Application Report
SPRABT2 – April 2013

# C2000 Dual VF Resonant Induction Cookers

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# 1 Basics

An induction cooker is a special kind of equipment that can heat iron pot. When a magnetically conducting material is placed in the magnetic field created by the induction cooker, the energy is transferred into this metal and heats it.

Induction heating has several advantages over traditional heating:

- **Efficiency**: The heating efficiency is as high as 95% because heat is generated directly in the pot. The efficiency for gas or oil, however, is around 50% due to heat transfer loss.
- **Save Energy**: Realize an energy savings of about 50% more than a gas or oil cooker. Also, because an induction cooker would not heat the ambient air, the work loading of air conditioner is light.
- **Speed**: Conductive heating can directly and quickly heat the pot with maximum power.
- **Safety**: There are no open flames, thus reducing the chance of fire.

Many kinds of induction cookers are present in the market, but they can be classified to appliance and commercial use. Most of them are single-switch topology and half- or full-bridge topology.

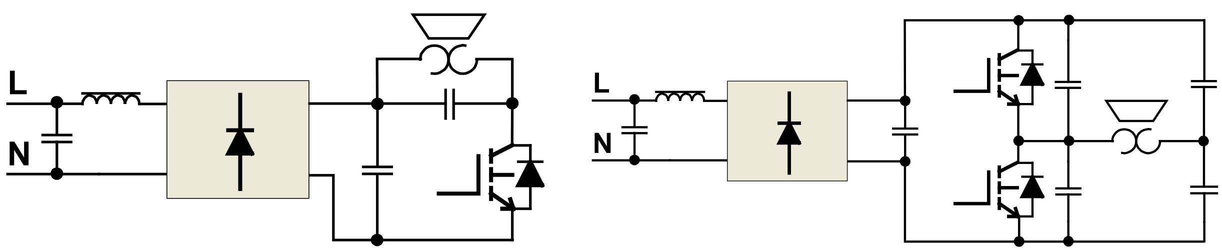


**Figure 1. Single-Switch Topology and Bridge Topology**

**Table 1. Comparison of Single-Switch Topology and Bridge Topology**

| | Advantages | Disadvantages | Solution/Comments |
|---|---|---|---|
| Single switch | Low cost and simple | Lower efficiency, usually used in home appliance and the power is less than 2 kW. | 8-bit SOC for single oven. The volume is high, to several millions. |
| Half or full bridge | Higher efficiency, for commercial heating and the power is 3 to 30 kW. | Higher cost than single switch and complex to control. | C2000 is a very good choice and can handle 2 to 4 ovens for commercial use. |

As to half- or full-bridge resonant induction cooker, the heating power can be changed by PWM switching frequency. When the switching frequency is closer to the LC resonant frequency, the heating power would be higher, and vice versa.

In this note, we will describe how to design half-bridge induction cooker and how one C2000 MCU can handle dual variable frequency (VF) resonant induction cookers.

# 2 C2000 MCU Solution

The induction cooker design consists of some simple blocks, as shown in Figure 2.

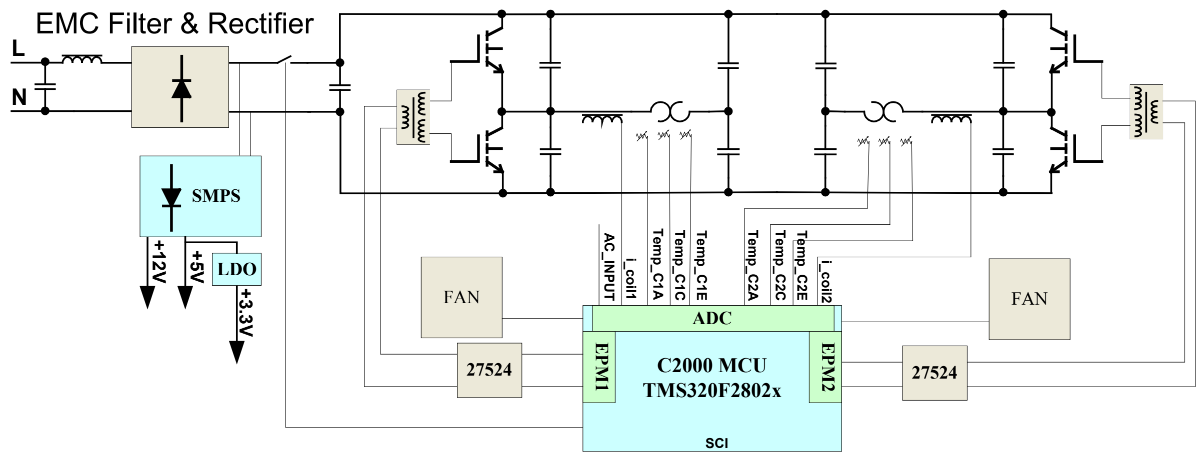


**Figure 2. Block Diagram of C2000 Dual VF Resonant Induction Cookers**

The main power supply is obtained directly from the grid or AC source, 220VAC 50 Hz.

The auxiliary power supply provides energy to fan, IGBT driver, detection circuits, and MCU.

The C2000 MCU controls the whole process and communications and drives the fan and the relay, and generates the PWM signal to drive the IGBTs.

In this solution, one C2000 MCU controls two resonant half-bridge converters.

# 3 Hardware Design

## 3.1 Power Stage

The AC power is filtered and is not applied directly to the power diode bridge. For safety reasons, AC power goes through a relay. This means that the DC voltage is not applied to the IGBT while the system is off.

The C2000 MCU drives the 12 VDC relay through a classic NPN transistor.

When the system is on—and the AC line is applied to the power diode bridge—the IGBTs are supplied with +311V. The resistive divider sends an image of the DC voltage to the MCU.

The +311VDC voltage is applied through a filter to the upper-side IGBT only when the safety relay is closed and the system is on. The resonant capacitor is divided in two identical capacitors, so that the amount of current flowing through each capacitor is reduced by half, while the voltage to the capacitors remains the same.

A current transformer is placed in series with the plate to provide plate feedback information to the MCU.

The IGBTs are driven by about 50% duty cycle PWM signals.

The PWM signal applied to the driver input pin is generated directly by the MCU. The frequency varies in a range from 30 to 70 kHz.

## 3.2 Auxiliary Power Supply

The auxiliary power supply is connected immediately after filtering of the AC source, without passing through the safety relay.

Twelve volts are used to supply the IGBT driver, fan, and relay, while 5/3.3 volts are needed to supply the rest of the ICs, including the C2000 MCU.

## 3.3 Detection Circuits

The most important feedback is the current signal, which sends the MCU an image of the current flowing through the plate. This signal is used to monitor the current amplitude and phase, and adjust the switching frequency in accordance with the working level.

In addition, the signal coming from the current transformer is sent to an operational amplifier. If for any reason the current increases beyond the alarm threshold set by the potentiometer, the MCU immediately takes action to prevent damage to the power stage.

A NTC resistor is populated on one of the IGBTs. The signal is sent to the MCU to monitor the IGBT temperature and drive the fan accordingly. In the same way, another NTC is placed in the middle of the plate to monitor the plate temperature. The signal is sent to the MCU for processing directly.

### 3.4 MCU Functions

The C2000 MCU controls the entire induction cooking system.

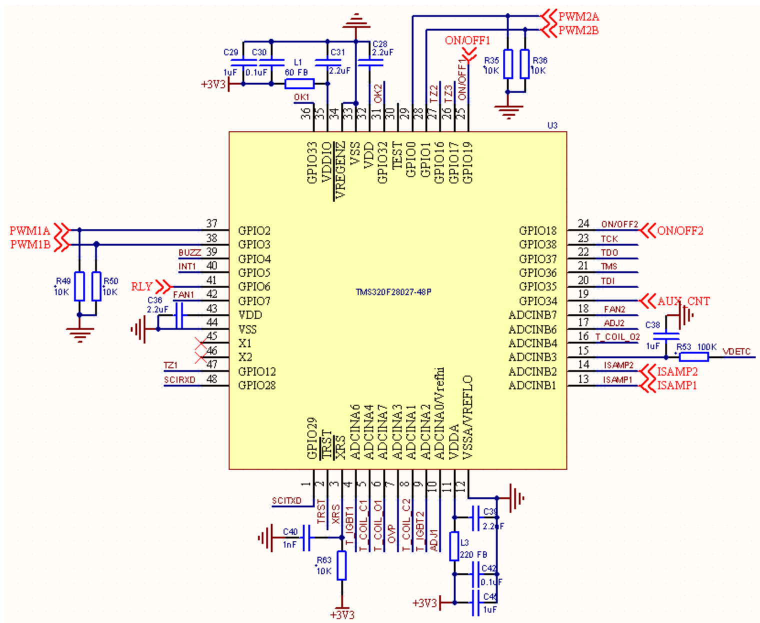


**Figure 3. MCU Signals Connection**

T_IGBT/COIL provides the MCU with the temperature information coming from the IGBT and plate, respectively.

The ISAMP feedback is processed as analog input. It is an image of the current flowing through the plate.

PWM units generate about 50% duty cycle PWM signals with a reasonable dead time. They are sent directly to the IGBT drivers.

RLY drives the safety relay in the mains circuitry.

FAN drives the fans, which are used to cool the heatsink next to the IGBTs and the power diode bridge.

This solution is very simple and there are no complex analog circuits. All detections and controls are fulfilled by one C2000 MCU.

### 3.5 PCB Layout Design

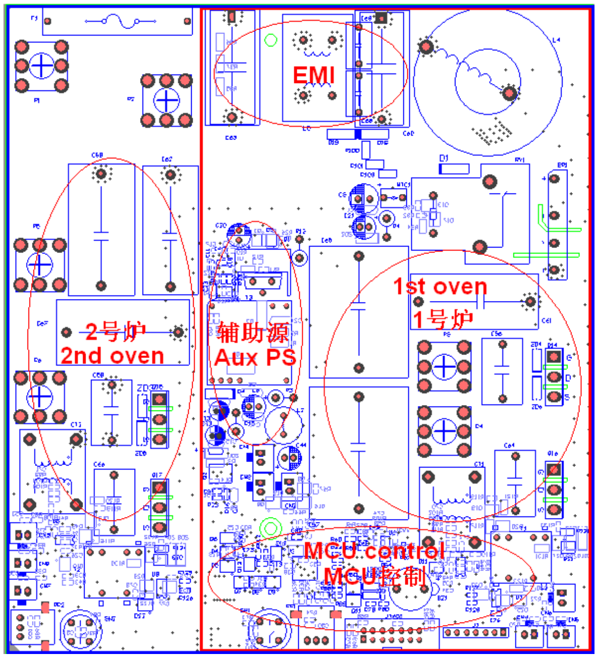


**Figure 4. PCB Layout Design**

- Board space：150mm x 175mm for dual ovens (100mm x 175mm for single oven)
- Height design (right side H < 25mm) for single oven in Midea model
- EMI circuit
- Safety circuit

## 4 Firmware Design

### 4.1 Firmware Tasks

#### *4.1.1 Functions*

The firmware of the system includes the following functions:

- Turn On/Off—The user can turn on or off the heating by pressing the turn-on/-off button.
- Pot detection—When the turn-on command is enabled, the system detects the pot automatically.

- Heating power regulation—There are nine power stages for the heating. Each power stage represents a reference heating power. After pressed the turn-on button, this system detects the power stage reference first, and then regulates the input power to the reference heating power.
- Buzzer control—The buzzer can alarm in different running status. After pressed the turn-on button, the buzzer beeps once, or it beeps three times if the pot is not appropriate. When there is a fault, the buzzer beeps continuously.
- FAN control—The FAN is enabled when the system is turned on. When the system is turned off from turning on mode, the FAN is cut off after 10 seconds.
- LED control—Each cooker has a status LED. When the system is turned off, the corresponding LED flashes every 1.2 seconds. When the system is turned on, the LED is lightened. When there is a fault, the LED is turned off.

### 4.1.2 Measurements

To control and monitor the system status, the following measurements are calculated.

- Grid voltage RMS
- Output active power of each pot
- Temperature

### 4.1.3 Protections

The system has some basic protection functions:

- ZVS protection—To ensure the IGBT can work in ZVS zone, the Vce of the IGBT must lead to the current. When the PWM phase of each half bridge cannot satisfy the ZVS condition, the system turns off immediately.
- Overcurrent protection—When the resonant current is over the setting value, the PWMs are turned off immediately.
- Over temperature protection—There are two channels of temperature for each pot. When the over temperature status is detected, the system limits the output power and lets the temperature degrade to the normal range. If the temperature continues to increase, the PWMs turn off.

## 4.2 Firmware Structure

### 4.2.1 Background and Task

The entire firmware system is a forward-background system. Figure 5 shows the background structure.

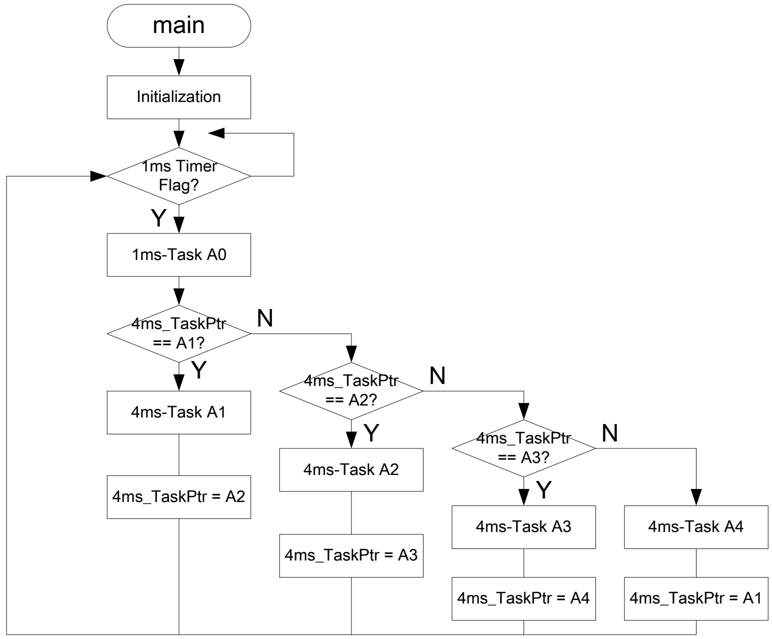


**Figure 5. Background Structure**

There are one 1ms task and four 4ms tasks in this system.

- 1ms-Task A0. The 1ms periodical task. In this task, the LED control is executed. Besides, the pot detection result check is also located in this task.
- 4ms-Task A1. The A1 4ms periodical task. The status machine processor.
- 4ms-Task A2. The A2 4ms periodical task. The PWM frequency is regulated in every 20ms.
- 4ms-Task A3. The A3 4ms periodical task. The user key detection and buzzer control. All the measurement calculation is executed here. Besides, the power regulation limitation and ZVS checking are also performed here.
- 4ms-Task A4. The A4 4ms periodical task. Check the reference power stage and detect the temperature.

### *4.2.2 Interrupt Sevice Routine*

The interrupt service routine (ISR) in this system is mainly used to implement the 1-MHz resonant current sensing, by which the ZVS condition of the IGBT can be detected. The resonant current sampling data can also be used to detect the pot. The interrupt is generated by the EPWM1 or the EPWM2, and the interrupt event occurs in every 2-PWM cycle.

Secondly, the ISR senses the other signals such as grid voltage, the temperature.

Thirdly, the ISR calculates the measurement accumulation, such as the sum of the squares.

Finally, the ISR can be used to get the debug data.

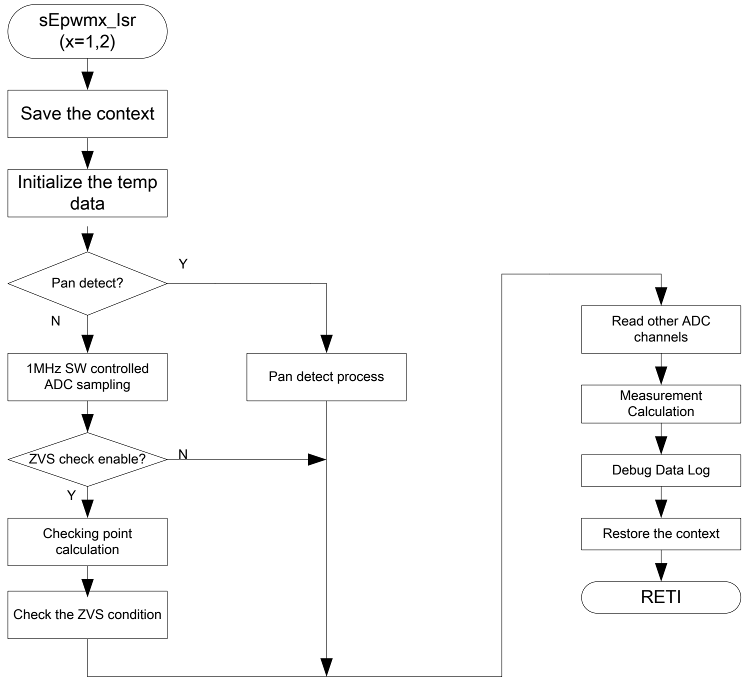


**Figure 6. The ISR Flow Chart**

## 4.3 The Key Algorithm

### *4.3.1 1-MHz ADC Sampling*

1-MHz ADC sampling is used to sense the resonant current, which can be used to check if the current lags to the IGBT Vce. When the IGBT is turned off, the Vce equals the DC link voltage. To realize the zero voltage switching, the Vce must degrade to zero before the gate turn-on signal enabled.

If the resonant current can be oversampled in a PWM cycle, it can use the software to check if the current lags to the voltage. In this system, the current is sampled in 1 MHz, so the sample points are enough to check the current phase.

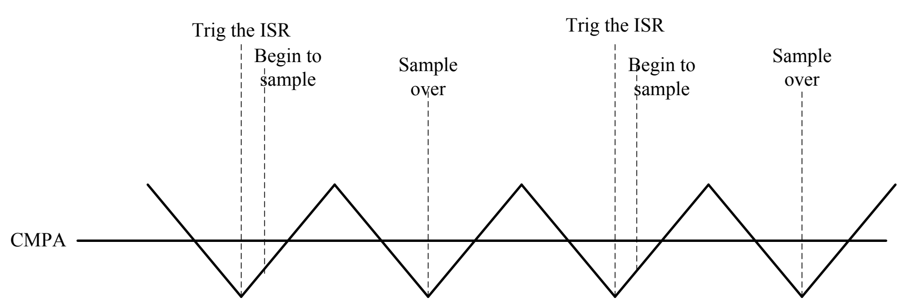


**Figure 7. 1-MHz Sample Begin and End**

When the ePWM1 or ePWM2 interrupt occurs, the ISR starts the 1-MHz ADC sample, and the software controls the sample period to about 1 µs. The total number of the sample point is calculated according to the PWM frequency. For example, when the PWM frequency is 30 kHz, the cycle time of is about 33 µs, then the number of the sample point number is 33.

To check the PWM ZVS condition, the counter value and the counter direction of the ePWMx module are recorded. The Up-check start point and the Down-check start point can also be calculated; these points are the turning on point and turning off point, respectively, of the PWM when the dead-time is ignored.

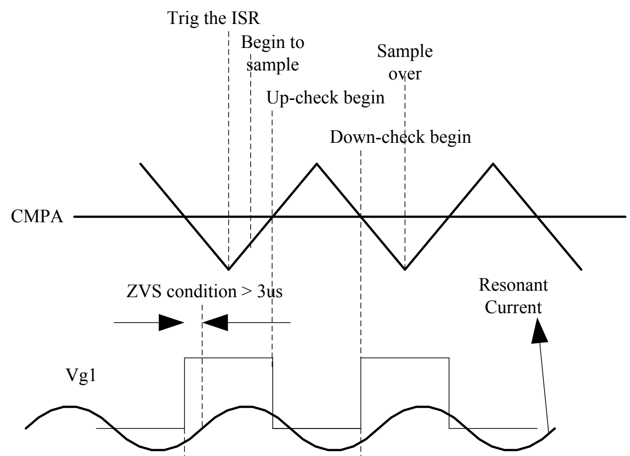


**Figure 8. The ZVS Checking Point**

The PWM ZVS condition is checked in every two switching cycles. When the two cookers are turned on together, the two checks are done in the EPWM ISR, which has a lower PWM frequency.

### *4.3.2 ZVS Checking*

When the 1-MHz ADC sampling completes, it is important to determine from which point the check operation starts. As previously mentioned, the 1-MHz ADC sampling not only records the current sensing value, but also records the counter value and the count direction at the same time. So from the counter value and direction, the start point can be determined. However, the CPU must check the counter value and the direction one by one, which will cost a lot of the CPU time. To save the CPU time, the calculation of the start point is needed.

Assume the CMPR is the compare value of the EPWM value, PRD is the period count of the PWM cycle. Cnt_Start_Sample is the counter value of the first ADC sampling. 1us_Cnt is the counter value per sample.

The up-check start point is:

UpCheckPoint = (CMPR – Cnt_Start_Sample)/1us_Cnt;

The down-check start point is:

DownCheckPoint = (CMPR – Cnt_Start_Sample + PRD/2)/1us_Cnt;

### 4.3.3 Pot Detection

Before the oven turns on, it must detect if the pot is on the plate. The difference between the pot existed and nonexisted is the inductance of the resonant bank. When the pot is existed, the inductance is reduced. The response characteristic of the RLC circuit can be used.

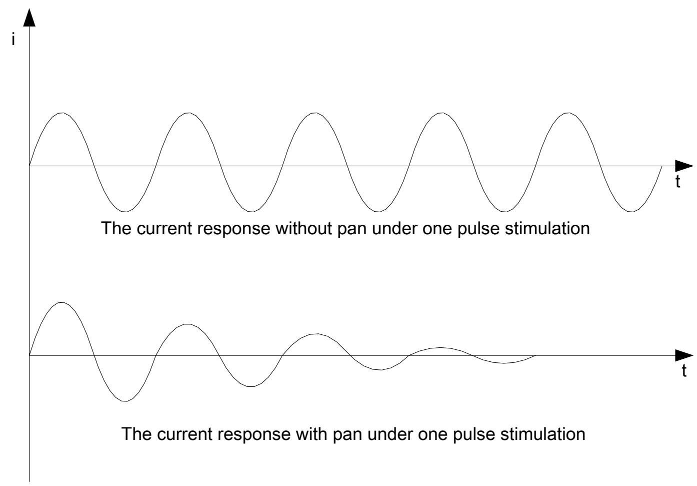


**Figure 9. The Current Response Under One Pulse Stimulation**

At the beginning of the detection, one pulse PWM is generated by the MCU, and 50% complementary duty is given to the half bridge. Then the 1-MHz ADC records the response current in the following two PWM cycles. When the sampling completes, the software checks the number of the current zero-crossing. When the pot is existed, the number is less than that of the nonexisted.

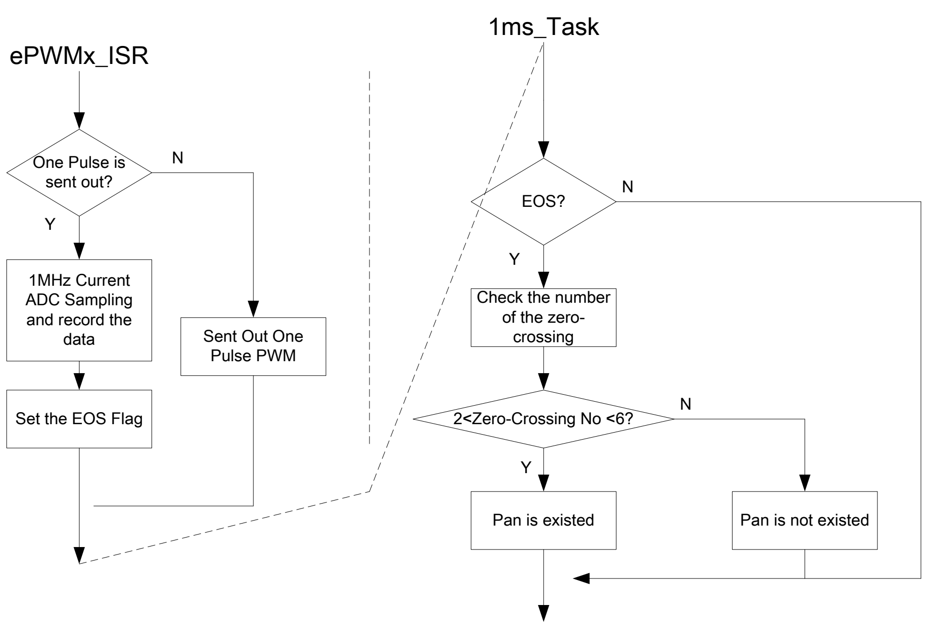


**Figure 10. The Flow Chart of the Pot Detection**

# 5 How the System Works

## 5.1 Sleep Mode

When there is no any action after plugged into AC source, this induction cooking system would go into sleep mode to save power. Pressing the ON/OFF button wakes up the induction cooking system.

## 5.2 Standby Mode

As soon as the induction cooking system is plugged into the mains, the system is running and the MCU goes into standby mode.

In this status, moving a pot to or from the plate has no impact on the function of the system. The safety relay contacts are open, so no DC voltage is applied to the resonant tank.

## 5.3 System On

The system is turned on by pressing the ON/OFF button again.

Each time the induction cooking system is switched on, it performs a sequence: safety relay first, then plate power-on. The safety relay contacts close, which applies the DC voltage to the resonant tank.

C2000 MCU starts the first procedure to detect the pot. The system returns to standby mode if there is no pot or the pot is not appropriate. This equipment starts to heat according to the power level if the pot is right. The lowest level is **1**. The maximum is **9**.

## 5.4 Safety Relay and Fan Management

The safety relay prevents the DC voltage from being applied to the resonant tank when the system is off. The relay contacts are connected in series with the plate, and they close when the system is turned on. To prevent oscillation or undesired relay commutations, an anti-bounce software routine is implemented. The relay turns off when the system turns off.

The fan helps the heatsink dissipate the heat while the system is working. It is turned on as soon as the heatsink temperature reaches 55 °C. The fan stays on for at least one minute, whether the system is on or in standby mode.

# 6 Measurements

The following oscilloscope waveform readings have been taken during the different operating phases. These signals are synchronized with the 50Hz voltage mains.

## 6.1 Sleep Mode

In sleep mode, the auxiliary power supply is also turned off. The power dissipation is very low to 0.4W, which is lower than most products on the market.

## 6.2 Working Without Pot

After pressed the ON/OFF button, the C2000 MCU starts its checking procedure. The buzzer buzzes three times to alarm the user if there is no pot or the pot is not appropriate.

## 6.3 Working With Pot

After pressed the ON/OFF button, the C2000 MCU starts its checking procedure. The system works if the pot is appropriate.

### 6.3.1 Working Level 1

When the pot is detected, the system moves to level 1, the lowest power working level.

The PWM signal applied changes accordingly. The lower the working level, the higher the PWM frequency applied to the half-bridge driver, and vice versa.

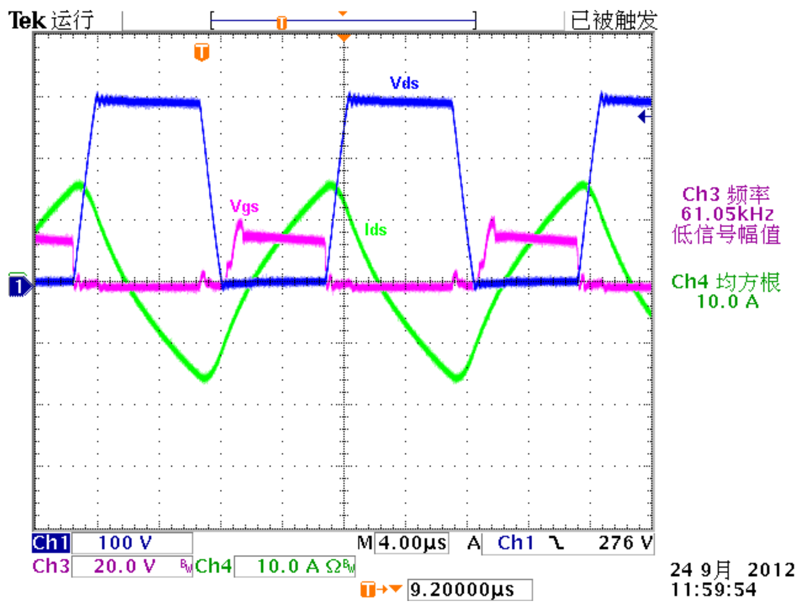


**Figure 11. Waveform of Level 1**

In this condition, the switching frequency is about 60 kHz. The Vds voltage goes down to 0V before the Vgs PWM beginning.

### 6.3.2 Working Level 9

At level 9, the system delivers the maximum output power.

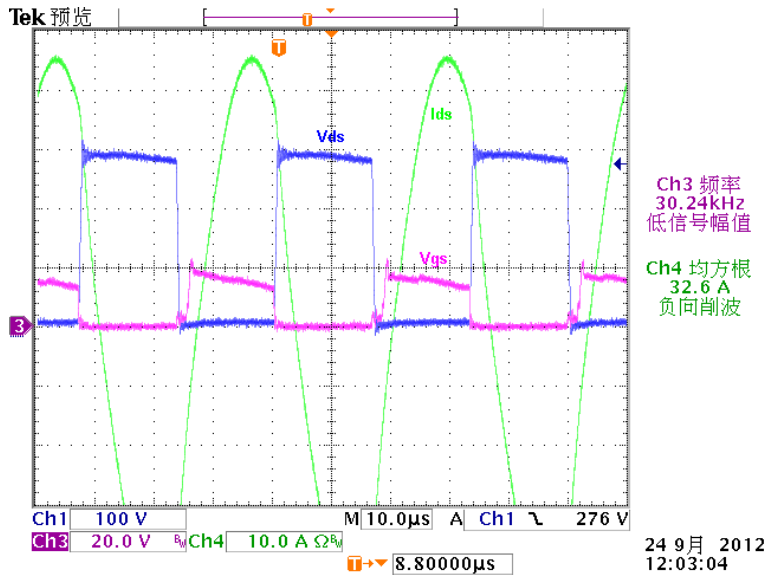


**Figure 12. Waveform of Level 9**

In this condition, the switching frequency is about 30 kHz. The Vds voltage goes down to 0V before the Vgs PWM beginning.

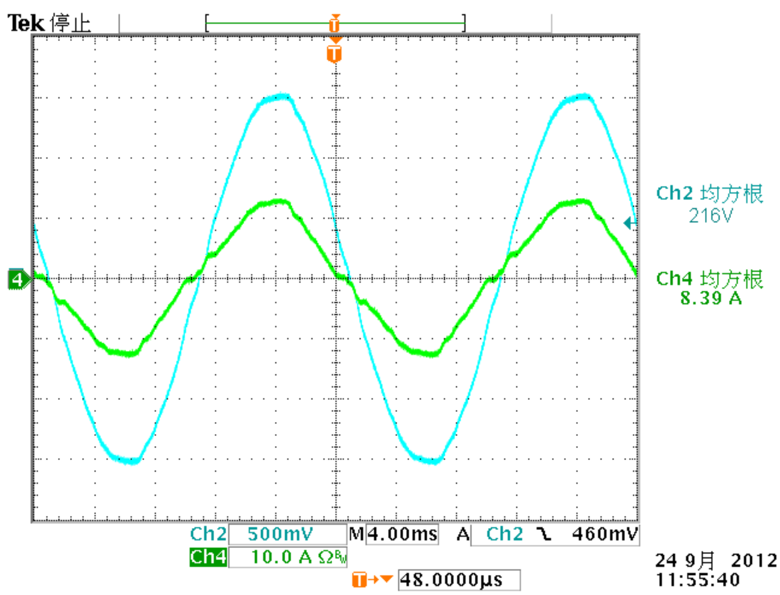


**Figure 13. Input Waveform of Level 9**

The power factor is 98.7%.

## 6.4 Current Control

As seen, the induction cooking system works on the principle of a series L-C resonant circuit. When the size of L and C are set, the resonant frequency is also set.

Unfortunately, this value does not depend only on the resonant tank. The size and material of the pot affect the resonant frequency too. This causes the system to have an oscillating resonant frequency strongly dependent on the type of pot placed on the plate at different times.

Therefore the nine working levels cannot be based on constant frequency levels. The PWM frequency must be adjusted to the selected level to work with the pot placed on the plate at that moment.

So each working level does not work on a constant PWM frequency, but rather a constant current.

By reading the current feedback signal, the MCU smoothly adjusts the PWM frequency to keep the current constant for the selected working level. Each level has a corresponding constant value of current.

# 7 Fault Management

The alarm circuit is necessary for monitoring any possible malfunctions, and to prevent the IGBTs, the driver, or any other circuitry from burning or being damaged.

The application described here features four different alarms on the pot:

- Over voltage (OVP)
- Over temperature (OTP)
- Over current (OCP)
- Wrong pot (WP)

An alarm occurs when the heatsink temperature exceeds 75°C or the plate reaches 200 °C.

If the coil current is over the OVP point, the OVP alarm occurs.

Similarly, during the power-on sequence, if a nonmagnetically conducting material is placed on the plate, an alarm occurs. In an alarm condition, the PWM frequency is immediately set to 30 kHz, and then smoothly increased to 60 kHz. The system is put in standby mode and the display shows which alarm occurred (refer to the letters in brackets).

# 8 User Interface

The user interface is very simple and sufficient. No special IC or PCB board is used.

There is only one ON/OFF button to power on/off this system and only one potentiometer to adjust the power level from 1 to 9.

# 9 References

1. *TMS320F28027/28026/28023/28022/28021/28020/280200 Piccolo Microcontrollers (Rev. I) data sheet, SPRS523I*

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