Bidirectional DC-AC Solution For Solar Application System, Based on the TMS320F28035 MCU

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ABSTRACT

This application note presents a detailed solution for implementing a 3-phase solar inverter application system based on the TMS320F28035 microcontrollers (MCUs). The solution design includes bidirectional 3-phase DC-AC algorithms, and the maximum power point tracking (MPPT) DC-DC algorithm for solar panel control.

The solar inverter has gained more and more attention in recent years. The solar inverter gets the solar energy input, then it feeds the solar energy to the grid. Grid-tie technology and protection are key considerations when designing a solar inverter system. This solution implements an isolated DC-DC stage with the MPPT algorithm, to make use of the full capacity of the solar panel. The solar inverter maintains its input voltage at the reference set point generated by the MPPT algorithm, and delivers power to a downstream DC-AC inverter when connected across its output. The bidirecion DC-AC inverter transfers power from the DC stage to the connected AC grid while the DC loading requirement is small. Or, the inverter transfers the power from the connected AC grid to the DC stage if the DC energy is insufficient for the DC loading requirement.

In this document, basic knowledge of the inverter is presented first. The hardware introduction, firmware design, and closed-loop controllers design is also described. Lastly, the test results and the waveform are shown.

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Trademarks

Piccolo is a trademark of Texas Instruments.
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1 Introduction

This application note presents a bidirectional 3-phase DC-AC solution used in solar application systems, based on the TMS320F28035 MCU (see Figure 1).

If the load must take energy from the AC grid, the solution could work in rectifier mode so that the system can transfer 3-phase AC power from the grid to the DC voltage. If the load can feed back the addition energy, then the solution can work in inverter mode so that the system can transfer DC power to the 3-phase AC voltage and provide feed back to the AC grid.

These solutions are developed in the solar application system that provides free transfer energy between the solar panel and the AC grid to the load, and complies with the MPPT feature, which could trace maximum solar panel efficiency. The system also provides full protection, including OV/UV, OC, phase unbalance, and grid disconnection.

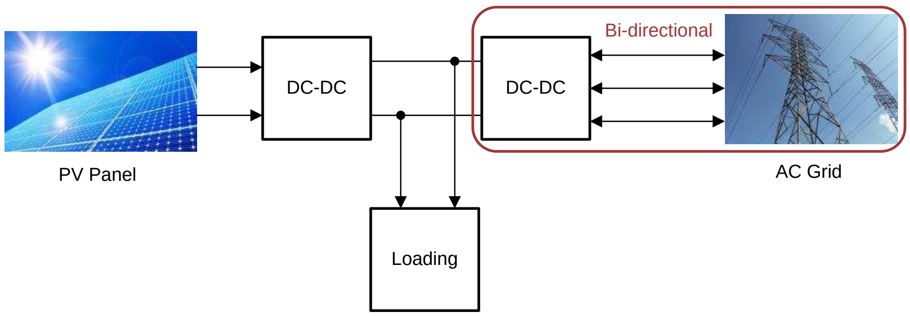

Figure 1. System Overview Block

2 System Specification

Table 1 lists the system specifications.

Table 1. System Specification

Feature
Power rating: 12 kW
Input voltage: 350-V DC to approximately 800-V DC
Output voltage: 380-V AC ±10%, 50 Hz ±0.5 Hz
Efficiency: >95% at rate power condition
THDi:<5% at rate power condition
Power factor: >99% at rate power condition
No transform isolation structure:
MPPT feature
Grid-tie feature
Anti-islanding protection
Overvoltage and undervoltage protection
Overcurrent protection

3 MCU Use Overview

The F2803x Piccolo™ family of microcontrollers from TI provides the power of the C28x core and control law accelerator (CLA), coupled with highly integrated control peripherals in low pin-count devices. This family is code-compatible with previous C28x-based code, and provides a high level of analog integration.

An internal voltage regulator allows for single rail operation. Enhancements have been made to the HRPWM module to allow for dual-edge control (frequency modulation). Analog comparators with internal 10-bit references have been added and can be routed directly to control the PWM outputs. The ADC converts from 0- to 3.3-V fixed full-scale range and supports ratio-metric VREFHI and VREFLO references. The ADC interface has been optimized for low overhead and latency.

- High-efficiency 32-bit CPU, 60-MHz device, CLA
- Single 3.3-V supply, no power-sequencing requirement
- Two internal zero-pin oscillators, missing clock detection circuitry
- On-chip flash, SARAM, OTP memory, 128-bit security key/lock
- Serial port peripherals input (1x SCI, 2x SPI, 1x I2C, 1x LIN, 1x eCAN)
- Enhanced pulse width modulator (ePWM), high-resolution PWM (HRPWM)
- Enhanced capture (eCAP) module, high-resolution input capture (HRCAP) module
- Enhanced quadrature encoder pulse (eQEP) supports all peripheral interrupts
- Analog-to-digital converter (ADC)
- On-chip temperature sensor module, comparator
- 56-, 64-, and 80-pin packages

Table 2 lists the pin assignment for the bidirectional DC-AC inverter system.

Table 2. MCU Pin Assignment

Pin No.	Peripherals	Pin No.	Signal Name	Function
18	ADC	ADCINA0	I_R	R-phase current
17		ADCINA1	I_S	S-phase current
16		ADCINA2	I_T	T-phase current
15		ADCINA3	V_RS	Voltage between R-S phase
14		ADCINA4	V_ST	Voltage between S-T phase
13		ADCINA5	V_TR	Voltage between T-R phase
12		ADCINA6	V_DC	DC BUS voltage
11		ADCINA7	I_DC	DC BUS current
24		ADCINB1	TEMP_EVM	IPM temperature
25		ADCINB2	TEMP_CASE	Sink temperature
26		ADCINB3	V_PV1	Voltage of first PV panel
27		ADCINB4	I_PV1	Current of first PV panel
28		ADCINB5	I_PV2	Current of second PV panel
29		ADCINB6	V_PV2	Voltage of second PV panel
55	Capture	ECAP1	V_RS_ZERO	RS-phase voltage zero crossing
47	Ext_Int	TZ1	FO	Error external trigger

Table 2. MCU Pin Assignment (continued)

Pin No.	Peripherals	Pin No.	Signal Name	Function
69	EPWM	PWM1A	RH	R-phase up IGBT driver
68		PWM1B	RL	R-phase low IGBT driver
67		PWM2A	SH	S-phase up IGBT driver
66		PWM2B	SL	S-phase low IGBT driver
63		PWM3A	TH	T-phase up IGBT driver
62		PWM3B	TL	T-phase low IGBT driver
50		PWM4A	IGBT_1	First PV panel DC-DC IGBT driver
43		PWM5A	IGBT_2	Second PV panel DC-DC IGBT driver
41	GPIO	GPIO18	RLY_T	T-phase relay driver
42		GPIO17	RLY_S	S-phase relay driver
44		GPIO25	RLY_R	R-phase relay driver
45		GPIO44	RLY_1	First PV panel relay driver
46		GPIO16	RLY_2	Second PV panel relay driver
48		GPIO41	LED_1	Run status display
49		GPIO7	LED_2	Fault error display
34	SCI	SCITXDA	TXD	UART transfer
40		SCIRXDA	RXD	UART receiver

4 Hardware Design

4.1 Basic System Topology Introduce

Figure 2 shows the basic system topology implementing a 3-phase DC-AC converter.

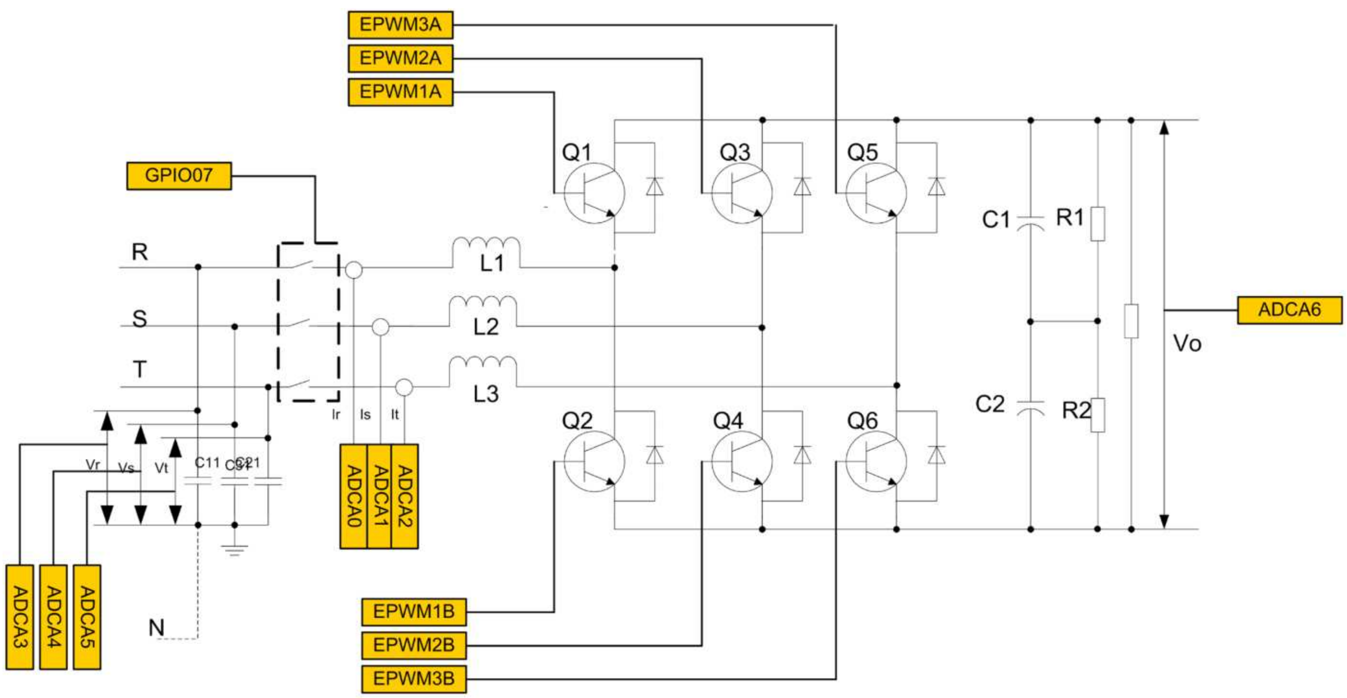

Figure 2. DC-AC Circuit Structure

Figure 3 shows an example description of the topology working principle. When Q2 is on, the L1 inductor current raises, the current flows from R phase, and then goes through the Q4 or Q6 body diode, and at last gets into S or T phase. Then the energy is stored in the L1 inductor.

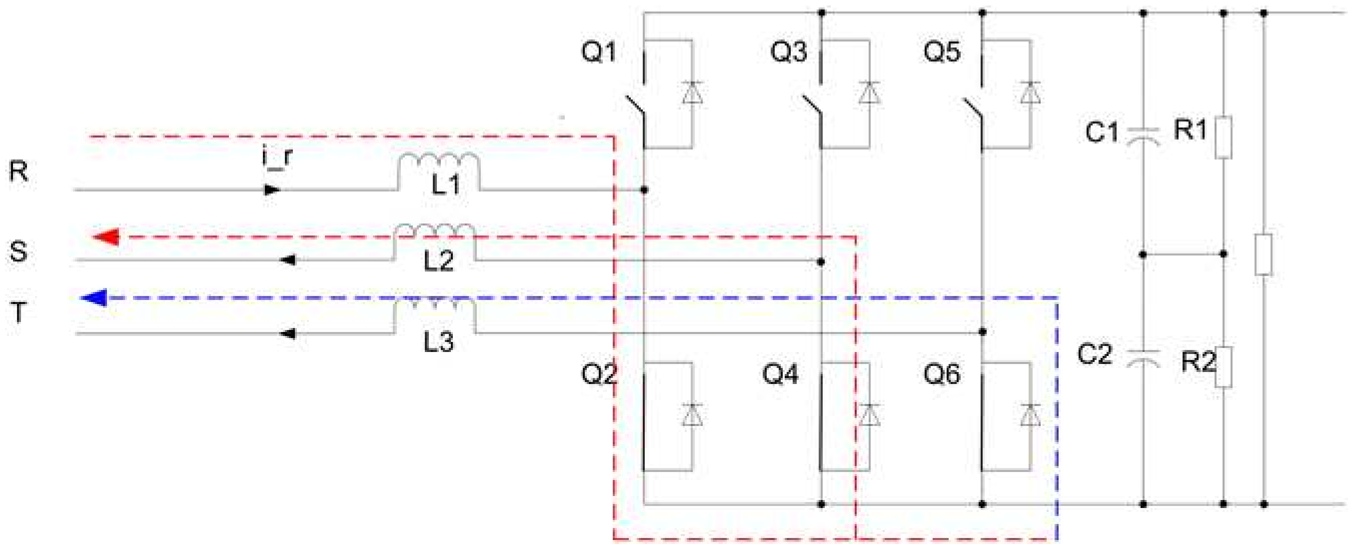

Figure 3. Circuit Analysis for Arm On

When Q2 is off, the L1 inductor current falls, the current flow goes through the capacitor, and then gets to S or T phase (see Figure 4). The energy stored in the L1 inductor is released.

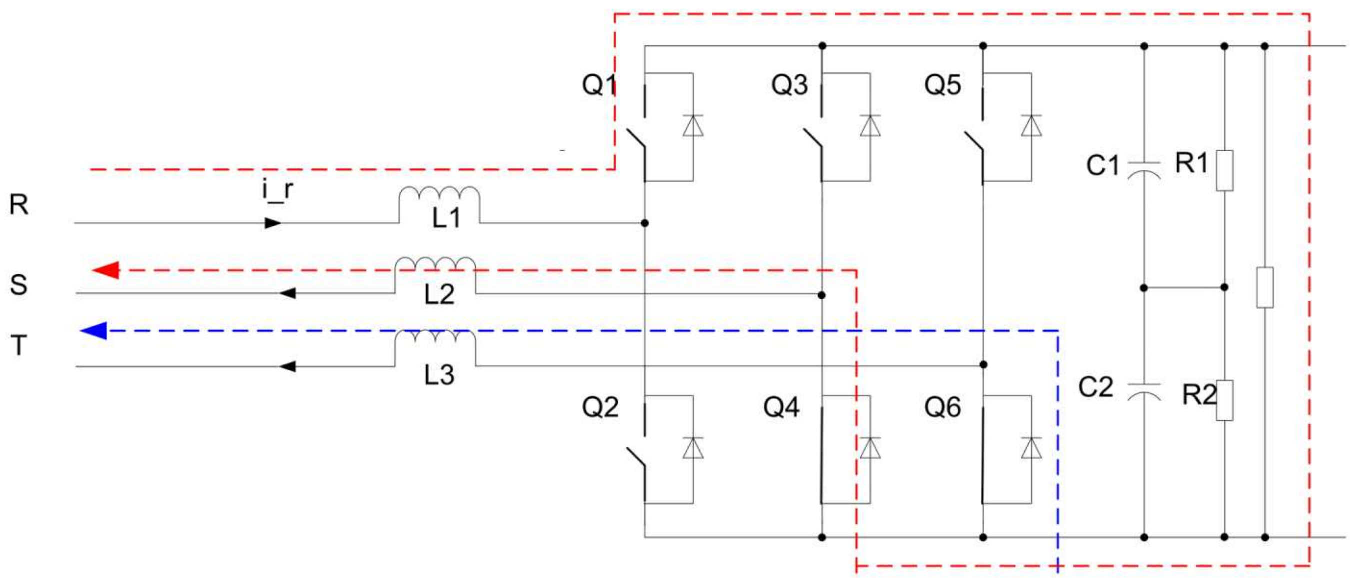

Figure 4. Circuit Analysis for Arm Off

4.2 MCU Key Peripheral Module

4.2.1 3-Phase Bridge Power Switcher Circuit

One ePWM module can output two PWM signals with dead-time complementation: EPWMxA and EPWMxB. Three ePWM modules are used to generate six PWM signals as UP and UN; VP and VN; and WP and WN, to drive the 3-phase power module (PM50CLA120), as shown in Figure 5, and switch the PN DC 700 V to the U/V/W AC 380 V port directly. The three ePWM modules are chained together through a clock synchronization scheme that allows six PWM signals and the frequency must be aligned.

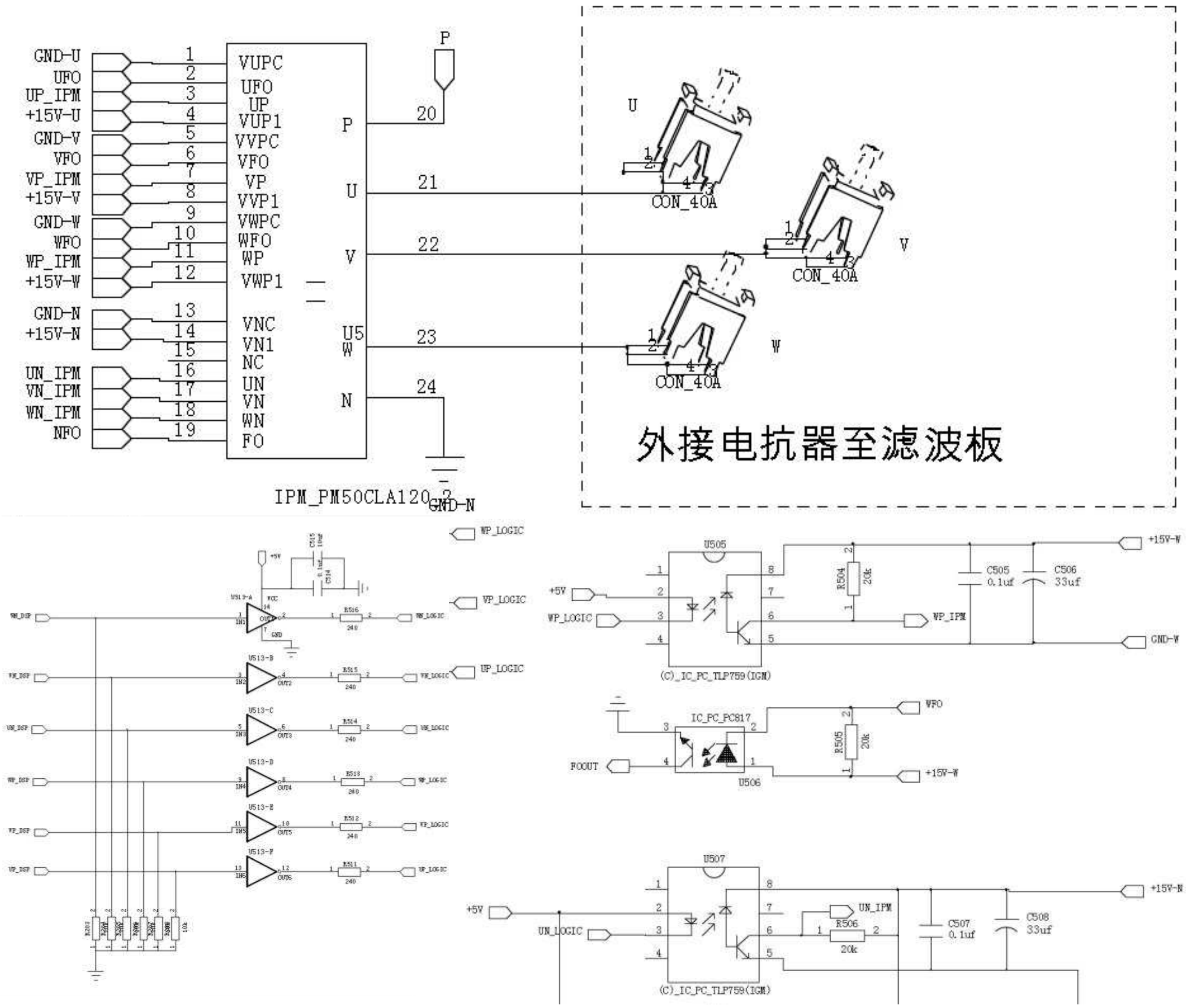

Figure 5. 3-Phase Bridge Driver Circuit

4.2.2 Interleave Boost Circuit

Another two ePWM modules are used to generate PWM signals as IGBT1 and IGBT2 in Figure 6 to drive the interleave boost DC-DC circuit. Each DC-DC circuit connects with a PV panel. Adjust the panel voltage and current according to the MPPT algorithm to trace maximum PV panel power. Two DC-DC circuits work independently so that the signal can interleave to connect the two PV panels.

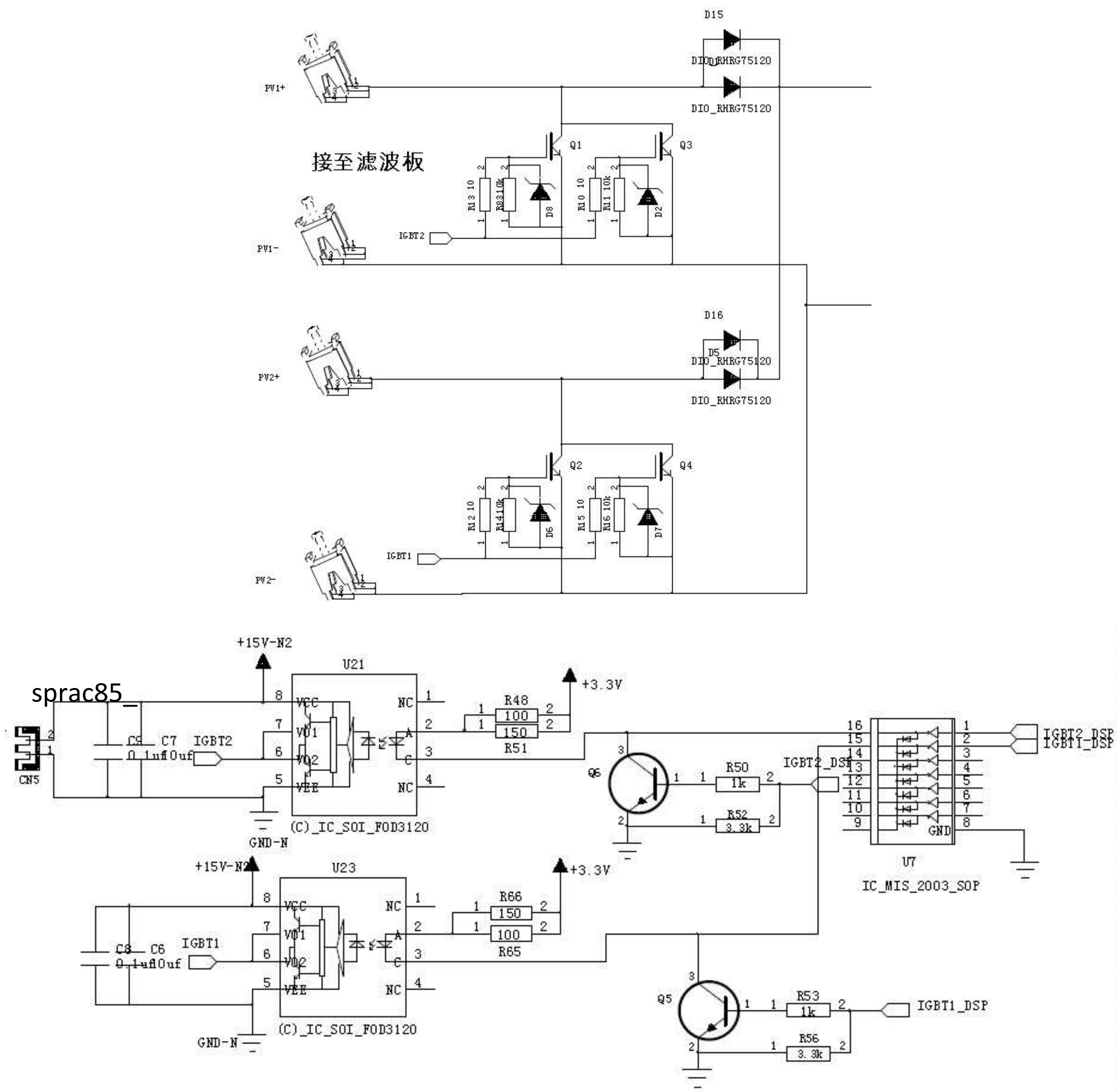

Figure 6. Boost Driver Circuit

4.2.3 Voltage Signal Sample Circuit

Three voltage phases (R, S, and T) and two solar panel voltages are sampled by both the internal 12-bit ADC of the F28035 device. A series resistor divider with different schemes is designed to adjust the sample signal range and filter the noise. Then, it transfers the two single signals through the external OPAMP and input to the MCU ADC (see Figure 7).

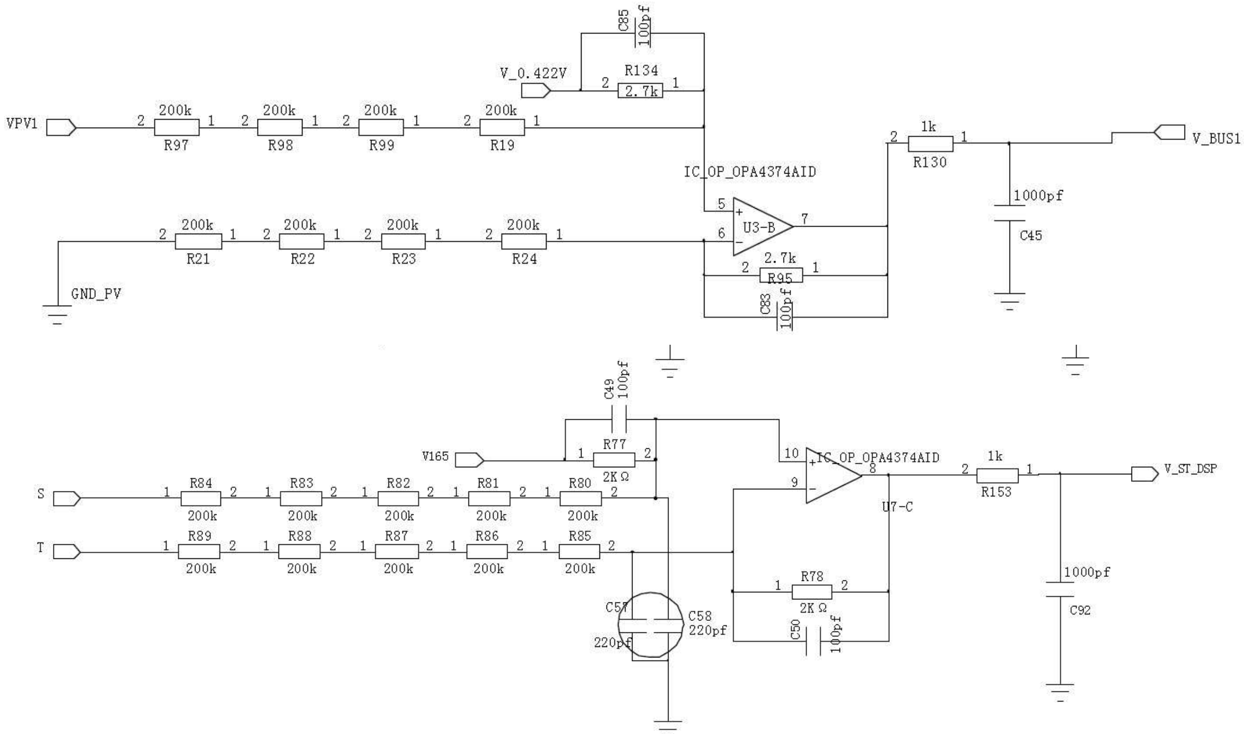

Figure 7. Voltage Signal Sample Circuit

4.2.4 Current Signal Sample Circuit

Three phase R, S, and T currents and two solar panel currents are both sampled by the internal 12-bit ADC of the F28035 device. A hall sensor is used to transfer the current signal into the voltage range of approximately 0 to 5 V with a 0.25-V offset. Then the sensor continues to transfer to the voltage range of approximately 0 to 3 V with a 0.15-V offset using the resistor divider and external OPAMP as the filter, lastly inputting to the MCU ADC (see Figure 8).

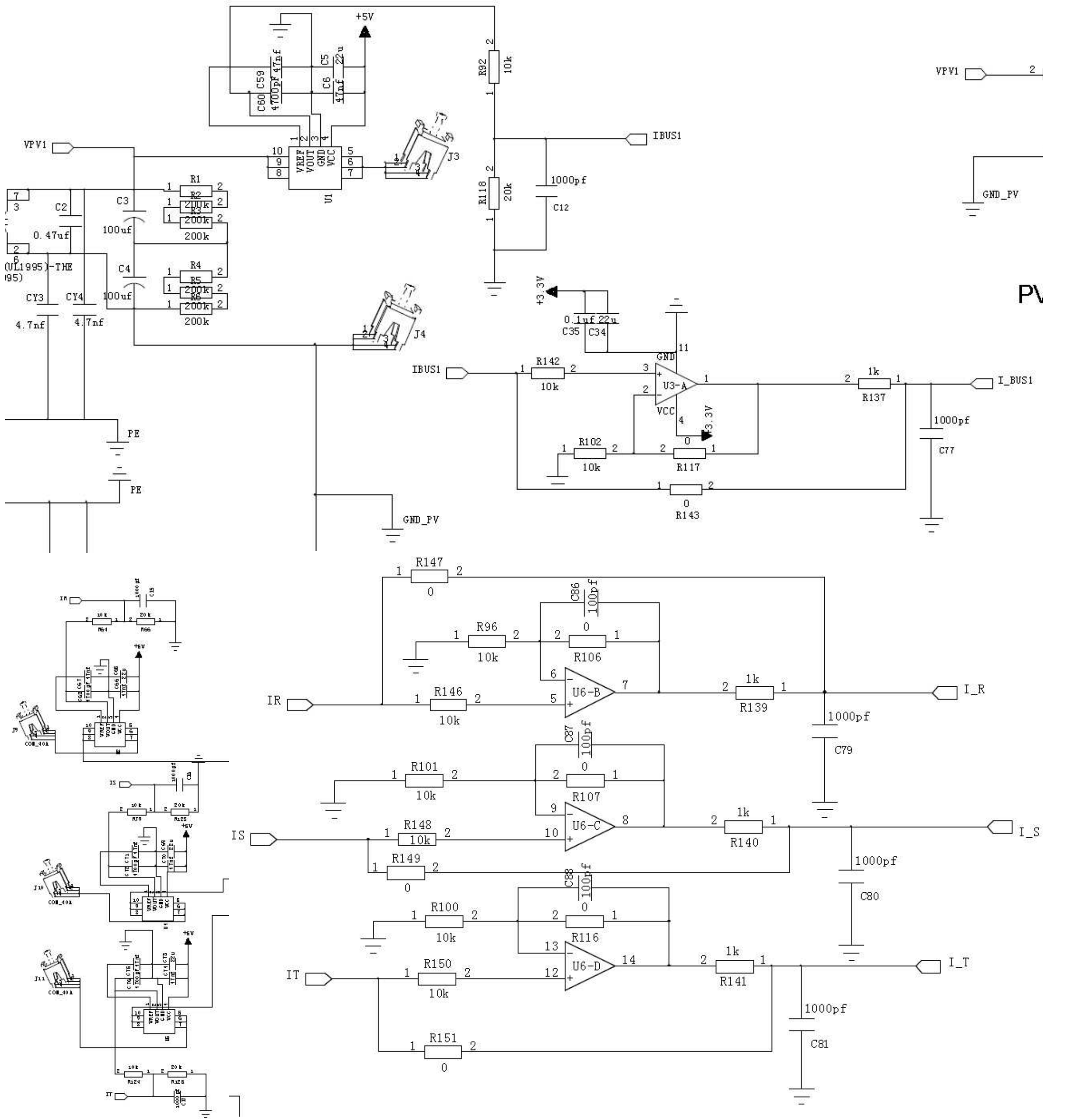

Figure 8. Current Signal Sample Circuit

4.2.5 AC Waveform Frequency Detection Circuit

An external comparator inputs RS-phase voltage and 1.65-V offset. The comparator outputs high level when the RS phase voltage is on a positive direction and outputs low level when the RS-phase voltage is on a negative direction, so that the sine wave RS-phase voltage is transferred to the pulse wave, according to zero voltage crossing.. The MCU CAP module detects the pulse signal and records the high level period and low level period to calculate the RS-phase voltage AC frequency (see Figure 9).

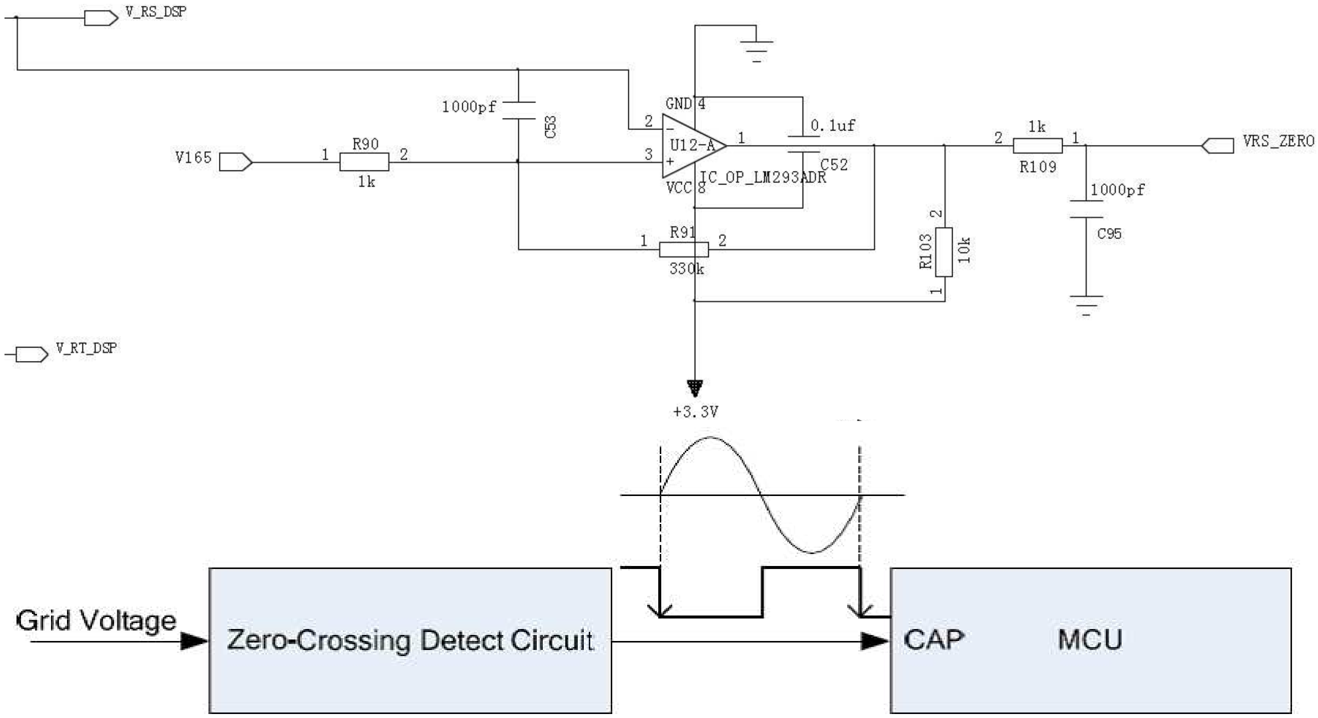

Figure 9. AC Waveform Frequency Detection Circuit

5 Firmware Design

5.1 Basic Theory for Bidirectional DC-AC

According to the 3-phase 2-level DC-AC principle, the energy transfer can be equivalent to Figure 10, which describes the equation.

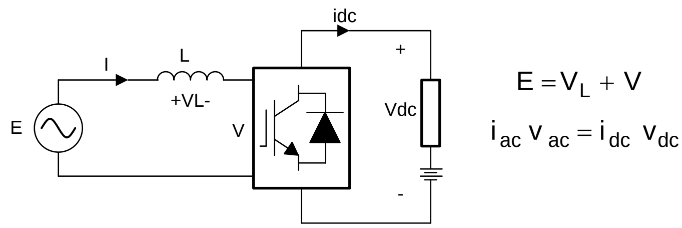

Figure 10. DC-AC Equivalent

When the V trace is from A to B (see Figure 11b), current I is the same phase with voltage E, so the converter works in rectifier mode, and we can get the highest power factor when the V is at B.

When the V trace is from A to D (see Figure 11d), current I is the total reverse phase with voltage E, so the converter works in inverter mode, and we can get the highest power factor when the V is at D.

In Figure 11a and Figure 11c, current I is the vertical phase with voltage E, so the active power P is nearly zero and all is reactive power Q. We must avoid this condition.

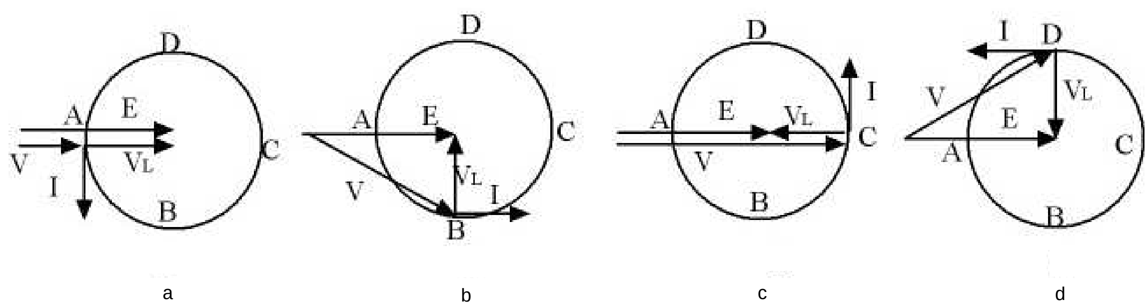

Figure 11. Current and Voltage Phase Relationship

5.2 Software Main Process Flow

For this bidirection AC-AC control system, Figure 12 shows the software main process flow chart.

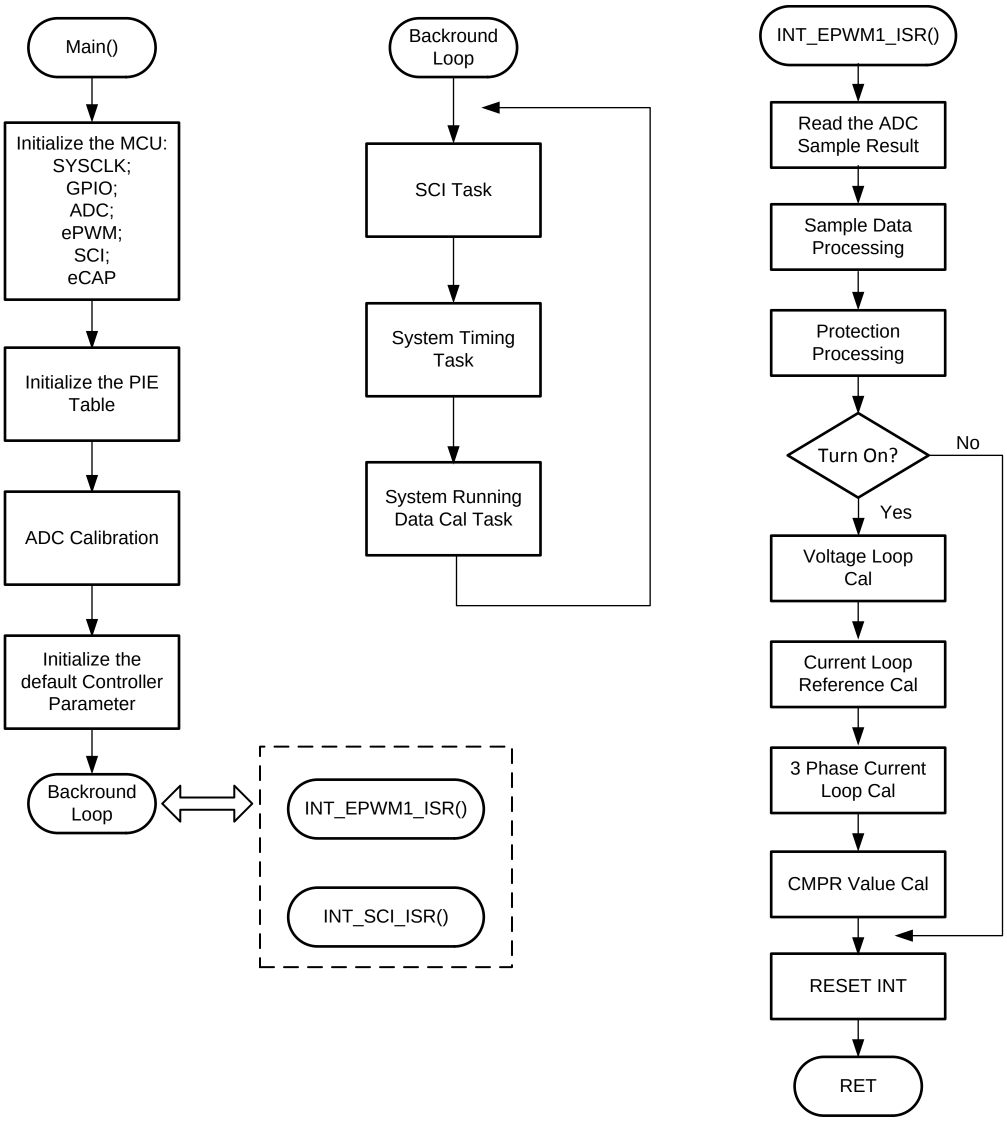

Figure 12. Software Main Process Flow

5.3 Closed-Loop Controller Design

5.3.1 Direct Current Closed Loop Diagram

Figure 13 shows the 3-phase currents are controlled by three independent closed loops.

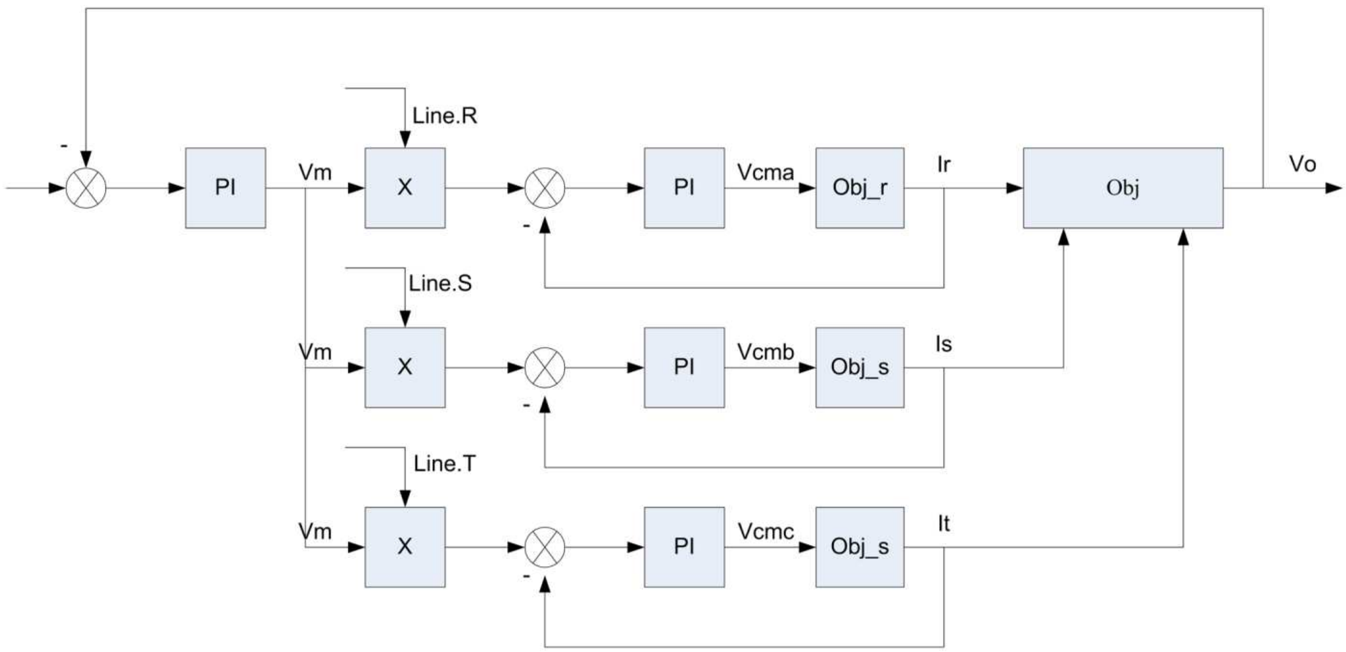

Figure 13. Current Closed Loop Flow

5.3.2 Current Loop Object Analysis

For phase R, Equation 1 is satisfied.

$$L\frac{dI_r}{dt} + rI_r = V_r - u_a \qquad u_a = d_1 V_o + V_{dc-} \quad \Rightarrow \quad L\frac{dI_r}{dt} + rI_r = V_r - d_1 V_o - V_{dc-} \tag{1}$$

From the same method, we can get Equation 2 and Equation 3.

$$L\frac{dI_r}{dt} + rI_r = V_s - d_2 V_o - V_{dc-} \tag{2}$$

$$L\frac{dI_t}{dt} + rI_s = V_t - d_3 V_o - V_{dc-} \tag{3}$$

If the 3-phase system is balanced, add up Equation 1, Equation 2, and Equation 2, then we can get Equation 4.

If we ignore the high order harmonic wave.

$$V_{dc-} = -\frac{1}{3}\left(d_1 + d_2 + d_3\right)V_{dc} \quad \Rightarrow \quad V_{dc-} = -\frac{1}{2}V_{dc} \tag{4}$$

Figure 14 shows the diagram from the lap conversion.

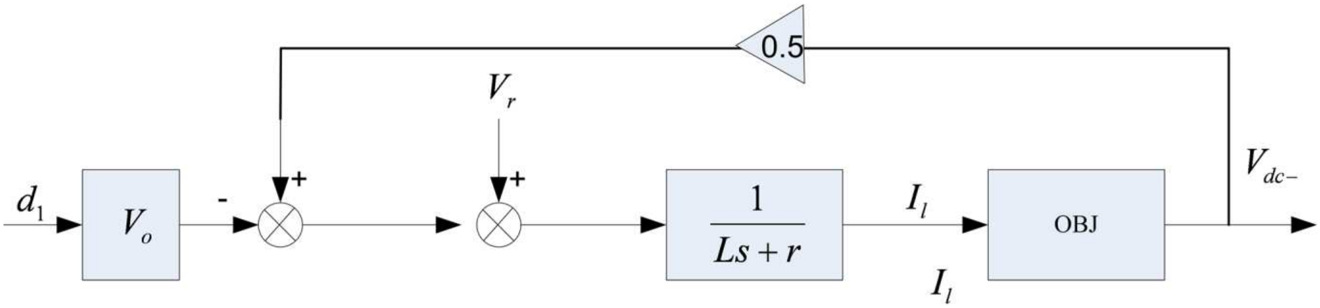

Figure 14. Lap Conversion Diagram

Figure 15 shows the current closed-loop diagram.

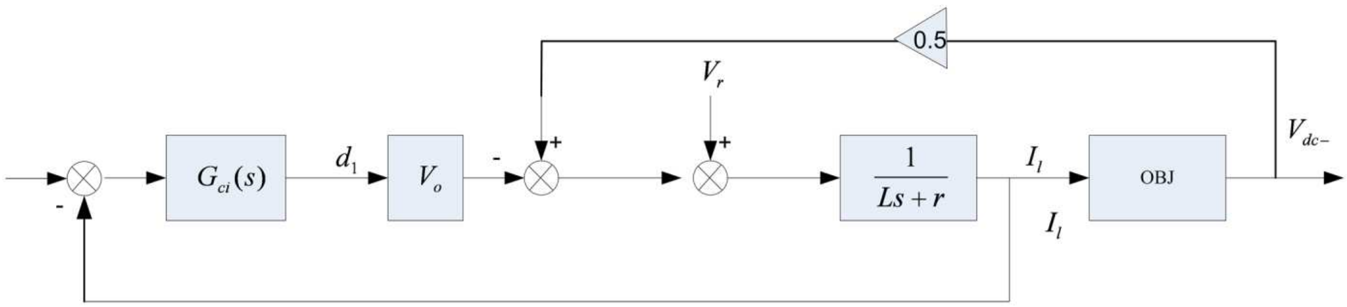

Figure 15. Closed-Loop Diagram

From Figure 16, we can see the Gs are enclosed by the current loop, so the open-loop transfer function is difficult to deal with. But the feedback linearization can be used to simplify the control loop.

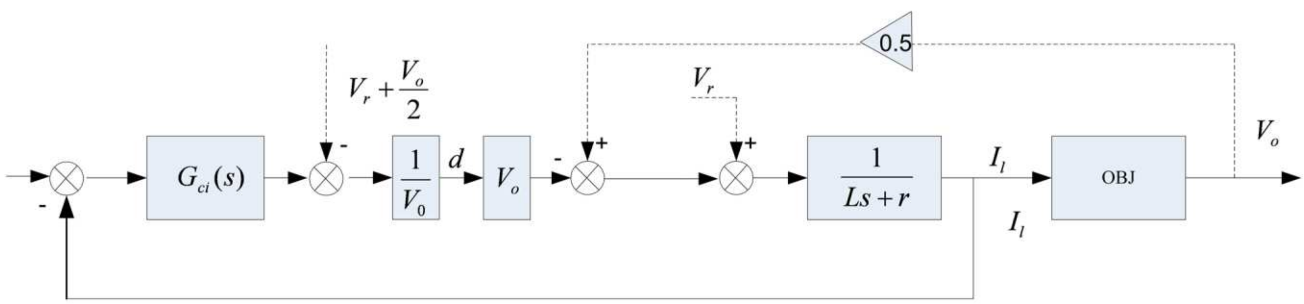

Figure 16. Simplified Control Loop

5.3.3 Current and Voltage Loop Controller

From the previous analysis, we can select the current closed loop controller and plot the Bode figure for the internal loop to fine tune the parameter effect (see Figure 17).

$$G_{ci}(s) = \frac{K(s+a)}{s(s+b)}$$

$$\downarrow$$

$$G_{ci}(z) = \frac{a_{c\_0} + a_{c\_1} z^{-1} + a_{c\_2} z^{-2}}{1 + b_{c\_0} z^{-1} + b_{c\_1} z^{-2}}$$

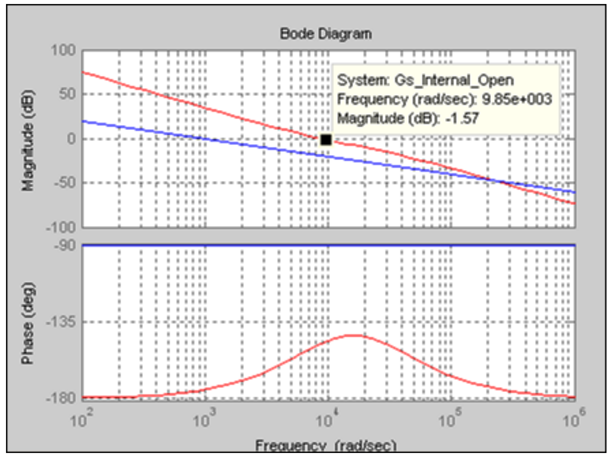

Figure 17. Current Loop Controller Analysis

Equation 5 shows the controller chosen as the voltage loops control, because the system has a large storage capacitor so the BUS voltage changes very slowly. We could fine tune the parameter for the voltage controller by experience.

$$G_{cv}(s) = \frac{K(s+a)}{s(s+b)} \tag{5}$$

5.4 DC-DC Controller With MPPT Feature

5.4.1 PV Panel Character Analyze

Figure 18 shows the V-I curves for the solar cell.

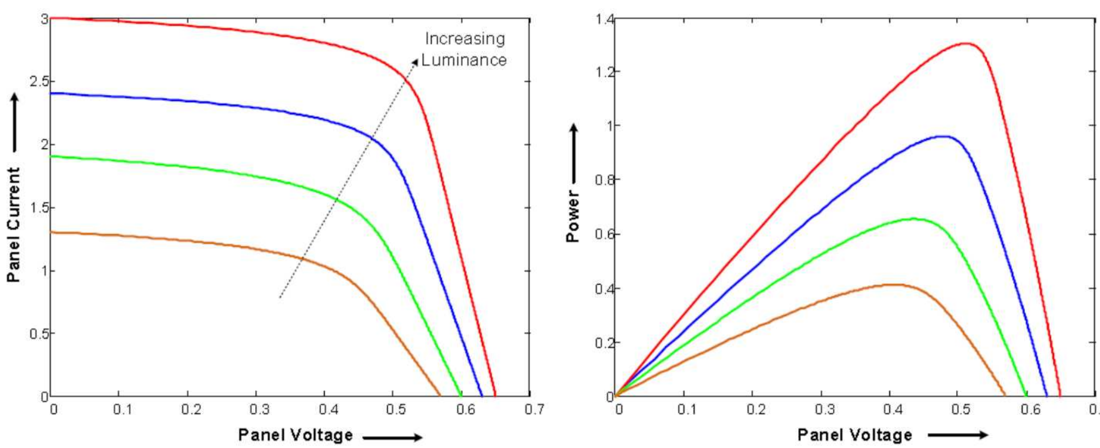

Figure 18. V-I Curves for Solar Cell

It is clear from the Figure 18 V versus I curve that PV does not have a linear voltage and current relationship. Thus the (P versus V) curve clearly shows a presence of a maximum. To get the most energy and use out of the PV system installation, it must be operated at the maximum power point of this curve. The maximum power point, however, is not fixed due to the nonlinear nature of the PV –cell and changes with temperature, light, intensity, and so on, and varies from panel to panel. Therefore different techniques are used to locate this maximum power point of the panel like Perturb and Observe, incremental conductance. MPPT algorithm is used to track the MPP.

5.4.2 DC-DC Controller Loop Diagram

Figure 19 shows the DC-DC interleaved boost converter control loops. This scenario uses current mode control. However, the goal is to control the PV panel output (Vpv), which is the input to the DC-DC stage. This allows the PV panel (array) to always operate at its maximum power point. Input current is regulated by adjusting the duty cycles of the power switches. Input voltage is regulated by adjusting the input current. A MPPT algorithm described in the Section 5.4.3 is responsible for determining the set point (Vpv_ref) for the PV panel voltage.

The input voltage control loop works quite differently compared to conventional feedback used in output voltage control. Under this control scheme, when the PV panel voltage (Vpv) tends to go higher than the reference panel voltage (Vpv_ref) set by the MPPT algorithm, the control loop increases the panel current command (reference current for inner current loop (Iind_ref) and thereby controls the panel voltage at its reference level (Vpv_ref). When the panel voltage tends to go lower than the reference, the control loop reduces the panel current command to reestablish the panel voltage to its reference level.

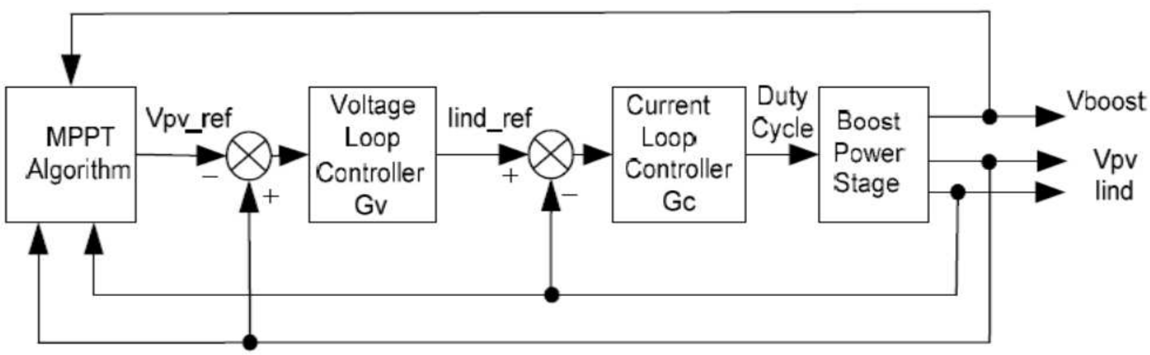

Figure 19. DC-DC Control Loop Diagram

5.4.3 MPPT Algorithm Analyze and Design

Tracking for the maximum power point is an essential part of PV system implementation. Several MPPT methods have been implemented and documented for PV systems. This software module implements a very widely used MPPT method called the Perturb and Observe (P&O) algorithm. MPPT is achieved by regulating the panel voltage at the desired reference value. This reference is commanded by the MPPT P&O algorithm. The P&O algorithm continue to increment and decrement the panel voltage to observe power drawn change. First, a perturbation to the panel reference is applied in one direction and power is observed. If the power increases, the same direction is chosen for the next perturbation, whereas if power decreases, the perturbation direction is reversed.

This module expects the following inputs:

- Panel voltage (Vpv): Sensed panel voltage signal sampled by the ADC. The ADC result is converted to per unit format.
- Panel current (Ipv): Sensed panel current signal sampled by the ADC. The ADC result is converted to per unit format.
- Step size (Stepsize): Size of the step used to change the MPP voltage reference output; direction of change is determined by the slope calculation done in the MPPT algorithm.

Upon macro call, Panel power (P(k) = V(k)*I(k)) is calculated, and compared with the panel power obtained on the previous macro call. The direction of change in power determines the action on the voltage output reference generated. If the current panel power is greater than the previous power voltage reference, it is moved in the same direction, as earlier. If not, the voltage reference is moved in the opposite direction.

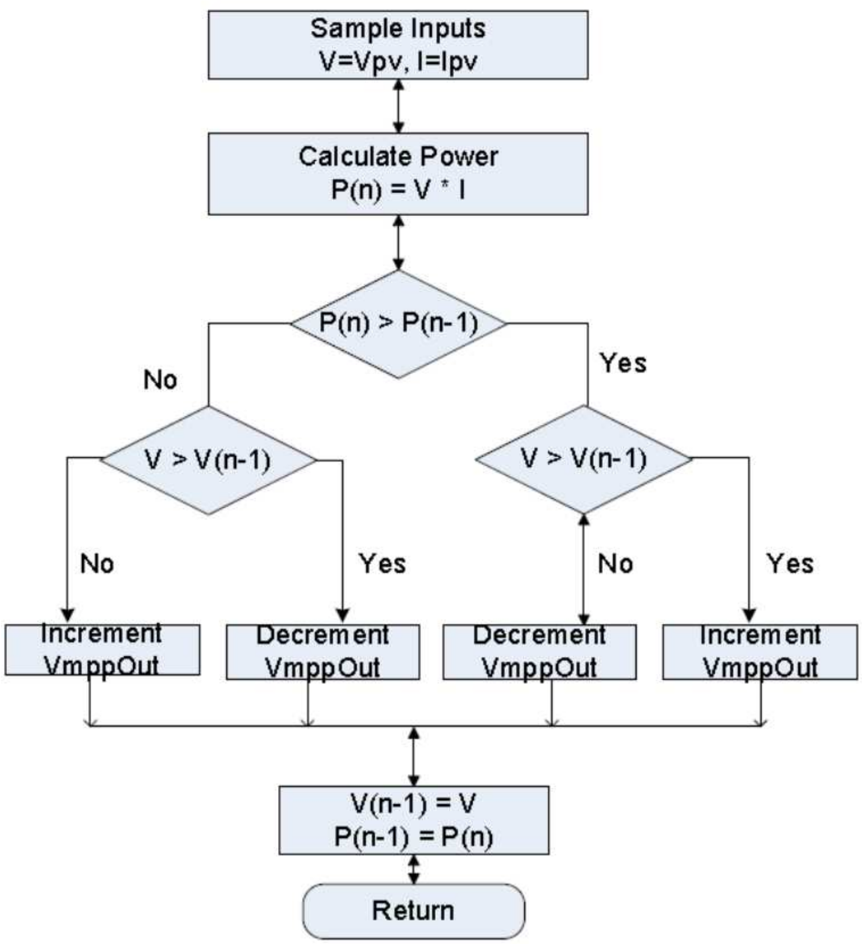

Figure 20. MPPT Algorithm Flow

5.5 Common Failure and Protection Mode

5.5.1 Overcurrent

When the current across the low-arm shunt resistor reaches a certain threshold level, the overcurrent protection circuit prevents damage to the inverter system by shutting down the PWM switching outputs of the control IC. When verifying new hardware, the overcurrent protection circuit should be tested early in the process.

5.5.2 Overvoltage

The overvoltage fault is detected when the DC bus voltage reaches a certain threshold level. If an overvoltage fault is detected, the system prevents damage to the inverter system by shutting down the PWM switching output of the control IC. The fault states restore when the DC bus voltage returns to normal range.

5.5.3 Undervoltage

The undervoltage fault is detected when the DC bus voltage falls beneath a certain threshold level. If an undervoltage fault is detected, the system prevents damage to the inverter system by shutting down the PWM switching output of the control IC. The fault states restore when the DC bus voltage returns to normal range.

5.5.4 Anti-Islanding

The anti-islanding fault is detected when the voltage of the AC grid powers off. If an anti-islanding fault is detected, the system prevents inverter independent output voltage from reaching the AC grid by shutting down the PWM switching output of the control IC. The fault states restore when the AC grid voltage turns on again.

6 Final Product Performance

6.1 Running Waveform

When the solar panel power is insufficient for running the air conditioning, the AC grid provides complementary energy to air condition. The system runs in PFC mode, and the current and voltage remain in the same phase.

When there is an excess of solar panel power, the surplus energy feeds back to the AC grid. The system runs in Inverter mode, and the current and voltage remains in 180c phase. These two modes are translated between each other automatically in real time.

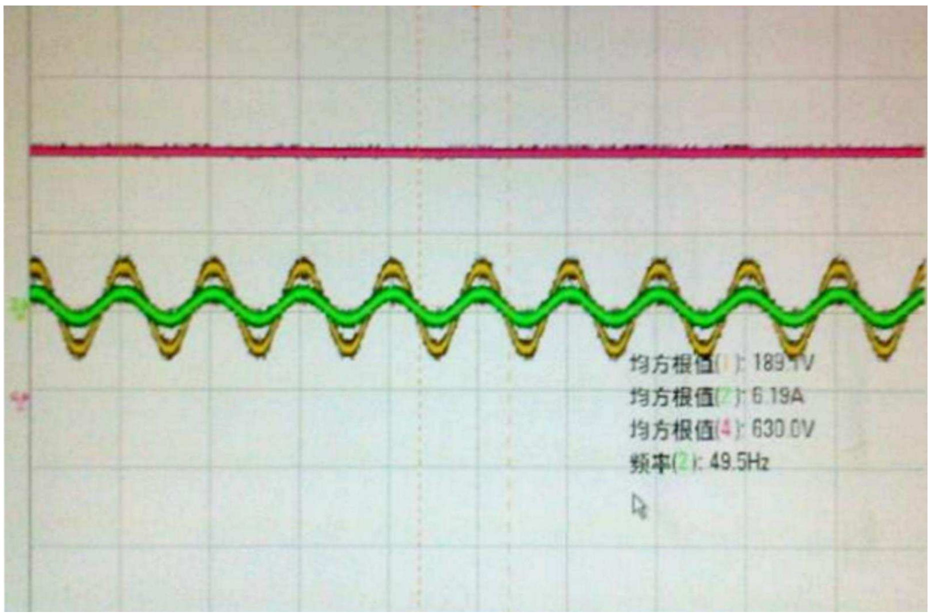

Figure 21. Current and Voltage Waveform in PFC Mode

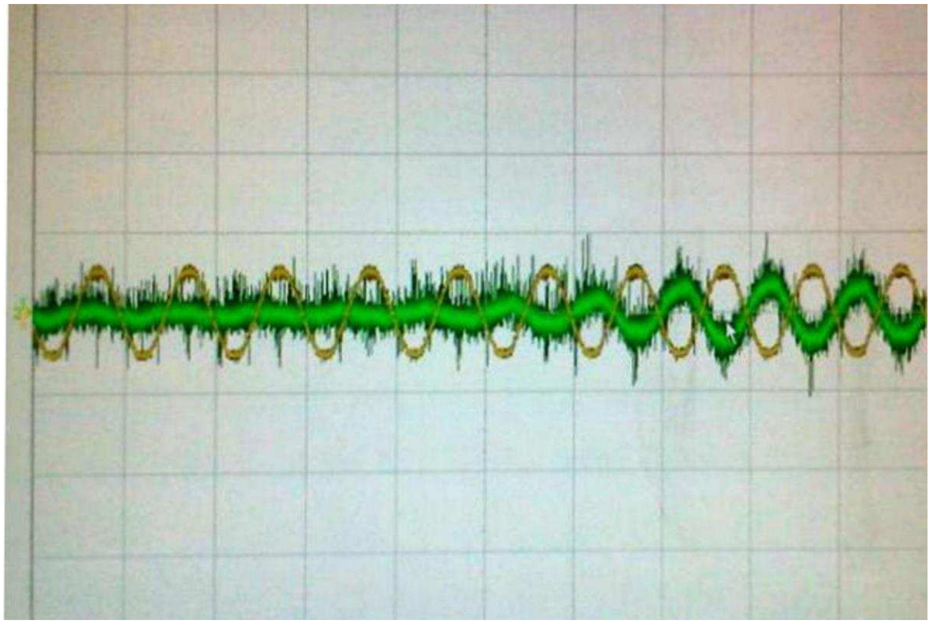

Figure 22. Current and Voltage Waveform in Translation Mode

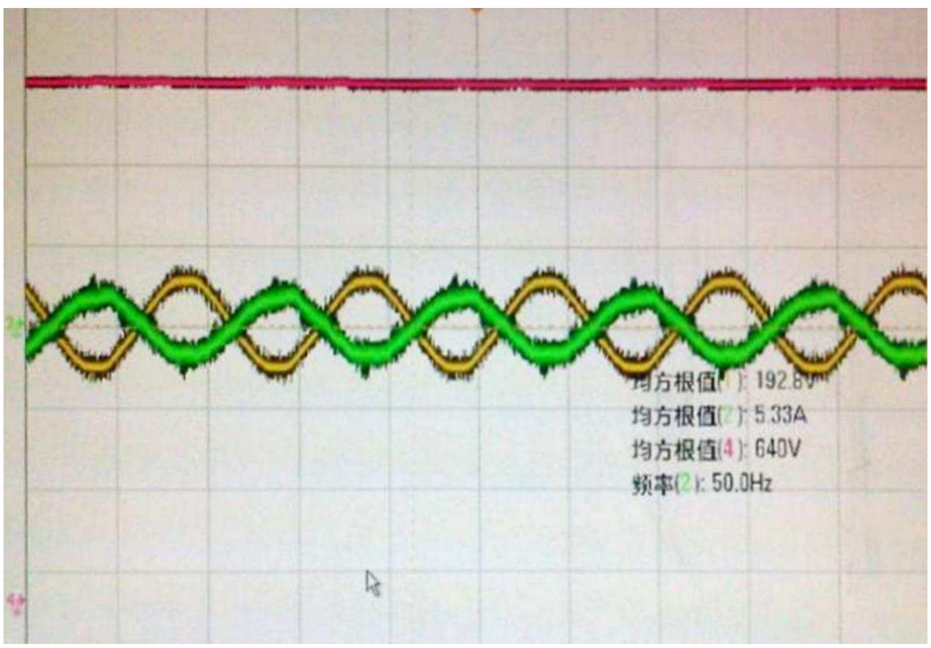

Figure 23. Current and Voltage Waveform in Inverter Mode

7 Related Documentation

1. Texas Instruments, *TMS320F28030/28031/28032/28033/28034/28035 Piccolo Microcontrollers*, Data Sheet
2. Texas Instruments, *TMS320x2803x Piccolo System Control and Interrupts Reference Guide*, Technical Reference Manual
3. Texas Instruments, UG_HV_SOLAR_DC_DC

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