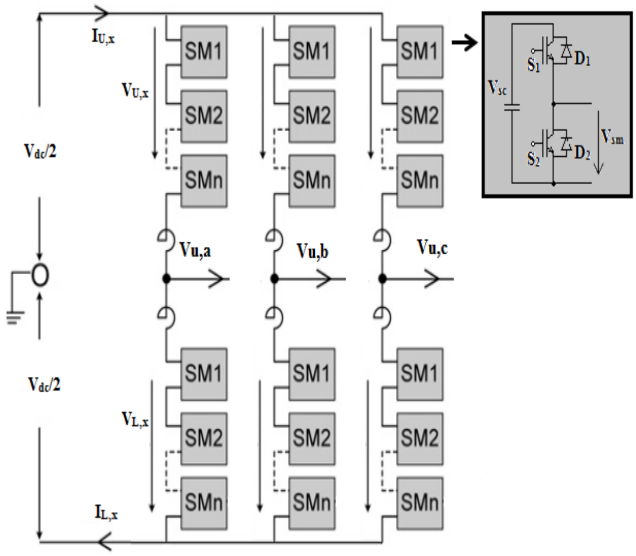

Fig. 5. Schematic diagram of three phase MMC

The basic working of MMC is based on the capacitor charging and discharging as represented in Table 2. The number of SM in each arm is determined by the equations vide (8) to (12), by referring [10].

$$N_{U,x} = \frac{(V_{dc}/2) - V_{u,x}\cos\omega o - V_{diff,x}}{V_{sc}} \tag{8}$$

$$N_{L,x} = \frac{(V_{dc}/2) + V_{u,x}\cos\omega o - V_{diff,x}}{V_{sc}} \tag{9}$$

Where V_{dc}- input voltage, V_{sc}- sub module capacitor voltage, $N_{U,x}$ & $N_{L,x}$- number of sub module in upper and lower arm of each phase (x= a, b, c phase), $V_{0,x}$- output voltage, $V_{diff,x}$- frequency component to eliminate the circulating current. The upper and lower arm current are given by

$$I_{U,x} = \frac{1}{2} i_{u,x} \cos(\omega t + \varphi) + \frac{m}{4} i_{u,x} \cos\varphi \tag{10}$$

$$I_{L,x} = -\frac{1}{2} i_{u,x} \cos(\omega t + \varphi) + \frac{m}{4} i_{u,x} \cos\varphi \tag{11}$$

$I_{0,x}$ is the magnitude of output current in each phase. The modulation index is calculated [11] as,

$$m = 2\frac{V_{u,x}}{V_{dc}} \tag{12}$$

Table 2

Workıng Prıncıple of MMC

Mode	S_1	S_2	V_{sm}	I_{sm}	State	Capacitor
1	1	0	V_{sc}	> 0	ON	Charging
2	1	0	V_{sc}	< 0	ON	Discharging
3	0	1	0	> 0	OFF	Uncharged
4	0	1	0	< 0	OFF	Uncharged

5. Control Techniques for Modular Multilevel Converter

The output voltage is regulated with different control techniques such as conventional PI controller, Fuzzy tuned PI controller and Fractional order controller (FOC). A heuristic method for tuning the PI controller gain value is Ziegler-Nichols method [10]. K_p and K_u value are tuned till the output of the control loop is stable.

$$K_p = 0.45K_u \tag{13}$$

$$K_I = \frac{T_u}{1.2} \tag{14}$$

Where K_u and T_u are the oscillation period to set PI gain values [10].

In fuzzy tuned PI controller the gain values are calculated using fuzzy logic control (FLC). The input to the FLC determines the K_P and K_I values based on the rules assigned using membership functions [23].

The fractional order controller [24]-[26] is easy to implement and the function given by

$$H(s) = s^{\mu}, \mu \in R^{+} \tag{15}$$

The schematic of FOPI controller and FO fuzzy tuned PI controller is shown in Fig. 6. Equations vide (16) to (21) are used by referring [24].

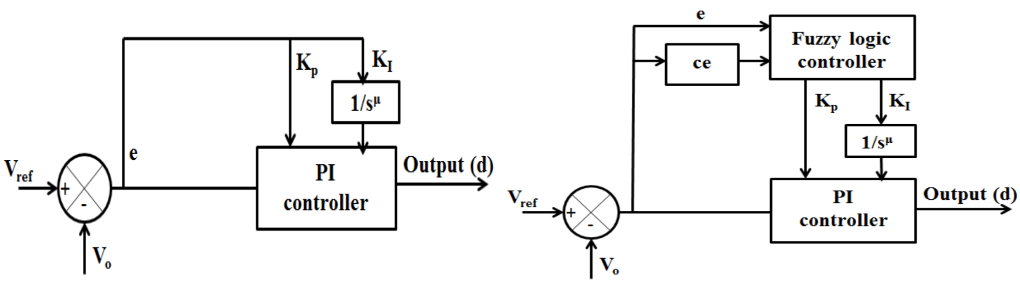

Fig. 6. Schematic of FO PI controller and FO fuzzy tuned PI controller

$$\hat{H}(s)=K_D \frac{\prod_{i=0}^{N}\left(1+\frac{s}{z_i}\right)}{\prod_{i=0}^{N}\left(1+\frac{s}{p_i}\right)} \tag{16}$$

Where frequency interval $\omega \in [\omega_b, \omega_h]$

$$K_D = \omega_c^{\mu} \tag{17}$$

Where ω_c is the cutting frequency given by

$$\omega_c = \omega_b \sqrt{10^{(\zeta/10\mu)-1}} \tag{18}$$

The coefficients are calculated based on frequency domain of ζ dB

$$a=10^{\zeta/10(1-\mu)},\ b=10^{\zeta/10\mu},\ ab=10^{\zeta/10(1-\mu)} \tag{19}$$

The poles and zeros of the rational function is given by

$$z_0 = \omega_c \sqrt{b} \quad z_i = z_0 (ab)^i \quad p_i = a z_0 (ab)^i \tag{20}$$

The number of poles and zeros is related to the desired band-width and the error criteria used by the expression

$$N = \left[\frac{\ln(W_{max}/p_0)}{\ln(ab)}\right]+1 \tag{21}$$

6. Simulation results

The simulation parameters of PV array and MMC are given in Table 3.The characteristics for uniform and different insolation is shown in Figure 7. The shading pattern considered in this work is shown in Fig. 8.

Table 3

Simulation Parameters of PV Array and MMC

Parameters	Values
V_{mpp} of single panel	16.54 V
I_{mpp} of single panel	2.25 A
PV array size/arm	14×1 (14 panels in series)
DC link voltage, V_{dc}	460 V (230 V/arm)
Grid Voltage	230 V (3-phase)
Arm inductor, L_{arm}	3.43 mH
Sub module capacitor, C_{sm}	3.49 mF
PI controller gain K_P & K_I	0.2 & 75
Fuzzy tuned PI gain values	0.1-0.2 & 75-85
Fractional order identity value, μ	0.76
ESC integrator	k=15, ω=100 rad/s, a=0.1; ω_h=50 rad/s

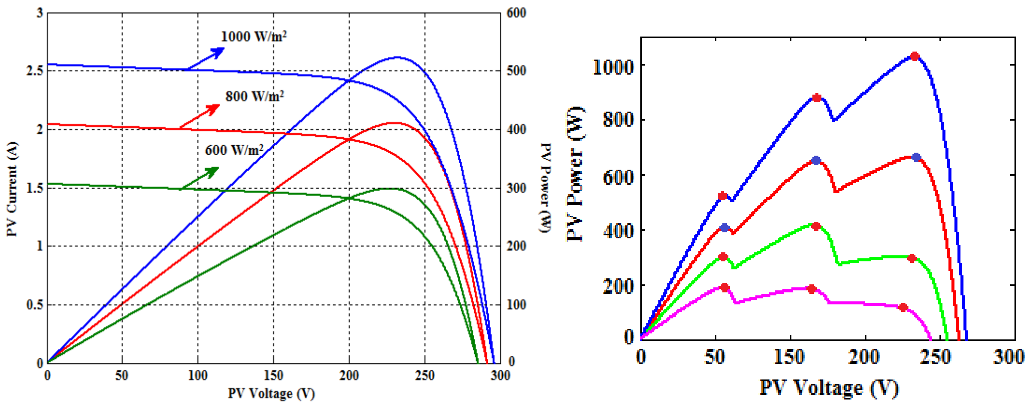

Fig. 7. Simulated characteristics curve of PV array under uniform & varying insolation

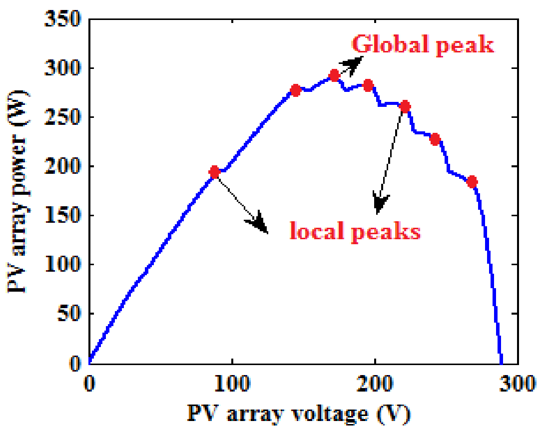

Fig.8. P-V characteristics of shaded PV array

The extremum seeking MPPT has been simulated through M-file and analysed under partial shading condition. The algorithm tracks all the local peaks in the graph and finally, the global peak power is determined. The maximum power is tracked using extremum seeking algorithms and conventional P&O MPPT technique as shown in Fig. 9. The results are compared with the steady state error and oscillation around the maximum peak power is minimum in case of extremum seeking MPPT algorithm. Hence in this work, the extremum MPP tracking technique is considered. The MMC is modeled using MatLab- Simulink based the designed parameters. The nine level output voltage waveform is obtained without using a filter on the load side as shown in Fig. 10. To obtain a sinusoidal waveform at the output for the grid connected system the LCL filters are used. The output voltage of MMC using the filter at output end is shown in Fig. 10.

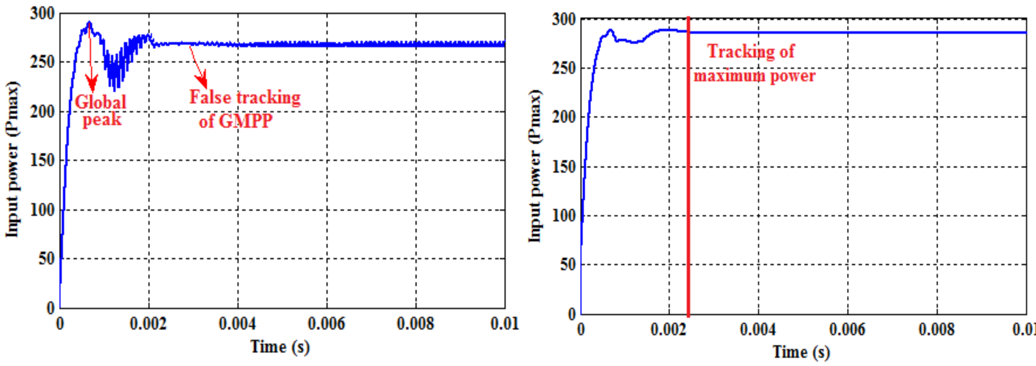

Fig.9. Tracking of maximum power of PV array using P&O MPPT & ESC MPPT algorithm

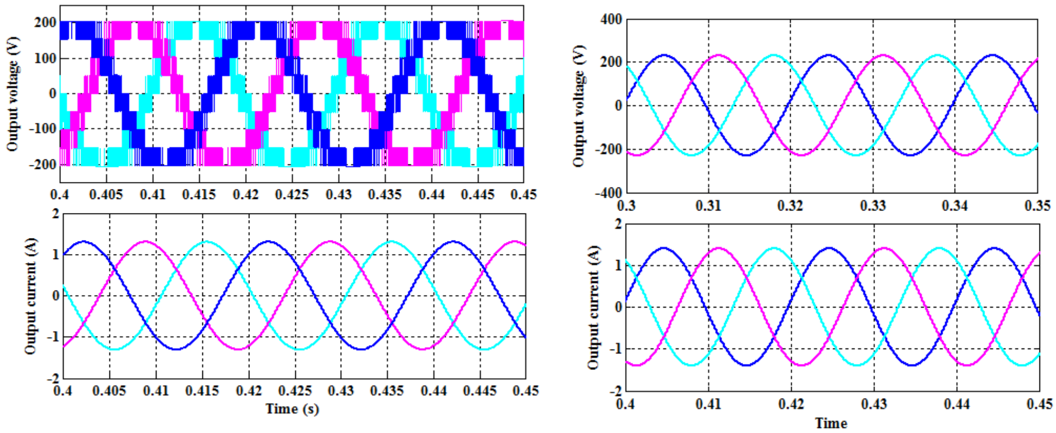

Fig.10. Output voltage and current of MMC in absence of filter & LCL filter

The various control methods have been implemented, and the performance of each controller is analyzed. The output voltage of MMC using a conventional PI controller and an FO PI controller is shown in Fig. 11. It is inferred that the balanced state is reached with less overshoot in the case of FOPI than a traditional PI controller. In Fig. 11 the output of the converter using fuzzy-tuned PI controller and FO fuzzy-tuned PI controller is shown in which the steady state and peak overshoot of FO fuzzy-tuned PI controller are furthermore reduced compared to conventional method.

The RMS value of peak output voltage for different controllers and the performance of the system is compared considering the settling time, peak overshoot and efficiency of the system. It is observed from Fig. 12 that the peak overshoot and settling time is less in proposed controller. And also, it is revealed that the settling time and overshoot is still reduced in fractional order fuzzy-tuned PI controller than fuzzy-tuned PI controller. The THD analysis of different controller is shown in Fig. 13. The RMS value of peak output voltage is considered and the performance of the different controller is analyzed shown is Table 4.

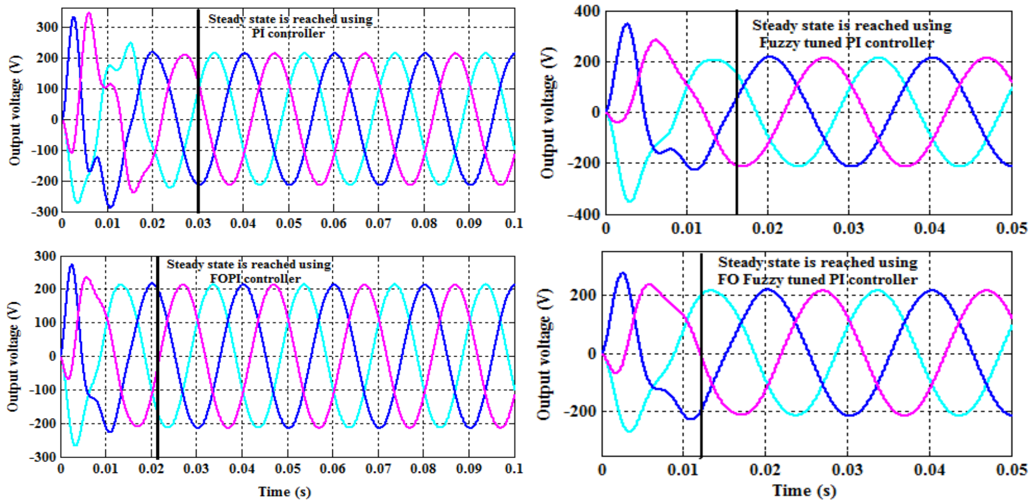

Fig.11. Output voltage of MMC using PI, FO PI controller, fuzzy tuned PI and FO fuzzy tuned PI controller

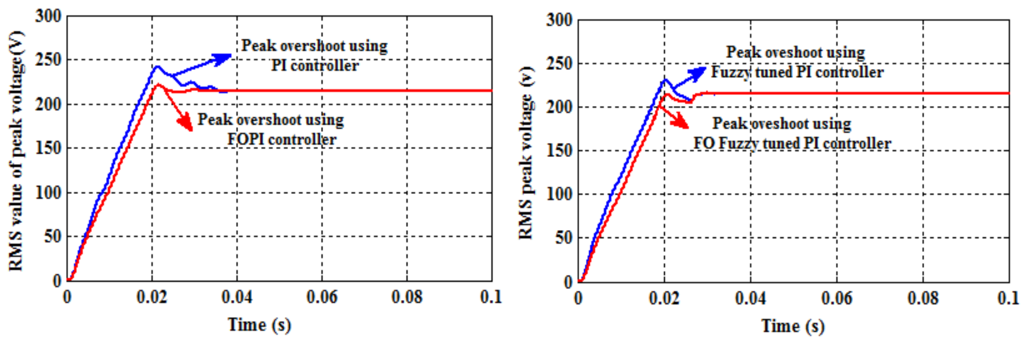

Fig.12. RMS peak voltage of MMC using different controller

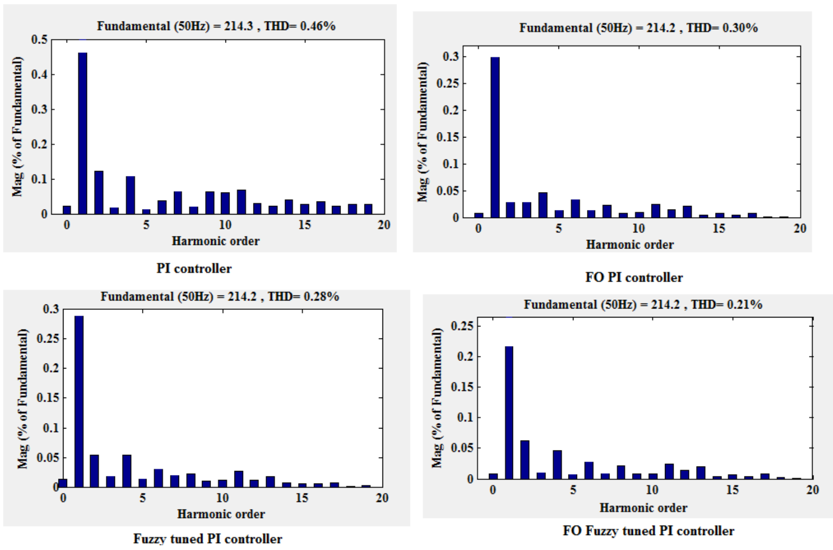

Fig.13. THD of output voltage of MMC using various controllers with filter

Table 4

Performance analysıs of dıfferent controllers

Controller / Parameter	PI controller	Fuzzy tuned PI controller	FO PI controller	FO Fuzzy tuned PI controller
Overshoot (%)	13.08	11.21	3.2	2.80
Settling time (s)	0.03	0.015	0.021	0.011
THD (%)	0.46	0.28	0.30	0.21

The performance analysis of the different controller is shown graphically in Fig.18.

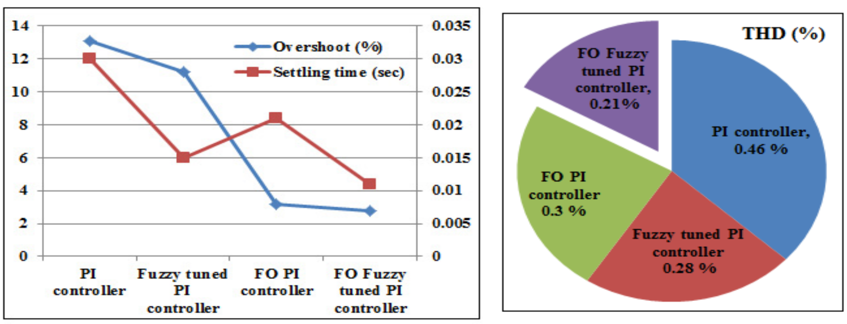

Fig. 14. Graphical analysis on performance of different control methods

From Fig. 14 it is revealed that the fractional order fuzzy-tuned PI controller has less overshoot and least settling and also the harmonic content is also reduced when compared to other control methods.

7. Hardware Implementation

The hardware shown in Fig. 15 is used to validate the proposed controller. For the dc supply to the MMC, the 500 W PV modules are designed. The maximum power from the PV array is tracked using an extremum seeking algorithm. The power switches of MMC are triggered using gating signals generated from the FPGA processor. The pulse from the processor is given to the optocoupler for the isolation purpose. The power supply to the optocoupler is given through the step-down transformer. The regulator 7812 ensures 12 V dc supply to both optocoupler and the transistor.

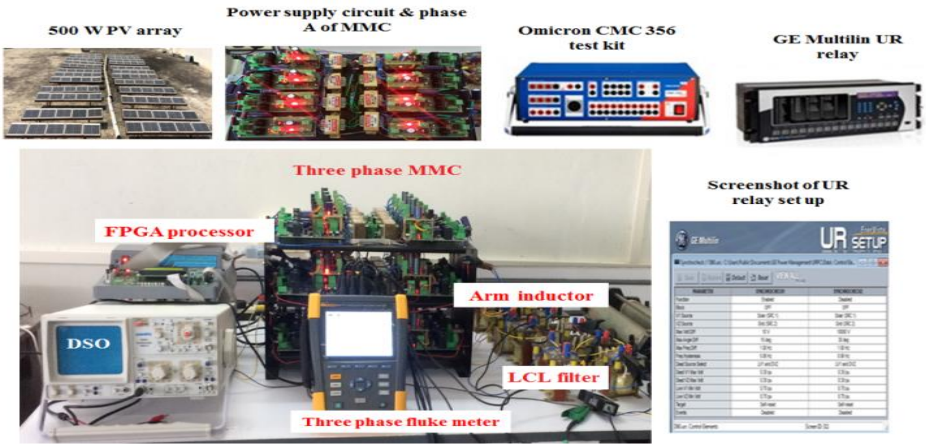

Fig.15. Measured PV array power under shaded condition

The generated pulse from the optocoupler is given to MMC in which multilevel waveform is obtained at the output. The nine level output is given to the filter to obtain proper sinusoidal waveform with reduced harmonic distortion. The grid reference signal is provided from Omicron CMC-356. It is connected to GE Multilin UR relay. The relay is tuned in such a way that it has a 10 V, 10^o and 1 Hz maximum variation of voltage, phase and frequency respectively as per IEEE standard [26].

The tracking of peak power using ESC based MPPT algorithm is shown in Fig. 16. The output voltage and current of MMC for each phase is shown in Fig. 17. The RMS peak output voltage of MMC with PI controller, Fuzzy tuned PI controller, Fractional order PI controller, Fractional order fuzzy-tuned PI controller are shown in Fig. 18,19,20 & 21 respectively. The THD graph of output voltage of MMC is shown in Fig. 22. The phasor diagram of the synchronized output voltage and current for grid tied system is shown Fig. 22. The THD of the output voltage is about 2.3 % which satisfy the IEEE 519 standards.

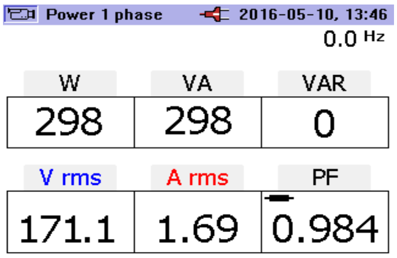

Fig.16. Measured PV array power on partial shaded condition

Fig. 17. Output voltage & current of MMC for phase A, B & C

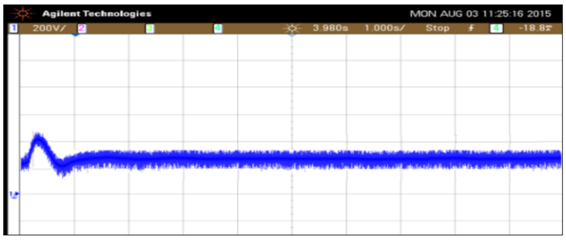

Fig. 18. RMS peak output voltage of MMC using PI controller

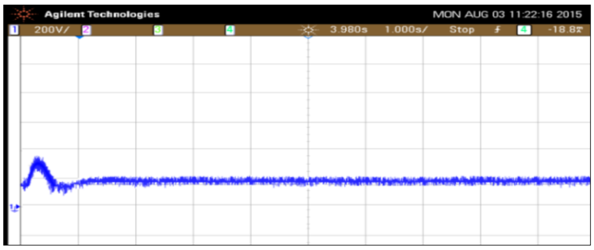

Fig.19. RMS peak output voltage of MMC using Fuzzy tuned PI controller

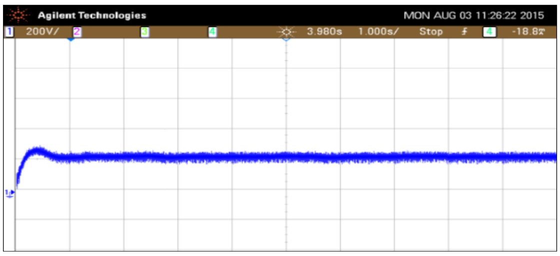

Fig. 20. RMS peak output voltage of MMC using FO PI controller

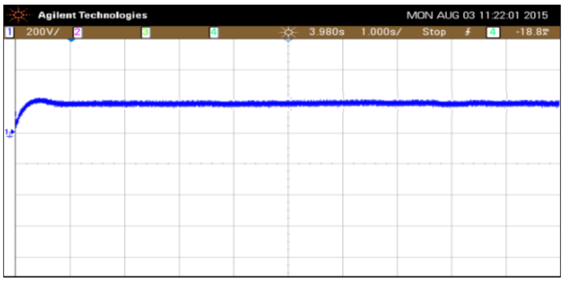

Fig. 21. RMS peak output voltage of MMC using FO fuzzy tuned PI controller

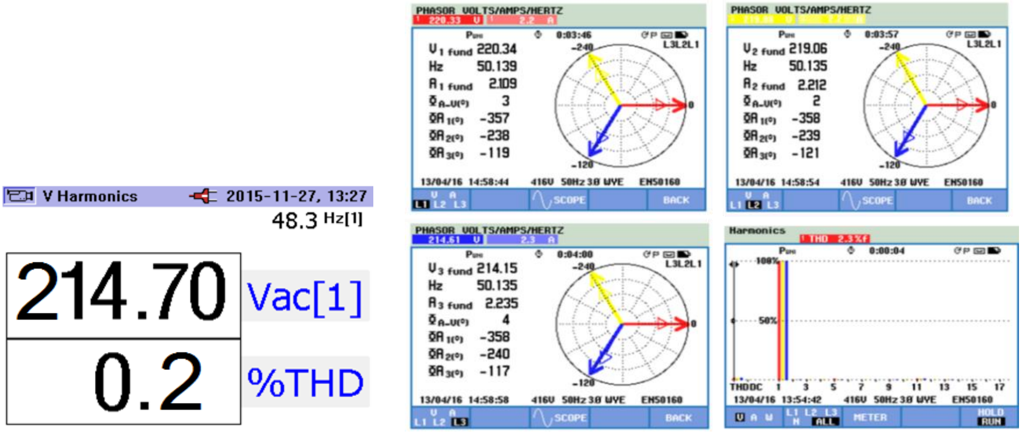

Fig.22. THD of output voltage MMC using FO fuzzy tuned PI controller & phasor diagram of synchronized output voltage and current

8. Conclusion

The performance analysis of grid connected PV fed modular multilevel converter for various controllers is carried out in this paper. From the obtained results it is inferred that, the tracking of maximum power is more effective in case of extremum seeking algorithm compared to conventional P&O MPPT technique under partially shaded condition. The proposed MPPT technique has a low oscillation around the maximum peak power. Various controllers have been implemented in which the fractional order fuzzy-tuned PI controller has less overshoot, short settling and low THD compared to other control techniques. The simulated results are verified experimentally.

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