Implementation of P&O Algorithm in MPPT Controlled Inverse Sepic Converter for Low Power Applications

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***Abstract*— This study is focused on implementation of perturb and observe (P&O) algorithm in inverted single ended primary inductor converter (SEPIC) maximum power point trackers (MPPTs) integration and operation of a single-phase inverter with for low power applications. Since the photovoltaic (PV) array voltage can vary from 0 to 21 V, especially with thin-film PV panels, the MPPT topology is formed with SEPIC converters to operate at the dc-bus voltage around 14 V to track the maximum power from the solar panel. A comparison between the conventional SEPIC MPPT and the proposed inverted SEPIC MPPT integrated with a PV inverter is also presented. Peripheral Interface Controller (PIC) microcontroller is used to control the SEPIC MPPT and sinusoidal pulse width modulation (SPWM) single phase inverter. Experimental results obtained from a 100W system have verified the discussion and feasibility.**

Keywords- SEPIC, Maximum Power Point Tracking, P&O, DC-Dc step up converter, SPWM, Single phase inverter

I. INTRODUCTION

The limited reserves of fossil fuels have significantly increased the interest in renewable energy sources. Solar energy is the most abundant and easily available renewable resource. The solar systems is the most widely used where the load is relatively small. In commercial, industrial sectors, and in rural areas where power shortage is chronic. Using a solar panel or an array of panels without a controller that can perform Maximum Power Point Tracking (MPPT) will often results in low output power, which ultimately results in the need to install more panels for the same power requirement [1] [2] [3] [4]. For smaller/cheaper devices that have the battery connected directly to the panel, without charge controller will result in premature battery failure. In short, not using an MPPT controller will result in a higher installation cost and, with time, the costs will escalate due to eventual equipment failure. Even with a proper charge controller, the prospect of having to pay 30-50% more up front for additional solar panels makes the MPPT controller very attractive. As the number of photovoltaic systems and electric vehicles increases, so does the demand for intelligent, high-power and high-efficiency battery chargers. Most systems on the market today use either lead-acid or lithium type batteries, requiring constant current/constant voltage charging algorithms. This paper contains the necessary information to build a 100W Zeta converter battery charger.

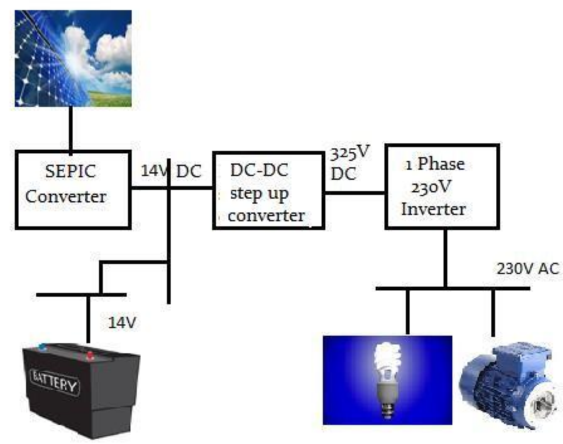


Fig.1 Block diagram of proposed SEPIC converter system integrated with 1-Phase inverter

The novelty consists in driving this topology synchronously, essentially pushing the efficiency over 95%. The Zeta converter has many advantages, such as input to output DC insulation, buck-boost capability and continuous output current[5]. The control scheme is also interesting, as it uses the Numerically Controlled Oscillator (NCO) peripheral to implement a form of fixed on-time, variable frequency control that allows 15 bits of resolution for the control system. Finally, since this implementation allows the control of the output voltage and current with a high resolution, it is quite easy to attach multi-chemistry battery charging algorithms to the basic output regulation loop, greatly increasing its usefulness. The complete implementation of the regulator and charger library uses only 1k words of program space and 55 bytes of RAM. Figure1 shows the block diagram of proposed SEPIC converter integrated with solar panel and inverter.

This paper describes the implementation of MPPT controller to solar system with battery storage, using the most popular switching power supply topologies. Even when using the simplest MPPT with a algorithm well-designed synchronous switching power supply, it can be expected that at least 90% of the panel's available power will end up in the battery, so the benefits are obvious. The topology presented in this is inverse SEPIC. In this case, the algorithm modifies the solar panel operating voltage by using a proportional integral (PI) control loop, which steers the voltage to the desired value 14V. To get the 230V ac from 14V dc output of SEPIC is converted to high dc using dc-dc step-up converter to achieve 325V dc, and is given to single phase SPWM inverter to drive AC loads. PIC16F1503 14 pin microcontroller is used to implement SEPIC MPPT controller, and PIC16F877A 40 has no NCO feature hence separate microcontroller is used to implement SPWM single phase inverter.

II. OPERATION AND ANALYSIS OF THE PROPOSED ZETA CONVERTER

Considered by many designers as an "exotic" topology, the ZETA converter (also known as the inverted SEPIC) offers certain advantages over the classical SEPIC.
This topology has the same buck-boost functionality as the SEPIC, but the output current is continuous, providing a clean, low-ripple output voltage make. This low-noise output converter can be used to power certain types of loads, such as LEDs, which are sensitive to the voltage ripple. The ZETA converter offers the same DC isolation between the input and

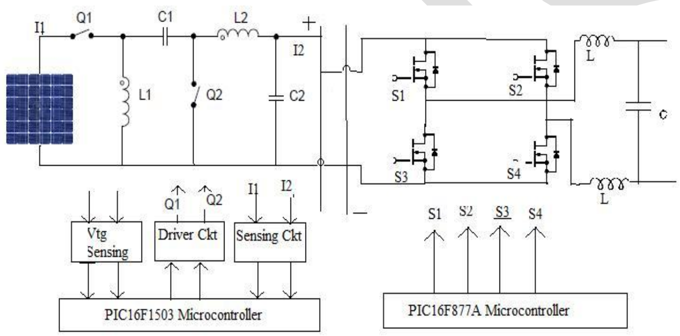


Fig. 2 Proposed Inverted SEPIC MPPT and inverter

output as the SEPIC converter, and can be used in high-reliability systems. This topology can also offer high efficiency, especially if the synchronous rectification is used. The synchronous rectification can be easily implemented here, because this topology, unlike the SEPIC converter, uses a low-side rectifier.

The SEPIC MPPT converter output is integrated to 14V dc bus. To this bus the DC load battery is connected. To the same DC bus inverter is connected through dc-dc resonant converter and the output is supplied SPWM inverter to connect AC loads. There are three different modes of operation with system considered,

I) When the solar panel is at its peak both the AC and DC load are supplied,

II) When the solar panel output is less than its peak value, then power generated is supplied to DC loads only, and AC loads are disconnected by sensing the output current of inverter if its below preset value.

III) When panel output at MPPT is too low then load is supplied by charged battery only to DC loads. In this way the continuity of supply is maintained to loads.

The ZETA converter power train is depicted in Figure 3.
The two switches, Q1 and Q2, operate out of phase. As with the SEPIC converter, there are two switching cycles that are presented in Figure 4(a) and 4(b).

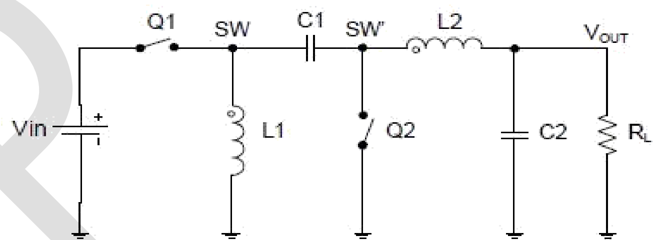


Fig. 3 Inverted SEPIC(Zeta) Converter

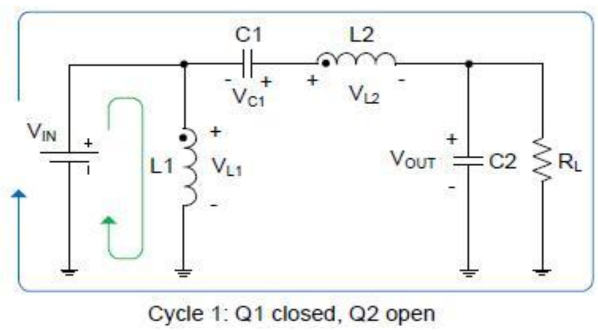


Fig. 4(a) Switching cycle 1 of Inverted SEPIC(Zeta) Converter

In the first cycle, Q1 is closed and the current begins to flow in the primary inductor L1 and through the load via the coupling capacitor C1 and inductor L2. In the second cycle, Q2 is closed and the energy stored in the L2 inductor is delivered to the load. The energy stored in the main inductor L1 will be reset to its initial value through the coupling capacitor C1.

The continuous current flow on the load is maintained by the output inductor L2. The voltage across the main switch (Q1) is the sum of the input and output voltages as is the case with the SEPIC converter. The voltage stress across the main

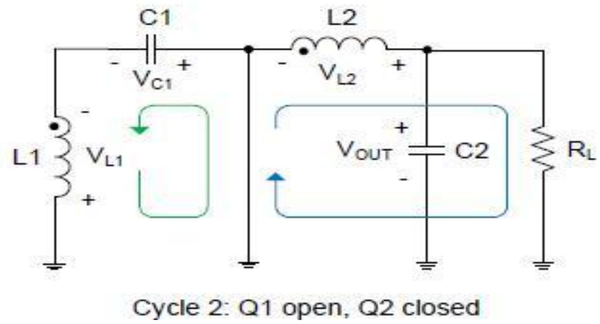


Fig. 4(b) Switching cycle 2 of Inverted SEPIC(Zeta) Converter

switch is higher and can increase the switching losses of Q1. The two inductors can be magnetically coupled, sharing the same magnetic core. This can greatly reduce the current ripple, as the mutual inductance will double the apparent value of the inductors.

"On State" $V_{L1} = V_{IN}$

$V_{L2} = V_{IN} + V_{C1} - V_{OUT}$

"Off State" $V_{L1} = -V_{C1}$

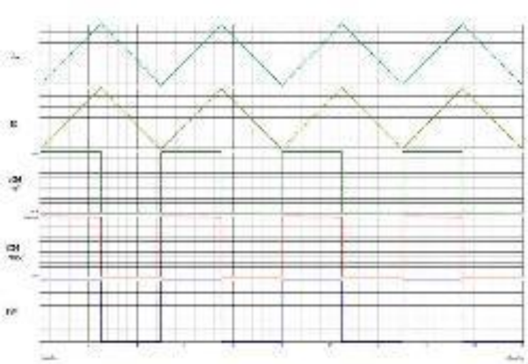
$V_{L2} = -V_{OUT}$…………………..(1)

$D * V_{IN} - (1-D) * V_{C1} = 0$

$D * (V_{IN} + V_{C1} - V_{OUT}) - (1-D) * V_{OUT} = 0$….(2)

$V_{OUT} = \frac{D}{1-D} * V_{IN}$……………..(3)

The typical waveforms of the ZETA converter are presented in below



PIC16F1503 is one of the enhanced core devices, which benefit from the recent line of peripherals, such as the NCO (Numerically Controlled Oscillator), CWG (Complementary Wave Generator) or CLC (Configurable Logic Cell). To implement a software-controlled regulation loop : - 2 ADC inputs (10-bit) for monitoring output voltage and current.

- 1 NCO output for the converter control signal
- 1 Timer for the main timer tick
- LED signaling, serial interface for logging

Since there is only one regulation loop, the firmware must decide if it needs to regulate the current or voltage at a certain time. The decision is simple enough: if the read voltage is over the set voltage reference, the converter will limit the voltage; if the read current is over the set current reference, then the converter will limit the current. The function cc_cv_mode() takes care of the transitions between the two working modes, and the variable cmode shows whether the current or voltage is currently regulated.
The PI function operates on the NCO increment, practically varying the duty cycle by varying the frequency. The NCO operates in Pulse Frequency mode configured for a 2 µsec pulse. At 500 kHz, we have 100% duty cycle, so the maximum increment value is clamped to 29500 (out of 32768), which gives 450 kHz or 90% duty.
With buck converter is a special case, since it has a linear voltage transfer function when operating in Continuous Conduction Mode (CCM). This simplifies things a lot, and the MPPT controller can be implemented by operating directly on the converter duty cycle. The other topologies have a nonlinear voltage transfer function, and operating directly on the converter duty cycle will yield unpredictable results, especially at high duty cycles.

A. Flow chart

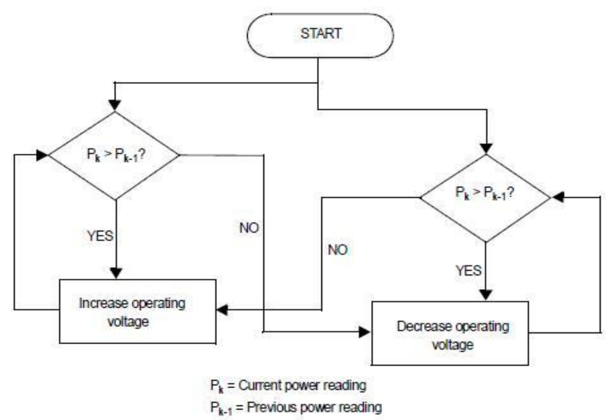


Fig. 5 P&O Algorithm for implementation of MPPT

P&O(perturb and observation) is one of the most discussed and used algorithms for MPPT [6]. The algorithm involves introducing a perturbation in the panel operating voltage.
Modifying the panel voltage is done by modifying the converter duty cycle. The way this is done becomes important for some converter topologies. Looking at Figure makes it easy to understand that decreasing voltage on the right side of the MPP increases power. Also, increasing voltage on the left side of the MPP increases power. This is the main idea behind P&O. The algorithm calculates the power drawn from the panel using the averaged readings of the input voltage (f_vin) and current (f_iin). The power

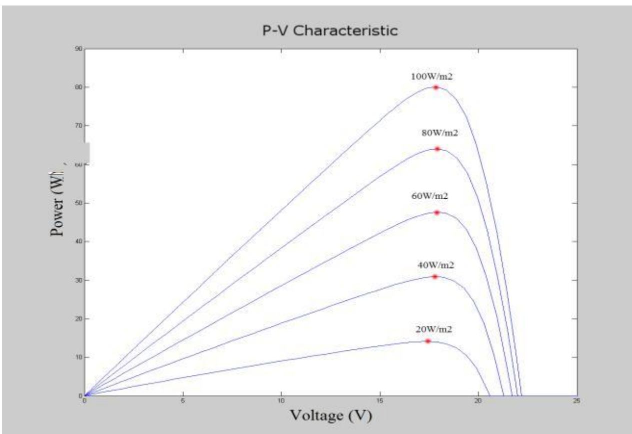


Fig. 6 Power-Voltage(P-V) characteristic with MPP points for different intensity illumination

value is memorized at each iteration and is compared to the calculated power. If power has decreased, the algorithm changes direction. The MPPT step is user definable. For this algorithm, simplicity and robustness are the main advantages, but because the panel operating voltage naturally oscillates about the MPP, some of the available power is lost.

B. Implementation of zeta converter

This implementation uses the fact that the device can either track the panel MPP, or regulate the output (but not both of them at the same time). While tracking the panel MPP, a number of input voltage and current samples are summed together for noise reduction, and then fed to the perturb and observe MPPT algorithm. The MPPT algorithm modifies the input voltage reference, and the PI (proportional integral) loop steers the panel operating voltage to that reference voltage. The PI control loop needs to run many times faster than the MPPT algorithm, so that the panel voltage has enough time to stabilize. If the output voltage or current are over the set limits, the Tracking mode ends and the control loop starts regulating output. This means that the panel can provide more power than the battery (or load) can absorb[7] [8]. The converter duty cycle is memorized when the tracking mode ends. Normally, the output voltage is fixed so when the panel voltage goes down, the duty cycle needs to be increased to maintain the output. If the duty cycle is increased above the memorized value, then the panel voltage has fallen below the MPP. This is a easy way of knowing that the main loop needs to return to the tracking mode. Other methods could use output current or voltage as indicators. If in Regulation mode, but not able to reach the set voltage or current, it is clear that the panel is not able to provide enough power for the load, and the main loop needs to switch back to tracking mode.

One other important thing is that the battery state machine will only update in output Regulation mode. In tracking mode, neither the output voltage, nor current limit is reached, so the charge termination protocols will not function properly. Even in low light conditions (slow charging), if the battery reaches the constant voltage stage, charge will be terminated as soon as the current falls under the threshold. To avoid keeping the cell or battery at high voltage, which is known to cause damage in the long run, another termination condition can be added to terminate charge if the current is too low, but the voltage is over a certain threshold. This is mostly required to protect Li-Ion chemistry batteries, since lead-acid is much cheaper and more tolerant to abuse.

C. MPPT Software Implementation

The PIC MCU used for this prototype is an 8-bit device without a hardware multiplier, so the computational power is limited. This makes everything extremely attractive from a cost standpoint, but also makes the implementation more challenging. Having a multi-step battery charger and an MPPT controller running on the same chip is a challenge due to the following issues:

- Device must regulate output current
- Device must regulate output voltage
- Device must track the panel MPP
- Device must run a battery-charging state machine
- Device has limited computational power and must run only one regulation loop

IV. SINGLE PHASE SPWM INVERTER

A common use of the H bridge is an inverter. The arrangement is sometimes known as a single-phase bridge inverter. The H bridge with a DC supply will generate a square wave voltage waveform across the load. Block diagram of Implementation of SPWM using Sine wave table is shown in fig 7. When digitally producing sine wave, we do so using a fixed number of square wave pulses. The larger the number, the cleaner the sine wave [9] [10].

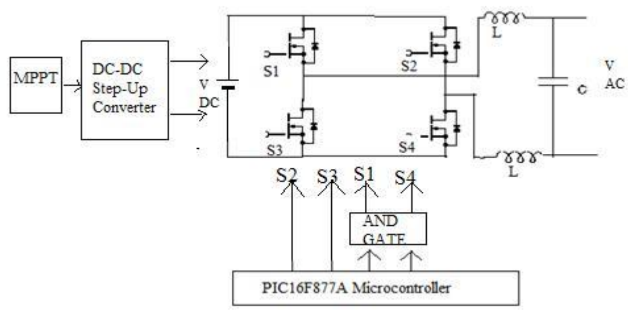


Fig 7. Block diagram of SPWM single phase inverter

So, for example, we use 10 samples, in practice, 10 is too less and usually at least 32 are taken.

So, we have y=sin(x). X varies between 0' to 360'. But we focus on one half and then reverse this to have the negative half. Since we have 10 samples, we divide the positive half of the sine wave into 10 parts. The first part is 0' to 18'.We will send pulses, one at 0' and other at 18', the next pulse at 36', then at 54' and so on. So, the values needed are shown in tableI:
We do not take sin(180) as this value will be next called when we implement sin(0), which both equal 0. Now, to implement this using PIC PWM. 1 represents 100% duty cycle, 0 represents 0% and 0.5 represents 50%.
To put these values into proper sine table PR2 is calculated as.

TABLE I Sine wave table

Y=sin(X)	Y%	Digital value
Sin(0)	0	0
Sin(18)	0.31	77
Sin(36)	0.59	147
Sin(54)	0.81	202
Sin(72)	0.95	237
Sin(90)	1	250
Sin(108)	0.95	237
Sin(126)	0.81	202
Sin(144)	0.59	147
Sin(162)	0.31	77

PR2= [PWM Perioed / (4*TOSC*{TMR2 Prescale Value})] - 1

Where PR2 and TMR2 is Timer2 period Register and Timer2 Module Register respectively.

Now, operating frequency is decided PWM (carrier frequency), with 16MHz crystal oscillator, carrier frequency is taken as 16KHz. Giving us, PR2=249

So we design 249 to PR2. The duty cycle register is CCPR1L. When CCPR1L=0, duty cycle=0, when CCPR1L= (PR2+1), duty cycle = 100%. This is because (PR2+1) = Period. So, CCPR1L/(PR2+1)= Duty cycle

So, here we generate the same SPWM (shown in fig 11) signals using just one CCP module which can be commonly found on many microcontrollers, this one signal is converted to four signals to four H bridge switches using AND gate. This allows much greater flexibility in microcontroller selection. H bridge is driven by IR2110 mosfer gate driver.

V. EXPERIMENTAL RESULTS

TABLE II. Key components of the SEPIC Converter

Specification	Value
PV Voltage	0-21 V
MPPT DC Outpt	14 V
Step up Dc-Dc converter	220 V
Output Power(max)	100 W
Inverter output	156 V

Table II shows the specification of the system, the desired value for step up dc-dc converter is obtained, The MPPT converter desired value and integration is being carried out.

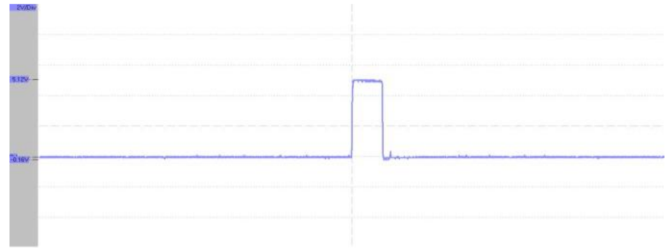
TABLE III. Key components of the SEPIC Converter

Component	Value
PIC microcontroller	PIC16F1503
Mosfet gate driver	MCP14628
Switches Q1,Q2	IRF740
Inductor L1,L2	10uH
Capacitor C1,C2	10uF
Battery	1.3Ah,12V

TABLE IV. Key components of the single phase SPWM Inverter

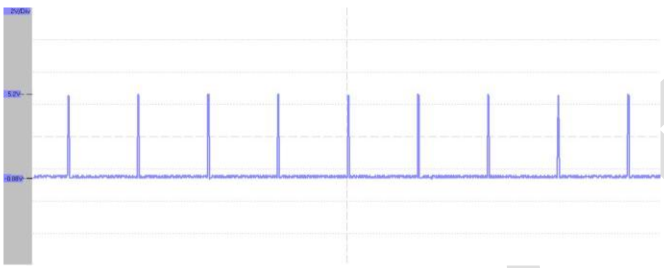
Component	Value
PIC microcontroller	PIC 16F 877A
Mosfet gate driver	IR 2110
H bridge switches	IRF740
L - Filter	8.37mH
C - Filter	10uF
AND gate	7804

To verify the PV inverter system with P&O MPPT algorithm, a 100W, SEPIC MPPT converter with single phase inverter was designed and implemented. The key components for SEPIC and inverter are shown in Table III and IV respectively.



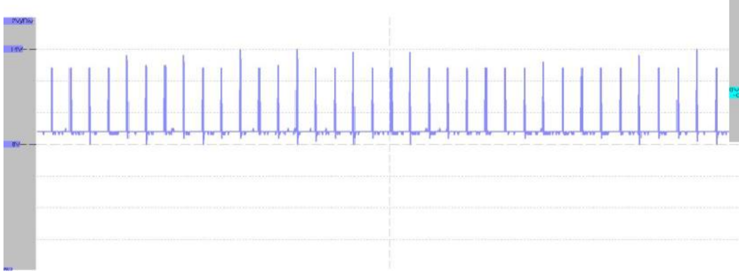
(2V/div, 5V pulse)
Fig. 8 Measured waveform of NCO output from SEPIC MPPT microcontroller

The control signal for MPPT from NCO of microcontroller is shown in fig 8 and fig 9 which is given as single input to the synchronous mosfet gate driver, which drives two switches

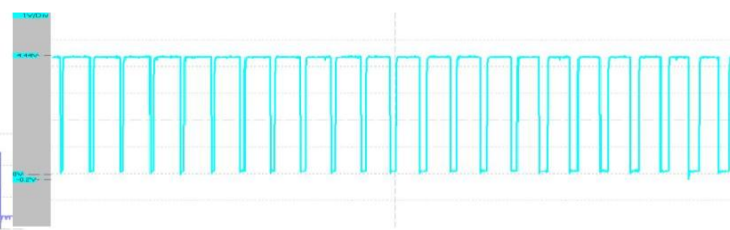


(2V/div, 5V pulse, 2.22usec)
Fig. 9 Measured waveform of NCO output from SEPIC MPPT microcontroller

5V/div, (6V)
Fig. 10 Measured waveform of SEPIC converter output



2V/div 5V peak
Fig. 9 SEPIC converter mosfet gate pulse



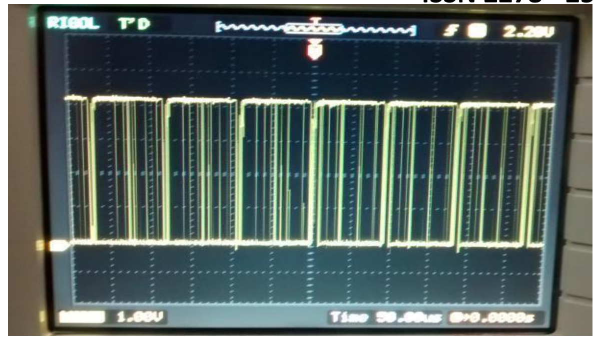
2V/div
Fig. 11 Measured SPWM waveform PIC16F877A for inverter

of inverse SEPIC MPPT converter. The measured waveform of gate pulses is shown in fig 9. The 6V output of the SEPIC converter is obtained, and shown in fig 10, desired value is expected in PCB circuit which is in progress.

The measured SPWM control signal waveform is obtained at 16kHz from microcontroller from one pin. It is given to AND gate to give to S1 and S4 switch of H-bridge. And two 50% duty cycle is given complimentary to S2 and S3.

The SPWM Waveform is show in fig 11 and 12.

The measured output waveform of the H-bridge is shown in fig 13, which will be given to low pass filter to obtain sinusoidal signal of 50Hz.



(1V/div, 5V)
Fig12 Measured waveform of SPWM continuously varying square wave pulse.

(5V/div, 20msec)
Fig .13 11Vp-p for H-bridge input of 15V

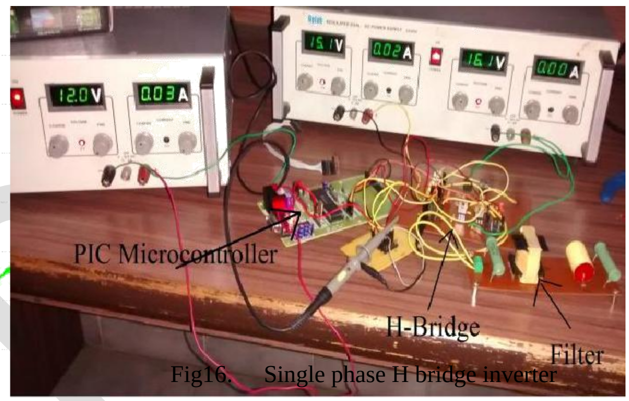


Fig16. Single phase H bridge inverter

VI. PROTOTYPE OF DESIGNED PV INVERTER SYSTEM

Fig. 14. 100W SEPIC MPPT converter

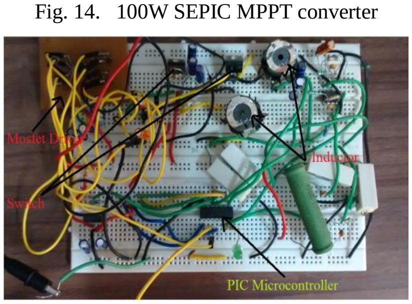


Fig. 15. DC-DC step-up resonant converter

CONCLUSION

Using MPPT with solar panel installations has clear advantages. The initial investment is smaller because smaller panel wattage is required and adding correct battery-charging algorithms will also decrease operating costs (batteries are protected and last longer).

The same code can be used with minimal tuning on other topologies like buck, boost and even for wind applications. By utilizing the techniques presented in this paper it is possible to optimize the cost and extend the life of any solar powered application ranging from a few watts to two hundred watts by adding MPPT.

Since the SEPIC MPPT prototype is done in breadboard the output of is not upto the desired value as for high frequency operation with above 5V the breadboard circuit does not provide accurate values. PCB design is in progress. Control signals are obtained from microcontroller and mosfet drivers and are shown for SEPIC MPPT.

Single phase H-Bridge SPWM is designed and implemented on PCB, and the square wave output is obtained, filter design is to be implemented. Integration of SEPIC and inverter through high dc-dc converter is to be carried out for a complete reliable power supply.

ACKNOWLEDGMENT

- The P & O algorithm was implemented with battery charge control in inverse SEPIC MPPT converter and control signals was verified.
- The same algorithm and circuit can be implemented for other converters like boost, and classic SEPIC converter.
- The single phase SPWM inverter with sine wave table was implemented and control signals was verified.
- The H-bridge is implemented with mosfet gate driver circuit for inverter operation.
- The efficiency is expected to be high as circuit involves synchronous rectification.

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