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Impact of modified perturb and observe control on MPPT of PV/battery fed three - port DC-DC converter

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ABSTRACT. This paper presents the modified perturb and observe (P&O) maximum power point tracking (MPPT) method for photovoltaic (PV) fed three-port DC-DC converter in PV/battery hybrid system. The proposed MPPT technique reduces the drift problem which occurs in the conventional MPPT methods by including the data of change in current (ΔI) in addition to the data used in the conventional P&O algorithm. The drift phenomenon and its effects are clearly demonstrated in this paper. The ability of the proposed P&O method to address this issue is proved by comparing the conventional P&O algorithm in different modes of operation. The performance assessment includes peak overshoot, settling time, MPP ratio and stability. The experimental validation was implemented using DSPIC30F4011 microcontroller. From the analysis and results, it could be seen that the modified P&O showed better performance in terms of accuracy in tracking the maximum power, less tracking time, high MPP ratio and reduced drift in the changing weather conditions.

Keywords: current-voltage characteristics, DC-DC power converters, drift, photovoltaic systems, power demand, pulse width modulation.

Impacto da modificação perturbar e observar de controle na MPPT de PV / bateria fed Três -port conversor DC-DC

RESUMO. Este artigo apresenta o método de monitoramento de ponto de potência máximo (MPPT) modificado e observado (P&O) para o conversor DC-DC de três portas alimentado por energia fotovoltáica (PV) no sistema híbrido PV/bateria. A técnica MPPT proposta reduz o problema de deslocamento (drift) que ocorre nos métodos MPPT convencionais, incluindo os dados de mudança na corrente (ΔI), além dos dados usados no algoritmo P&O convencional. O fenômeno do deslocamento (drift) e seus efeitos estão claramente demonstrados neste artigo. A capacidade do método de P&O proposto para resolver este problema é comprovado comparando com o algoritmo de P&O convencional em diferentes modos de operação. A avaliação de desempenho inclui o superávit do pico, tempo de estabilização, relação de MPP e estabilidade. A validação experimental foi implementada usando o microcontrolador DSPIC3o30F4011. A partir da análise e dos resultados, verificou-se que o P&O modificado mostrou melhor desempenho em termos de precisão no rastreamento da potência máxima, menor tempo de rastreamento, alta relação de MPP e deslocamento reduzido nas condições climáticas em constante mudança.

Palavras-chave: características corrente-tensão, conversores de potência DC-DC, deslocamento, sistemas fotovoltáicos, demanda de energia, modulação de largura de pulso.

Introduction

In recent years, generation of power from the PV source has been increased tremendously and it is treated as an alternative resource to supply the power constantly (Chen, Shen, Shu, Qin, & Deng, 2007; Andrejasic & Jankovec, 2011; Long, Liao, & Zhou, 2011). The abundant availability of inexhaustible and clean PV source promises many applications. As the PV source is non-linear depending on the atmospheric conditions like insolation and the temperature, its energy conversion efficiency is less which is improved by using MPPT algorithm. MPPT is used to extract maximum power from the PV source.

As the conventional P&O algorithm is simple and easy for implementation it has been widely used in many applications (Mellit, Rezzouk, Messai, & Medjahed, 2011; Tafticht, Agbossou, Doumbia, & Cheriti, 2008). But the drawback is its incapacity to as certain whether the increase in power occurs due tothe change in insolation or change in duty cycle. Hence continuous oscillation occurs in and around the operating point at reduced insolation and there is a possibility to deviate from its original operating point with reduced time response (Yu, Jung, Choi, & Kim, 2004).

In most of the applications, boost converter is used as the power conditioning unit to interface PV source and the load. But due to the advantage of centralized control, low cost and compatibility, the multi-port converter is used in many applications. Hence the use of multiport converter in integrating renewable energy sources, energy storage device and the load has increased significantly (Femia, Petrone, Pagnuolo, & Massimo, 2005). Three-port converters have been widely used to interface photovoltaic system, battery and the load (Bajpai & Dash, 2012; Jiang & Fahimi, 2011; Hu, Xiao, Cao, Ji, & Morrow, 2015). Depending on the availability of the PV power generation, the three-port DC-DC converter operates in different operating modes namely, single input single output (SISO) mode, dual input (DI) mode, and dual output (DO) mode.

Centralized controller not only provides control over individual interfacing devices but also controls the entire system such that the power balance is maintained in the system under different operating modes (Wu et al., 2011; Khaligh, Cao, & Lee, 2009; Zhao, Round, & Kolar, 2008; Chen, Liao, Hung, Ming, 2015). The usage of MPPT algorithm enables PV port to operate at maximum power point at different insolation levels. Depending upon the atmospheric condition and load requirement, there is a possibility for the transition from one operating mode to the other mode. The availability of the PV source varies with the insolation. Under constant loaded condition, when the insolation increases/decreases there is transition in the operating modes. When there is transition from the DO mode to the DI mode or to the SISO mode i.e., when the insolation decreases, the usage of the conventional P&O MPPT algorithm holds good without drift problem. But when the transition takes place from SISO mode to the DI mode or to the DO mode i.e., when the insolation increases, drift problem rises due to confusion in tracking the maximum power point.

Conventional P&O algorithm can be implemented either by voltage reference control or by direct duty ratio control method. Tracking performance of the P&O is determined by the tracking time and steady state oscillations, which depends on the perturbation step size (ΔD). Smaller perturbation step size results in lower oscillations as well as slower response. On the other hand, large perturbation step size increases the steady state oscillations. Hence to improve the performance of P&O, a variable perturbation step size was utilized (Masoum, Dehbonei, & Fuchs, 2002; Femia, Granozio, Petrone, Spagnuolo, & Vitelli, 2007; Pandey, Dasgupta, & Mukerjee, 2008).

The conventional P&O uses only the data of change in power (ΔP) and voltage (ΔV) which may lead to take wrong decision of changing the duty cycle initially when the insolation increases. This leads to the drift phenomenon. Hence a modification is introduced in the existing P&O algorithm to avoid or reduce the drift by including the data of the change in the current (ΔI). The solution to avoid the drift problem is given by applying a constraint on perturbation step size (Esram & Chapman, 2007; Sera, Teodorescu, Hantschel, & Knoll, 2008, Piegari & Rizzo, 2010; Killi & Samanta, 2015).

In this paper, three-port DC-DC converter is interfaced to the PV/battery hybrid system to validate the performance of modified P&O algorithm to reduce the drift problem for increase in insolation i.e., when transition occurs between DI mode and DO mode. This paper also deals with the working principle of three-port DC-DC converter along with the comparison between the conventional and the modified P&O algorithm. The detailed analysis of the drift reduction using modified P&O algorithm interfacing proposed converter is presented in the following sections:

Material and Methods

Operating Principle of Three-port DC-DC Converter

The three-port DC-DC converter used to interface PV source, battery and the load is obtained by combining two SEPIC/ZETA bidirectional converters in parallel and by fusing with the full-bridge converter (Wu, Xu, Hu, Zhou, & Xing, 2014). This converter is capable of operating in three different operational modes depending upon the availability of PV source. The converter operates in SISO mode when the power generated by the PV source is zero. The battery is discharged to supply the required load. Similarly, when the generated PV power is less than the required load power, the battery along with the PV source supplies the required load thereby operating in DI mode. When the generated PV power is more than the required load power, the surplus power supplies the load as well as charges the battery there by operating in DO mode. Hence the change in different operating modes occurs due to the changes in the insolation. The schematic representation of three-port DC-DC converter interfacing PV, battery and the load is shown in Figure 1.

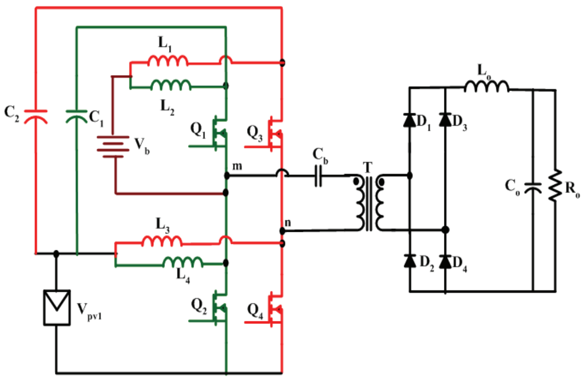


Figure 1. Three-port DC-DC converter.

The control structure developed for the three-port converter consists of three control loops like output voltage regulator (OVR) for the load port, input voltage regulators (IVR) for the source port, battery voltage regulator (BVR),and the battery current regulator (BCR) for the battery port. The main objectives of the control loops are to regulate the output voltage to a desired value, thereby providing control in the power balance between the two input ports and the load. Control strategy using the four regulators enables the extraction of maximum power from PV port, maintaining maximum depth of discharge of the battery besides controlling the output voltage to the reference value.

The schematic representation of the control strategy using centralized (proportional Integral) PI controller is shown in Figure 2.

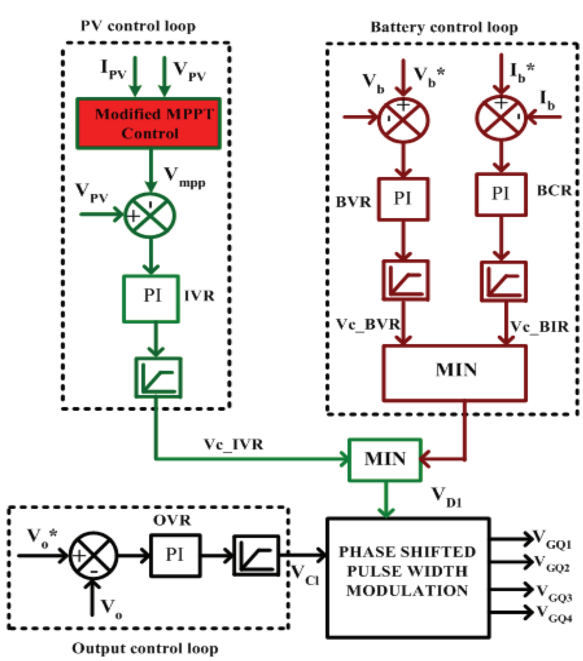


Figure 2. Proposed control structure .

The purpose of using IVR loop is to control the PV panel voltage to its reference value as specified by the MPPT controller. Therefore, the PV control loop is meant for the MPPT realization. Hence performance comparison between the conventional and the modified P&O is made for the increase in the insolation condition.

The phase shifted pulse width modulation (PS-PWM) control strategy is used to manage simultaneous power flow between three ports in the proposed converter topology. The phase shift and the duty cycle are the two control variables used to regulate the output voltage and the power balance. It utilizes two control signals like VC1 and VD1. The modulated control signal applied in three different modes of operation is shown in Figure 3.

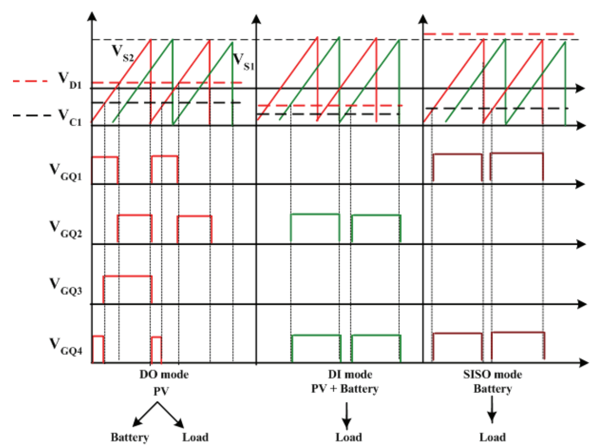


Figure 3. Pulse width modulation.

Analysis on Modified Perturb and Observe MPPT algorithm

A single diode model with five parameters is considered in this work (Batzelis, Kampitsis, Papathanassiou, & Manias, 2015; Elgendy, Zahawi, & Atkinson, 2012). The two vital parameters involved in any MPPT algorithm are perturbation time and perturbation step size. The mathematical Equations (1) to (6) involved in the development of the PV model are given below:

$$I_{PV}=\frac{D_1^2}{\eta R_o(1-D_1)^2}V_{PV} \tag{1}$$

$$I_{PV}=I_{sc}-I_o(e^{\frac{V_{PV}}{aV_t}-1})-\frac{V_{PV}+R_sI_{PV}}{R_{sh}} \tag{2}$$

$$V_{PV}\frac{D_1^2}{\eta R_o(1-D_1)^2}=I_{sc}I_o\frac{V_{PV}}{aV_t}+\frac{V_{PV}}{R_{sh}}+\frac{R_s}{R_{sh}\eta R_o(1-D_1)^2}V_{PV} \tag{3}$$

$$V_{PV}\Big|G = \frac{I_{sc}\Big|G}{\eta R_o(1-D_1)^2(1-\frac{Rs}{R_{sh}})+\frac{I_o}{aV_t}-\frac{1}{R_{sh}}} \quad (4)$$

$$I_{PV}\Big|G = \frac{D_1^2}{\eta R_o(1-D_1)^2}\frac{Neu}{Den} \quad (5)$$

$$Neu = I_{sc}\Big|G$$

$$Den = \eta R_o(1-D_1)^2 \frac{D_1^2}{\eta R_o(1-D_1)^2}(1-\frac{Rs}{R_{sh}})+\frac{I_o}{aV_t}-\frac{1}{R_{sh}} \quad (6)$$

$$I_{sc}\Big|G = \frac{G}{G_n}(I_{sc,n}+K_I\Delta_T)$$

$$\Delta V = \frac{dV_{PV}}{dG}$$

$$= \frac{(I_{sc,n}+K_I\Delta_T)\frac{1}{G_n}+K_I\frac{G}{G_n}\frac{dT}{dG}}{\frac{D_1^2}{\eta R_o(1-D_1)^2}(1-\frac{R_s}{R_{sh}})+\frac{I_o}{aV_t}-\frac{1}{R_{sh}}} > 0 \quad (7)$$

$$\Delta I = \frac{dI_{PV}}{dG} = \frac{D_1^2}{\eta R_o(1-D_{PV})^2}$$

$$X\frac{(I_{sc,n}+K_I\Delta_T)\frac{1}{G_n}+K_I\frac{G}{G_n}\frac{dT}{dG}}{\frac{D_1^2}{\eta R_o(1-D_1)^2}(1-\frac{R_s}{R_{sh}})+\frac{I_o}{aV_t}-\frac{1}{R_{sh}}} > 0 \quad (8)$$

where:

I_{PV} - PV array current (A)

D_1-Duty cycle under step mode of operation

R_o -Load resistance (Ω)

η- Efficiency of a PV cell (It is defined as the ratio of peak power to input solar power)

V_{PV} -PV array voltage (V)

I_{sc}- Short circuit current (A)

I_o - Reverse saturation current (μA)

a - Cell deviation from the ideal p-n junction characteristics (1< a < 5)

V_t = (KT/q) - Thermal voltage (V)

K - Boltzman's constant (1.381×10^{-23}J/K)

q - Electron charge (1.602×10^{-19}coulombs)

R_s- Series resistance of the PV module

R_{sh} - Shunt resistance of the PV module

G -Absolute Insolation (W/m^2)

G_n-Nominal insolation (W/m^2)

n - Diode ideality factor (0 <n < 1)

K_I-Short circuit current temperature coefficient

dV_{PV}- Derivatives of V_{PV} (V)

dI_{PV}- Derivatives of I_{PV} (A)

dG - Change in insolation (W/m^2)

$\Delta T = (T - T_n)$ - Change in temperature (°C)

T -Absolute temperature of the PV cells (°C)

T_n-Nominal temperature of the PV cells(°C)

dT - Change in absolute temperature of the PV cells (°C)

ΔV - Change in voltage (V)

ΔI - Change in current (A)

From Equations (7) and (8), it is inferred that increase in insolation causes increase in the voltage and the current.

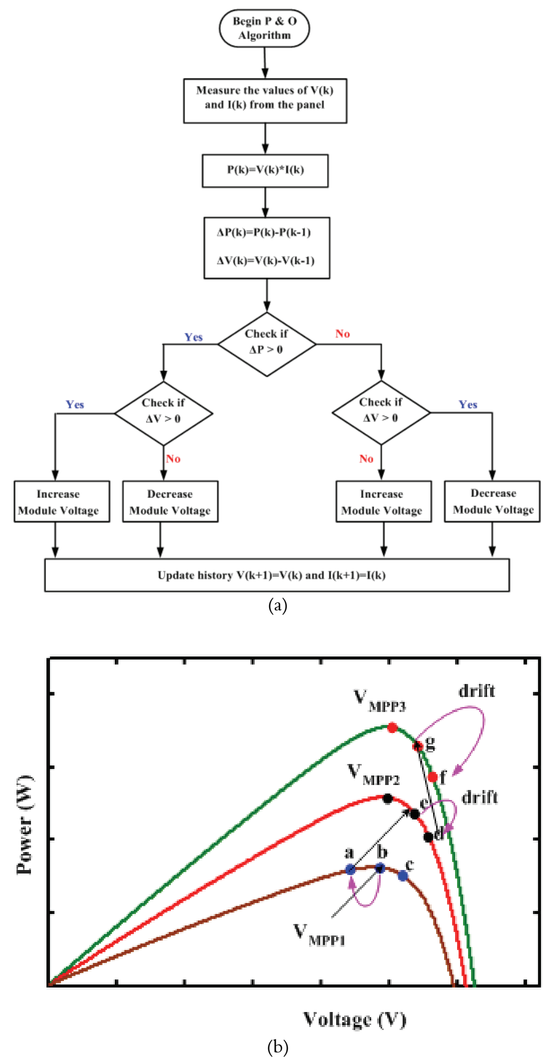
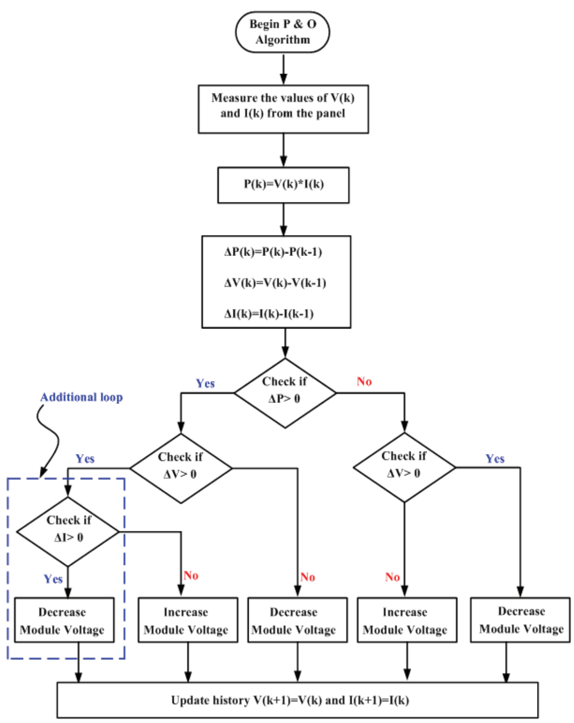


Figure 4. (a) Flowchart of conventional P&O MPPT algorithm. (b) Drift analysis using conventional P&O.

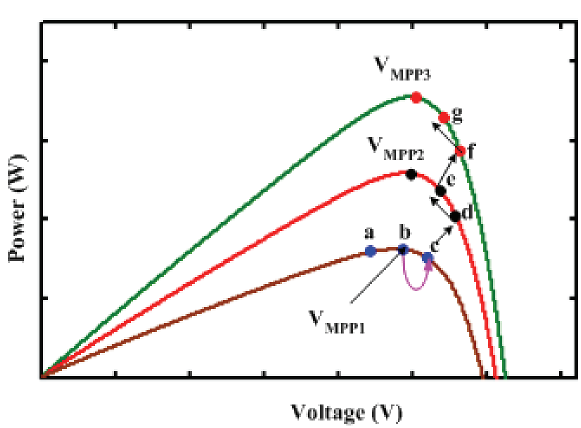
Figure 4 (a) shows the flowchart of the conventional P&O algorithm and the V-P characteristics corresponding to the conventional P&O algorithm is shown in Figure 4 (b).

From the curve, it is inferred that under particular insolation the operating point is at point 'b'. When the insolation changes, the operating point shift towards the point 'e' through point 'a' in which both ΔP and ΔV are positive. Hence as per the conventional algorithm the duty cycle decreases if both ΔP and ΔV being positive. This decrease in duty cycle tends to move the operating point towards 'd' which is far away from the MPP leading to drift. At this condition, if the insolation changes suddenly, there occurs severe drift due to confusion in the MPPT technique. This particular drift problem is minimized using the modified P&O algorithm.

The flowchart incorporating the additional loop in the conventional P&O algorithm is shown in Figure 5 (a). While using this modified algorithm, if there is an increase in insolation at operating point 'b' as in Figure 5 (b), then this operating point moves to 'c'.



(a)



(b)

Figure 5. (a) Flowchart of modified P&O algorithm. (b) Drift analysis using modified P&O.

It has a tendency to move towards the new operating point 'd' directly with increase in insolation. While analyzing the characteristics of the PV array at this particular instance, it is inferred that ΔI, ΔP, and ΔV are positive. Either the perturbation or the increase in insolation causes the positive value of ΔP.

But only the sudden increase in insolation causes the positive value of ΔV and ΔI. Therefore, the increase in insolation can be detected by using the additional parameter ΔI, thereby increasing the duty cycle which can eliminate the drift problem by moving the operating point closer to the MPP.

The addition of ΔI loop in the existing P&O algorithm overcomes the drift problem. Therefore, by using modified P&O algorithm, the number of oscillations to reach the exact operating point is reduced there by reducing the time taken to reach the exact operating point.

Results and discussions

Using MatLab / Simulink environment, the PV module was developed and interfaced to the three-port DC-DC converter. Table 1 shows the design specification of the three-port DC-DC converter. To supply the required load power under various operating conditions, optimal sizing of the battery and the PV ports was done.

The exact panel rating was calculated from the available panel rating of 37.08 W_p under the assumption that the sun light is available for 8 hours per day with 2 sunless days in a week. Table 2 shows the parameters of the solar PV module used for the optimization at the insolation of 1000 W m^{-2}.

Table 1. Design specifications.

Parameter	Value
PV voltage, V_{mpp}	(46 ~ 50) V
Output voltage, V_o	100 V
PV power, P_{mpp}	(306 ~ 450) W
Turns ratio, n	1 : 2
Switching frequency, f_s	100 kHz
Blocking capacitor, C_b	220 nF
Capacitance, C_1, C_2, C_o	470 μF
Battery voltage, V_b	84 V ± 10 %
Inductance, L_1, L_2, L_3, L_4	470 μH
Output power, P_o	(300 ~ 500) W
Shunt resistance, R_{sh}	109.25
Series resistance, R_s	0.3525
Load resistance, R_o	28 ~ 50 Ω
Nominal temperature, T_n	25°C
Nominal insolation, G_n	1000 W m^{-2}
Temperature coefficient, K_I	0.0017A °C^{-1}

The PV array of size of 3 × 4 was formed to obtain the required PV voltage of 50 V and the current of 9 A. The performance curve corresponding to different insolation is shown in Figure 6.

Table 2. Parameter of solar PV module.

Parameter	Value
Rated Power, P_{max}	37.08 W
Voltage at Maximum power, V_{mp}	16.48 V
Current at Maximum power, I_{mp}	2.25 A
Open circuit voltage, V_{oc}	21.24 V
Short circuit current, I_{sc}	2.55 A
Total number of cells in series	36

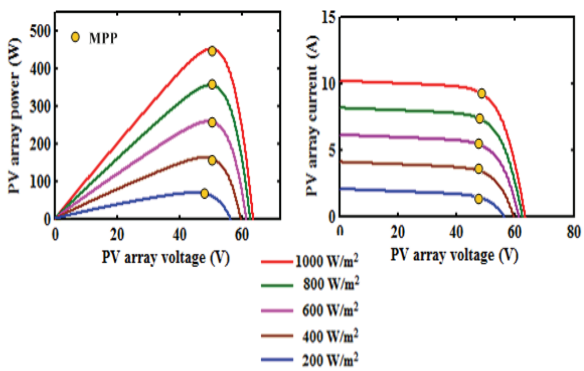


Figure 6. PV array characteristics.

The maximum power generated at 1000 W m^{-2} was 450.8 W and at 400 W m^{-2} was 275.9 W. The proposed algorithm using three-port converter for different modes of operation was tested by changing the insolation. The transitions in different operating modes were tested under constant loaded condition. The required load power was set at 350 W with the required load voltage of 100 V. The perturbation step size (ΔD) was chosen as 1 % of the tracking waveforms with the reduced drift in modified.

P&O compared with conventional P&O method being shown in Figure 7 (a) and the zoomed view at the transition instance being shown in Figure 7 (b). It could be seen that both methods were efficiently tracking the corresponding MPP, but the conventional P&O was suffering from the drift, whereas in the proposed method the drift was reduced.

From 0 to 0.3 s there is no insolation, hence no power is produced by the PV source, implying that the system operates at SISO mode. At 0.3 s the insolation increases to 400 W m^{-2} the power produced by the PV source is insufficient to supply the load. The battery and the PV source supply the required load, thereby operating in DI mode. Similarly, at 0.4 s the insolation further increases to 1000 W m^{-2}, now the generated power is more than the required load. Under this condition, the required load power is supplied and the remaining power is stored in the battery, thereby operating the system in DO mode. Hence by changing the insolation, transition from one mode to the other can be effectuated. Using the modified P&O algorithm the oscillation and tracking time can be improved. The PV module voltage using both the MPPT technique and the zoomed view at the transition instance are shown in Figures 8 (a), (b), (c), and (d) respectively.

The desired output voltage obtained in the load port at different operating modes using conventional P&O and modified P&O methods are shown in Figures 9 (a), (b), (c), and (d) along with the zoomed view at the transition instance.

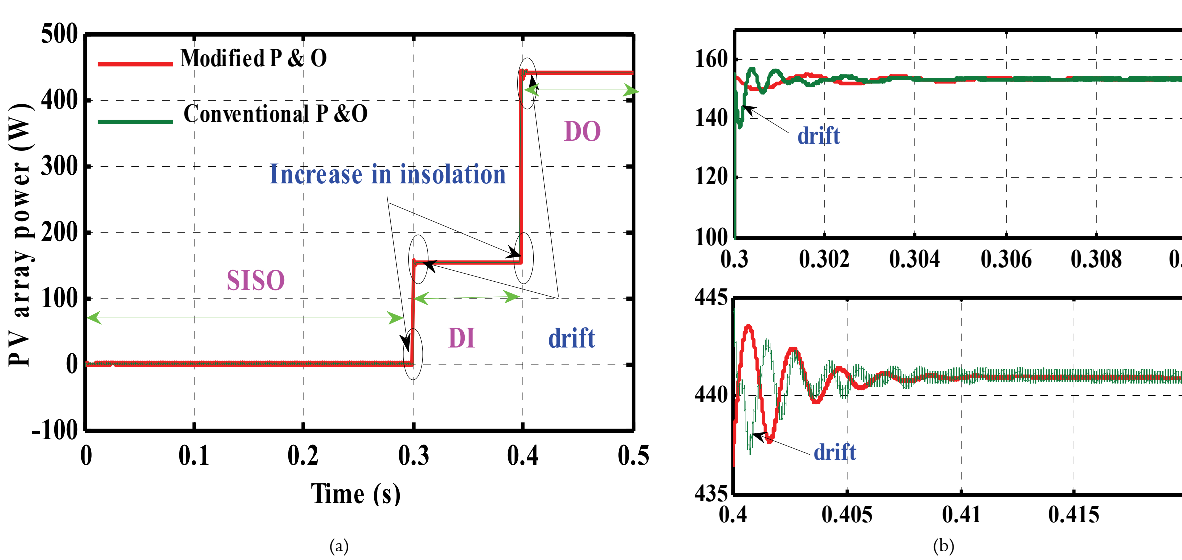


Figure 7. (a) PV array power during transition. (b) zoomed view.

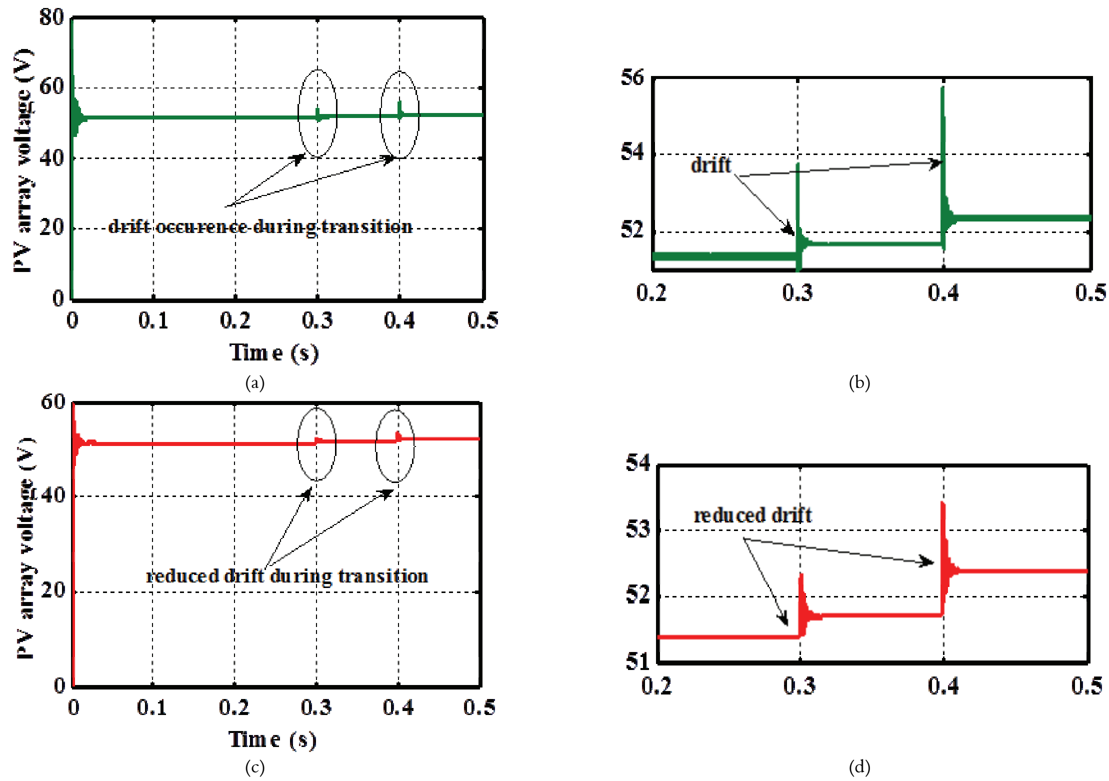


Figure 8. PV array voltage (a) Using conventional P&O algorithm. (b) Zoomed view using P&O. (c) Using modified P&O algorithm. (d) Zoomed view using modified P&O.

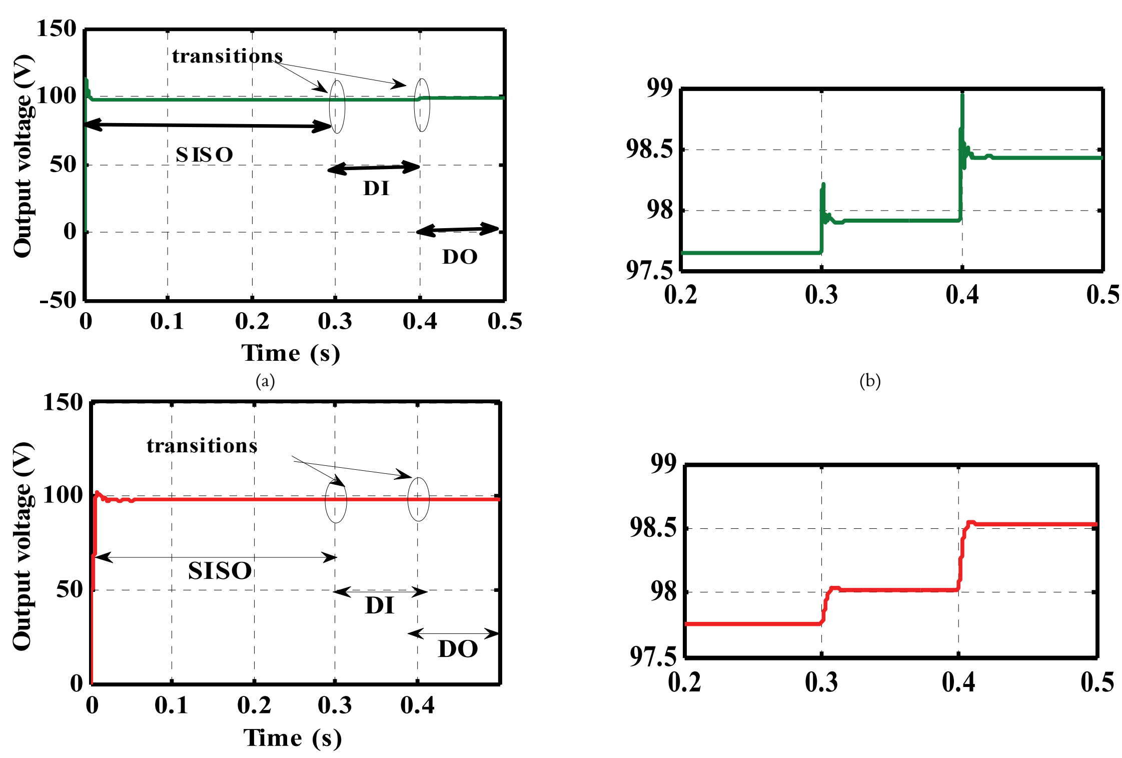


Figure 9. Output voltage (a) Using conventional P&O algorithm. (b) Zoomed view using P&O. (c) Using modified P&O algorithm. (d) zoomed view using modified P&O.

To validate the functionality and performance of the modified P&O MPPT technique, a prototype of three-port DC-DC converter with the control circuit was developed. An experimental measurement was done on a clear sunny day to validate the performance of the PV array interfacing three-port DC-DC converter. The insolation, temperature,voltage and current data has been fed to the PC using corresponding sensors and data acquisition system. (Dynalab weather tech data logger with sensors). The observed performance parameters using P&O algorithm and the conventional P&O algorithm is shown in Figure.10.

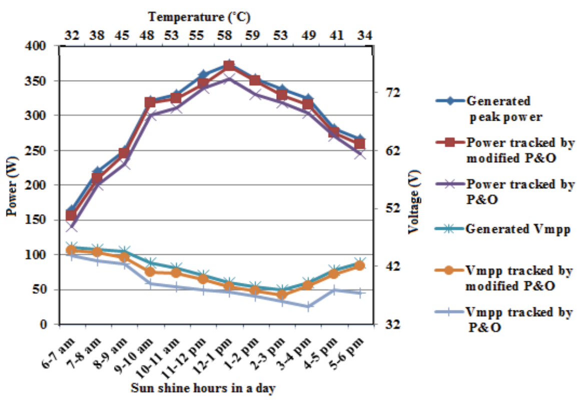


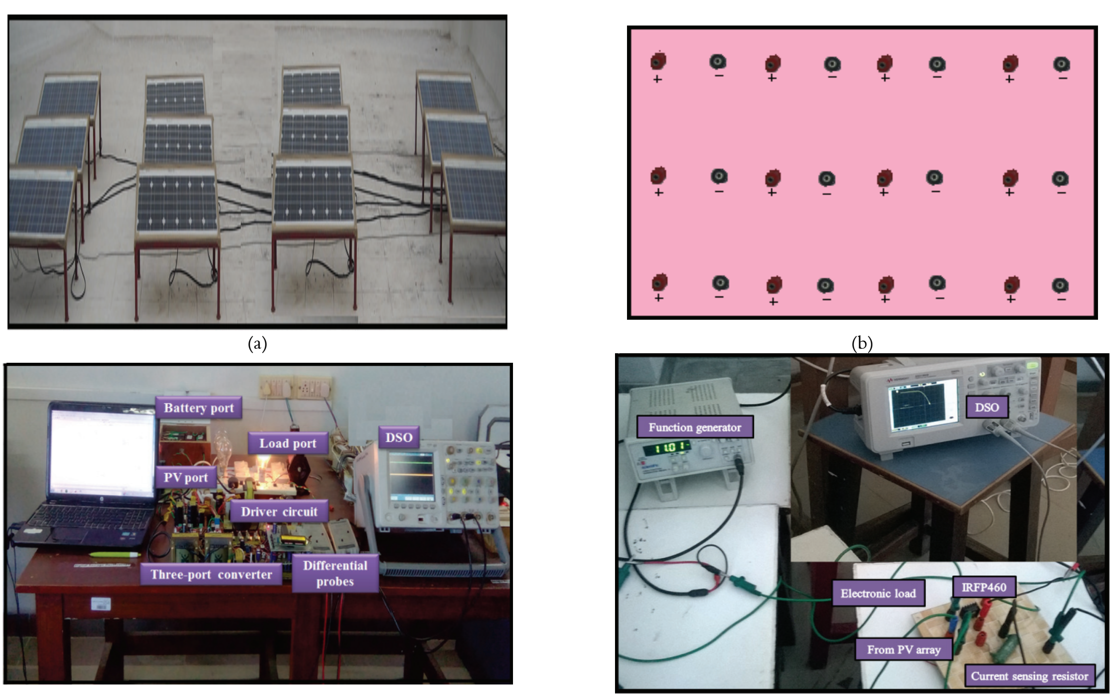
Figure 10. Experimental measurement of PV array parameters for an operating day.

The MPP ratio is the ratio ofthe reference value generated by MPPT algorithm to the expected maximum value. The observed effective gain interfacing three-port converter using modified perturb and observe method is calculated as 99.61% whereas for conventional P&O method it is 92.5%.

Figures. 11 (a) and (b) show the PV array with its panel board connection for the experimental verification. The photograph of the experimental set-up developed for validating the simulation studies in different operating modes are shown in Figures. 11 (c) and 11 (d) respectively.

The solar PV voltage and the current to obtain the V-I characteristics using electronic load set-up is shown in Figure. 12 (a) and the corresponding VI characteristics is shown in Figure. 12 (b). The control signals measured to obtain the required output voltage in DO mode, DI mode, and SISO mode of three-port converter are shown in Figures. 13 (a), (b), and (c) respectively.

The measured PV port voltage and current in DO mode of operation are also shown in Figure 14 (a). The power balance achievement in different operating modes to obtain the desired output voltage is shown in Figures. 14 (b), and (c) respectively.



(a) (b) (c) (d)

Figure 11. (a) PV array. (b) PV panel board. (c) Hardware prototype model of three-port converter. (d) Hardware prototype model to measure the characteristics of PV array.

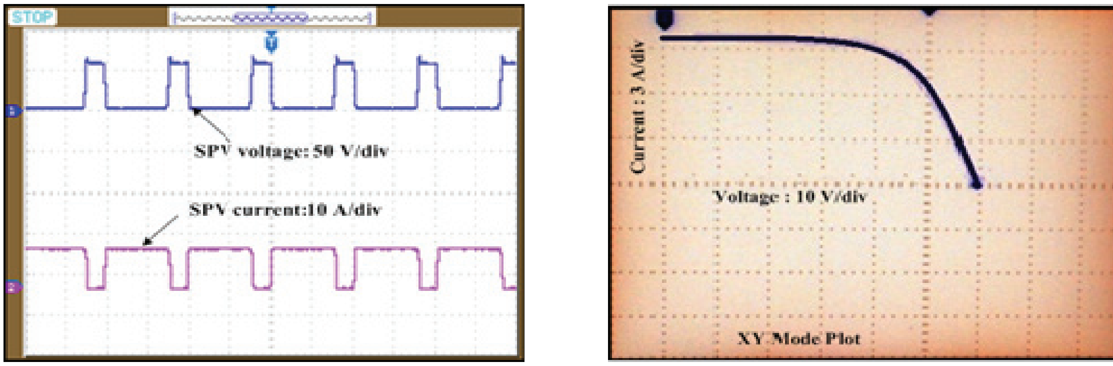


Figure 12. (a) Measured PV voltage and the current. (b) V-I characteristics.

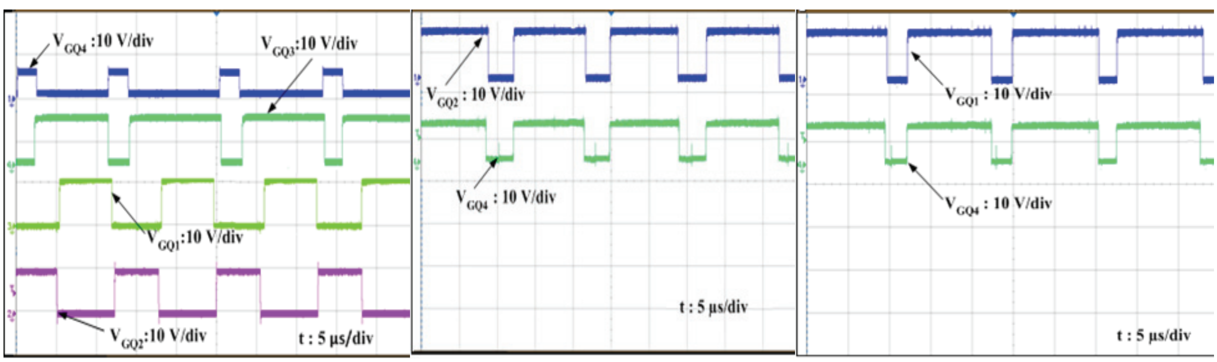


Figure 13. PWM signal (a). DO mode. (b) DI mode. (c) SISO mode.

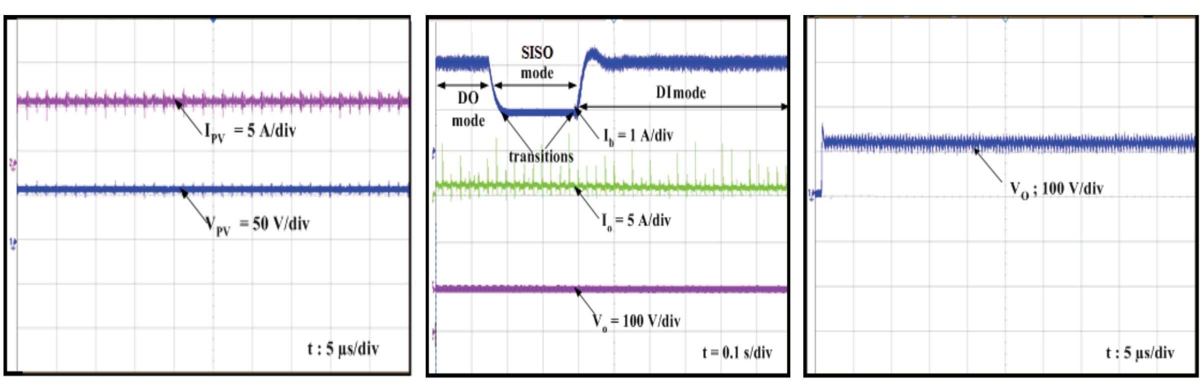


Figure 14. Measured experimental results (a) PV voltage and current. (b) transition between DO mode and DI mode. (c) Converter output voltage waveform.

Table 3 shows the performance parameter comparison using conventional P&O and modified P&O for the PV array power and the converter output voltage. From the comparison, it is clear that the modified P&O contributes less drift with fastest time response and high MPP ratio for the PV array power and less peak overshoot and less settling time for the converter output voltage.

Table 3. Performance parameter comparison.

Parameter	MPP algorithm	MPP Tracking time	MPP ratio	Peak overshoot
PV array power	P&O	10 ms	90 - 95 %	6.5 W
	Modified P&O	2 ms	95 - 100 %	3.4 W
Parameter	MPP algorithm	Settling time	Steady state error	Peak overshoot
Converter output voltage	P&O	15 ms	1.57 V	10 V
	Modified P&O	7 ms	1.3 V	1.5 V

Conclusion

This paper presented a new MPPT algorithm to reduce the drift phenomenon, by including an additional loop to the existing conventional P&O algorithms. Steady state and dynamic simulation results confirmed the best performance of modified P&O MPPT algorithm. It also achievesstability and power balance under different operating modes with high MPP ratio, reduced oscillation, less tracking time, and overshoot. The proposed algorithm was validated by means of numerical simulations, considering the PV panel that had been experimentally identified and characterized. Moreover, laboratory tests were performed to validate the effectiveness of the proposed algorithm. The proposed algorithm improved the efficiency of the PV system by gaining the extra power during drift compared with the conventional P&O algorithm. The tracking time in the PV array power could be improved by 80% using the modified P&O algorithm.The peak overshoot in the converter output voltage could be reduced by 85% and the settling time could be improved by 54%.

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