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Design and Analysis of SEPIC Converter Based MPPT for Solar PV Module with CPWM

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Abstract - The main objective of this paper is to design DC-DC MPPT circuit using chaotic pulse width modulation to track maximum power from solar PV module for space application. The direct control method of tracking is used to extract maximum power. The nominal duty cycle of the main switch of DC-DC SEPIC converter is adjusted so that the solar panel output impedance is equal to the input resistance of the SEPIC converter which results better spectral performance in the tracked voltages when compared to conventional PWM control. The conversion efficiency of the proposed MPPT system is increased when CPWM is used as a control scheme

Keywords: CPWM, MPPT, SEPIC Converter, PV module

1. Introduction

Solar power is a renewable energy source that might replace fossil fuel dependent energy sources. However, for that to happen, solar power cost per kilowatt-hour has to be competitive with fossil fuel energy sources. Currently, solar panels are not very efficient it has 12-20% efficiency to convert sunlight to electrical power. The efficiency can drop further due to other factors such as solar panel temperature and load conditions. In order to maximize the power derived from the solar panel, it is important to operate the panel at its optimal power point. To achieve this, a type of charge controller called a Maximum Power Point Tracker will be designed and implemented.

The MATLAB / PSPICE model of the PV module is developed [1-4] to study the effect of temperature and insolation on the performance of the PV module. MATLAB-based modelling and simulation scheme suitable for studying the *I-V* and *P-V* characteristics of a PV array under a non-uniform insolation due to partial shading [5] was proposed. The mathematical model of solar PV module is useful for the computer simulation. The power electronics interface is connected between a solar panel and a load or battery bus, is a pulse width modulated (PWM) DC-DC converter or their derived circuits is used to extract maximum power from solar PV panel [6]. I-V characteristic curve of photovoltaic (PV) generators based on various DC-DC converters [7-10] was proposed and concluded that SEPIC converter is the best alternative to track maximum power from PV panel.

Shagar et al. [11] described the closed loop mechanism of the SEPIC converter and the simulated results are presented. The inherent nature of SEPIC converter is that additional input filters are not necessary to filter out high frequency harmonics. The SEPIC (Single Ended Primary Inductor Converter) topology is an excellent choice for a maximum power point tracking (MPPT) converter in small solar energy systems. Simulation and experimental validation are given by Kashyap et al. [12]

The maximum power tracking for PV panel using DC-DC converter is developed [13] without using micro controller. The nominal duty cycle of the main switch in the SEPIC converter is adjusted to a value, so that the input resistance of the converter is equal to the equivalent output resistance of the solar panel at the MPP. This approach ensures maximum power transfer under all atmospheric conditions. The analogue chaotic PWM is used to reduce the EMI in boost converter. The conversion efficiency is increased when CPWM is uses as a control technique [14-15]. The chua's diode and chua's oscillator was used to generate chaotic PWM. The spectral performance has been improved in induction drives when CPWM is used [16].

This paper proposes to implement Chaotic PWM as a control method to improve the steady state performance of the DC-DC SEPIC converter based MPPT system for solar PV module. The nominal duty cycle of the main switch of DC-DC SEPIC converter is adjusted, so that the solar panel output impedance is equal to the input resistance of the dc-dc converter which results better spectral performance in the tracked voltages when compared to conventional PWM control. The conversion efficiency of the proposed MPPT system is increased when CPWM is used.

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2. MATLAB Model of L1235-37W Solar PV Module

A solar cell is a kind of p-n junction semiconductor

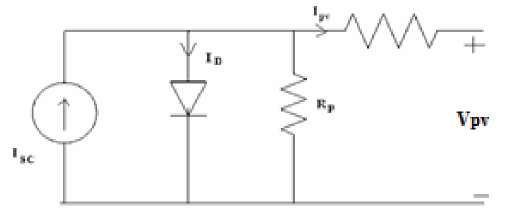

Fig. 1. (a) Equivalent circuit of solar PV module

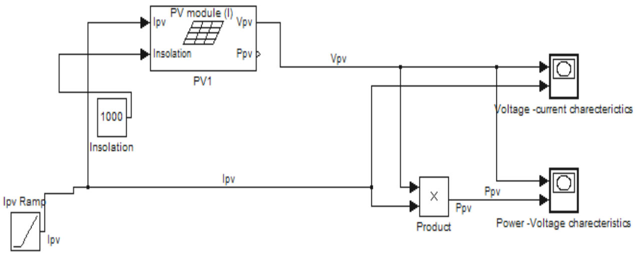

Fig. 1. (b) MATLAB model for PV module

Table 1. Specifications of l1235-37W solar PV panel

Short circuit current (I_{sc})	2.5A
Voltage at MPP(V_m)	16.4
Current at MPP(I_m)	2.25
Open circuit voltage (V_{oc})	21V
Length	645mm
Width	530mm
Depth	34mm
Weight	4kg
Maximum power (P_{max})	37W

device and converts light energy into electrical energy. The output characteristics of the solar PV module depend on the irradiance and the operating temperature of the cell. The equivalent circuit of PV module is shown in Fig. 1(a).

From the Fig. 1(a), the current equation is given by

$$I_{sc} = I_D + I_{PV} + (V_D / R_p) \quad (1)$$

$$V_{pv} = V_D - (I_{pv} * R_s) \quad (2)$$

where diode current is, $I_d = I_o + (e^{(V_D / V_T)} - 1)$.

Based on the electrical Eqs. (1) and (2), the solar PV module is modelled in MATLAB as shown in Fig. 1(b). Which is used to enhance the understanding, predict the V-I characteristics to analyze the effect of temperature and irradiation variation. If irradiance increases, the fluctuation of the open circuit voltage is very small. But the short circuit current has sharp fluctuations with respect to irradiance. However, for a rising operating temperature, the open-circuit voltage is decreased in a Non-linear fashion [1].

The V-I characteristics are validated experimentally in the L1235-37Wp solar module shown in Fig. 2(a). The Table 1 shows the technical specifications of L1235-37W solar module under test. The Fig. 2(b) shows the V-I characteristics is based on the experimental results under irradiation (G) =1000W/m^2, temperature =25°C.

Fig. 2. (a) L1235-37W solar module under test

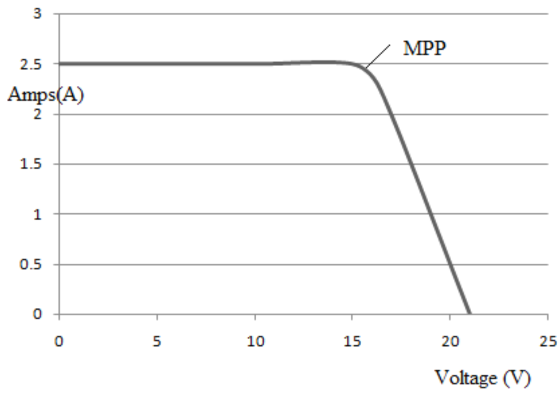

Fig. 2. (b) V-I characteristics of L 1235-37W solar panel

2.1 Modelling of SEPIC converter

The relation between input and output currents and voltage are given by

$$\frac{V_o}{V_{IN}} = \frac{D}{(1-D)} \quad (3)$$

$$\frac{I_{IN}}{I_O} = \frac{D}{(1-D)} \quad (4)$$

The Table 2 shows the components used in simulation and hardware setup for the power circuit. The duty cycle of the SEPIC converter under continuous conduction mode is given by

$$D = \frac{V_{OUT} + V_D}{V_{IN} + V_{OUT} + V_D} \quad (5)$$

V_D is the forward voltage drop across the diode (D), The maximum duty cycle is

$$D_{max} = \frac{V_{OUT} + V_D}{V_{IN(min)} + V_{OUT} + V_D} \quad (6)$$

The value of the inductor is selected based on the below equations

Table 2: Specification of SEPIC converter

Input inductor L_1	500e-6 H
Filter inductor L_2	500e-6H
Capacitor C_1	220e-6F
Filter capacitor C_2	220e-6F
Resistive load R	2Ω
Switching frequency	25kHz
Switch : MOSFET	IRF510
Optocoupler	MCT2E
Diode	MUR450

$$L_1 = L_2 = L = \frac{V_{IN(MIN)} * D_{MAX}}{\Delta I_L * f_S} \quad (7)$$

ΔI_L is the peak-to-peak ripple current at the minimum input voltage and f_s is the switching frequency. The value of C_1 depends on RMS current, which is given by

$$I_{c1(rms)} = I_{out} * \sqrt{\frac{V_{OUT} + V_D}{V_{IN(MIN)}}} \quad (8)$$

The voltage rating of capacitor C_1 must be greater than the input voltage. The ripple voltage on C_1 is given by

$$\Delta V_{c1} = \frac{I_{(OUT)} * D_{MAX}}{C_1 * f_S} \quad (9)$$

The parameters governing the selection of the MOSFET are the minimum threshold voltage $V_{th(min)}$, the on-resistance $R_{DS(ON)}$, gate-drain charge Q_{GD}, and the maximum drain to source voltage $V_{DS(max)}$. The peak switch voltage is equal to $V_{in} + V_{out}$. The peak switch current is given by

$$I_{Q1(Peak)} = I_{L1(PEAK)} + I_{L2(PEAK)}$$

The RMS current is given by

$$I_{Q1(rms)} = I_{out} \sqrt{\left(V_{OUT} + V_{in(min)}\right) * \frac{V_{OUT}}{V_{in(min)^2}}}$$

The total power dissipation for MOSFETs includes conduction loss (as shown in the first term of the above equation) and switching loss as shown in the second term. I_G is the gate drive current. The $R_{DS(ON)}$ value should be selected at maximum operating junction temperature and is typically given in the MOSFET datasheet.

$$P_{switch} = (I_{Q1(rms)} * R_{DS\,(ON)} * D_{max}) + (V_{in(min)}) + V_{out}) * I_{Q1(Peak} * (Q_{GD} * f_S) / I_G$$

The output diode must be selected to handle the peak current and the reverse voltage. In a SEPIC converter, the diode peak current is the same as the switch peak current $I_{Q1(peak)}$. The minimum peak reverse voltage the diode must withstand is,

$$V_{RD} = V_{in(max)} + V_{out\,(max)}$$

2.2 Dynamic input characteristics of a SEPIC converter at MPP

The input voltage and the equivalent input resistance of the converter are Vs and R_i respectively. As the input power ρ_i to the converter is equal to the output power ρ_o of the solar PV module

$$\rho_i = \rho_o = \frac{V_S^2}{R_i} \quad (10)$$

The rate of change ρ_i with respect to V_S and R_i can be shown below

$$\partial\rho_i = \frac{2V_S}{R_i}\partial V_S - \frac{V_S^2}{R_i^2}\partial R_i \quad (11)$$

At the MPP, the rate of change of p_i equals zero and $R_i = r_g$

$$\partial\rho_i = 0, \text{ hence } \frac{\partial V_S}{\partial R_i} = \frac{V_S}{2R_i} \quad (12)$$

The equation gives the required dynamic resistance characteristics of the tracker at MPP.

3. Generation of Chaotic PWM

In order to improve the steady state performance of Solar PV powered system, direct control Chaotic Pulse width modulated (CPWM) SEPIC converter is proposed to track maximum power from solar PV module. Therefore, in order to get chaotic frequency f_Δ or chaotic amplitude A_Δ, chaos-based PWM (CPWM), as shown in Figs. 3 (a) and (b) is analyzed to generate chaotic PWM. The analogue chaotic PWM has its advantages over the digital in its low costs and easy-to-design, making it suitable for high-frequency operation and situations when design flexibility, high converter conversion efficiency and low cost. In order to generate chaotic pulse width modulation chua's diode is used to trigger the main switch of SEPIC converter, and to be used for reducing spectral peaks in tracked converter voltage.

The CPWM adopts sawtooth to modulate, but its carrier period T_Δ' changes according to

$$T_\Delta' = \frac{X_i}{\text{Mean}(x)} * T_\Delta$$

Where T_Δ is invariant period, X_i, I = 1,2,….N, a chaotic sequence, $x=(x_1,x_2\ldots x_N)$, and Mean(x), average of the sequence, defined as

$$\text{Mean}(x) = \lim_{N\to\infty}\sum_{i=1}^{N}|X_i|\frac{1}{N}$$

Similarly the CPWM also adopts sawtooth to modulate,

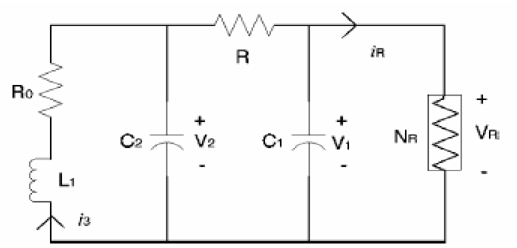

Fig. 3. (a) Chua's diode

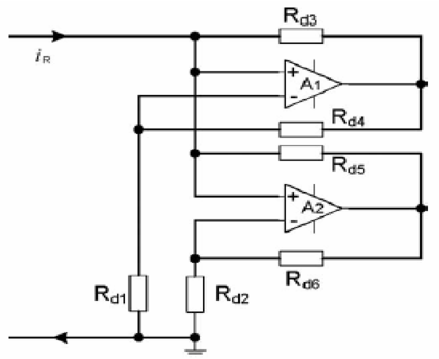

Fig. 3. (b) Chua's oscillator

but its carrier amplitude A_Δ' changes according to

$$A_\Delta' = \left\{1 + K\frac{X_i}{\text{Mean}(x)}\right\}A_\Delta$$

Where A_Δ is the invariant amplitude, X_i, i= 1,2,….N, a chaotic sequence,

x= ($x_1,x_2\ldots x_N$), and Mean (x), average of the sequence, and K is the modulation factor of the amplitude which can be set required in practice. The value of K is selected as low so that the ripple in the output voltage of the SEPIC converter is low. Also the ripple in the output voltage controlled by Chaotic PWM is low.

The analog chaotic carrier is generated based on the circuit shown in Fig. 3(a). The resistances (R_{d1} … R_{d6}) are used to realise linear resistor called Chua diode. The parameters for Chua's diode are designed and chosen as R_{d1} = 2.4 kΩ, R_{d2} = 3.3 kΩ, R_{d3} = R_{d4} = 220Ω, and R_{d5} = R_{d6} = 20 kΩ. The other parameters of Chua's oscillator used in the experiment are L_1 = 2.2 mH, C_1 = 4.7 nF, C_2 = 500 pF, and R = 1.75 KΩ.

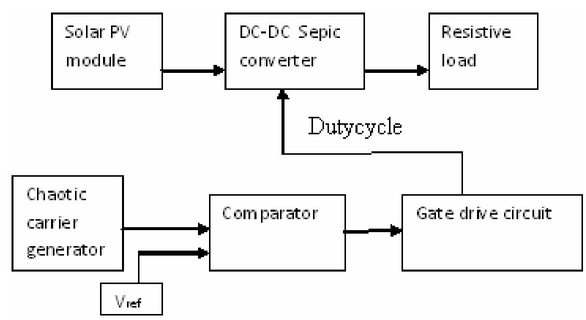

Fig. 4. Block diagram of the proposed MPPT system

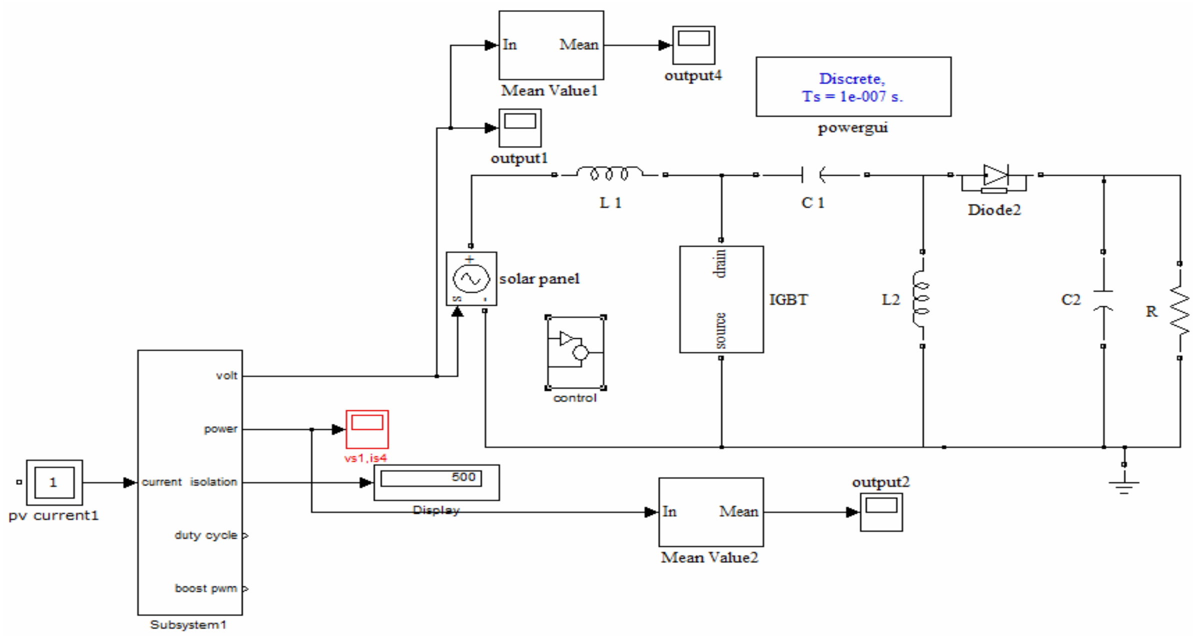

Fig. 5. Closed loop simulation of MPPT system using CPWM for solar PV module

4. Simulation Result

The block diagram of the hardware setup is shown in Fig. 4. The closed loop simulink model of SEPIC DC-DC converter based maximum power tracking using Chaotic PWM is shown in Fig. 5.

The generated chaotic carrier and Chaotic PWM are shown in Figs. 6 and 7. The conventional PWM is shown in Fig. 8.

The Fig. 9 shows the tracked power from the solar PV module is 36.5W corresponds to 1000W/m^2 and 13W corresponds to 500W/m^2. The tracking efficiency is 98.6% without considering the efficiency of the solar PV module and the converter. The duty cycle of the main switch of the SEPIC converter is 45%. The converter conversion efficiency is increased from 86% to 92% because of the lower average switching frequency in CPWM.

5. Experimental Setup

Fig. 10 shows of experimental setup of the proposed SEPIC converter-based MPPT for solar PV module, which is constituted by a power stage and a control circuit. The power stage includes an inductor L_1, L_2, capacitor C_1, C_2, a switch S, a load resistance, a solar PV module (L1235-37Wp).

The generated chaotic carrier and periodic carrier are shown in Figs. 11 and 12. The corresponding conventional

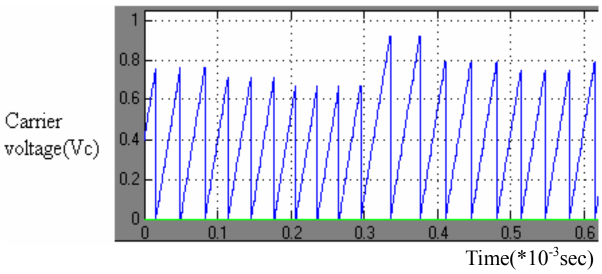

Fig. 6. Chaotic carrier

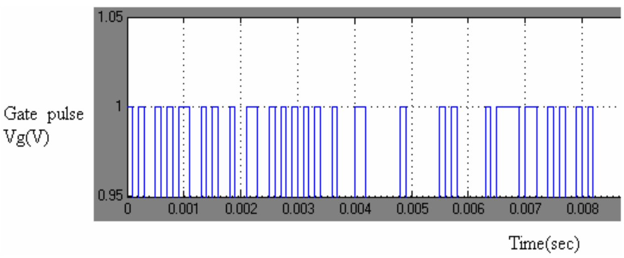

Fig.7. Chaotic PWM

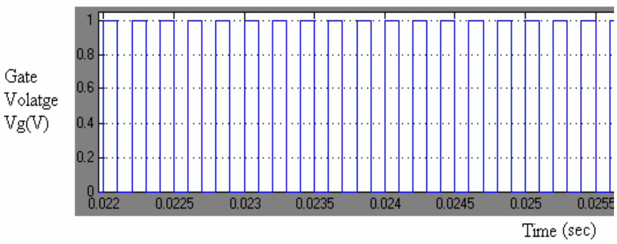

Fig. 8. Conventional PWM

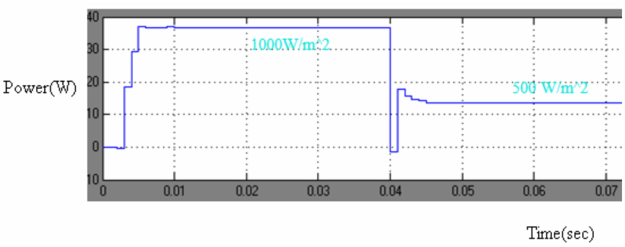

Fig. 9. Tracked power using DC-DC SEPIC converter

Fig. 10. Hardware setup

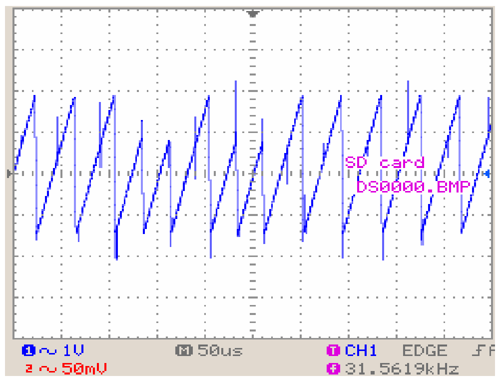

Fig. 11. Chaotic carrier

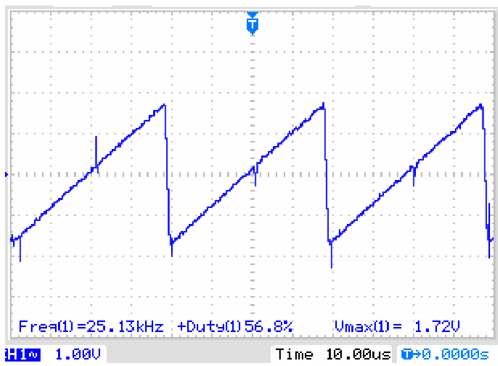

Fig. 12. Periodic carrier

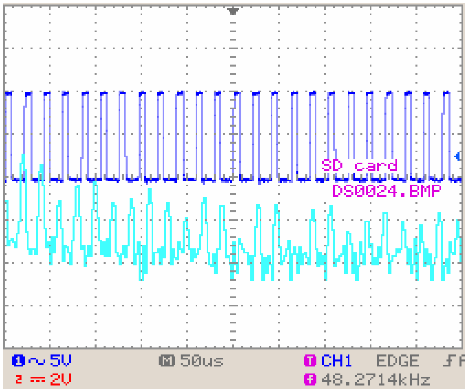

Fig. 13. PWM

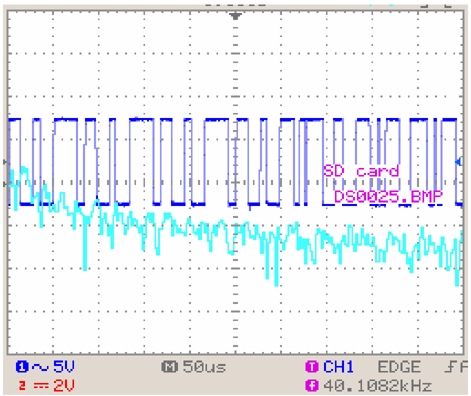

Fig. 14. Chaotic PWM

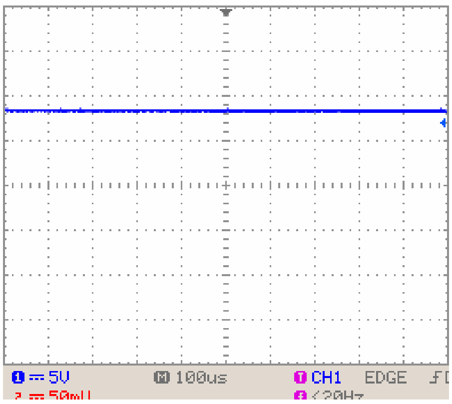

Fig. 15. Tracked input voltage from solar PV module

PWM and chaotic PWM are shown in Figs. 13 and 14.

The tracked input and output voltage from the solar PV module is shown in Figs. 15 and Fig. 16. The ripple voltage of the converter output voltage is analyzed using FFT. Fig 17 shows the ripple voltage in the output voltage is 200 m V. The spectrum of output voltage using conventional PWM is shown in Fig. 18. It implies that the db magnitude corresponds to fundamental frequency (25KhZ) is -10db Vrms when convention PWM is used as control method.

The SEPIC converter output voltage ripple using CPWM control method is shown in Fig. 19. The ripple voltage is

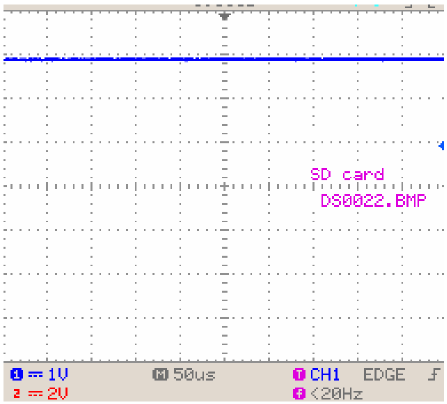

Fig. 16. SEPIC converter output voltage (multiplier=5)

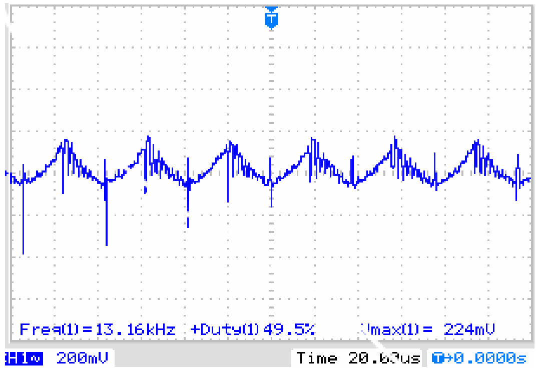

Fig. 17. Output Voltage Ripple (PWM)

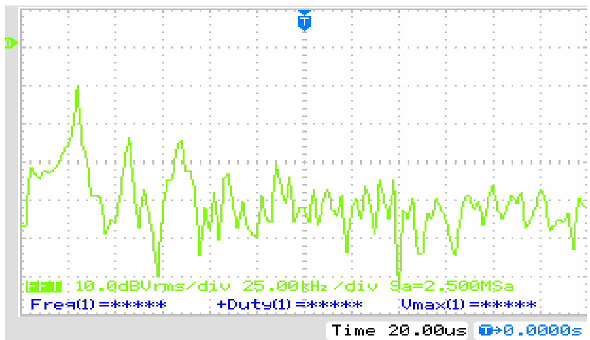

Fig. 18. Spectral analysis of output voltage using FFT

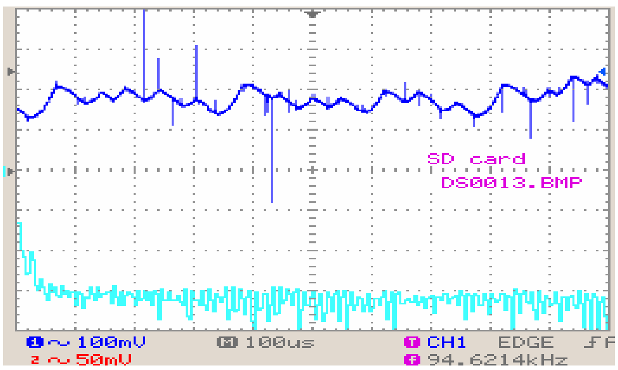

Fig. 19. Output voltage ripple and its spectrum analysis using FFT (Y-axis: 20 db)

only 80mV. The db magnitude corresponds to fundamental frequency is -40db Vrms. Hence high frequency harmonic peaks are eliminated to great extent.

6. Conclusion

The analogue chaotic PWM is generated and used as a control scheme to track the maximum power from PV module in order to improve the conversion efficiency of the MPPT system. The tracking efficiency is 98.6% without considering the efficiency of the solar PV panel and converter. The converter conversion efficiency is increased from 86% to 92% because of the lower average switching frequency in CPWM. The nominal duty cycle of the main switch of DC-DC SEPIC converter is adjusted so that the solar panel output impedance is equal to the input resistance of the SEPIC converter which results better spectral performance in the tracked voltages when compared to conventional PWM control.

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