Isolated Single Phase PV String Inverter with DSP Based Multi-Loop MPPT Control

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Abstract— This paper describes the design and implementation of a Digital Signal Processor (DSP) based PWM controlled isolated single-phase inverter that produces a symmetric AC output voltage of desired magnitude and frequency. Compared with the traditional analog approach, a 16-bit fixed point DSP controls a dc-ac inverter—reducing its size, increasing its efficiency and cutting total harmonic distortion in the presence of highly nonlinear loads. A new multi-loop Maximum Peak Power Tracking (MPPT) control system has been developed, consisting of a Flyback topology dc/dc converter, which is controlled by DSP. The resulting system is highly effective for low output power applications and can be applied to provide DC power supply for micro-inverters either for grid-connected or standalone system. The performance of the proposed PV MPPT control system is compared by implementing the multi loop control algorithm on 16/32-bit DSPs and tested on a 200W MOSFET-based inverter switching at 20 kHz. It is concluded that the proper choice of controller can drive out more output power from PV panel even from a simple control algorithm. Simulation and prototype results describe the performance of the proposed design prototype and in agreement with the predictions of theoretical analysis, 16 bit DSP TMS320LF2401A, 32 bit DSP TMS320F28027 and 32 bit DSP with floating point unit TMS320F28069 are used to compare the performance of the proposed design.

Index Terms— single phase string inverter, MPPT, fly-back converters, photovoltaic system, PWM, DSP.

I. Introduction

With an increasing world-wide interest in sustainable energy production and use there is renewed focus on the power electronic converter interface to DC energy sources. An inverter is a circuit which converts a DC power into an AC power at desired output voltage and frequency to satisfy the regional norms. The AC output could be a fixed or variable AC power at desired output voltage and frequency to satisfy the regional norms. The AC output could be a fixed or variable output voltage of desired magnitude and frequency. This conversion can be achieved either by controlled turn on and turn-off devices (e.g. BJT, MOSFET, IGBT, and MCT etc.) or by forced commutated thyristor, depending on application. The output voltage waveform of an ideal inverter should be sinusoidal. The voltage waveforms of practical inverters are however, non-sinusoidal and contain certain harmonics. Square wave or quasi-square wave voltage may be acceptable for low and medium power application and for high power application low distorted, sinusoidal waveform are required.

Low-cost, high-performance, high-density AC-DC inverters are key elements in UPS, fuel cell, solar, and wind array systems. A cost effective solution to inverter design is based on advances in digital signal processor (DSP). Powerful 16-bit, fixed point DSPs incorporate all the necessary circuitry required by power electronics applications such as: PWM channels, A/D converters, CAN interface internal and/or external memory, serial ports, event timer, and encoder interface.

A 16-bit fixed point DSP controller can be effectively used to reduce the size of a DC-AC inverter, increase efficiency, and improve the total harmonic distortion (THD)—especially in the presence of highly nonlinear loads. Generally the size of the DC-AC inverter is determined by its output LC filter. It can be of small size by using higher switching frequency; however, this increases overall losses and requires bigger heat-sinks with more cooling [1].

Traditionally, adding a current loop with the effect of dumping the LC filter leads to a lower THD, however distortion is still present in the output voltage, especially if the switching frequency is well below 20 kHz. Adding a current loop also makes the system more difficult to analyze and generally requires an accurate isolated current transducer and either a large, bulky, expensive inductor or the use of a high switching frequency to remove the switching ripple [2].

A new “converter-per-module” offers many advantages including individual module MPPT, which gives great flexibility in module layout, replacement, and insensitivity to shading, better protection of PV sources, and redundancy in the case of source or converter failure, easier and safer installation and maintenance, and better data gathering [3].

Placing a DC-DC converter on each sub string, and then connecting these strings in series avoids many of the problems such as shading and loss of system-efficiency due to difference in individual characteristics of the panel.

In order to increase the performance of PV systems, it is important to note that the output characteristic of a photovoltaic array is nonlinear and changes with solar irradiation and cell’s temperature. Therefore, an efficient modeling of the panel is required for the experimental validation and a Maximum Power Point Tracking (MPPT) technique is needed to maximize the produced energy.

For controlling the output voltage of DC/DC converter a multi-loop control scheme was proposed which consists of: a fast inner current loop and slower outer voltage loop corresponding to input PV current and voltage respectively. A comparatively slow MPPT loop was also running setting the reference point.
A. Converter interface of PV Modules

In grid-connected inverters for PV applications, a number of different approaches have been developed and used over the last 20 years. An excellent review of such systems was given in [4]. Only the two more common approaches used in smaller residential scale installations (1-3kW) were compared here.

Single DC string, single DC-AC inverter: In a residential system of say 2kW or less, all the PV panels on the rooftop can be connected electrically in series, to create a high voltage low current DC source. This source is connected to a single inverter within the roof or house. The AC then runs to the residential switchboard.

Individual DC-AC inverters (per module): In this more recent approach, each PV panel has its own DC-AC inverter, mounted at the panel on the rooftop. A 240Vac connection from the switchboard runs to the rooftop, and loops from inverter to inverter, panel to panel. Each panel is now effectively placed in parallel, via its own dedicated inverter.

In particular, without lack of generality, we will focus our attention on a stand-alone photovoltaic system constructed by connecting each solar panel with its own DC-DC converter followed by individual DC-AC inverter with AC load as shown in Fig.1. The DC-DC converter is controlled by implementing the Perturb & Observe (P&O) MPPT algorithm and the Proportional Integral (PI) compensator on various controller cards based on 16-bit & 32-bit DSPs and the performance of the system is compared. An H-type full-bridge MOSFET based DC-AC inverter topology with LC filtering is also implemented to produce a symmetric AC output of desired magnitude and frequency.

II. PV Modeling / Characteristics

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor. The simplest equivalent circuit of a solar cell is an ideal current source in parallel with a diode and is shown in Fig.2.

The equation which describes the I-V characteristics of PV cell is:

\[
I = I_{ph} - I_0 \left[ \exp \left( \frac{q(V + IR)}{AKT} \right) - 1 \right]
\]

Where, \(I\) is the PV array output current (A); \(V\) is the PV array output voltage (V); \(q\) is the charge of an electron; \(k\) is Boltzmann’s constant; \(A\) is the p-n junction quality ideality factor; \(T\) is the cell temperature (K); and \(I_0\) is the cell reverse saturation current. The factor ‘\(A\)’ in (1) determines the cell deviation from the ideal p-n junction characteristics [5].

III. System Description

To test the performance of the proposed system with different controller cards, the setup shown in Fig. 1 was implemented. It consists of a solar panel, a DC/DC converter, Control boards (16 & 32-bit DSP), inverter module and DSO and a PC.
problem in P&O algorithms is that the array terminal voltage is perturbed every MPPT cycle; therefore when the MPP is reached, the output power oscillates around the maximum, reducing the generable power by the PV system.

B. Solar Panel

The solar panel used for the experimental purpose was the PAE SE-15. They are made using the Copper Indium Gallium diSelenide (CIGS) solar cells. CIGS perform well over a range of light – levels and climatic conditions, providing more kWhr per day compared to conventional silicon technology. The technical specifications of the panel are given in Table I.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Maximum Power</th>
<th>Voltage at MPMP</th>
<th>Current at MPMP</th>
<th>Open Circuit Voltage</th>
<th>Short Circuit Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{mpp}</td>
<td>15 W</td>
<td>18 V</td>
<td>0.81 A</td>
<td>28 V</td>
<td>1.05 A</td>
</tr>
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</table>

C. DC / DC Converter

The DC/DC converter of Flyback topology working at a switching frequency of 21.59 kHz was implemented. The isolation is achieved through a coupled inductor. The ideal gain in CCM is

\[ V_o = n \cdot \frac{d}{1 - d} \cdot V_{in} \]  

Where \( V_o \), \( V_{in} \), \( d \) and \( n \) represents the converter output, input voltages, duty cycle and number of turns in secondary coil respectively. The output ripple frequency is the same as switching frequency. Fig. 4 shows the waveforms associated with the flyback converter at MOSFET and diode.

D. DSP Control Board

The MPPT algorithm, the control of the DC/DC converter and the control for the inverter were implemented on TI’s TMS320LF2401A, TMS320F28027 and TMS320F28069 DSPs. The DSP measured the input current and input voltage through the A/D module and calculated the power obtained from the panel. The duty cycle was used as the control variable in order to simplify the control structure of the system [8]. The update rate of the MPPT algorithms with different controllers were found experimentally by setting it as fast as possible without causing instability to the system, too fast update rate may cause the system to become instable due to the relatively long time constant of the power stage [9]. The scheme used in the experiment is as shown in Fig. 5.

E. DC / AC Inverter

H-type full bridge DC/AC Inverter was implemented using MOSFET IRF3710 as shown in Fig. 6.
The inverter bridge was switched with 20kHz. bipolar PWM signal. The PWM signals were coupled to the power switches of the bridge using MOSFET driver.

The HIP4082 is a bootstrap medium frequency, medium voltage H-Bridge N-Channel MOSFET driver IC. It independently drives four N-Channel FET in half-bridge or full-bridge configurations. It also has shoot-through and under-voltage protection capability. The bridge is divided into four groups with the ac load connected across the middle of the “bridge” thus forming an “H” pattern. The H-Bridge design efficiency is dependent mostly upon the quality of the transistors used and the number of transistors in parallel. Most of the losses in this design take place in the transistor switches, so as transistors improve the performance of H-Bridge based inverters will also improve.

IV. CONTROL SCHEME

The proposed control consisted of three loops: the outer most MPPT loop set the Vin_PV_ref corresponding to the panel input voltage, the slower outer voltage PI loop set the Iin_PV_ref for the faster inner current PI loop which finally controls the pulse width of the PWM signal which drives the MOSFET gate, the fast inner PI loop regulate the PV array output voltage with respect to Iref which is set in the outer PI loop [10]. The block diagram of the MPPT control and the compensator for digital implementation are shown in Fig. 7 [11]. The functions of all the three loops are performed by controller/DSPs. The controller senses the solar panel current and voltage to calculate the solar array output power, Vref, Iref and the pulse width for maximum power control. The performance of the control algorithm can further be improved by scheduling these loops on RTOS [12].

The above-described scheme was used to test the MPPT algorithms. Fig. 8 shows the output waveform of the experiment, the PWM signal, the input current and voltage. The oscillations of the P&O algorithm around the maximum power point can easily be seen from the oscillation of the current waveform in Fig. 8.

![Multi-loop control scheme implemented in the system.](image)

Fig. 7. Multi-loop control scheme implemented in the system.

![Output waveforms of experiment. C1: Pulse Width, C2: Iin_PV, C3: Vin_PV](image)

Fig. 8. Output waveforms of experiment. C1: Pulse Width, C2: Iin_PV, C3: Vin_PV

Fig. 9 shows the frequency (timing) for various subroutines of the multi-loop control scheme implemented in the microcontroller. Table III tabulates the execution time required by various function loops controlling the system from low to high end controllers.

![Timings of subroutines at NXP89V51RD2. C1: T0 Interrupt, C2: ADC Filtering, C3: PI Control loop, C4: MPPT_PNO loop](image)

Fig. 9. Timings of subroutines at NXP89V51RD2. C1: T0 Interrupt, C2: ADC Filtering, C3: PI Control loop, C4: MPPT_PNO loop

<table>
<thead>
<tr>
<th>Table III. Timing of the Control Loops with Various Controllers</th>
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<tbody>
<tr>
<td>Control Loops</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>ADC Read (msec)</td>
</tr>
<tr>
<td>PI loop (msec)</td>
</tr>
<tr>
<td>MPPT Loop (msec)</td>
</tr>
<tr>
<td>PWM Frequency (kHz)</td>
</tr>
<tr>
<td>ADC Clock (kHz)</td>
</tr>
<tr>
<td>MPPT update time (msec)</td>
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</tbody>
</table>
Different test points of the inverter are shown in Fig. 10-13.

**Figure 10.** $V_{DS}$ of bottom MOSFETs of bridge: C1: $V_{DS1}$, C2: $V_{DS2}$.

**Figure 11.** Half bridge $V_{DS}$ signals: C1: $V_{DS1}$, C2: $V_{DS2}$.

**Figure 12.** Bridge driver (HIP4082) input control signals with 1us dead band: C1: Top, C2: Bottom Left, C3: Bottom Right.

**Figure 13.** Output of the inverter: C1: PWM signal, LC Filtered PWM: C2: $C=2\mu F$, C3: $C=1\mu F$.

**CONCLUSIONS**

This paper discussed the implementation of a multi-loop controlled PV system, using flyback topology which is used to compare the performance of the PV system based on different DSP controllers.

The controller board is able to produce the inverter output frequency at nearly 50 Hz, overall voltage and current THD found to be less than 3% and 4% respectively. The method used to control the inverter switches is sinusoidal pulse width modulation (SPWM). The control circuit using TI DSPs were developed, therefore the inverter control circuit hardware was reduced. Using microcontroller unit, the frequency modulation ratio, dead time period and duty cycle can be easily change through programming without further hardware changes.

DC-AC per-module inverters must step from a low DC voltage directly to a high AC voltage. Every module must have an AC inverter and associated protection and filtering components. This imposes an efficiency and cost penalty on this approach.

Numerical results were provided and validated by experimental studies and it has been concluded that the performance of the low end controller is comparable with their high end counterpart, if the production cost, the architectural complexity and the development time were considered. The resulting performance of the MPPT algorithm can further be improved using appropriate high performance DSPs. The proposed system provides a feasible approach to manage low-cost PV power systems.

**APPENDIX**

- $I_{ph}$: Photon or light generated current
- $I_0$: PN junction saturation current
- $q$: Electronic charge
- $A$: Ideality factor
- $k$: Boltzman’s constant
- $R_s$: Series resistance
- $R_p$: Shunt resistance
- $T$: Operating cell temperature
- $G$: Solar Insolation in W/m².
- $V_i$: Input of DC/DC converter
- $V_o$: Output of DC/DC converter
- PI: Proportional Integral
- STC: Standard Test Condition
- I&V: Cell output current and voltage
- NOCT: Normal operating cell temperature
- MPOP: Maximum power operating point
- RTOS: Real Time Operating System
- $V_{DSx}$: Drain to source voltage (x = 1,2,3,4)

**REFERENCES**


**Biographies**

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