CHAPTER 5

HARDWARE IMPLEMENTATION AND PERFORMANCE ANALYSIS OF CUK CONVERTER-BASED MPPT SYSTEM

5.1 INTRODUCTION

In coming up with a direct control adaptive perturb and observer MPPT method with Cuk converter, one of the more important factors that was considered is the simplicity of the design. The goal was to model a simple MPPT that would effectively extract the most power from the PV module. The components used are readily available and the MPPT does not require a complex tracking mechanism. However, to further improve the control performance and increase the functionalities for solar PV MPPT systems, a low-cost micro-controller is preferred. A micro-controller can replace multiplying analog and digital components, such as the error amplifier circuit and the PWM gate drive circuit.

Most micro-controllers incorporate timers, PWM Input and Output, ADC and DAC interfaces, interrupts for timing control and communications. They can also perform comparison functions.

A simple micro-controller, the ATMEGA16, is being evaluated and its features which include 16K bytes of self-programmable flash memory, 512 bytes of EEPROM, 8-channel- 10-bit ADC can be used to control a MPPT power circuit and tracking operation. The use of a micro-controller
provides more benefits as the MPPT operation can be enhanced by implementing a digital control strategy. An effective digital control strategy will better match the PV module’s output to the maximum power point when compared to the analog control method.

It is proposed to set up four different hardware environments to execute adaptive PAO algorithm using ATMEGA16 micro-controller: 1. Cuk converter with periodic carrier, 2. ZVS-Cuk converter, 3. ZCS-Cuk converter, and 4. chaotic PWM Cuk converter

5.2 COMPONENTS USED FOR DEVELOPING HARDWARE BOARD

- Power supply unit
- Micro-controller (ATMEGA16)
- Power circuit (Cuk converter, ZVS-Cuk converter, ZCS-Cuk converter, chaotic PWM Cuk converter

5.2.1 Design of Power Supply Unit

Power supply transfers electric power from a source to a load using electronic circuits. Some of the requirements of power supply unit are small size, lightweight, low cost, and high power conversion efficiency. It is also possible to generate multiple voltages using linear power supplies. In multi output power supply, a single voltage must be converted into the required system voltages (for example, +15V, +12V and -12V) with very high power conversion efficiency. The multi output power supply is used in the hardware board to supply power. The following devices are used to design the power supply unit.
1. Step down transformer (230/18v, 1A)

2. Diodes (DIN4007) - 4 NOS

3. Filter capacitor $C_1 = C_4 = 2200\mu\text{F}$
   
   $C_2 = C_3 = 0.1\ \mu\text{F}$

4. Voltage regulator (7812)

The hardware design diagram of implemented power supply unit is given in Figure 5.1

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**Figure 5.1 Power supply unit**

### 5.3 IMPLEMENTATION OF APAO MPPT ALGORITHM USING MICROCONTROLLER

The ATMEGA16 micro-controller is used to generate PWM. ATMEGA16 has four PWM channels. They are as follows:
1. Channel 0: This is an 8 bit PWM channel

2. Channel 1A: It consists of two channels channel 1A and channel 1B, both are 16 bit channels.

3. Channel 2: This is an 8 bit channel.

In AVR microcontrollers, PWM signals are generated by timers. There are two methods by which PWM is generated from timers:

1. Fast PWM

2. Phase Correct PWM

There are three basic registers associated with channel 0:

1. Timer Counter Control Register (TCCRO): This is an 8 bit register. By setting different bits of this, register mode of operation can be selected.

2. Timer Counter 0 (TCNT0): This is an 8 bit counter register.

3. Output Compare Register (OCR0): This is an 8 bit register. The counter register TCNT0 is compared with OCR register. Maximum value that can be stored in this register is 0xFF or 256. The output pin for channel 0 is OC0.

Suppose the value of OCR0 is 64, TCNT0 counter counts from 0. Initially OC0 pin is high. When TCNT0 counts 64, OC0 pin gets low but TCNT0 counts up to 255. After 255 count by TCNT0, TCNT0 is set to 0. The PWM is generated using timer 0 as shown in Figure 5.2
5.3.1 Fast PWM Mode with Timer/Counter 2 to Implement MPPT Algorithm

The fast Pulse Width Modulation or fast PWM mode provides a high frequency PWM waveform generation option. The fast PWM differs from the other PWM options by its single-slope operation. The counter counts from BOTTOM to TOP, then restarts from BOTTOM. In non-inverting Compare Output mode, the Output Compare (OC1x) is cleared on the compare match between TCNT1 and OCR1x, and set at BOTTOM. In inverting Compare Output mode, output is set on compare match and cleared at BOTTOM.

Due to the single-slope operation, the operating frequency of the fast PWM mode can be twice as high as the phase correct PWM mode that uses dual-slope operation. This high frequency makes the fast PWM mode well suited for power regulation, rectification, and DAC applications. High frequency allows physically small sized external components (coils, capacitors), thereby reducing total system cost. In fast PWM mode, the
counter is incremented until the counter value matches the MAX value. The counter is then cleared at the following timer clock cycle.

The PWM frequency of the output can be calculated by the following Equation

\[ F_{PWM} = \frac{F_{\text{clock}}}{N+256} \]  

(5.1)

where \( N \) is the prescale factor.

5.4 CODING FOR APAO MPPT ALGORITHM

Seven steps are involved in writing embedded C coding in AVR CODEVISION software tool in order to embed the APAO MPPT algorithm into ATMEGA16 micro-controller. The steps are

- Clock frequency selection and function declaration
- Timer 2 and ADC clock frequency initialization
- Analog to digital conversion for input data
- Selection of FAST PWM mode with Timer 2
- Computation of power and comparison
- PWM computation
- LCD initialization to display

The following program in Figure 5.3 shows the adaptive PAO MPPT algorithm used to track maximum power from solar PV module.
#include <mega16.h>
#include <delay.h>
#include <math.h>

// Function Declaration.
void lcdinit();
void lcdcmd(char);
void gotoxy(char,char); //x,y ; x-char position(0 - 16) y-line number 0 or 1
void lcddat(char);
void printstr(char *,char,char);
void split_numbers(unsigned int number);
void Read_Adc_Channel();
void PT_Calculation();
void Disp_Volt_ct();

// Timer/Counter 2 initialization
// Clock source: System Clock
// Clock value: Timer 2 Stopped
// Mode: Normal top=FFh
// OC2 output: Disconnected
ASSR=0x00;
TCCR2=0x69;
TCNT2=0x00;
OCR2=PWML;

// External Interrupt(s) initialization
// INTO: Off
// INT1: Off
// INT2: Off
MCUCR=0x00;
MCUCSR=0x00;

// Timer(s)/Counter(s) Interrupt(s) initialization
TIMSK=0x00;

// Analog Comparator initialization
// Analog Comparator: Off
// Analog Comparator Input Capture by Timer/Counter 1: Off

Figure 5.3 (Continued)
ACSR=0x80;
SFIOR=0x00;

// ADC initialization
// ADC Clock frequency: 1000.000 kHz
// ADC Voltage Reference: AREF pin
// ADC Auto Trigger Source: None
// Only the 8 most significant bits of
// the AD conversion result are used
ADMUX=ADC_VREF_TYPE & 0xff;
ADCSRA=0x83;
lcdinit();
printw(str,0,0);
printw(str1,0,1);
delay_ms(1500);
printw(str2,0,0);
printw(space,0,1);
printw(space,0,0);
printw(space,0,1);
while (1)
{
    Read_Adc_Channel();
    PT_Calculation();
    Disp_Volt_ct();
}

void Read_Adc_Channel()
{
    unsigned char i,PPT_Current_var;
    PPT_Volt = 0;
    PPT_Current = 0;
    PPT_Current_var = 0;
    for(i=0;i<60;i++)

Figure 5.2 (Continued)
```c
{ 
PPT_Current_var = read_adc(0);
PPT_Current = PPT_Current + PPT_Current_var;
}
PPT_Current = PPT_Current / 60;
PPT_Volt = read_adc(1);
PPT_Volt = (PPT_Volt / 5);
}

void PT_Calculation()
{
    // PWML = 0X32;
    char i;
    int power_result;
    Peak_ct = PPT_Current * 5;
    Power = Peak_ct * PPT_Volt;
    power_result = 1;
    power_result = (int)(Power - Power_Prev);
    if(power_result >= 0) // added =;
    {
        Power_Prev = Power;
        PWML = PWML + 2; // prev 4
        count1++;
        ASSR=0x00;
        TCCR2=0x69;
        TCNT2=0x00;
        OCR2=PWML;
        delay_ms(30);
    }
    Else
    {
    /* Power_Prev = Power;
```
PWML = PWML - 2;
count1++; 
ASSR=0x00; 
TCCR2=0x69; 
TCNT2=0x00; 
OCR2=PWML; 
delay_ms(30);*/
} 
// ASSR=0x00; 
// TCCR2=0x69; 
// TCNT2=0x00; 
// OCR2=PWML; 
/*if(temp == 0) 
  
  for(i=0;i<3;i++) 
  
  { 
    PWML = PWML + 4; 
    OCR2=PWML; 
  } 
  temp = 1; 
  } 
if(Power > Power_Prev) 
{ 
if(PWML < 0XB0) 
{ 
  Power_Prev = Power; 
  PWML = PWML + 2; 
  count1++; 
} 
ASSR=0x00; 
TCCR2=0x69; 
TCNT2=0x00; 
OCR2=PWML; 

Figure 5.3 (Continued)
} else if(Power <= Power_Prev)
{
if(PWML > 0x10)
{
Power_Prev = Power;
PWML = PWML - 2;
count2++;
}
ASSR=0x00;
TCCR2=0x69;
TCNT2=0x00;
OCR2=PWML;
}
else if(Power == Power_Prev)
{
Power_Prev = Power;
ASSR=0x00;
TCCR2=0x69;
TCNT2=0x00;
OCR2=PWML;
} /*
{
Power_Prev = Power;
ASSR=0x00;
TCCR2=0x69;
TCNT2=0x00;
OCR2=PWML;
} */
{
Power_Prev = Power;
ASSR=0x00;
TCCR2=0x69;
TCNT2=0x00;
OCR2=PWML;
} */

Figure 5.3 Embedded C code for APAO MPPT
The direct control used to extract maximum power from the solar PV module is carried out and tested with rheostat (0-50 Ω/5A) for the irradiation of 1000 W/m². The duty cycle of the main switch S in the Cuk converter varied to equalize solar PV module output resistance with load resistance to ensure the maximum power extracted.

In automatic or closed loop control, the Adaptive Perturb and Observer MPPT algorithm has been coded in Codevision AVR-C compiler to embed into ATMEGA16-8 bit micro-controller.

5.5 EXPERIMENTAL RESULTS

Figure 5.4 illustrates the hardware setup used to analyze the performance of MPP tracking using Cuk converter. The voltage and current are measured from the solar PV panel and given to the input ADC pins of the micro-controller. After the flash programming, the APAO algorithm shown in Figure 5.3 is embedded into the ATMEGA16 micro-controller chip. Large perturbation amplitudes are selected when the measured power is far away from the actual maximum power point and smaller perturbation amplitudes are selected when the measured power is closer to MPP. The micro-controller gives the PWM pulse which is used to trigger the main switch of the converter.

This process is a continuous closed loop and repeated until the maximum power point is reached. When the tracked power is equal or nearby actual maximum, the variation in the duty cycle of the gate pulse is nil. The so-obtained control PWM pulse, properly insulated and amplified, to trigger the MOSFET (IRF510) of a ZVS-PWM Cuk converter. Also TLO84CN-IC is used to compare the 25 kHz ramp signal with DC voltage to generate the PWM pulse for open loop control. Figure 5.5 shows the generated carrier and gate pulse waveform for the switches S₁ and S₂.
Based on the data given by the solar centre, Indian Metrological Department, the average solar irradiation data for Chennai city, Tamilnadu, INDIA, for the year 2012 is shown in Table 5.1 and the experimentation is conducted to validate the MPPT algorithm.

Table 5.1 Annual solar irradiation data for Chennai

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar irradiation MJ/m² (1MJ/m²=0.27KWH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>7.58</td>
</tr>
<tr>
<td>February</td>
<td>6.88</td>
</tr>
<tr>
<td>March</td>
<td>7.25</td>
</tr>
<tr>
<td>April</td>
<td>8.05</td>
</tr>
<tr>
<td>May</td>
<td>9.20</td>
</tr>
<tr>
<td>June</td>
<td>10.56</td>
</tr>
<tr>
<td>July</td>
<td>11.02</td>
</tr>
<tr>
<td>August</td>
<td>11.18</td>
</tr>
<tr>
<td>September</td>
<td>9.48</td>
</tr>
<tr>
<td>October</td>
<td>8.52</td>
</tr>
<tr>
<td>November</td>
<td>7.75</td>
</tr>
<tr>
<td>December</td>
<td>7.62</td>
</tr>
</tbody>
</table>
5.5.1 Control Circuit Design to Generate Chaotic Carrier

The control circuit to generate chaotic carrier is designed by coupling a Chua diode with a 555 timer triangular wave generator. This circuit contains only resistor, capacitor and operational amplifier. By selecting the proper values of element, the control circuit experimentally generates chaotic carrier.

Analogue carriers used for the DC–DC converters, such as triangle waves and sawtooth waves, are generated by charging and discharging of a capacitor. A simple circuit shown in Figure 5.6 which contains a (555 timer) triangular wave generator and a three segment piecewise linear resistor is known as a Chua diode. The operational amplifiers and the associated resistances ($R_{d1}$ …… $R_{d6}$) are used to realise linear resistor called Chua diode. The parameters for Chua’s diode are chosen as $R_{d1} = 2.4 \, k\Omega$, $R_{d2} = 3.3 \, k\Omega$, $R_{d3} = R_{d4} = 220\Omega$, and $R_{d5} = R_{d6} = 20 \, k\Omega$.

The resistor R is a potentiometer and can be used to tune the circuit to observe chaotic behavior. The 555 timer circuit uses two comparators,
comparing $V_T$ against 1/3 and 2/3 of $V_{cc}$ (15V) to determine whether to flip the output state. The capacitor voltage is charged up or down by turning on or off a discharge transistor. This transistor pulls charge out of the capacitor, or when off, it allows the capacitor to charge up toward the positive supply. The astable mode of operation is preferred in order to generate sawtooth waveform and it is operated in the passive mode.

The charging and discharging times of the capacitor generally are different depending on whether the transistor in 555 timer is turned on or off.

$$t_1 = 0.693(R_1 + R_2)C \quad \text{charging, output HIGH}$$

$$t_2 = 0.693R_2C \quad \text{discharging, output LOW}$$

The frequency of oscillation is given by the inverse of the period, where the period is $t_1 + t_2$, or in terms of $R$ and $C_T$

$$F = \frac{1.44}{(R_1 + 2R_2)C_T}$$

**Figure 5.6 Control circuit for generation of chaotic carrier**
The hardware generated chaotic carrier, chaotic PWM, the solar PV module output voltage (converter input voltage) and converter output voltage, measured input voltage, and input inductor current of the converter are shown in Figures 5.7, 5.8, 5.9, 5.10, and 5.11, respectively.

Figure 5.7  Chaotic carrier (Horizontal scale: $100 \times 10^{-6}$ sec/div, Vertical scale: 2V/div)

Figure 5.8  Chaotic PWM (Horizontal scale: $50 \times 10^{-6}$ sec/div, Vertical scale: 5V/div)
Figure 5.9  Input and output voltage waveforms during MPP tracking  
(Horizontal scale: $10 \times 10^{-6}$ sec/div, Vertical scale: 5V/div)

Figure 5.10  Tracked Input voltage waveform of the converter  
(Horizontal scale: $50 \times 10^{-6}$ sec/div, Vertical scale: 5V/div)

Figure 5.11  Measured input inductor current waveform  
(Horizontal scale: $20 \times 10^{-6}$ sec/div, Vertical scale: 500mV/div=500mA/div)
5.5.2 Effectiveness of APAO Algorithm under Partial Shaded Condition

The effectiveness of Adaptive Perturb and Observer MPPT algorithm to track the maximum power under partially shaded condition is experimentally tested. The shading effect was artificially generated by covering three cells of the L1235-37Wp solar PV module with partially transparent gelatin paper. The average solar flux on the solar PV module was considered as 940 W/m² that is in accordance with the average solar flux at 11:45 A.M. on November 5, 2012 at Chennai, India. The tracked input voltage under partial shaded condition is shown in Figure 5.12. The tracked power from the solar PV module is lowered when solar cells are shaded. The Adaptive Perturb and Observer MPPT algorithm tracks maximum power under shaded condition by avoiding local maxima successfully since the step size is high when the operating point is far away from MPP, which are shown in Figures 5.13 and 5.14.

Figure 5.12 Tracked input voltage under 3 PVcells are in shaded condition (Horizontal scale: 50*10⁻⁶ sec/div, Vertical scale: 5V/div)
The discrepancies in the curves at some points may be due to the change in irradiation over a time span during which the measurements are carried out.

5.6 SPECTRAL ANALYSIS OF CUK CONVERTER-BASED MPPT SYSTEM WITH DIFFERENT CONTROL METHODS

Normally, the strength of the EMI is measured by the estimation of the system harmonics, by deriving the power-spectral density based on fast Fourier transform. This approach can provide better results for signal
processing and it assumes the harmonics to be integral multiples of the fundamental frequency. FFT can detect the fundamental frequency and its integral multiples.

The output voltages with ripple measurement of the Cuk converter based MPP tracking with four different control methods, i.e., traditional PWM with periodic carrier, ZVS-soft switching, ZCS-soft switching and PWM with chaotic carrier. The power spectrum of output voltage is also shown using FFT analysis.

The block diagram of MPPT system with closed loop control using Cuk converter, ZVS-PWM Cuk converter, ZCS converter, chaotic PWM Cuk converter is illustrated in Figure 5.15. To verify the functionality and performance of the proposed adaptive PAO algorithm, a 37Wp low power test bench as shown in Figure 5.4 was set up experimentally.

![Block diagram of MPPT system with four control methods](image)

Figure 5.15  Block diagram of MPPT system with four control methods

The voltage across the main switch S (Drain to source voltage $V_{ds}$) and the switch current wave form for Cuk converter, ZVS-Cuk converter,
ZCS-Cuk converter and chaotic PWM Cuk converter are shown in Figures 5.16, 5.17, 5.18, and 5.19. In Figure 5.20, the ripple content in output voltage of converters is observed during the MPP tracking, the presence of transients in the output voltage is low.

**Figure 5.16** Voltage ($V_{ds}$) and current ($I_d$) waveform across main switch $S$ of Cuk converter (Horizontal scale: $10*10^{-6}$sec/div, $V_{ds}$: Vertical scale= $2V*10$/div, $I_d$: Vertical scale= $2A$/div)

**Figure 5.17** Drain to source voltage ($V_{ds}$) across the switch $S_1$ of Cuk and ZVS-PWM Cuk converters (Horizontal scale: $20*10^{-6}$sec/div, Vertical scale: $2V*10$/div)
Figure 5.18 Voltage ($V_{ds}$) and current ($I_{d}$) across switch S in ZCS-Cuk converter. (Horizontal scale: $10\times10^{-6}$ sec/div, $V_{ds}$: Vertical Scale = $2V\times10$ div, $I_{d}$: Vertical scale = 1 A/div)

Figure 5.19 Voltage ($V_{ds}$) and current ($I_{d}$) waveform across main switch in chaotic PWM Cuk converter. (Horizontal scale: $25\times10^{-6}$ sec/div, $V_{ds}$: Vertical scale = $2V\times10$ div, $I_{d}$ : Vertical scale = 1 A/div)
Figure 5.20  Ripples in the output voltage of the converters. (Horizontal scale: 20*10^{-6} sec/div, Vertical scale: 200mV/div)

Figure 5.21 shows the FFT analysis on the output voltages of the converters. It is proved that the high frequency harmonic components are eliminated and hence the EMI is low in case of ZVS-Cuk converter-based MPP tracking when compared in Figure 5.22 with Cuk converter-based tracking. The PSD value corresponding to fundamental frequency is -10db for ZVS-PWM Cuk converter-based MPP tracking which is low in Cuk converter. Hence, it is concluded that electromagnetic compatibility is improved when soft switching is performed on the Cuk converter

Figure 5.21  FFT analysis of output voltage of ZVS-Cuk converter
(Horizontal scale: 25kHz/div, Vertical scale= 10dBV_{rms}/div)
To improve the electromagnetic compatibility and the converter conversion efficiency, zero current switching and chaotic PWM are implemented on the Cuk converter-based MPP tracking.

From Figure 5.23, the PSD value is -42db in ZCS-PWM Cuk converter and it is good when compared with Cuk converter-based MPP tracking. From the FFT analysis in Figure 5.24, it is evident that ZCS-Cuk is the better choice for MPP tracking since the EMI is low at the high frequency operation.
It is seen from the spectral analysis of Figure 5.24 that the high frequency harmonic components are eliminated and hence the EMI is low in case of chaotic PWM-Cuk converter based MPP tracking when compared with soft switching and Cuk converter based-MPP tracking. The PSD value corresponds to fundamental frequency is -48dB for chaotic PWM-Cuk converter. Hence, it is concluded that electromagnetic compatibility is improved when chaotic PWM- Cuk converter is used for MPP tracking.

Figure 5.24  CPWM-Cuk converter-output voltage ripples and their FFT spectrum (Horizontal scale: 100*10^{-6} sec/div, Vertical scale: 100mV/div, FFT spectrum vertical scale: 20dB V_{rms}/ div)

5.7 PERFORMANCE COMPARISON OF MPPT CIRCUITS WITH FOUR CONTROL METHODS

The four different control methods are implemented in DC-DC Cuk converter-based direct control MPPT method. From the spectral analysis of tracking system, the performance comparison of MPPT circuits is shown in Table 5.2.
Table 5.2  Performance comparison of Cuk converter-based PV system with various control methods

<table>
<thead>
<tr>
<th>MPPT tracking circuits</th>
<th>Converter conversion efficiency</th>
<th>PSD value in output voltage ripples (Fundamental frequency =25kHz)</th>
<th>Output voltage ripples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuk converter with periodic carrier</td>
<td>86.26%</td>
<td>+4 DB</td>
<td>200mv</td>
</tr>
<tr>
<td>ZVS-Cuk converter</td>
<td>91.26%</td>
<td>-10 DB</td>
<td>180mV</td>
</tr>
<tr>
<td>ZCS-Cuk converter</td>
<td>91.12%</td>
<td>-42 DB</td>
<td>54mV</td>
</tr>
<tr>
<td>Chaotic PWM Cuk converter</td>
<td>93.1%</td>
<td>-48 db</td>
<td>80 -100mV</td>
</tr>
</tbody>
</table>

The direct control chaotic PWM Cuk converter-based MPPT circuit has better spectral performance. It eliminates higher order harmonic in the output voltage of MPPT system. The converter conversion efficiency is increased from 86.26% to 93.1%.

5.8  CONCLUSION

The Adaptive Perturb and Observe algorithm is implemented using ATMEGA16 micro-controller. Cuk converter is used to interface solar PV module and a load. The proposed direct control APAO MPPT method eliminates PI control loop which is available in conventional MPPT method. Four different control methods for DC-DC Cuk converter were proposed for Maximum Power Tracking Circuits in order to reduce peaky EMI in the DC-
DC converter output voltage. The converter conversion efficiency is increased when direct control chaotic PWM Cuk converter is used as MPP tracker circuits. Both simulation and experimental results have confirmed that chaotic PWM based Cuk converter reduces peaky EMI in MPPT solar powered system and it offers better spectral performances than soft switching DC-DC converters.